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TOOL AND PROCESS MONITORING - STATE OF ART AND FUTURE PROSPECTS

Quest for process automation driven by growing costs of human labour and quality demands makes monitoring in manufacturing systems inevitable. Although numerous tool and process condition monitoring systems are now available in the market and many have been installed in industry, users generally still consider them unreliable, often not worth money they cost. The bulk of the paper is centred on reasons of that defeat and measures undertaken nowadays to improve TCM/PCM systems reliability. First, the major tasks and general structure of the tool and process condition monitoring systems are presented. Then all basic elements of the monitoring systems: sensors, signal processing, feature extraction, and strategies were reviewed in terms of hitherto drawbacks and ongoing research works. The paper does not pretend to give a complete review of existing systems. Only examples illustrating discussed problems are quoted here.

1. INTRODUCTION

Rising labour cost makes production automation an important priority in the major industrial countries. One of the most important factors limiting the progress in introduction of unattended machine tool operation is tool condition monitoring (TCM) and process condition monitoring (PCM). The main focus areas of TCM/PCM are:

- tool condition monitoring:
  - tool wear monitor (detecting end of tool life)
  - catastrophic tool failure (CTF) detection
- chip-breaking detection
- chatter detection
- others (eg detection of BUE formation, burr formation, collision),

Numerous different phenomena can be employed for monitoring and a variety of sensor types are available on the market. In Fig. 1 numbers of recent research publications on sensing and sensor systems [5] are shown. The numbers express research activity level in the field of tool and process monitoring in machining. It shows that the bulk of the activity is in tool wear monitoring, and tool fracture detection. Quantities most often

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employed in TCM/PCM monitoring is acoustic emission and cutting force components or measured variables derived from these components (extension of machine elements, bending/displacement of the tools, torque, drive power motor current, etc.). Vibration and noise are also the focus of research work and industrial applications. Other phenomena are used occasionally, mainly in laboratories.

![Graph showing sensor research and development categories](image)

**Fig. 1. Categorisation of sensor research and development [5]**

Tool and process monitoring has been subject of intensive research work for several years and numerous commercial monitoring systems are available on the market. Nevertheless it is widely recognised nowadays, that the systems do not meet shop floor requirements having too many drawbacks. In the users’ opinion [6, 12], system manufacturers give very optimistic promises (recommendations) which are not fulfilled in practice, so the systems are often switched off after one year. Since the price of additional sensor systems is high, and its reliability is still inadequate, machine manufacturers and users are reluctant to pay the cost. Main deficits in the field of tool and process monitoring can be summarised as follows:

- There is no single sensor or sensor system capable of covering all or even the majority of the possible applications.
- Some of the sensors used in research work are not designed for the tough machine tool environment. This is particularly true for cutting force dynamometers and AE sensors, which have often been developed for non-destructive materials testing.
- Detecting end of tool life is especially difficult, and is generally possible only after teach-in.
- Most of the research results have been obtained off-line. Monitoring systems working in real time are still uncommon. There has still been no real-time realisation of some process and tool monitoring methods.
- There is no effective combination of monitoring units with CNC controls, lack of interface specification, standardisation.
Before discussing the efforts undertaken to overcome these deficiencies, let us look closer at the structure of the tool and process monitoring system (Fig. 2). The cutting process can be characterised by a variety of physical quantities. Appropriate sensors transform the selected ones into corresponding electrical quantities (signals), which can be electronically processed and transmitted. The signal processing can be more or less complex, consisting of e.g. filtering (LPF, HPF, BPF), A/C conversion, FFT, RMS, waveform conditioning, standard deviation, mean value, skew, kurtosis, crossing rate, regression analysis and many others. As a result, signal representation (feature vector), sensitive to the parameters of interest in the process, is extracted from the signal. Based on this representation and a suitable strategy, a decision of monitored process state is generated. The strategy itself is developed basing on knowledge and experience contained in the model of the process.

Deficiencies of existing monitoring systems and recent trends of their development aiming at meeting users' demands, are connected with all cells of this structure. That is how they will be presented here.

