engineering proceedings

Proceeding Paper

Study on AE-Based Tool Conditioning Monitoring in CFRP Milling Processes †

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† Presented at the 12th International Electronic Conference on Sensors and Applications (ECSA-12), 12–14 November 2025; Available online: https://sciforum.net/event/ECSA-12.

Abstract

Industry 4.0, in its search for improvements in processes and efficient products, has increasingly invested in the use and development of high-performance materials for its production lines. We have seen this, with the introduction of CFRP in the aeronautical industry, since these composite materials have reduced the weight of aircraft and improved their performance. For the construction of large structures, drilling processes are also necessary to fix the parts. However, this machining process can end up causing failures in the structure as a whole. These structural failures occur due to fragmentation, tearing, or detachment of the matrix fiber, significantly reducing the quality and reliability of the final equipment. In this scenario, it is important to preventively detect these intrinsic production failures that end up condemning the final parts. One of the indirect detection methods is through acoustic emission. This work presents a feasibility study focused on the application of data-driven methods for delamination detection and tool wear monitoring in composite machining. A setup for a helical interpolation end milling drilling process were performed under varying machining conditions, from mild to severe, on CFRP composite plates. Acoustic emission (AE) signals were acquired at each machining pass. The methodology involved selecting an optimal frequency band, to obtain information about the wear of the drilling tool, through RMS and power spectral density (PSD) analysis, followed by using correlation indices to characterize tool wear progression. The results demonstrate the potential of spectral and statistical techniques to support real-time monitoring and decision-making in advanced composite manufacturing.

Keywords: Industry 4.0; CFRP composite; acoustic emission; EA signal processing; tool wear monitoring

Academic Editor(s): Name

Published: date

Citation: Dias, V.; Lopes, T.; Silva, M.; Rodrigues, A.; Dotto, F. Study on AE-Based Tool Conditioning Monitoring in CFRP Milling Processes. *Eng. Proc.* **2025**, *volume number*, x. https://doi.org/10.3390/xxxxx

1. Introduction

To develop new, increasingly efficient and lightweight materials, while also reducing emissions and environmental impacts [1], industries and researchers are increasingly investing in high-performance composite materials [2]. One example is carbon fiber-reinforced polymer (CFRP). This structure offers characteristics such as low density, high strength, stress, fatigue resistance, corrosion resistance, low thermal expansion, and high flexibility [1–3]. These properties make CFRP an ideal material for a variety of applications that require strength and lightness, gradually replacing metallic materials in industries such as aeronautics, naval engineering, automotive, construction, biomedical, and energy [1].

While composite materials have excellent mechanical characteristics and can be molded to their final design, they also present several challenges in their use, as they can suffer structural damage during the assembly and joining processes. Machining processes such as drilling, milling, turning, and grinding are still essential to ensure quality and precision [1–3]. Therefore, the main damage to the material is delamination, fiber fragmentation, fiber pullout, and fiber-matrix debonding. All these defects are caused by the machining process [3], which reduces quality and generates material erosion. Carbon fiber is quite resistant, and a commercial example is PAN (polyacrylonitrile fibers), with tensile moduli between 230 and 588 GPa [4]. Abrasiveness, tension, and low thermal conductivity increase friction with the tool and its wear [3]. Furthermore, according to [1], the temperature at the tool contact point accelerates the protection of the material's surface. Delamination and other types of failures, in addition to tool wear, lead to failures, rework, premature wear, and unnecessary tool and part replacements, all of which lead to reduced efficiency and increased production costs for composite materials. Therefore, it's crucial to ensure both the integrity of the CFRP structures and the condition of the tools used in this process to ensure the quality of the final product, avoiding reduced strength or part failure.

The major problem is that this type of damage occurs internally and, because it is not evident or visible to the naked eye, must be regularly inspected using non-destructive testing to ensure the integrity of the equipment [5]. Among the tests, thermography can be used either directly or through microwave-induced propagation techniques, ultrasound [5], or acoustic emission (AE) [6].

