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Diagnostics of Milling Head Using Acoustic Emission

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Monitoring and diagnostics of cutting tools are crucial for ensuring production efficiency and product quality in the machining industry. This study uses acoustic emission (AE) to non-invasively detect damage and monitor tool condition in real time. Experiments assessed cutting inserts in a milling head, both used and new. Results showed AE effectively diagnoses tool wear, with significant differences in signals from worn and new inserts. Fast Fourier Transform (FFT) analysis determined the frequency range of signals during machining, confirming AE's usefulness. Microscope verification supported the AE findings on tool wear. This research highlights AE's potential in non-destructive diagnostics, enhancing production efficiency and product quality.

Keywords: Acoustic Emission (AE), Tool Wear Detection, Non-Invasive Diagnostics, Signal Analysis, Cutting Inserts

1 Introduction

In today's rapidly evolving industrial environment, monitoring and diagnostics of machining processes have become crucial for maintaining production efficiency and product quality. One promising technique in this field is the use of acoustic emission (AE), which allows for non-invasive detection of damage and real-time monitoring of the condition of cutting tools during typical operations. The AE technique relies on the detection of ultrasonic waves generated by processes such as deformations (elastic and plastic), crack propagation, friction, corrosion, or leaks, making it highly sensitive to any anomalies in the workpiece or tool material [1-2].

Recent studies in the field of machining, including milling, indicate a significant potential for the application of AE in optimizing cutting parameters, detecting tool wear, and monitoring the condition of the machined material. Studies by [3] and [4] have shown that AE enables effective optimization of machining parameters while ensuring high surface quality of machined parts. Additionally, [5] and [6] have applied AE to detect tool cracks and wear, significantly reducing the risk of damage to machined components and enhancing the safety of production processes.

An approach based on AE signal analysis also shows high effectiveness in predicting and detecting process instabilities, such as vibrations during cutting. Works by [7-9] provide valuable insights into the possibilities of using AE to monitor and control the condition of machine tools and machining processes. Moreover, the application of advanced signal processing methods and machine learning in the analysis of AE data, as demonstrated by [10-11], opens new possibilities for automating diagnostics and real-time monitoring.

The development of tool condition monitoring systems based on various measurement strategies, including acoustic emission measurement, demonstrates the potential of this technology in a range of applications, from milling to turning, where the ability to detect tool damage under different machining conditions is crucial for ensuring production continuity and efficiency [12-13]. Particular attention is given to the possibilities of applying AE in combination with advanced signal processing methods and data analysis, which not only enables the identification of damage but also the prediction of tool wear and optimization of cutting parameters [14-15].

Current research also focuses on analyzing the impact of various machining parameters on the characteristics of AE signals, allowing for a deeper understanding of the mechanisms of acoustic emission in the context of the specific material being machined and the cutting conditions [16-17]. These studies, combined with the development of predictive models based on neural networks and data fusion strategies from various sensors, open new perspectives for tool condition monitoring and process diagnostics [18]. The use of the acoustic emission method in milling process diagnostics [19-20] has prompted the desire to verify the potential of this method for identifying milling head wear and confirming the results obtained in the previously mentioned studies.

A review of the literature indicates a dynamic development of AE technology as a tool for advanced monitoring of machining processes. The integration of these technologies with modern data analysis methods creates opportunities for further optimization of production processes, increasing their efficiency, reducing costs, and improving the quality of final products. In recent years, there has been a noticeable increase in interest in the application of advanced measurement techniques and signal analysis in the diagnostics of machining processes. It has been shown that the use of the Discrete Wavelet Transform (DWT) enables effective filtering of cutting force signals and allows for the extraction of diagnostically relevant features related to cutting edge load [21]. Relationships between cutting parameters and tool–workpiece interaction forces have also been analyzed in the context of milling difficult-to-machine materials using monolithic ceramic cutters [22]. With regard to measurement precision, the importance of reliable estimation of tool radius measurement uncertainty using probing systems in CNC machines has been emphasized [23]. These findings support the integration of modern sensing methods and signal analysis techniques as an effective approach for monitoring and diagnosing the condition of cutting tools.

In today's world, where production efficiency and precision are crucial for market competitiveness, finding methods that allow for early detection of damage and assessment of the condition of cutting tools becomes essential. Diagnostics based on acoustic emission (AE) measurement offers a unique opportunity for non-invasive monitoring and detection of changes in the technical condition of tools, which can significantly improve the efficiency of production processes [24-26]. For this reason, a decision was made to conduct research focused on the use of this method. These studies aim not only to confirm the technical capabilities of the AE method but also to explore its potential applications in the machining industry. The implementation of this research aligns with the goal of increasing the reliability and safety of production processes, as well as optimizing tool usage.

