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Damage Detection in Machining Tools Using Acoustic Emission, Signal Processing, and Feature Extraction †

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Abstract: The wear of tools in machining is one of the primary issues in manufacturing industries. Direct measurements of tool wear, such as microscopic observation, lead to increased machine downtime and reduced production rates. To improve this situation, real-time tool condition monitoring systems (TCMs) are needed, which utilize indirect measurement of tool wear through sensors and signal processing. This project focuses on the use of acoustic emission (AE) sensors for experimental analysis of tool damage under various milling conditions. The proposed approach involves designing condition indicators to quantify this damage by implementing infinite impulse response (IIR) digital filters, specifically Butterworth filters, and fast Fourier transform (FFT), in addition to root mean square (RMS), using different frequency bands of the acoustic signals collected during the process. The results from implementing this study show promise for optimizing the process through an alternative TCM system in manufacturing operations, avoiding the drawbacks of the direct method, and extending the equipment's lifespan and efficiency. It's worth noting that this document presents partial results of this implementation, which is still in progress.

Keywords: tool condition monitoring; acoustic emission; feature extraction; industrial automation

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1. Introduction

The degradation of the quality of industrial assets due to wear and the increased product cost due to frequent tool replacement is the primary issue in high-speed machining (HSM). The deformation or damage of the cutting edge of a tool during machining due to interactions between the tool and the workpiece is referred to as tool wear. In manufacturing industries, maintenance costs and downtime increase, and production rates decrease due to the failure of cutting tools [1].

Tool condition monitoring systems (TCMs) are useful for these industries as they reduce downtime and increase productivity. The monitoring process helps prevent tool and workpiece damage, improves the productivity and quality of the machined product, and predicts tool wear [2]. According to Quintana and Ciurana [3], the early identification of regenerative vibration (when vibration has just begun and has not fully developed) is essential to minimize its negative effects, such as catastrophic damage to the tool and workpiece. These researchers have chosen vibration recognition strategies in processes as a key line of investigation regarding vibration, emphasizing the importance of obtaining relevant and useful signals and finding efficient signal processing algorithms.

Furthermore, Jantunem [4] extensively studied signal sources (motor spindle currents, acoustic emissions, vibrations, and sounds) as well as TCM analysis methods for drilling, emphasizing that the tool life could not be satisfactorily achieved without TCM due to variations in the actual tool life.

This study was validated through experimental analysis conducted in the milling process, a machining process involving the removal of material from the surface of a workpiece using a rotating cutting tool, called a milling cutter. This tool features multiple cutters or cutting edges, enabling precise cutting and the creation of various shapes and features on the workpiece. The wear of this milling cutter is a gradual damage that occurs over operations, directly affecting dimensional accuracy and surface finish quality. Thus, TCMs become essential. The proposed system in this paper utilizes wireless technologies to collect and transmit acoustic signals generated during milling, which is a key aspect that differs from previous contributions based on traditional acoustic emission systems [5,6]. This approach involves the design of condition indicators that quantify the damage incurred through the implementation of Butterworth-type digital filters, FFT, and the RMS, to quantify the tool wear and validate the effectiveness of the acoustic emission strategy.

The study was conducted by testing different frequency bands of the acoustic signals collected during the process through FFT calculations. The results of this research are significant for increasing productivity, reducing manufacturing costs and material waste, optimizing the life of the milling cutter, reducing the risks of higher-order damage in the process, and taking quick actions when damage occurs. These findings are relevant for the optimization of the manufacturing process.

2. Materials and Methods

2.1. Experiments

For the study, a machining tool, machine tool, acoustic frequency pickup sensor, carbon plate, and three devices for fixing the carbon plates were used, made of resin, steel, and aluminum. The data acquisition system was composed of a wireless piezoelectric AE sensor, which was responsible for detecting information relating to the condition of the tool and which was expressed through electrical signals digitized on a computer using an acquisition board at sampling rates of the order of 250 kHz. In total, 18 tests were carried out, but only from the seventh signal onwards was it possible to capture them correctly, resulting in 12 useful signals. The milling process diagram is shown in Figure 1.