2. SENSORS

2.1. FORCE RELATED QUANTITIES

Cutting force components or variables derived from these components are quantities most commonly employed in industrial TCM/PCM systems. Therefore a lot of sensors are available on the market. System producers and users have to face fundamental choice being compromise between two contradictory demands. On the one hand high accuracy both static and dynamic is required. It means that sensor should be as close to the machining point as possible. On the other hand, sensor should be easy to retrofit without major changes in the machine tool construction and with no reduction in the static and dynamic stiffness of the machine tool. In early stages of TCM/PCM development producers of machine tools were eager to ensure their customers that machines they offered were equipped with monitoring systems. Therefore power or motor current measurement was quite popular those days.
The ring sensor measuring changes in the electrical current supplied to feed or spindle drive motors or servos (Fig. 3) is still available on the market. A single conductor from the power cable supplying the feed motor is fed through the current sensing ring. The current carried by the conductor passing through the sensor ring is transformed into a voltage signal proportional to the feed force [26]. It can be easily installed into almost all types of machine tools without any special engineering design and provide a comparatively low-cost yet effective (according to the producer) tool monitoring system in new or existing machines.

It should be stressed however, that because of the long distance between the machining point and the sensor, a signal obtained from any motor current sensor is time lagged and has low sensitivity. Moreover, if the current supplied to a spindle drive motor is monitored in the case of turning and milling, the system sensitivity is even lower due to weak main cutting force dependence on tool wear (see below, point 4.2). Systems based on such sensors can hardly be recognised as successful [20].

Other example of the sensor that is easy to retrofit, requiring no special design work for adaptation and not reducing stiffness of the machine tool is the piezoelectric strain transducer shown in Fig. 4 [29].

This sensor detects the cutting force via the extension of force-carrying machine elements. Despite easy retrofitting, the suitable fitting position for the sensor can only be determined by time-consuming experimentation. The sensor was used in some commercially available systems [16, 30].
Both sensors described above possess a low level of sensitivity and are suitable only for major catastrophic tool failure identification during rough machining.

Feed force sensor, suited for integration with a bearing pocket supporting a rotating shaft or spindle (Fig. 5, [24]), can be an example of a compromising design. The sensor consists of two concentric rings (Fig. 5a). The profile of the inner ring has a special form, providing two force sensing zones, on which strain gauges are mounted. Despite much better correlation between the actual feed force and the signal in this case, still significant inaccuracies should be taken into account [11]. Fig. 6a presents a typical feed force signal ($F_T$) during air travel with programmed feed rate at the beginning of operation. Characteristic sinusoidal shape of the signal generates the feed screw bearing itself, without any relation to the real cutting force, which is equal to zero. Such sinusoidal changes in the signal can be also observed during longitudinal cutting with constant cutting parameters when real cutting force is approximately constant (Fig. 6b). Moreover the average value of the signal slowly increases due to cumulation of the stresses in the kinematic chain, especially on the slideways.

The best cutting force measurements can be achieved with force transducers placed close to the cutting edge, directly in the path of the transmitted force [2, 31, 35].
Commercial dynamometers are extremely stiff and have a large measuring range. They consist of four three component force transducers fitted under high preload between a baseplate and top plate. Because they are based on the piezoelectric effect, it is difficult to measure static forces over a long period without drift, but today a realistic time of 15 minutes with acceptable static signal level is possible. Static measurements are therefore always quasi-static. Because of this and the temperature drift problem, piezoelectric transducers have to be reset prior to measurement, thus guaranteeing a correct measuring value. Since the whole force is transmitted through the transducers they are not overload-protected in case of collision, and can be easily destroyed. Dynamometers are widely used for fundamental studies of machining processes and force-based monitoring, but are unsuitable for industrial applications because of their lack of overload protection and their high cost.

For this purpose force-measuring plates can be used. They consist of thin intermediate plates in which piezoelectric or strain gauge elements are embedded. They can be installed between the turret housing and the cross slide, or between the turret and the turret housing. The plate presented in Fig. 7 [21] is 10 to 15 µm thinner than the transducers, and, by pre-loading the arrangement, the transducers are compressed until the measuring plate takes up the load [21]. Only less than 15% of the full load passes through the transducers, while the main force is passed through the plate body surrounding the transducers. Although this diminishes the accuracy of the measurement, it also considerably increases protection against transducer failure. These plates (or rings) are comparatively easy to retrofit, and are offered on the market by several producers [21, 23, 27, 31].