Since machining is a stage of the manufacturing process where a part can develop flaws, a tool that is not in good condition, worn, or damaged, can produce defects in the composite material, compromising its integrity. On the other hand, the machining process itself, even with the tool in good condition, over time, due to the process dynamics, execution configuration, friction, and abrasiveness of the composite, causes the tool to wear out over time, and the cycle repeats itself. Therefore, it is beneficial to perform a non-destructive test during milling. This allows us to indirectly monitor the condition of the tool and the integrity of the part being monitored [7].

Tool condition monitoring (TCM) is essential for achieving higher-quality, more efficient, economical, and safer machining [7,8] This monitoring can occur occasionally through routine inspections or through the integration of a system into the equipment. According to [7], online TCM responds quickly to failures predictively, with real-time feedback allowing for adjustments to cutting parameters during the process.

In the case of acoustic emission (AE), transient elastic waves travel through the material, being affected by microstructural changes, such as fractures. These changes are detected by piezoelectric transducers, which convert vibrations into electrical signals, enabling early detection of material failures [6,7]. After the signal is detected by the AE sensor, the data is consolidated in the computer through an acquisition system. The next step is signal processing to extract relevant information about the state of the monitored structure. This processing is performed using mathematical and statistical tools, or even by applying artificial intelligence, machine learning, and deep learning techniques [9]. Refs. [10,11] evaluated CIRP publications on sensor-based machining monitoring and proposed a workflow that begins with sensor signal detection, followed by data processing, extraction of relevant features from the signals, and decision-making based on the information obtained. Finally, it culminates in the execution of corrective actions or process adjustments. Ref. [6], 12 proposed AE signal processing with continuous emission in organic composite matrices in a noisy environment with a high hit rate, that is, filtering the signal before extracting the features, where the hit rate is the number of times the signal exceeds the threshold, as seen in Figure 1a. Ref. [13] systematically analyzed the CFRP drilling process, characterizing the damage including exit delamination by push-out, entry delamination by peel-up, burr, and fiber removal, through damage suppression techniques based on damage control strategies, contributing to an optimization based on the process, drilling conditions, tool design optimization, and the integrated application of multiple techniques, as seen in Figure 1.

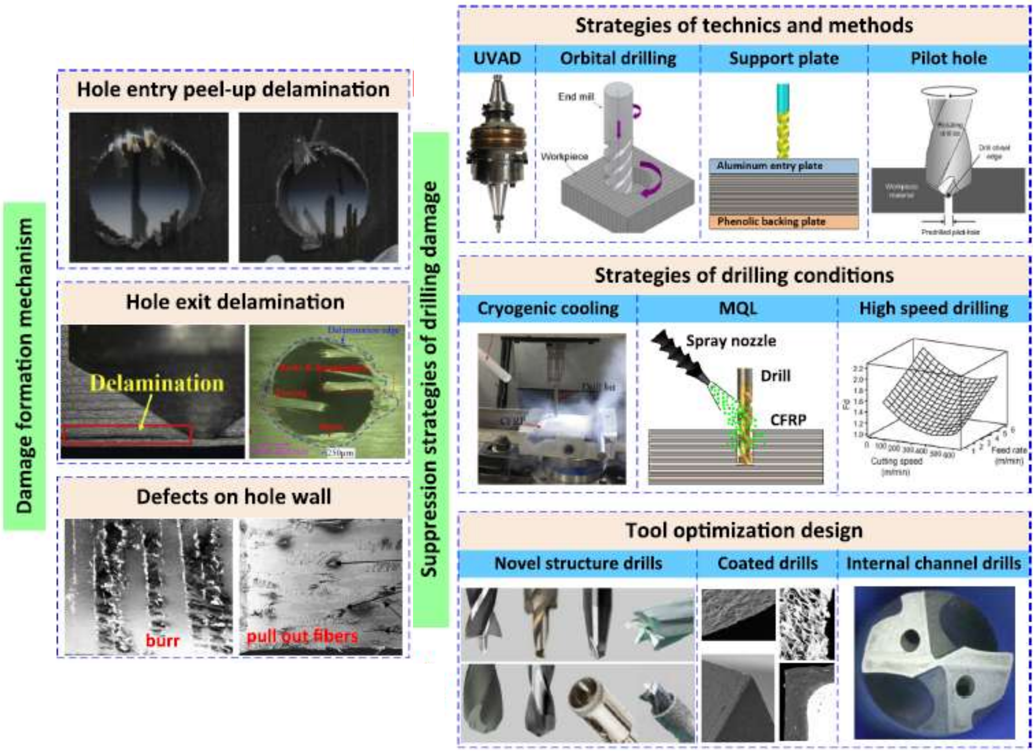

Figure 1. Logical relationship of the damage formation mechanism. adapted from [13].

