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APPLICATION OF A COMPUTER TOOL MONITORING SYSTEM IN CNC MACHINING CENTRES

Abstract

The article presents practical knowledge about production process optimisation as a result of implementing a specialized system monitoring the work of machining tools. It features complex results of the conducted research with use of dedicated equipment and software, whose unconventional application may appear to be an effective IT tool for taking operational and strategic decisions in the machining area. This results from the possibility of analysing the obtained data in both current and long-term perspective, and taking decisions on this basis, which significantly conditions the rationality of using this type of solutions.

1. INTRODUCTION

The automotive industry has already achieved a lot, but still car manufacturers continue striving for increasing processes efficiency to retain the profitability level and achieve competitive advantage. Among numerous mechanical manufacturing techniques, machining is the most commonly used (60–70%) and consumes more than half of the energy necessary for production processes (Wittbrodt, 2014). It seems to have a bright future – it is estimated that precise,

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high-speed machining will develop in the years to come, especially in the automotive sector and in aviation. Financial aspects related to production cost cutting and continuously rising customer requirements result in creating even more complicated product shapes by designers and constructors (Więcek, 2013). This often causes a decreased element mass, and, consequently, problems during manufacturing (this relates also to tools). The subject of tools can also be considered here from the logistic point of view in form of tools management. Many authors in their works on machining economy assume tool cost on the level of 2–8% of general manufacturing costs (Wittbrodt, 2014). However, machining tools market analysis and practical research of manufacturing processes show that the actual cost of tools can reach far above 10 per cent. Despite inaccurate data, it is possible to state that the cost is rather high, so rational tool management is one of the solutions for production cost reduction.

Although many research centres are engaged in building machining process monitoring systems, and this issue has been extensively described in many publications (Jurko, 2007; Kuljanic & Sortino, 2005; Kuryjański, 2011; Storch, 2001), the production practice in many companies shows that that the issue of tool condition and the machining process monitoring and forecasting has not been solved and is still present. Factors like production processes complexity, automation and robotization of the manufacturing processes, common usage of flexible production systems, growing requirements related to elements' accuracy contribute to the need of implementing and using the technologies which allow for effective machining process monitoring (Nouri, Fussell, Ziniti & Linder, 2015).

However, modern machining tools require complex and very detailed control for three reasons. The first one are progressive changes in tools' construction, like direct coolant (oil mist) supply to the machined area, based on the MQL system (Minimal Quality Lubrication), which, to some extent, leads to 'weakening' of the tool construction. The second reason is a consequence of the first one – new constructional solutions result in increased tool prices (new projects, technologies, materials, etc.). The last factor concerns the phase of tool testing, conducted in order to research tool quality before they are launched to the market – production practice is the best test, particularly in the automotive industry, where machining is the dominant technique.

The aim of the article is to present the conducted analyses and research with the use of an advanced system monitoring the work of tools used in the machining process. This type of solution allowed, above all, for a precise visualization of the machining process by means of a specialist Digital Way–WP Visu_C software, which, subsequently, created a basis for taking decisions related to the need and way of optimization. The research range covered aspects like detecting chippings and fractures and monitoring machining tool wear, parameterization and optimization of the machining process, researching the influence of material structure on its machinability, as well as regenerated tools' analysis. The presented part of research is a result of unconventional application of the mentioned system, whose target effect is widely understood production cost reduction due to manufacturing process optimization and reasonable tool management. The presented issue is a current representation of one of many challenges faced by the automotive industry, in which searching for innovative solutions to problems is an ongoing process.

2. TOOL STRENGHT AND TOOL WEAR MONITORING

During machining, a tool, and in fact its cutting edge, plays a crucial role, as it undergoes mechanical, and thermal processes, as a result of which its working capability is worsened due to changing its properties and appearance of damages in its material. The progressing tool wear brings about even worse tool work performance, until it is not sufficient. Such wear may cause complete tool damage, and can even damage the material of the machined element.

Tool wear can also be considered from the tool endurance point of view. This is so called catastrophic tool failure, which can lead to a production break. This is a very dangerous phenomenon, which, with limited supervision, may cause a complete tool failure, damages to the machined product, and even machine tool damage. Catastrophic tool failure may take following forms – fig.1.