Fig. 7. Force measuring plate [21].

Fig. 8. Sensor for torque and force measurement within the tool holder [28].
Recent trends of cutting force sensors development may be listed as follows:

- "intelligent sensors"
- wireless signal transmission
- new concepts of force measurement
- multicomponent and integrated sensors

Fig. 8 presents an example of an intelligent tool: toolholder for drilling and tapping operations equipped with strain gauge dynamometer [28]. Depending on the application toolholder can monitor thrust, radial force and torque. The sensor comprises integrated preamplifier, A/C converter and microprocessor, protectively housed in the tool adapter. System comprises also wireless signal transmission head and interface unit. Main disadvantage of the system is that each tool requires to be fitted with the sensor system, making this alternative very expensive [2].

Fig. 9. Eddy current torque sensor for tool monitoring at drilling operations [36].

Another approach based on changes in the permeability of the ferromagnetic material under mechanical stress is still under development. Fig. 9 presents eddy current torque sensor for tool monitoring at drilling operations [36]. It enables torque measurement without rebuilding the machine tool structure causing reduction in stiffness.

The magnetostrictive torque sensor shown in Fig. 10a [1] has the same advantage. The long and slender films (upper and lower) which are composed of strong magnetic material are deposited on a shank with an angle of 45 or -45 degrees to the centre axis of the shank. Changes of strain in the magnetic films caused by torque have the effect for changing magnetic permeability of the films. The films are magnetised by the surrounding circular coils 1 and 2. The change in magnetic permeability is equivalent to the change in inductance of the coil. This means that the cutting forces can be estimated by measuring the change in
coil inductance. Such sensor can be installed on a rotary tool shank surface (e.g., end milling cutter [1]) or machine tool spindle (Fig. 10b, [4]).

The combination of different, inexpensive sensors is ever increasing to overcome insufficiency of single sensor approach [2]. It could be achieved either by using one sensor that allows measurement of different variables or different sensors attached to the machine tool to gain different quantities.

Fig. 11 presents an example of the so-called dual-mode sensor [3]. It permits the simultaneous measurement of acoustic emission and one to three orthogonal force components. Integrated in the middle of a force measuring ring is an AE sensor. The advantage of this dual-mode sensor is the backing-up of the force measurement by another process variable, the acoustic emission, necessitating only one installation point.
2.2. ACOUSTIC EMISSION AND VIBRATIONS

Although many different sensors are available for AE measurement, only few can be used in a machine tool environment where aggressive ambient conditions occur [2]. Most of the transducers were designed for non-destructive inspection or research work, meaning they can not withstand the high temperatures, large coolant volumes and abrasive wear chips. Moreover they can be too sensitive for strong AE signal generated by the cutting process. Let us for example consider AE transducers of Brüel & Kjør:

- 8312 - broad-band AE transducer with built-in preamplifier
- 8313 - resonance transducer, resonance frequency at ~200 kHz
- 8314 - resonance transducer, resonance frequency at ~800 kHz

The resonance transducers are used with preamplifier type 2637 equipped with interchangeable plug-in circuit boards:

- a 200 kHz octave bandwidth filter (OBF) for use with 8313 transducer
- a 800 kHz octave bandwidth filter for use with 8314 transducer

![Fig. 12. Signals from Brüel & Kjær AE sensors obtained for worn out tool (KT ≈ 0.25 mm) in WUT [7].](image)

Fig. 12 presents examples of AE signals obtained for worn out tool (KT=0.25 mm) in WUT [7]. Brüel & Kjær transducers were positioned on the lathe toolholder. Signal obtained from broad-band 8312 transducer (Fig. 12a) contains high frequency components interesting for the TCM, but also low frequency components (here ~16 kHz). Characteristic cut out of the signal evidences an overload of the preamplifier. Employment of the 8313 resonance transducer with the 2637 preamplifier equipped with the OBF 200 kHz
eliminated the low frequency components leaving useful band only. Nevertheless AE signal was still too strong causing preamplifier overload. Therefore the preamplifier has been modified by lowering its first amplification step by 10 (20 dB). Obtained result is shown in Fig. 12c. Another way of resolving the problem is to apply the 8314 transducer with the original 2637 preamplifier with 200 kHz OBF, designed for use with the 8313 transducer, thus “unsuitable” - Fig. 12d.