Although CFRC is generally manufactured in pre-used form with very accurate dimensions, the final part quality, dimensional and positional accuracy, significantly impacts the mechanical properties, reliability, and durability of the materials. To ensure compliance with the dimensional tolerances, shape, and positioning accuracy required by the design, the component is often subjected to a secondary machining process after manufacture [14].

Connection holes between components are very common, especially in aircraft. For example, the Airbus A350XWB requires more than 36,000 holes to connect the fuselage and more than 5000 holes in the tail. The quality of this process and the risk of hole damage are directly related to the component's strength, stiffness, and reliability [13]. Due to the rigidity of carbon fiber and the composition of CFRP, its machining is difficult, yet delicate, since the rupture of the fiber or matrix generates burrs and cracks that easily lead to delamination and other damage, making it difficult to guarantee the quality of the machining [13].

When working with finished material, secondary machining often contributes to material failures. Consequently, the main damage to the material is delamination, fiber fragmentation, fiber pullout, and fiber-matrix debonding, all resulting from the machining process [15], as shown in Figure 2. Interface degradation further contributes to severe debonding, matrix cracking, and surface pitting. Therefore, monitoring and managing the machining temperature is essential [1].

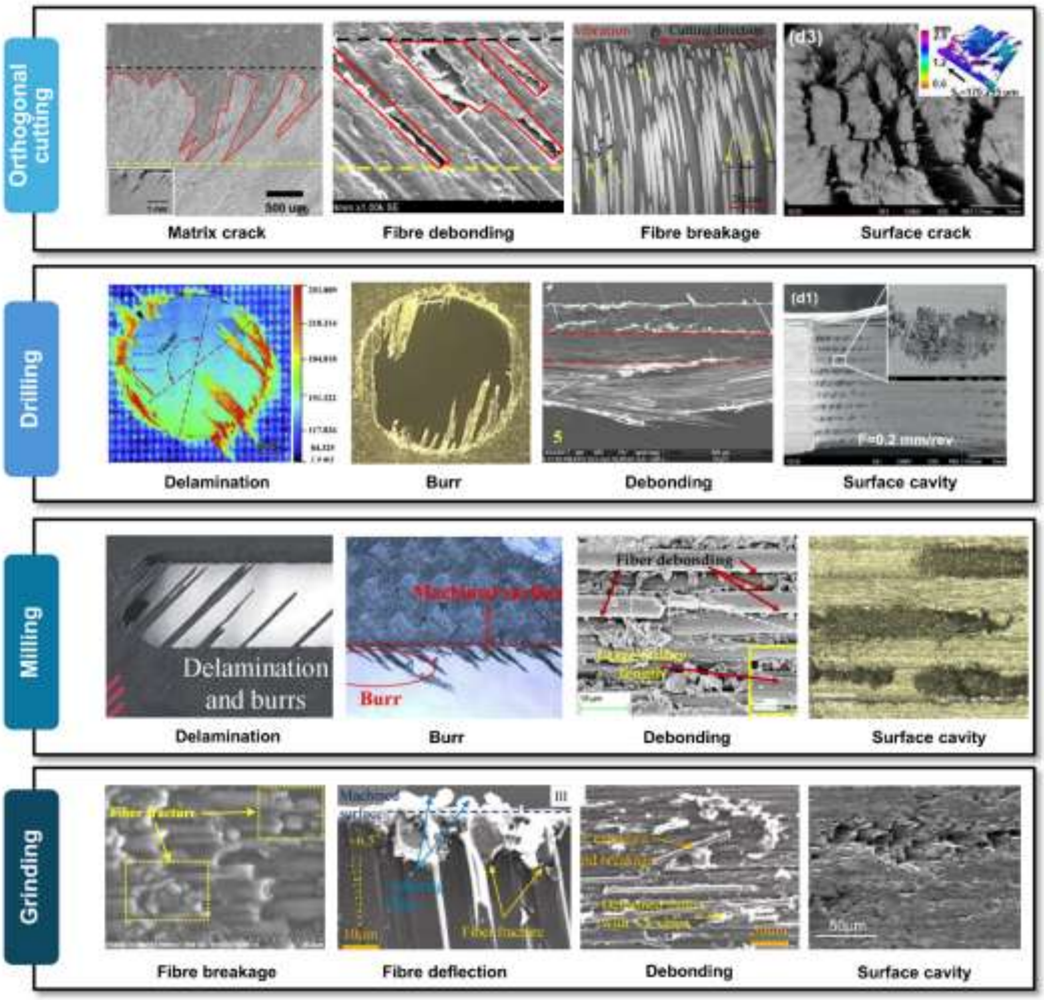

Figure 2. Typical CFRP damage generated in machining processes [1].

2. Materials and Methods

The work is based on a matrix of composite plate machining experiments whose data were collected by an AE sensor. This experiment was conducted in partnership with SENAI São Carlos. For this study, a PU resin device was initially fabricated to allow the clamping and collection device to be attached to the machining center (the blue item seen in Figure 3).

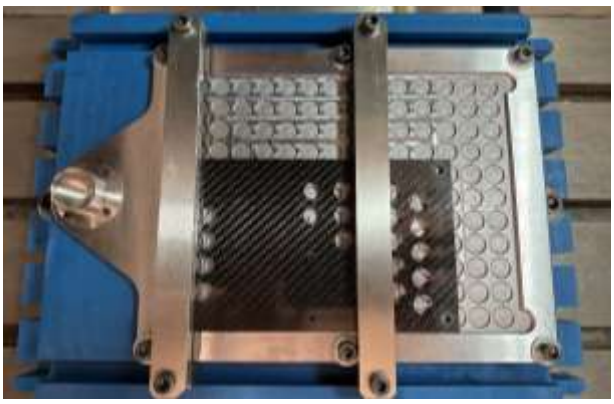

Figure 3. Device fixed to the Romi D400 machining center at Senai College in São Carlos.