2 Materials and methods

All the studies conducted using the acoustic emission (AE) method to diagnose the technical condition of the milling head were performed using the AMSY-6 system and equipment produced by the German company Vallen Systeme GmbH. This device is designed for diagnostic activities using the AE method. The unit used allows for the use of two channels for AE measurement and four additional channels for receiving reference signals from sensors such as pressure, stress, force, torque or displacement sensors. In the conducted study, two Vallen Systeme piezoelectric sensors model VS370-A2 were used. Their frequency range is 170 - 590 kHz. The preamplifiers, which mediate between the sensors and the signal analyzing device, are also part of the setup. The measurement equipment used in the study included Vallen Systeme GmbH products, models AEP5 and AEP5H. [Fig. 1] shows the complete diagram of the measurement setup constructed for the study.

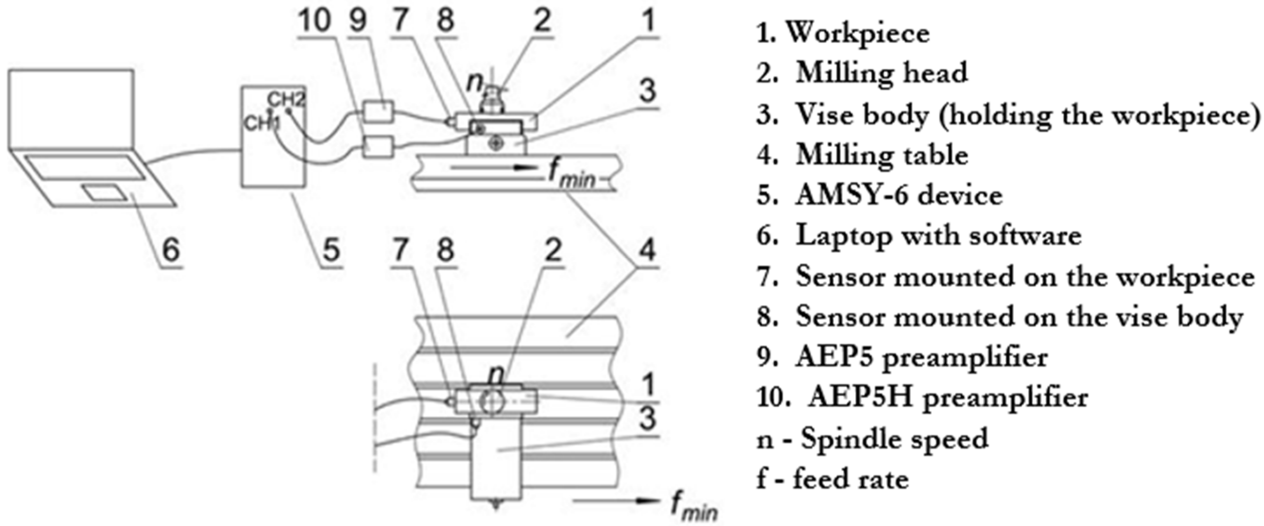

Fig. 1 *Measurement setup diagram*

The numbers 1 to 4 shown in the diagram are elements of the setup that are not part of the measurement apparatus. They are either the objects being tested or essential components for conducting the test. A conventional FWD32J milling machine was used for the experiments. The selected milling head is a Pafana R390 with six cutting edges. The element numbered 5 in the diagram is the AMSY-6 measurement system connected to a laptop (number 6 in the diagram) with software specifically designed for the used equipment.

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The connection between elements 5 and 6 was made using a USB 3.0 cable. Signal cables were connected to the channels of the AMSY-6 device (number 5) that receive AE signals. For the proper functioning of the sensors, additional AE signal amplifiers were required, which were placed between the AMSY-6 and the sensors on the tested objects (numbers 7 and 8 in the diagram). The AEP5 and AEP5H preamplifiers (numbers 9 and 10 in the diagram) were used. Signal cables connected the preamplifiers to the AMSY-6 device on one side and to the sensors mounted on the workpiece and the vise body on the other side. Technical petroleum jelly was used as a transmitter for the AE signal, placed between the sensors and the workpiece and the vise body. The AE sensors were mounted: one directly on the tested object and the other on the jaw of the machine vise, as shown in the diagram at numbers 7 and 8. [Fig. 2] contains photographs illustrating how the measurement setup depicted in the diagram looked in practice. This method of mounting the sensors was intended to test the usefulness of the AE signal recorded on the vise jaw, which is more convenient in practice than mounting the sensor on the workpiece each time.