In recent years, AE sensors specially designed for monitoring purposes, avoiding most of the disadvantages mentioned above, were brought on the market, ([2, 3, 12, 13], Fig. 13). Most of the transducers have to be attached to the machine surface but a new concept is using a coolant stream to transmit AE signal from the workpiece to the sensor. Also for AE transducers the inductive wireless signals transmission from the sensor to a receiver was implemented. Another new approach is thin film AE sensor fitted directly under a throw-away insert (Fig. 14). The main advantage is that the sensor is very close to the cutting area, however it is also extremely vulnerable.

Vibration sensors have been used in industrial applications much longer than AE sensors, especially for machine diagnostics. Nevertheless these sensors also become more robust, better fulfilling requirements of tough machine tool environment. Fig. 15 presents sensor for vibration - based monitoring which was originally designed to be used as a knock detector on gasoline engines [13].
3. SIGNAL PROCESSING AND FEATURE EXTRACTION

Analogue (electrical) signal from the sensor is usually (after basic signal conditioning, e.g., primary filtering) converted to a digital form. Thus obtained time series is then processed to extract signal features that are sensitive to the parameters of interest in the monitored process. A variety of processing methods can be used like further filtering, calculation of average value, RMS, spectrum or amplitude in selected band and many others. Here only examples will be presented.

The simplest feature that can be extracted from the signal is its magnitude (amplitude). Fig. 16 presents tool condition monitoring at drilling operations [36], based on tracking of torque sensor (Fig. 9) signal amplitude. Extensive tool wear causes eminent increase in the torque and consequently in signal magnitude.

Influence of the tool wear on the cutting forces is well known and has been described many times. In the case of turning and milling, this influence is substantially smaller in the main cutting force or the torque than on the passive force and feed force. Moreover cutting force increase due to the tool wear is strongly dependent on other cutting conditions. Fig. 17 presents, as an example, results of two experiments [7]. In both cases the same tool and uncut chip cross-section was applied. The cutting speed ensuring similar tool life was selected. In the first case work material was alloy steel 34HNM. Dominant form of the tool wear was then flank wear VB_C, accompanied by distinguished increase in feed force F_f and passive force F_p. Such eminent increase is easy to measure thus very convenient for monitoring. Nonetheless while machining carbon steel 45 (the second case, Fig. 17 right), when decisive role in the tool wear was played by crater wear KT, cutting force increase due to the tool wear was much smaller. In both cases main cutting force F_c did not change significantly.
Fig. 17. Influence of tool wear on cutting forces [7].

Fig. 18. Direct and relative feed force changes due to tool wear for three different uncut chip cross section areas [7]. It shows, that usage of direct cutting force value is inconvenient since separate thresholds force value have to be predetermined for each cutting parameters. Much more advantageous is to use a relative force increment also shown in Fig. 18:

\[
\frac{\Delta F_f}{F_{f_0}} = \frac{F_f - F_{f_0}}{F_{f_0}}
\]

where \( F_{f_0} \) - feed force value obtained with fresh tool (at the beginning of the test)

Similar problems emerge while the vibration amplitude in selected band is employed for tool wear monitoring [32\textsuperscript{–}34]. Sample results are presented in Fig. 19. Likewise the cutting force increase, relative increase in the vibration amplitude appeared to be more convenient as it is better correlated with cutting speed.

Percentual integral value of the vibration signal was employed for tool life monitoring of small HSS drills (Fig. 20, [12]).

Another interesting example of looking for informative signal features is the chip form monitoring based on acoustic emission (Fig. 21, [12]). Analogue RMS value of the signal is here converted to digital output clearly indicating disturbances in chip breaking.
Fig. 19. Vibration amplitude changes due to tool wear for three different cutting speeds [32].

Fig. 20. Tool life monitoring of small HSS drills using vibration signals [14].
4. PROCESS MODELS AND MONITORING STRATEGIES

4.1. CATASTROPHIC TOOL FAILURE DETECTION

Every monitoring strategy must be based on a model of the monitored process. The model itself is developed on the base of observations of the real process. Modelling and detecting of the catastrophic tool failure (CTF) with cutting force signal will be used here as an example.