Next, to ensure the CFRP plate remained fixed during machining, a steel plate was developed to accommodate the material, lock it so it would not move during milling, and allow for the coupling of the AE measurement sensor, identified as the metal part in Figure 3. A rectangular cavity was machined in the steel plate with several holes larger than the holes that will be drilled in the carbon plates. These holes serve as relief for the tools to exit, without them coming into contact with the steel plate, which would hinder the machining test with the composites.

Four different milling cutters were used in this work, as shown in Figure 4:

1. Carbide helical milling cutter with a diameter of 10 mm, length of 100 mm, helix angle of 35°, 4 flutes, coated with titanium carbide nitride, and hardness of 50 HRC.
2. Carbide helical milling cutter with a diameter of 10 mm, length of 100 mm, helix angle of 35°, 4 flutes, coated with naco4 nano coating, and hardness of 55 HRC.
3. Carbide helical milling cutter with a diameter of 10 mm, length of 100 mm, helix angle of 35°, 4 flutes, coated with nano blue, and hardness of 65 HRC.
4. Solid carbide helical milling cutter with a diameter of 10 mm, length of 100 mm, and a double helix angle of 40°, model COROMILL PLURA 2P460-OA–Sandvik.
5. Solid carbide helical milling cutter with a diameter of 10 mm, length of 100 mm, and a double helix angle of 40°, model COROMILL PLURA 2P350-OA–Sandvik.

Figure 4. Milling Cutters used (1) Titanium Carbo-Nitride Coating, (2) Naco4 Coating, (3) Nano Blue Coating, (4) Coromill Plura 2P460-AO and (5) Coromill Plura 2P350-AO.

A setup for a helical interpolation end milling drilling process were performed under varying machining conditions, from mild to severe, on CFRP composite plates. It was decided to measure the tools every 80 holes, with 77 wear holes on the designated plate, 3 holes for acoustic signal collection on a designated plate, and two plates per tool. This is the machining and measurement cycle adopted. Three initial holes were drilled with each tool to serve as a reference. After data collection using the acoustic sensor, holes were machined in five carbon plates. The tools were analyzed using a confocal microscope at EESC-USP and a digital altimeter at SENAI.