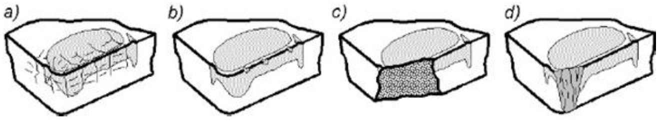

Fig. 1. Forms of blade endurance wear (Jemielniak, 2002)

Cutting edge cracks usually takes place during intermittent machining, in the conditions when the cutting edge undergoes numerous thermal and mechanical hits. The thermal fatigue causes cracks which are perpendicular to the edge, whereas mechanical wear produces parallel ones. During further machining, the cracks are growing, get connected, often causing cutting edge fracture. Cutting edge chipping is caused by local excess of its endurance. As a result of this process, the edge's geometry - actually of the chipped fragment – is violently changed in a very adverse way. In the place of chipping the load and susceptibility to further chipping increase, which, the course of action, may lead to early complete wear, and even a fracture. In case of breakages, the causes can be similar to chipping, but breakages are significantly larger, which means that in the moment of breaking off the tool instantly loses its cutting properties. Breakages and chipping most frequently take place if a tool is excessively used, and their occurrence during initial work phases can be related to wrongly selected parameters and cutting conditions, or insufficient quality of the tool itself (Jemielniak, 2002; Kuryjański, 2011).

If a tool does suffer any of the above described defects, its durability is limited by the time of dulling the cutting edge, which is equal to losing its cutting properties necessary to realize a given machining operation. The opposite process is sharpening, in order to bring back the lost cutting properties. The two issues set the period of cutting edge durability, which means the time of its work between two subsequent blunting cases, with unchanged machining conditions. The sharpening process cannot be repeated infinitely. There comes a moment when bringing back cutting properties is impossible. The sum of tool durability periods, from the beginning to the end of its exploitation, determines tool life.

There are many factors influencing the need to implement machining monitoring systems in production industry (Nouri et al., 2015). Currently, producers on the market of monitoring systems of machining tools condition provide very differentiated offer with different efficiency. The monitoring techniques applied in these systems can generally be divided into 2 groups: direct and indirect methods (Wittbrodt, 2014).

Direct methods, based on geometric measures of cutting edge wear, are used occasionally due to difficulties related to their application, like lack of access to the cutting area during machining, low effectivity and accuracy of measurements, high time consumption. This type of methods involve, among others, optical, electro-resistant, induction, radiometric or pneumatic techniques.

Indirect methods find much wider application in industry. They consist in monitoring tool variables on the basis of signal, where, thanks to special analysis, a given (forecast) level of tool wear can be determined. These methods generate signal measure when a tool is working, which allows for conducting current control. They are based on measuring the effects, not the wear itself, where cutting edge wear level is assessed by means of measuring physical dimensions, among which cutting force (Kious, Ouahabi, Boudraa, Serra & Cheknane, 2010) and derivative measurements (torque, engine power), acoustic emissions (Barreiro, Fernández-Abia, González-Laguna & Pereira, 2017) and vibration measurements are predominant (Addona & Teti, 2013; Nouri et al., 2015). In comparison to direct methods, they are characterized by technically simpler estimation of wear features. However, the obtained results are usually burdened with uncertainty and a need of two-stage operation: the first step is to measure a given physical value, and the next one is to develop proper dependences which make it possible to assess tool condition. For each machining process, proper sensors are selected and installed for monitoring purposes, depending on the physical measures interesting for a user. Thanks to the signals received by the sensors, own transmission systems generate the measured signals and inform the user, who can take appropriate action if the results are worrying (Wittbrodt, 2014).

3. AN EXAMPLE OF TOOL WEAR MONITORING SYSTEM

This part of the article concern the issue of an exemplary implementation of an advanced tool wear monitoring system and its practical usage. Despite long-term research conducted in this area, it is very problematic to find many practical solutions and realized implementations, mainly due to financial reasons.