CTF is accompanied by characteristic pattern of cutting force (Fig. 22) [7, 8].
Its main features can be summarised as follows:

- Chipping of the cutting edge causes sudden increase (during about 1÷3 ms) in the feed force $F_f$ or/and the passive force $F_p$ due to deterioration of the cutting edge geometry.

- A substantial breakage of the insert is accompanied by an instant increase followed by a drop in the cutting forces. A magnitude of this decrement is dependent on a reduction of the uncut chip cross-section.

- In both cases all cutting forces remain on a new level for one workpiece revolution. Entering a defect left behind on the workpiece is accompanied by a steep rise of the feed and passive forces. The tool leaves next, smaller fault on the workpiece surface. This sequence repeats exactly with every revolution of the workpiece, however every time changes in the forces are smaller and last longer. Finally the average values of the cutting forces stabilise.

Basing on above-mentioned the real pattern of the cutting force changes caused by CTF, models of the process and strategies of CTF detection are developed. The simplest model assumes that CTF causes substantial increase in the cutting force [25]. The strategy based on this model can be described as follows (Fig. 23a). In learning mode (cutting with fresh tool), tool monitoring system detects maximum value of the cutting force signal during operation. From this value and level factor ($L_2F$) programmed by the operator, system calculates alarm level. When operating in monitoring mode, system interprets exceeding of the level II longer than time delay $L_2t$ as a tool breakage. Comparison of the cutting force changes caused by CTF (Fig. 22) with those presumed in this strategy (Fig. 23a) leads to an instant conclusion that it allows to detect only a major tool breakage, usually far too late - Fig. 23b.

Strategy developed in Aachen [14, 22] is much more sophisticated. It is based on the described above characteristic variation of the cutting force, associated with the tool breakage. Here, special role plays steep-flanked signal peak emerging at the instant of CTF. The monitoring system constantly (every 1 ms) calculates upper and lower limits from the mean value of the cutting force $F_m$ and an amplitude of dynamic component of the force $F_d$ (Fig 24a). The resulting tolerance band time-lags the original signal thus easily follows gradual changes in the cutting force, due for example to changing depths-of-cut. Upon tool breakage change in the cutting force is too fast (1÷2 ms) to be followed by the tolerance band thus the limit is violated. For CTF, the upper limit is crossed in both direction. If the
lower limit is then crossed within a very short time $t_1$, a breakage alarm is initiated (Fig. 24b). In cases where the upper limit is not crossed, a breakage signal occurs only if the lower limit is crossed for a time span $t_2$ (Fig. 24c).

Since this strategy is based on recognition of particular pattern of cutting force changes, exact value of the force is not very important, so cutting force measurements do not have to be accurate. Although this strategy is much better than that based on a rigid or learned threshold, it still has some disadvantages:

- Response time lag of the sensor have to be small enough to measure fast cutting force changes. It means that natural frequency of the machine structure, from the tool to the sensor, should not be lower then some 3 kHz. Only sensors close to the tool (like measuring plates Fig. 7) can be used for the strategy.
- Even a serious breakage of the tool does not have to be connected with an eminent reduction of chip cross-section area and consequently a distinguish cutting force decrease (Fig. 22, right). If the force is disturbed, the tolerance band calculated from the dynamic component of the force could be too wide to be violated by the force change.

Strategy developed in WUT [8] overcomes these drawbacks. Basic principles of the strategy are shown in Fig. 25a. Original value of the cutting force $F$ (upper part of the picture) is low-pass filtered to obtain mean value $F_{m}$ used for monitoring. Further filtering gives $F_{ml}$ value from which upper and lower limits are obtained:

$$L^+ = F_{ml} \left[1 + 2^{-c+2}\right]; \quad L^- = F_{ml} \left[1 - 2^{-c+2}\right]$$

where $c = 1\div3$ - detector sensitivity coefficient

The thresholds can be violated by $F_{m}$ not only due to catastrophic tool failure, but also
by other disturbances. Therefore if the mean value $F_m$ exceeds the limit plausibility check is performed: $F_m$ must remain out of the tolerance band at least for pre-set time duration $del$. In the meantime calculations of the limits are suspended - they remain on their last computed levels. To make return of the $F_m$ value between the limits easier, it is filtered by an auxiliary filter, much weaker than the main one, what is shown as a broken line in the middle of Fig. 25a. If the $F_m$ value does not return within the limits before the time delay $del$ is over, the detector recognises CTF and generates an alarm signal. The signal is emitted until $F_m$ is within the limits again.