The AE sensor used to measure the frequency emitted by the tools during machining was a patented piezoelectric broadband sensor. The signal is captured during machining on a dedicated plate. The data, collected at a sampling frequency of 1.11 MHz, retrieved, and processed in MATLAB, as shown in Figure 5.

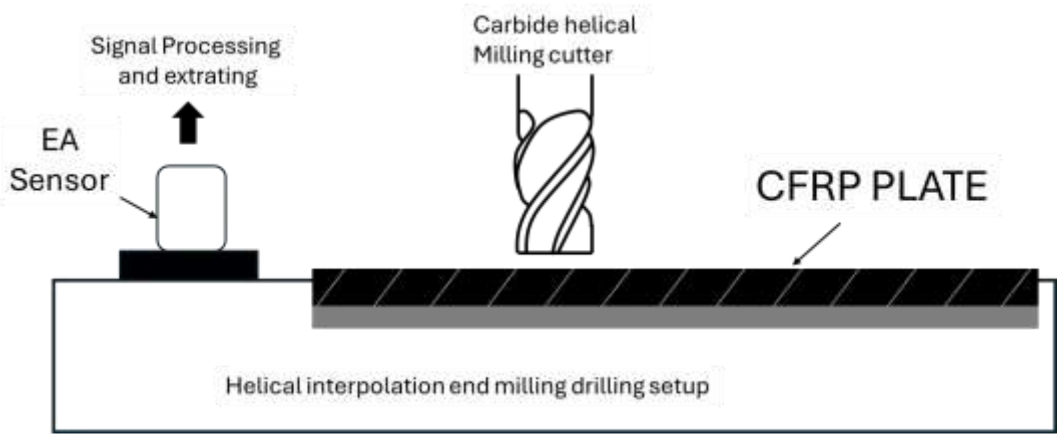

Figure 5. Process of capturing and processing frequency signals.

The data was collected and natively stored in binary format, with some characteristics such as: operating mode, sampling rate, gain, temperature, battery, trigger, time, and sampled signal. This binary data was converted into a Matlab table for processing.

3. Results

Initially, the MATLAB code responsible for signal processing was developed and tested. It proved effective in analyzing data from a well-known tool wear dataset. The same algorithm is currently being applied to the collected signals. It is expected that some characteristics related to the energy level and onset of tool wear may be identified, if this was collected during the analysis. With the methodology applied above, it is believed that it will be possible to identify the signal's characteristics.

Figure 6 shows the signal collected at a frequency of 1.11 MHz, with a gain of 45, RAW mode, ambient temperature between 25 and 30 °C, as measured by the sensor, trigger of 0.0993, and duration of 4500 s.

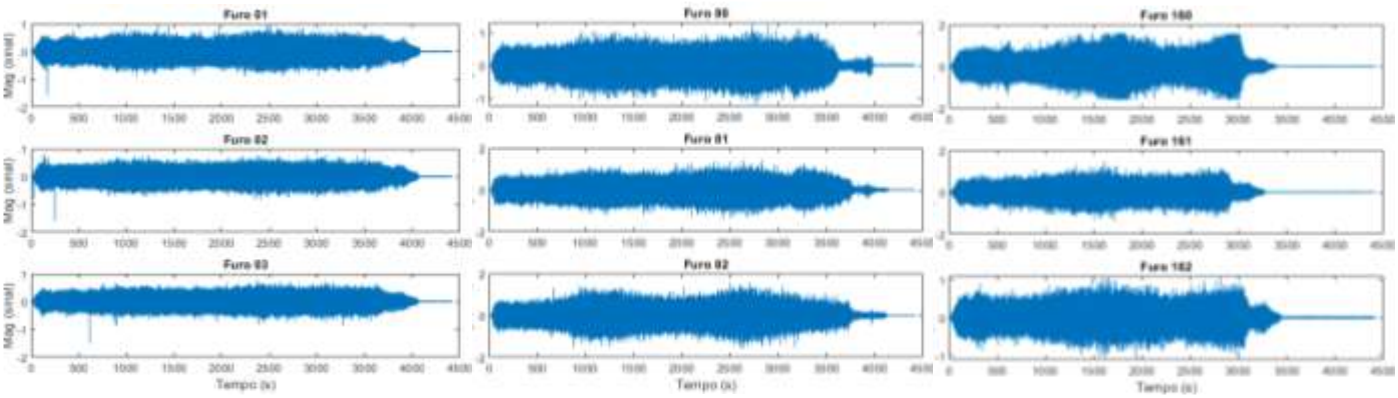

Figure 6. Signal collected.