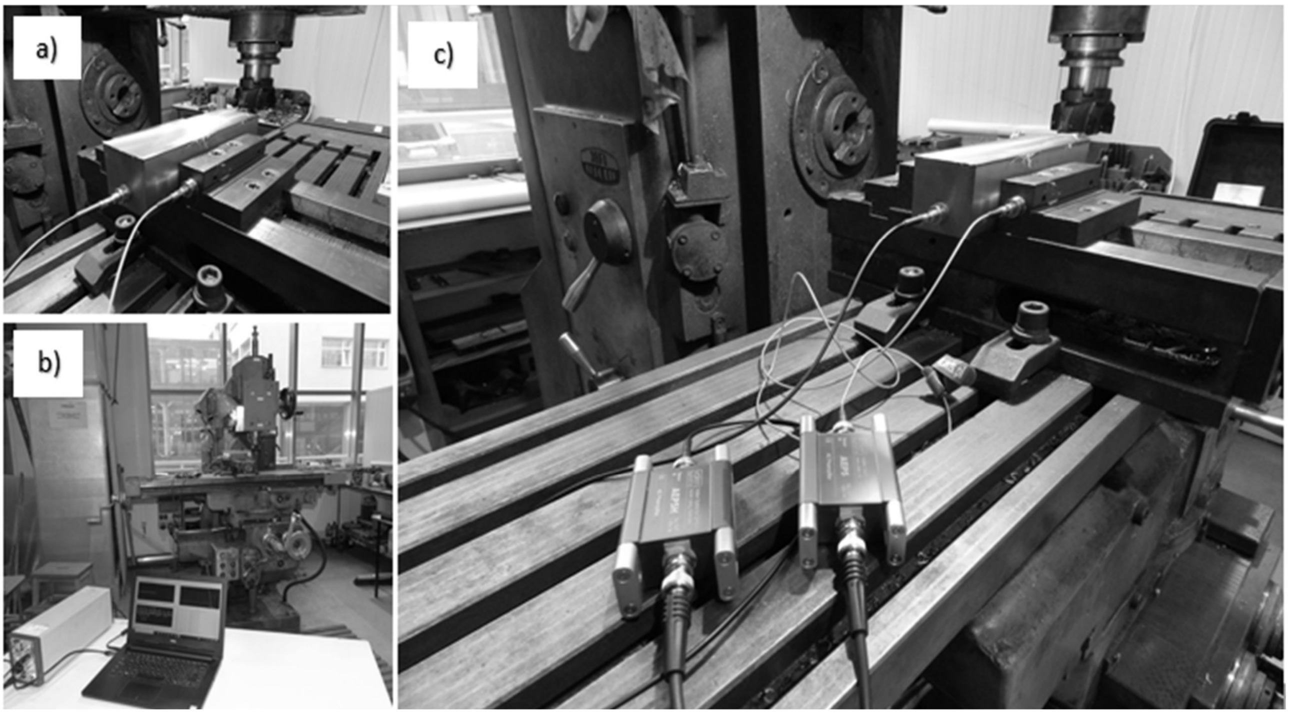

Fig. 2 *a) The workpiece with magnetically mounted AE sensors (model VS370) on the workpiece and on the machine vise jaw, prepared for milling with a cutter R390-063Q22-11H; b) Conventional (manual) milling machine with an acoustic emission measurement path; c) The workpiece clamped in the machine vise with AE sensors mounted directly on the workpiece and on the vise jaw, equipped with signal amplifiers*

The study was conducted using the Vallen AE-Suite application set developed by Vallen Systeme GmbH, dedicated to the measurement equipment used. The Acquisition application is responsible for controlling the data reception performed by the AMSY-6 apparatus. This application reads information transmitted by the sensors mounted at the test site and delivered to the apparatus using preamplifiers. The VisualAE application is used after measurements are taken by piezoelectric sensors and the AMSY-6 apparatus. This program processes the data and then presents the measurement results graphically. The Alarm Manager application has a control function. In its window, the user can set threshold values for various parameters, upon reaching which the software reacts by informing the user with an audible signal, displaying an appropriate message on the screen, or illuminating an LED on the chassis.

In the studies, the operating parameters of the milling machine were based on typical ranges for conventional milling machines, the milling head, and the cutting inserts used in the study [Tab. 1]. The determination of the Threshold, DDT (Duration Discrimination Time), and RT (Rearn Time) parameters was carried out through preliminary experimental studies.