![Fig. 25. Strategy of CTF detection developed in WUT (a), and results of two example tests (b) [7, 8].](image)

Monitoring mean value of the signal ($F_m$) instead of original one ($F$) makes it possible to use much narrower tolerance band than used in the strategy developed in TH Aachen, therefore to detect a smaller CTF (Fig. 25b). Moreover the later strategy is not so demanding as far as a sampling frequency or ability to measure very fast cutting force changes are concerned. It can even use signals obtained from feed force sensors (Fig. 5 [9]).

### 4.2. TOOL WEAR MONITORING

Tool wear influences a variety of phenomena. Number of monitoring systems utilise the fact that tool wear causes an increase in the cutting force and force related quantities (Fig. 16÷18), AE and vibration amplitude (Fig. 19 and 20) and others. Therefore the simplest strategy of the tool wear monitoring is the use of a rigid threshold. If the threshold is crossed by the signal, the tool wear can be detected [25]. So it is similar to the CTF detection strategy described above (Fig. 23), however respective limit ($L_{1F}$) is lower and time delay ($L_{t1}$) is longer.

Strategy developed in TH Aachen is somewhat more complex (Fig. 26, [16, 22]).
Monitoring system measures the cutting force with each workpiece. Sliding mean value $F_{sn}$ is calculated from every group of three measured values $F_n$ of the cutting force:

$$F_{sn} = \frac{(F_n + F_{n-1} + F_{n-2})}{3}$$

From this sliding mean value of the first three workpieces ($F_0$) and from the C-value (admissible force rise value) the system further determines the admissible limiting value $F_T$:

$$F_0 = \frac{(F_1 + F_2 + F_3)}{3}$$

$$F_T = F_0 (\frac{C}{100} + 1)$$

After every further workpiece the sliding mean value is formed from the last three individual values $F_n$ and compared with the limiting value. If $F_{sn}$ exceeds the limiting value $F_T$, this is reported at the end of the machining cycle as expire of the tool life. Characteristic for this strategy is that the tool is considered worn out also if the sliding mean value decreases more than $F_X$:

$$F_X = F_0 \cdot \frac{C}{100} \cdot X$$

where $X$ - experimentally established coefficient.

The AE signal magnitude decrease, at the end of the tool life, can sometimes also be observed (Fig. 27, [10]).
All above-mentioned phenomena depend not only on the tool wear, but also on a variety of other parameters such as type of wear, tool geometry, cutting conditions, cutting material and work material. Moreover tool wear - signal magnitude relationship is very complex and has rather statistical than strict, predictable nature (see eg Fig. 18). Sometimes signals from the sensor are not exactly equivalent to the measured feature, but disturbed by other phenomena (see eg Fig. 6). Values of parameters used in process models are somewhat uncertain, eg material properties can vary considerably from one batch to the next. Therefore it is now widely acknowledged, that reliable tool wear monitoring based on one feature is impossible.

5. FEATURE INTEGRATION

The combination of different features today is ever increasing to overcome drawbacks of single sensor approach. Feature integration lessens the diagnosis uncertainty due to randomness in sensor signal reduction. Weighting of features provides a more reliable information than a single sensor. Moreover feature synthesis can provide greater resolution in parameter estimates.

Fig. 28. Sensor fusion [3, 13]: combination of different sensors (left) and dual mode sensor approach (right).
Two different approaches are possible here:

- extraction of several features from one sensor
- employment of several different sensors

The former can be for example amplitude of vibration signal in different frequency bands [32, 33], different features of AE signal [10] and others. The latter can be achieved either by combination of different, inexpensive sensors attached to the machine tool to gain different variables, or by using one sensor that allows measurement of different physical quantities.

Fig. 28 shows examples of the sensor fusion approach application. In Fig. 28 (left) acoustic emission sensor and piezoelectric strain transducer were fitted to the turret base [2, 13]. The signal curves obtained during two turning tests are also presented there. In the first one (upper chart) the catastrophic tool failure emerged. At the instant of breakage, there is a sudden jump in the AE signal and a drop in the strain signal. During the second presented test (lower chart) there was a hole in the workpiece. While the strain signal is very disturbed by interrupted cutting, there is no significant change in the AE signal, so interrupts do not trigger false alarms.