This signal alone is incapable of providing relevant information for identifying tool wear. To identify the frequencies that contained a signal that could better identify the state of the tool, an FFT of the collected pure signal was made, and a separation of the frequency bands in which we could identify some indication of the signal intensity for each state of the milling cutter.

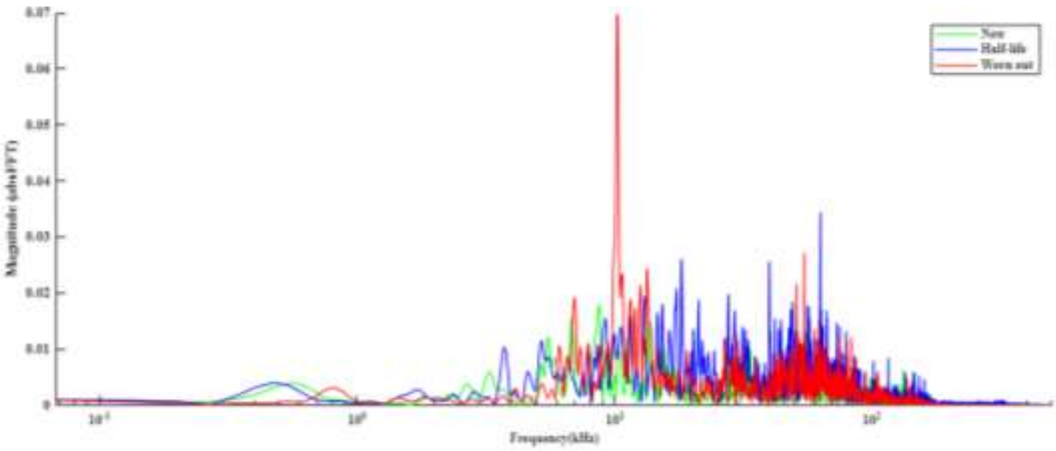

Figure 7. AE frequency spectra of three wear conditions milling cutters.

The fast Fourier transform can provide information about the magnitude identified in each of the signal's frequency bands. However, as we have a random and aperiodic signal, we are still unable to identify any other frequency band information that indicates possible tool wear. However, by using this information we can do the stratification of the RMS energy level, that was carried out for each of the frequency bands considered. A graph was drawn in Figure 8, in which we can identify the relationship between this RMS and tool wear, allowing us to select the bands in which we have a better distinction between new, half-life and worn.

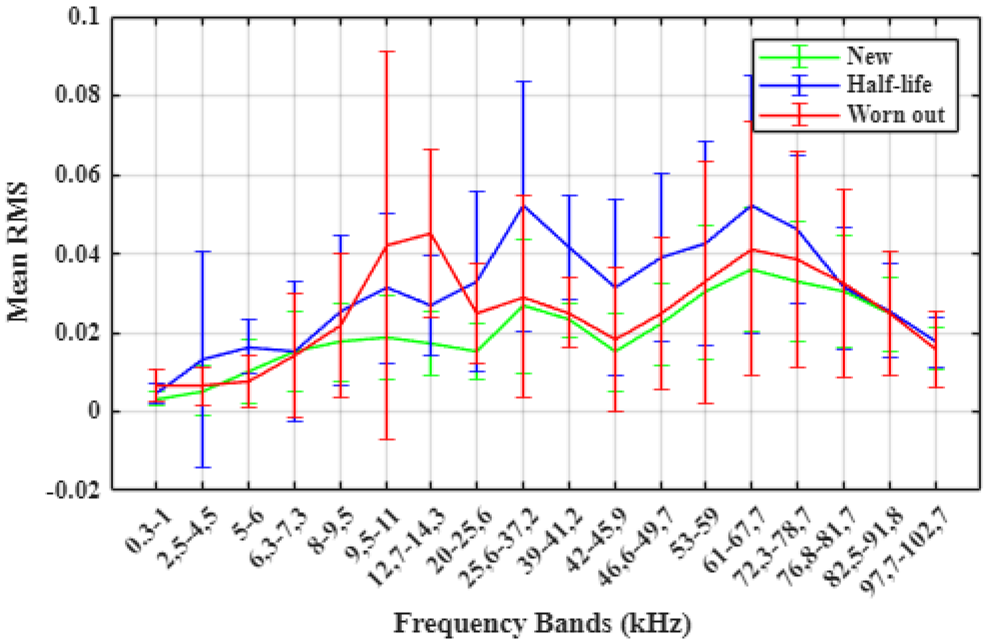

Figure 8. Values of RMS signal as a function of frequency bands.

To verify the effectiveness of the frequency bands selected by the previous method, we performed event counting to analyze acoustic emission activity. For comparison, we used the raw signal and the filtered signal using one of the relevant frequencies in Figure 8, which better distinguishes the tool's wear status. For event counting, we used a threshold based on the crest factor value for a sample of 2048 events, the same one used to calculate the RMS. Figure 9 shows a reduction in AE activity, with a significant shift for the worn tool compared to the half-life tool, which had only a few dozen events, and the new tool had no counts.

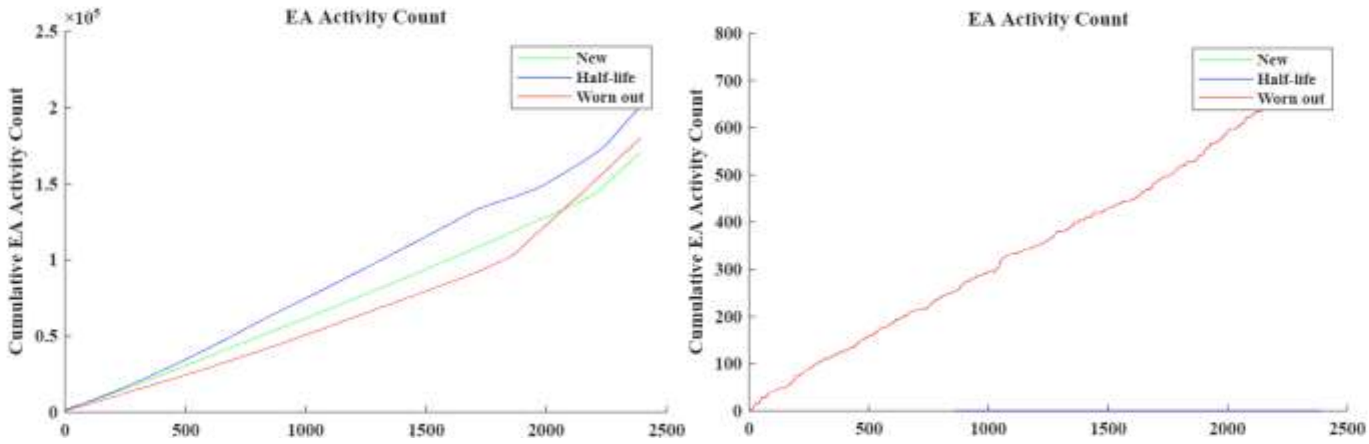

Figure 9. Accumulated EA activity count (**a**) unfiltered signal (**b**) filtered signal from 9.5 to 11 kHz.

Although the RMS analysis performed yields good results, it is somewhat simplistic. Therefore, the signal's power spectral density was also estimated using the Welch nonparametric technique, with a Hanning window of 8192 points, and a DFT calculated on the peridogram of a 2^{21}-point segment, with a 50% overlap rate. This resulted in a signal with the characteristics shown in Figure 10, which could then be manually analyzed to identify the frequency with the greatest power variation, thereby enabling identification of the tool's quality.