Tab. 1 *Cutting parameters adopted for determining Threshold, DDT, and RT parameters*

Spindle speed n [rpm]	Cutting speed V_c [m·min^{-1}]	Feed rate f [mm·min^{-1}]	Depth of cut a_p [mm]
710	140	112	1

At the beginning of the study, a spectral analysis of the recorded AE signals was conducted using the Fast Fourier Transform (FFT). Initially, this was performed for worn inserts (Fig. 3). Dominant frequencies appeared in the range of approximately 80 to 140 kHz. A similar graph was prepared for new inserts (Fig. 4). In this case, the dominant range was observed between 95 and 120 kHz. The comparison of the signals thus revealed differences in amplitudes and dominant frequencies, which enabled the determination of the frequency range of acoustic emission sensitive to the condition of the cutting insert. The frequency range was determined to be between 95-141 kHz.

To determine the Threshold level, measurements were taken with the filter set to a frequency range of 95-141 kHz. All measurements started with the Threshold parameter set at 70 dB, and its value was gradually increased up to 93 dB. For the accuracy of comparison, the measurements were conducted using both old and new milling inserts. Based on the results, the Threshold level was determined to be 88 dB. For this value, the greatest difference in the number of acoustic emission hits between new and worn inserts was obtained. The graph [Fig. 5] shows the acoustic emission recorded by two sensors. The blue color represents the sensor mounted on the workpiece, and the orange color represents the sensor mounted on the machine vise jaw. On the left side, the results for new inserts can be observed, while on the right side, the results for worn inserts are shown. It is evident that the measurement on the vise jaw is less sensitive; however, the signal level still allows for correlating the recorded emission on the vise jaw with the tool condition. Such a measurement is much more convenient in industrial conditions but is subject to additional uncertainty related to varying levels of damping for different mounts, surface roughness, or clamping force.

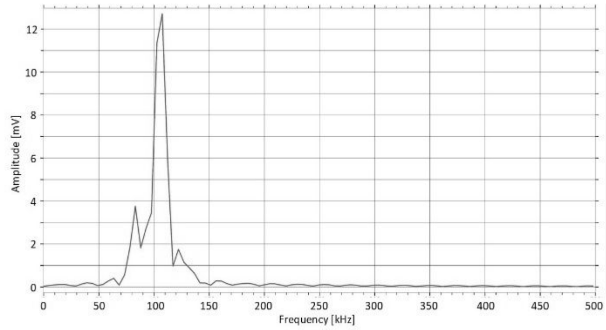

Fig. 3 *Analysis of the signal emitted during the worn insert examination*

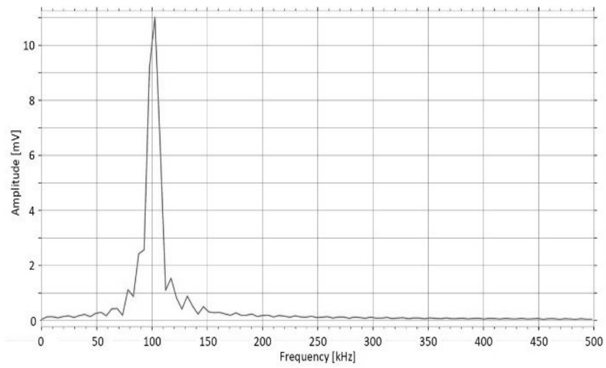

Fig. 4 *Analysis of the signal emitted during the new insert examination*

Fig. 5 *Number of hits per second for new and worn inserts at different sensitivity thresholds; Data from sensors on the workpiece and the machine vise jaw*

To properly set the DDT and RT parameters, trial measurements were conducted. Initially, during the measurements, the DDT level was gradually increased from the initial value of 50 μs to 90 μs. Then, during similar measurements, the RT value was gradually increased from 50 μs to 170 μs. With a complete set of readings for the specified ranges, the parameters at which the measurement system showed the greatest sensitivity to the condition of the cutting inserts were determined. These parameters are listed in Table [Tab. 2].

***Tab. 2** Parameters adopted for the series of tests*

Threshold [dB]	DDT [μs]	RT [μs]
88	50	120

3 Results

The studies focused on assessing the technical condition of cutting inserts using acoustic emission (AE) measurements, utilizing two sets of inserts: worn and new. The first analysis was performed for the same parameters for which the Threshold, DDT, and RT values were determined. The analysis showed significant differences in the number of AE signals generated by both sets, with nearly 13 times more hits for the worn inserts. This suggests that acoustic emission can be an effective tool in diagnosing the wear degree of cutting tools for milling heads operating on conventional milling machines.

Subsequently, the main part of the research was conducted, where measurements were taken using different parameters to verify the existence of relationships between AE signal occurrences and the technical condition of the milling head. To this end, a measurement program was implemented, encompassing milling at various cutting speeds and depths, for both new and worn inserts. The following results were obtained (Tab. 3).