At the right side of Fig. 28 the tool breakage detection by use of dual mode sensor (shown above in Fig. 11) is presented. First the tool was chipped and after one workpiece revolution it was broken. On the instances of both events all signals change significantly making cross-check possible, and thus CTF detection more reliable.

Information extracted from one or several sensors' signals have to be combined into one tool or process condition estimate. It can be achieved by various means like statistical methods, auto-regressive modelling, pattern recognition, expert system and others [2, 35]. Neural network approach has recently been the most intensively studied method for feature fusion (eg [15, 32, 34, 35]). The key issue in many monitoring systems is the reduction of large flows of data from numerous sensors to a few well defined, reliable features, that can be used for process monitoring [3]. The main goal of the research presented in [15] was to develop a strategy for monitoring tool wear while drilling with a multip spindle drilling machine. The whole spectrum of interactions while machining was taken into consideration and various methods of selection and evaluation of correlating features were studied. AE, vibration and motor current were determined as the basis for the system. At the next step, a selection of significant sensor features for the appropriate objective - either tool failure or wear was conducted. Statistical analysis and clustering, genetic algorithms and neural networks were used and compared in this case. Finally, the Feed Forward Back Propagation neural network was applied to evaluate the selection conducted and to model the relationship between the selected features and drill wear.

Another interesting application of neural network is estimation of cutting tool life by processing tool image data [37]. The camera and light are fixed at a position which reveals the states of flank and crater wear (Fig. 29). The grade of brightness caused by surface roughness is transmitted to the colour data control device, and is divided into 12 colours. The colour at each intersection of the mesh is exchanged for the numerical value dependant on brightness. Then three layer neural network is employed. First (input) layer, consisting of 256 elements, deals with tool image data and cutting conditions. Output layer of 6
processing elements gives data on the test of tool life and wear types.

6. CONCLUSIONS

Despite many shortcomings of hitherto available TCM/PCM systems, especially those of earlier stages of their development, monitoring necessity drives intensive research and development activities aiming at steady improvement of these systems. Significant attention is directed towards:

- improvement in sensor’s reliability, meaning splash protection, moisture-proofing, resistance to aggressive media and flying chips, also completely new sensors and sensor concepts, very simple sensors, intelligent sensors, multicomponent sensors, wireless signal transmission
- developing better in-process real time signal processing methods for extracting signal features that are rich in information regarding the monitored process parameters but relatively insensitive to other parameters
- development of more reliable monitoring strategies
- implementation of multisensor approach supported by new feature evaluation and decision making techniques.

It can be foreseen that TCM/PCM systems will become much more reliable in the not far away future.
REFERENCES


DIAGNOSTYKA NARZĘDZIA I PROCESU SKRAWANIA - STAN DZISIEJSZY I PERSPEKTYWY NA PRZYSZŁOŚĆ

Dążenie do automatyzacji spowodowane rosnącymi kosztami siły roboczej oraz wymagań jakościowych sprawia, że diagnostyka systemów wytwórczych staje się niezbędna. Mimo iż na rynku dostępnych jest wiele układów diagnostycznych narzędzi i procesu skrawania, a szereg z nich znalazło zastosowanie w praktyce przemysłowej, użytkownicy tych układów w dalszym ciągu uważają je generalnie za niewiaroogodne, nie warte ponoszonych nakładów. W tym opracowaniu skoncentrowano się na przyczynach tej porażki i środkach podejmowanych współcześnie w celu udoskonalenia układów DNIPS. Po pierwsze przedstawiono główne zadania i ogólną strukturę układów diagnostycznych. Następnie przeanalizowano wszystkie ogniwa tej struktury: czujnik, obróbka sygnału, wybieranie jego charakterystycznych cech (miar) oraz strategie, z punktu widzenia dotychczasowych niedostatków i biejących prac badawczych. Referat nie jest kompletnym przeglądem istniejących systemów. Przedstawiono w nim jedynie przykładowe rozwiązania ilustrujące omawiane zagadnienia.