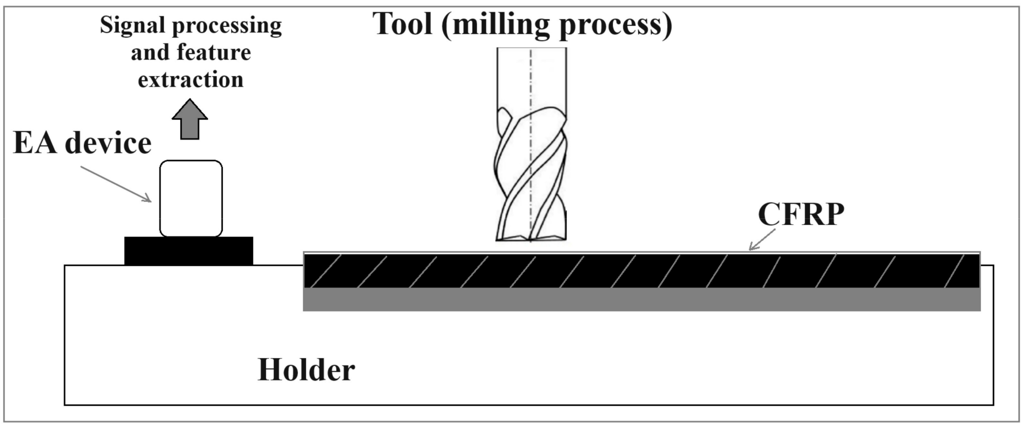

Figure 1. Schematic of the milling process and data collection by the sensor.

2.2. Feature Extraction

The signals were pre-processed and consolidated for data processing and analysis using the proposed methodology, which involved preprocessing to prepare, filter, and eliminate noise. The generated dataset was labeled for use in digital processing routines through MATLAB® software (version 9.13/2022b).

After collecting the signals in the time domain and importing them into MATLAB®, the FFT was calculated for the most relevant signals (avoiding redundant support) using an 8192-point Hanning window. Subsequently, four frequency ranges were selected, which proved to be relevant for the study as they had the highest magnitudes, excluding very low frequencies, as these are highly susceptible to noise, such as electromagnetic noise from the 60 Hz electrical network and thermal noise. One of these specific ranges is a high-frequency range, which was chosen to determine if high frequencies are relevant for the analysis of milling cutter wear.

To calculate the mean of the RMS signals, the signals were first filtered in the time domain within specific chosen frequency bands to isolate certain signal ranges and identify patterns. This was done using a 5th-order Butterworth digital IIR bandpass filter. Subsequently, the mean RMS of these signals was calculated to analyze their behavior at different frequencies.

3. Results and Discussion

The analysis of the results was carried out by observing the most relevant characteristics related to the tool condition extracted using the proposed method. This was based on the comparison of the different levels of damage with their reference (the tool condition before the start of the experiment). Repetitions of the analyses were also performed to ensure reliability in the acquisition of information.

3.1. Tool Wear Analysis

During the experiments, it was observed that the tool exhibited rapid wear due to the abrasiveness of the composite material throughout the drilling process. Figure 2 illustrates a microscopic image of the tool after the experimental tests. It can be observed that the edges experienced wear, resulting in a loss of cutting ability and consequently affecting the accuracy of the drilling operation. In addition, the edge showed a slight rounding, making the cutting inefficient and increasing the delamination effect in composite material.

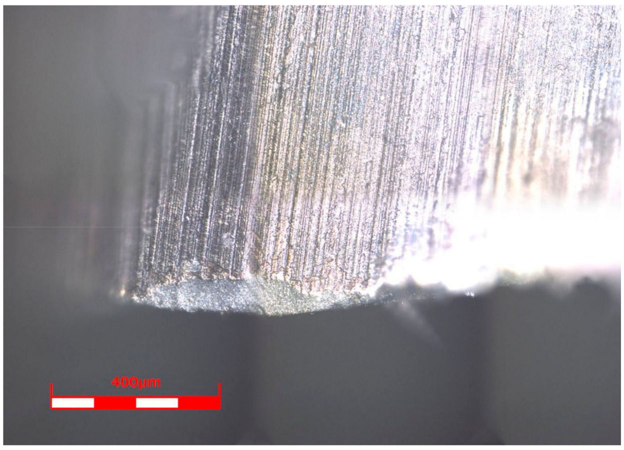

Figure 2. Tool wear analysis.