The accuracy of the applied system comes from the fact of gathering and processing own data. The appliance has a unique patented measuring system and its own calculation algorithm. The measuring part is connected in series with a spindle motor, whereas the processing part communicates with numerical controller (NC) and programmable logic controller (PLC). By means of a dedicated software, it visualizes machining curves, the level of tool wear, alarm curves, and makes it possible to change control parameters. The system's operation scheme is presented in fig. 3. There is a possibility of connecting to a computer system, which will store machining data for the sake of long-term analysis. In order to monitor a given process, it is necessary to define the following base functions (fig. 2):

- control beginning and end on the level of the machining program,
- a learning curve - introducing an optimal model into the system,
- control beginning and end in the dedicated application
- upper tolerance range - the admissible upper level of machining set as a percentage in relation to the learning curve (optimal course),
- lower tolerance range - the admissible lower level of machining set as a percentage in relation to the learning curve (optimal course).

Defining the learning curve is performed by realizing a machining process on a new tool. Tolerance ranges, selected on the basis of empirical experience, provide a strict framework, within which a proper course of the process is assumed. In case of exceeding the given parameters by any machining process, the systems stops it, preventing from producing faulty products and machine breakdowns.

The system registers and illustrates the power parameter during tool's operation in form of 3 functions: absolute power, corrected power, derivative power. Absolute power is a value measured from the beginning till the end of spindle's work, within which there is a certain fragment responding to tool's operation in a given cycle, in order to learn the structure of the given process and determine the beginning and the end of control for the tool itself. Corrected power is a value reflecting operation of the tool, without considering the spindle's work and is used to detect tool chipping. Derivative power is a value which registers fast changes of torque applied to the tool (formula 1) and is used for advanced analysis of tool work, informing a user about even a microscopic tool losses suffered during the machining process.

$$P' = \frac{\Delta P}{\Delta t} \tag{1}$$

where: P' – power derivative,
ΔP – power value change between successive readings,
Δt – passage of time between successive readings.

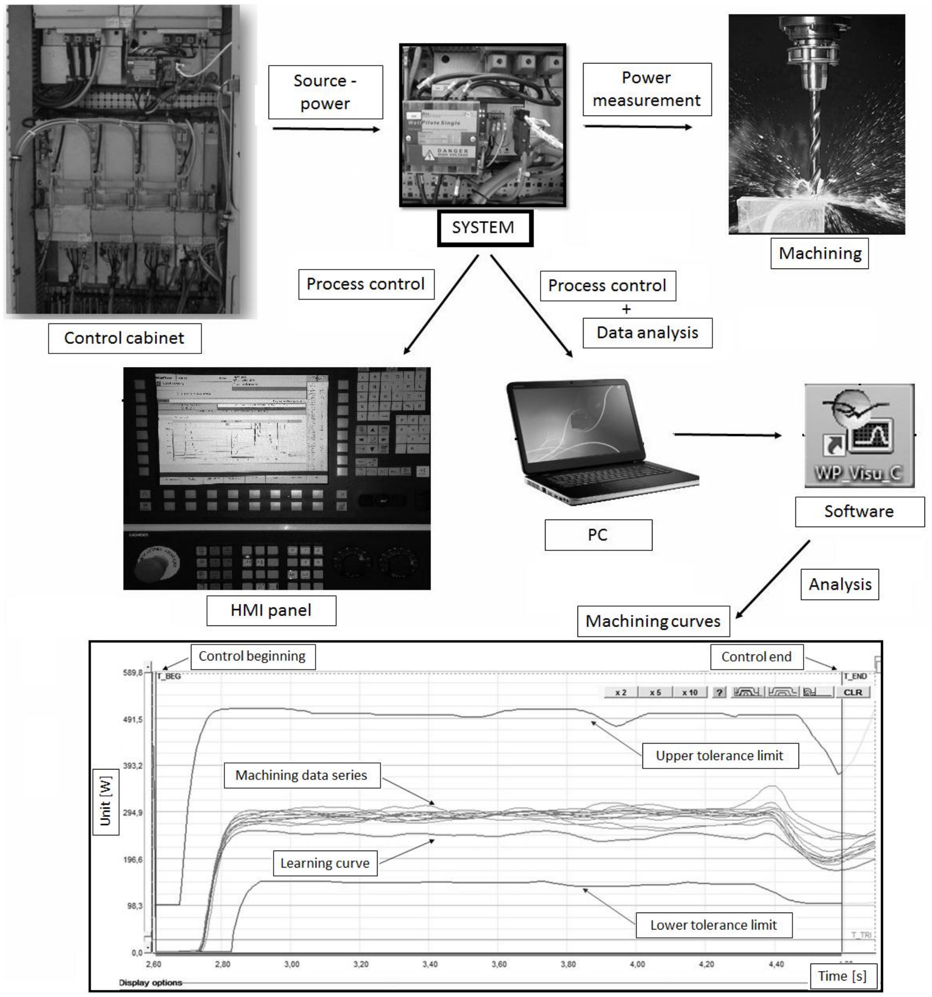

Fig. 2. System's operation scheme with visualization of the machining process

The most important system’s parameters are the following:

- maximum number of controlled machining cases: 120,
- minimal control time: 0.07 s, maximal: 50 min,
- sampling speed: 40 kHz,
- simultaneous control of power, power derivative and energy,
- measurement accuracy: 0.01%.

The main aim of using this type of systems is early detection of tool defects, spindle protection against collision with a workpiece and protection against producing faulty products, which influences the reduction of costs related to tool management and manufacturing in general.

4. PRACTICAL APPLICATIONS

Basing on production practice, chosen applications were presented for the system, whose practical implementation options depend on user’s needs and invention.

Tools’ operation monitoring

The first step involves observing the machining process before any action or decision is taken about changes to process structure. The system installed in a tool machine allows for 2 monitoring modes: current control (stopping the process by exceeding the set parameters) and ‘passive’ observation for process analysis.

The following research fragment was conducted on the basis of experimental drilling process with an installed monitoring system. The task of this system was to gather data in order to observe a full course of the machining process throughout the whole tool life. General process structure and the first series of the gathered data are presented in figure 3, with the assumed tool life of 600 pieces. After the drill performed about 80 machining cycles, the first chippings were observed (fig. 4), the so called death symptoms.

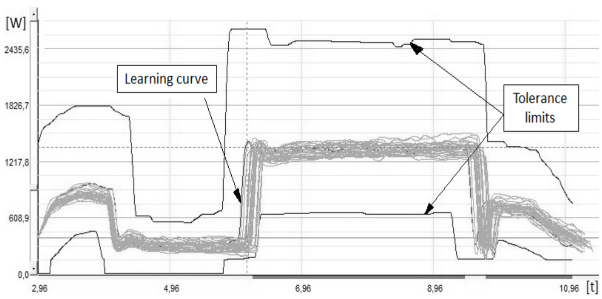

Fig. 3. The first series of data, stable process, close to the ideal course

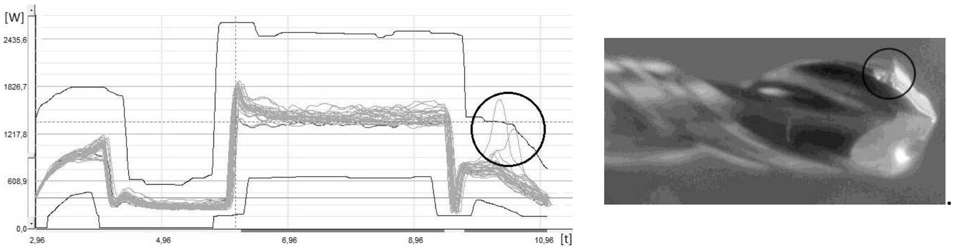

Fig. 4. Next series of data – first tool chipping is visible

In such a case in normal conditions the process should be stopped. In a further part of the experiment progressive partial chipping of the tool was observed, up to 484. machining – when tool fracture occurred (fig. 5).