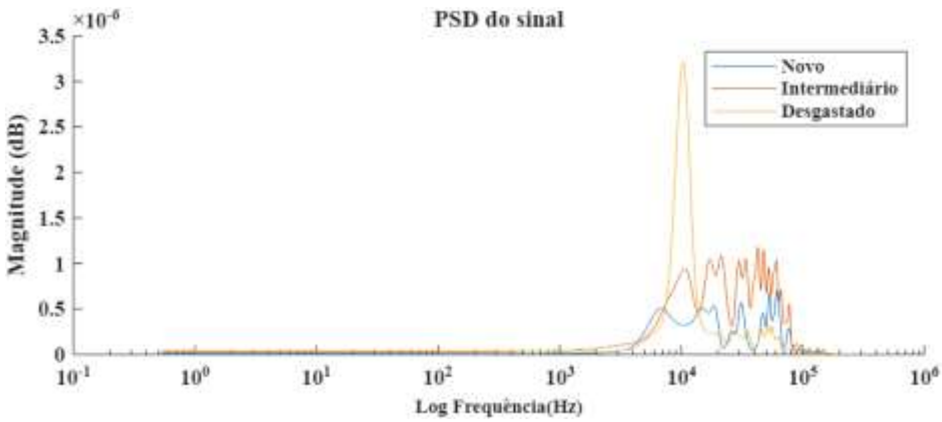

Figure 10. Power Spectral Density of the collected signal.

In the context of the previous study, frequency band delimitation was used as a key characteristic for the tool wear classification process. To achieve this goal, the Power Spectral Density (PSD) signal was subjected to filtering processing that used one of these bands as a criterion.

As a result, we observed on Figure 11 a clear classification of tool wear in the PSD of the filtered signal, which can be used as a method for pattern classification.

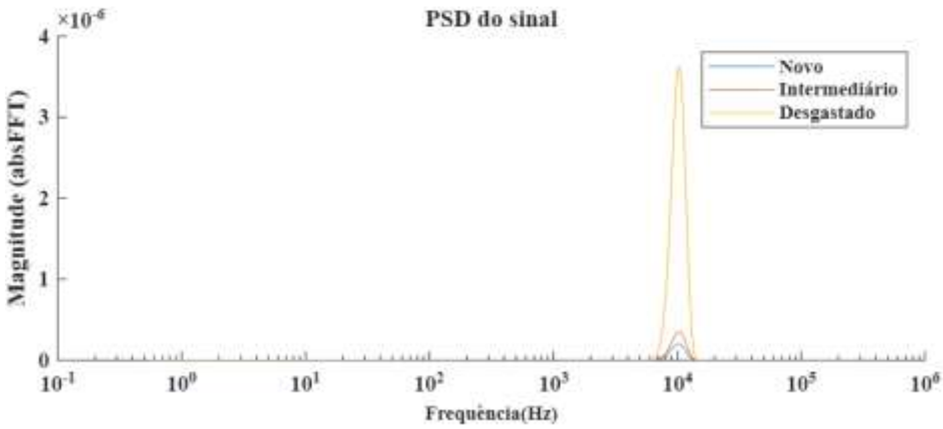

Figure 11. Power Spectral Density of filtered signal from 9.5 to 11 kHz.

4. Conclusions

This study investigated the feasibility of applying acoustic emission (AE)-based methods for tool condition monitoring in carbon fiber reinforced polymer composite (CFRP) milling processes. The methodology employed the selection of an optimal frequency band, Root Mean Square (RMS) and Power Spectral Density (PSD) analysis, along with correlation indices to characterize tool wear progression. The results demonstrate the significant potential of spectral and statistical techniques to support real-time monitoring and decision-making in advanced composites manufacturing.

Specifically, the RMS analysis, while considered simplistic, provided promising indications. The PSD analysis, performed using the nonparametric Welch technique with a Hanning window of 8192 points and DFT calculated on a 221-point segment with a 50% overlap rate, allowed manual identification of the frequency with the greatest power variation, directly correlating with tool quality. Notably, a clear classification of tool wear was observed in the PSD of the filtered signal using RMS function of frequency band as shown, suggesting its applicability as a robust method for classifying wear patterns. These findings reinforce the potential of acoustic emission as an effective tool for the preventive detection of intrinsic production failures and tool wear monitoring in composite materials, contributing to the optimization of efficiency and cost reduction in Industry 4.0.

Author Contributions:

Funding:

Institutional Review Board Statement:

Informed Consent Statement:

Data Availability Statement:

Conflicts of Interest:

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