3.2. Time Domain

Figure 3 shows the raw (unprocessed) signals in the time domain on the resin, aluminum, and steel supports. As expected, it can be observed that the behavior of AE (acoustic emission) from the milling cutter changed according to the support material. It is noticeable that the amplitudes (in volts) on the steel and aluminum supports were higher than on the resin support, which was expected, as resin, due to its mechanical properties, tends to dampen vibrations (which generate acoustic emissions), which is not the case with steel and aluminum. However, in the time domain, it can be difficult to discern differences between signals from the same support, making frequency domain analysis necessary for studying milling cutter wear.

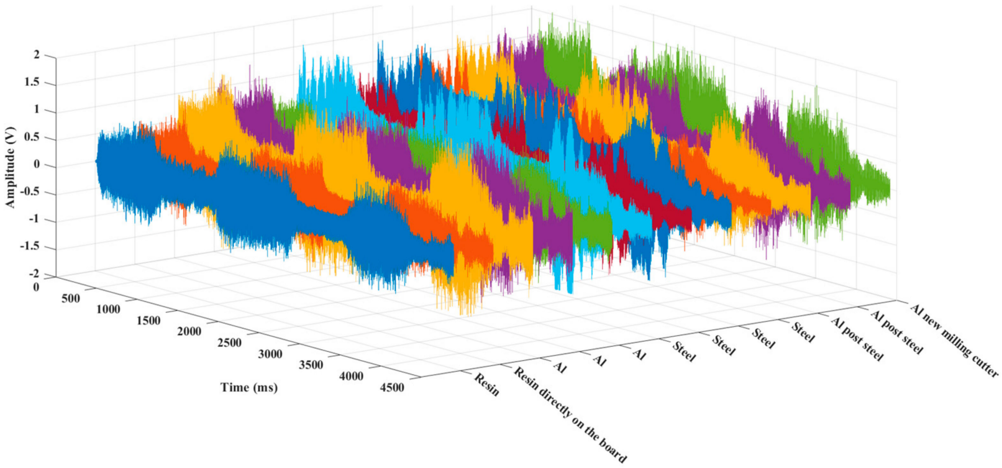

Figure 3. All 12 relevant signals are plotted side by side, on their respective supports, in the time domain.

3.3. Frequency Domain

In Figure 4, the FFTs of some signals, considered the most relevant (avoiding repetition of support), are presented. Initially, there are significant amplitudes at low frequencies, near 0 Hz, but this range was disregarded for analysis due to the presence of a lot of electromagnetic noise from the 60 Hz power grid, as well as thermal noise. Therefore, frequency ranges from 40 to 80 kHz, 10 to 20 kHz, and 20 to 40 kHz were identified in decreasing order of relevance, based on their significant magnitudes in the signals. Finally, the range from 140 to 170 kHz was chosen to examine the signal behavior at high-frequency ranges and determine its relevance for the analysis.

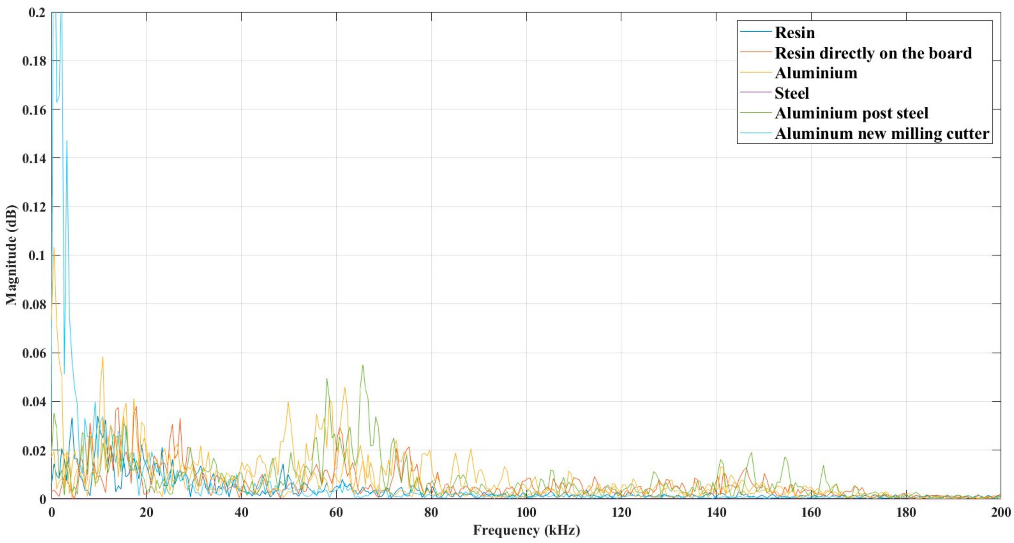

Figure 4. FFT of the main AE signals studied, in the range from 0 to 200 kHz.