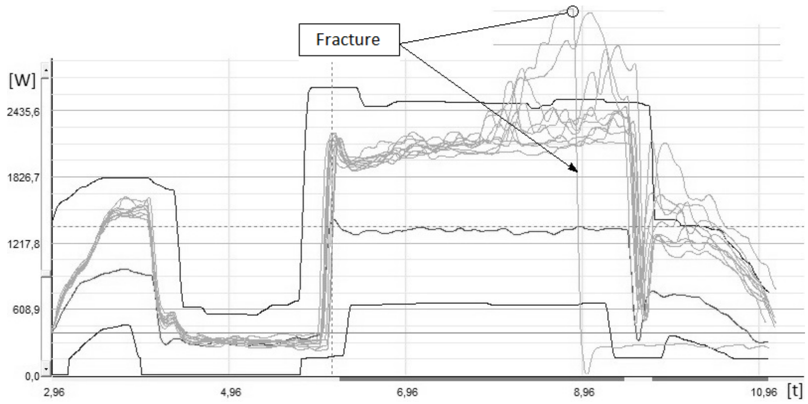

Fig. 5. Premature tool fracture

As a result, the tool was damaged in such a degree that its regeneration was not possible. Conducting this type of research aims at analysing the process itself and carrying out attempts, if the set tolerance ranges are effective and can stop the process in a right moment, protecting the tool, the workpiece and the machine against damages.

The presented example illustrates graphs of the corrected function, used mainly to detect significant chipping, fractures and tool faults. Figure 6 features another program's function – derivative function – which is used to even more advanced analysis of tool work. By means of this function, the system is able to alarm a user about even a slight tool fault occurring during the machining process.

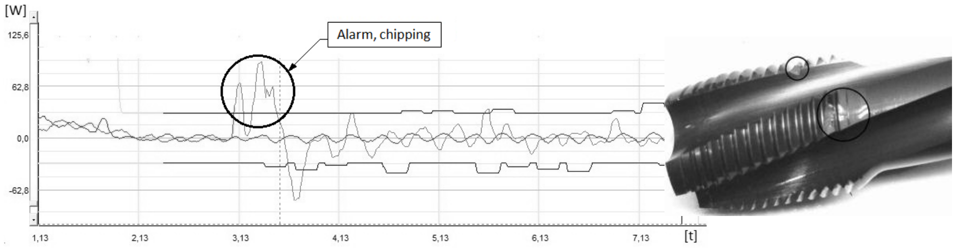

Fig. 6. Derivative function graph with a curve illustrating tool chipping and a sample image of a chipped screw tap detected during machining

In practice, defining appropriate work tolerance limits for a given tool in a process is difficult and requires conducting thorough process and applying many advanced parameters and additional functions.

Achieving tool life

The following analysis is a continuation of research works related to the previously presented drilling process and concerns an attempt to systematise the achieved tool life (a drill for deep drilling). A long-term data analysis focused on this one tool in a given production process showed very unstable work. As a result, with assumed tool life on the level of 600 pieces declared by the producer, a significant part did not perform even a half of the assumed number. Figure 7 presents an example of a tool which was chipped after machining 300 pieces.

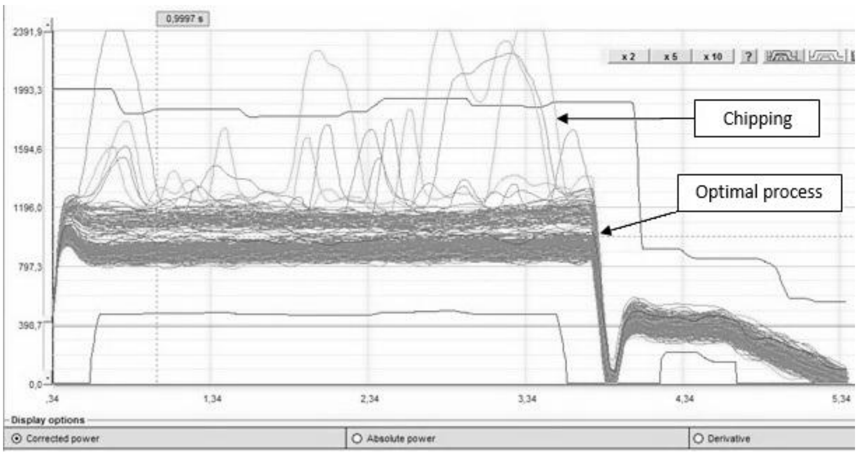

Fig. 7. Visualization of about 300 machining curves (deep drilling) – with signs of process instability

Within the conducted project, in order to achieve the assumed tool life level, activities related to tool geometry verification and modification were undertaken, basing on the gathered and visualized data from the course of tool work in the period of several months.

Another graph (fig. 8) relating to the same machining process, performed on the database of 1000 machining cycles using one tool, is a result of a developed concept of new tool geometry, which in the phase of further usage (testing) showed that, the applied changes respond to customer requirements and they achieve, and even exceed the tool life declared by the producer.