The comparison of the number of hits resulting from exceeding the lower threshold parameter set in the software indicates that this number is significantly higher when using worn inserts compared to new inserts for tests conducted at various cutting speeds. These results confirm the assumption that the level of acoustic emission is correlated with the condition of the milling head's cutting edges and allows for the assessment of the milling head's technical condition regardless of the rotational speed used during the operation of the machine. Additionally, based on the results from the table above, it can be observed that the higher the rotational speed of the head, the more AE signals the measuring apparatus receives. During measurements conducted at different cutting depths, the number of hits in the measurement window was always several or several times higher when using a worn insert compared to a new insert. However, when changing the cutting depth settings, the previously observed pattern, where the higher the value of the changed parameter (previously rotational speed, and here cutting depth), the more hits the apparatus records, was not observed. This pattern was confirmed for the old inserts. In the context of new inserts, more hits were recorded at a cutting depth of 0.5 mm than at 1 mm. However, the most hits were recorded at a cutting depth of 1.5 mm.

***Tab. 3** Number of AE signals resulting from the use of worn and new inserts in acoustic emission tests*

Cutting speed V_c ($m \cdot min^{-1}$)	Spindle speed n (rpm)	Feed rate f ($mm \cdot min^{-1}$)	Feed per tooth f_t ($mm \cdot tooth^{-1}$)	Depth of cut a_p (mm)	Insert type	Average number of hits per second	Ratio of hits in new insert to hits in worn insert (%)
140	710	112	0.026	1	worn	57	7
					new	4	
178	710	112	0.026	1	worn	135	30
					new	41	
221	1120	140	0.026	1	worn	177	25
					new	45	
140	710	112	0.026	0.5	worn	33	36
					new	12	
140	710	112	0.026	1	worn	57	7
					new	4	
140	710	112	0.026	1.5	worn	72	51
					new	37	

The results obtained through acoustic emission measurements were correlated with the condition of the applied inserts, whose condition was recorded under a microscope. The verification of the cutting edge condition under the microscope [Fig. 6] confirmed the conclusions from the acoustic emission analysis, showing a significant difference in the wear degree between new and worn inserts. The defects and damages visible on the worn inserts correlated with the number of AE hits, confirming the value of the acoustic emission method in assessing the wear of cutting tools.

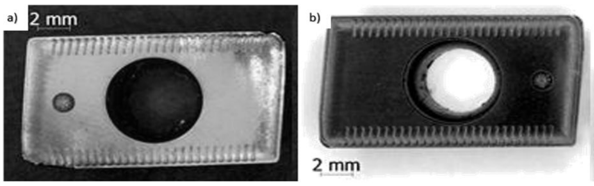

Fig. 6 *Cutting inserts used in the study; a) worn; b) new*

In summary, the results of the studies described in this section indicate that the acoustic emission method allows for the diagnosis of the overall technical condition of milling heads. This is primarily confirmed by the significant difference in the number of AE hits recorded during measurements taken with new and worn cutting inserts, which show visible signs of wear.

4 Conclusion

In the context of the increasing demands of the machining industry, the development and implementation of advanced diagnostic techniques for effectively monitoring and assessing the technical condition of cutting tools have become crucial. This study focused on using the acoustic emission (AE) method for the non-invasive detection of damage and real-time monitoring of cutting tools. The presented analysis is based on detailed measurements of acoustic emission generated by different wear states of cutting inserts, both new and worn, processed on a conventional milling machine. The application of Fast Fourier Transform (FFT) to analyze AE signals allowed for the analysis of amplitude and frequency characteristics associated with the technical condition of the tools, providing a basis for drawing significant conclusions regarding the diagnostic capabilities of this method.

This study highlights the importance of acoustic emission as a potentially groundbreaking technique in cutting tool diagnostics, offering tangible benefits in terms of quick and accurate wear assessment and contributing to increased production efficiency and product quality improvement. The key findings of this study can be summarized as follows:

- The utility of acoustic emission (AE) for diagnosing the technical condition of milling heads has been verified. It was confirmed that AE signals can effectively indicate differences in the technical condition between new and worn cutting inserts.
- It was found that inserts in worse technical condition generate significantly more AE signals than those in good condition, which was confirmed by subsequent measurement series and microscopic analysis of the inserts.
- The conducted experiments demonstrate that acoustic emission can be used to assess the technical condition of milling heads, potentially contributing to the development of modern, non-destructive diagnostic methods.

Further research is necessary to help develop a universal system that correlates the number of emitted signals with the precise level of wear of the cutting inserts.

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