3.4. RMS Signals

In Figure 5, you can see the averages of the bandpass-filtered RMS signals in the chosen frequency ranges. Firstly, the range from 40 to 80 kHz proved to be the most important for the TCM (tool condition monitoring) study, as it showed the highest magnitudes of acoustic emission between passes and supports, as well as greater variations. This allows for the derivation of values that indicate wear, breakage, or fractures in the milling cutter. Additionally, the range from 10 to 20 kHz was also significant, exhibiting considerable amplitude variations, especially for the aluminum support, which varied significantly between passes. Furthermore, the range from 20 to 40 kHz also yielded good results, though it was of lesser importance compared to the other two treated ranges.

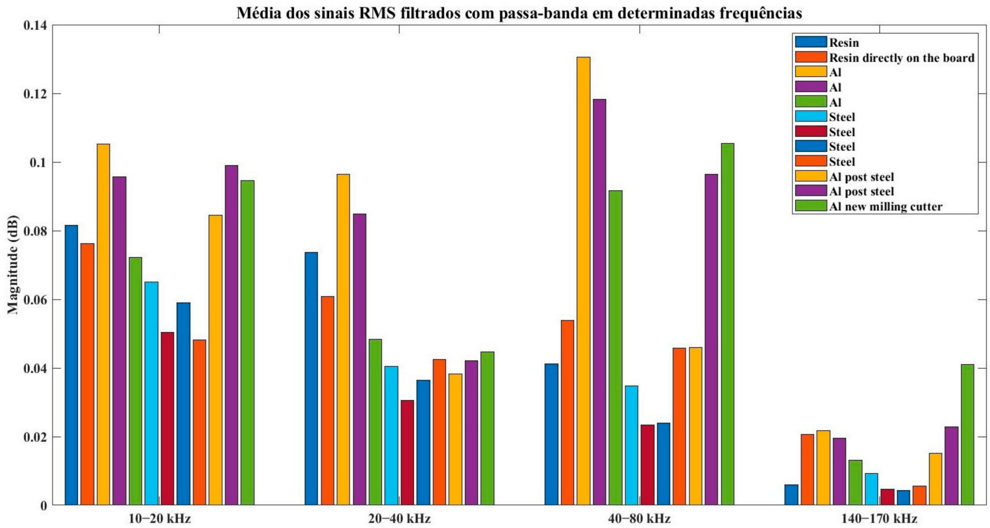

Figure 5. Mean of the 12 bandpass-filtered RMS signals in the chosen frequency ranges.

Lastly, the range from 140 to 170 kHz was deemed irrelevant for the study of milling cutter wear, as its magnitudes were much lower compared to the other selected ranges. This suggests that a significant portion of these magnitudes is noise rather than essential signals for TCM, indicating that high-frequency ranges are not relevant for predicting tool life in milling using acoustic emission.

4. Conclusions

To ensure the quality of precision large-scale components while enhancing productivity, this study presents an alternative TCM technique to prevent tool failures and obtain comprehensive information about its state during milling through a wireless data acquisition system. It was found that AE signals contain relevant information that, with proper signal processing, enables the extraction of features that can prevent failures in the milling process. After obtaining the acoustic signals using a piezoelectric AE sensor and using MATLAB® to process these signals and extract features, applying FFT and RMS, it was concluded that the frequency ranges of 40 to 80 kHz, 10 to 20 kHz, and 20 to 40 kHz are, in that order, the most important for analyzing milling cutter wear. Additionally, it was concluded that high frequencies are of little importance for wear analysis in the process using AE sensors. In conclusion, the results of this research are significant for increasing productivity, reducing manufacturing costs, optimizing tool life, reducing the risks of higher-order damage in the milling process, and taking swift actions when needed.

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