In influence of regeneration on tool work

The next analysis is related to economical aspects – regenerating tools. It is much more profitable (less costly) to finish using a given tool for machining early enough, not to lead to excessive wear, chipping or breakage (fig. 9) and be able to regenerate it and use it the process.

The cost of tool regeneration (that is bringing back its original geometry) is often a few times lower than the cost of a new tool. However, it happens that tools after regeneration are not suitable for further work much earlier than initially assumed (fig. 9). The research conducted in this area also showed the results of inappropriately performed regenerations.

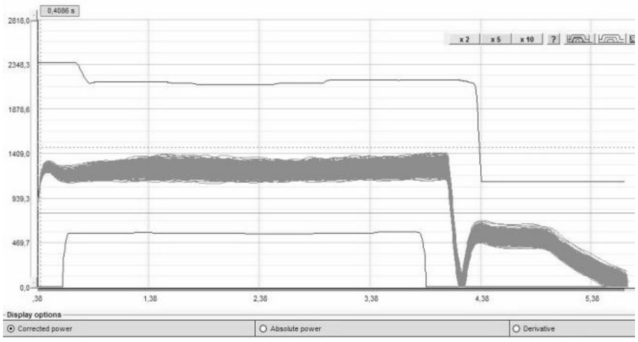

Fig. 8. Visualization of 1000 machining curves – optimal process

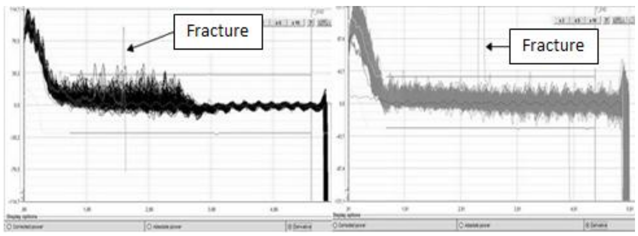

Fig. 9. Regenerated screw tap – syndromes of improper sharpening, too many curves exceeding the assumed tolerance limits (own study)

On the basis of this example the tolerance limits were narrowed, as in the end the tool was broken anyway. Solving this type of problem is not easy. The difficulty lies in finishing the work of a new or regenerated tool early enough, so that it can undergo regeneration as long as possible and that the regeneration makes sense – the greater the tool wear, the weaker effect its regeneration will bring.

The influence of material structure on its machinability

It often happens in production practice that due to optimization of final product characteristics, there is a need to introduce technological changes and changes to the machined material composition. Figure 10 presents machining of 2 components produced from alloy of different hardness. On the basis of the data gathered by the system it was stated that ‘type2’ detail made from the harder alloy exhibits better machining properties, with lower load of the machine-tool system. This lets us suppose that in the long-term tool life will be prolonged, however, this process requires further observation and analysis.

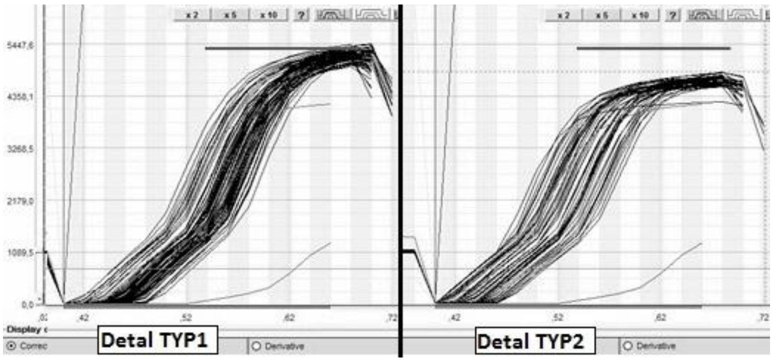

Fig. 10. Machinability tests of details manufactured from materials of different composition

Reducing cycle time and control frequency

Most machining centres are equipped with a mechanism used to control tool presence of lack of tool (also fractures) by means of contact. This solution aims at informing an operator about machine ‘condition’ after the performed work. Each tool control performed in this way takes about 1.5–2 seconds. With a tool work monitoring system, it is possible to completely resign from this type of control, as the system will do the same in real time, informing a user about actual tool condition, even in case of minor chipping. As a result, machining cycle time for one element on a unit using 10 machining tools can be reduced by 20 seconds.

A fully implemented and properly parametrised system, after a series of studies and analyses, can, in the long run, reduce the frequency of statistical process control, which is particularly time consuming in the automotive sector due to rigorous quality requirements. This will contribute to full automation of the control process, its quality and widely understood cost reduction.

5. SUMMARY

The level of machining processes optimization using advanced tool wear monitoring systems will be strictly dependent on the experience of staff operating a given system. Using this kind of software in practice may lead to increased requirements faced by tools manufacturers on the basis of growing awareness of technologists and engineers in the area of advanced inter-process monitoring techniques. Conducting long-term analyses is a starting point to identify abnormalities in own process due to tool faults (with excluded share of material faults), and a signal to start conducting common research and development projects with tool suppliers. Another aspect is an emerging possibility of using a connection between a tool monitoring system and a specialized and innovative software as elements of Industry 4.0. Connecting the tool monitoring system, its software on the operator's panel, and additionally plugged PC panel with a well-developed application for data analysis made it possible to diagnose early symptoms of an approaching anomaly related to electrospindle's operation. This way the conducted research reached a practical aspect and contributed to initiating works on a new application aimed at diagnosing and early warning, according to the idea of 'talking machines'. These analyses will also facilitate the decisions related to tool purchasing and parameterization. The described solutions allow also to conduct research on tool quality offered by different producers, thanks to which we can achieve a balanced management level in the area of own tool management costs. Continuous development in the automotive industry, all information and innovative solutions which allow to increase effectiveness of the conducted production activity create a chain of added value, which significantly increases widely understood enterprise competition on the dynamically changing global market.

REFERENCES

Addona, D. M. D., & Teti, R. (2013). Image data processing via neural networks for tool wear prediction. *Procedia CIRP*, *12*, 252–257. doi: 10.1016/j.procir.2013.09.044

Barreiro, J., Fernández-Abia, A. I., González-Laguna, A., & Pereira, O. (2017). TCM system in contour milling of very thick-very large steel plates based on vibration and AE signals. *Journal of Materials Processing Technology*, 246, 144–157. doi:10.1016/j.jmatprotec.2017.03.016

Jemielniak, K. (2002). *Automatyczna diagnostyka stanu narzędzia i procesu skrawania*. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.

Jurko, J. (2007). Monitoring and Diagnosis of Drill Wear and the Thermodynamic Phenomenas of Material Removal by drilling of Stainless Steels. In: E.E. Gdoutos (Ed.) *Experimental Analysis of Nano and Engineering Materials and Structures* (vol. 37, 77–78). Dordrecht: Springer. doi: 10.1007/978-1-4020-6239-1_37

Kious, M., Ouahabi, A., Boudraa, M., Serra, R., & Cheknane, A. (2010). Detection process approach of tool wear in high speed milling. *Measurement, 43,* 1439–1446. doi:10.1016/ j.measurement.2010.08.014

Kuljanic, E., & Sortino, M. (2005). TWEM a method based on cutting forces monitoring tool wear in face milling, *Mach. Tools Manuf. J.*, *45*, 29–34. doi:10.1016/j.ijmachtools.2004.06.016

Kuryjański, R. (2011). *Obróbka skrawaniem i obrabiarki*. Warszawa: Expol.

Nouri, M., Fussell, B. K., Ziniti, B. L., & Linder, E. (2015). Real-time tool wear monitoring in milling using a cutting condition independent method. *International Journal of Machine Tools and Manufacture*, *89,* 1–13. doi:10.1016/j.ijmachtools.2014.10.011

Storch, B. (2001). *Podstawy obróbki skrawaniem*. Koszalin: Wydaw. Politechniki Koszalińskiej.

Więcek, D. (2013). Implementation of Artificial Intelligence in Estimating Prime Costs of Producing Machine Elements. *Advances in Manufacturing Science and Technology, 37,* 43–53. doi: 10.2478/amst-2013-0004

Wittbrodt, P. (2014). Nadzorowanie i prognozowanie stanu narzędzi skrawających w procesie skrawania. *Innowacje w Zarządzaniu i Inżynierii Produkcji* (cz. 1, 833–834). Zakopane: Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją.