Exploiting sound signals for fault diagnosis of on-site machining

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Abstract

On-site machining is a specific domain where damaging vibrations can be generated by the dynamic interaction between the tool and the workpiece. These vibrations are often the cause of the degradation of the machined part and the cutting tool. It is, therefore, necessary to suppress and or control this phenomenon. For this purpose, we present the acoustic characterization of a machining defect. We present our work on cutting tool monitoring through the acquisition of sound signals during on-site machining operations. We implemented a dual-microphone treatment to filter out ambient noise, including industrial noise. Following this, we carried out experimental tests to observe the gradual degradation of the machining inserts. Observations have shown the links between the degradation of the cutting plates and the recorded sound signal. Moreover, we show that the customer specifications are respected as long as we do not notice a difference of 10 dB in the sound signal.

1 Introduction

In today's industrial world, corrective and preventative maintenance plays a crucial role in limiting production losses. It is even more so if industrialists cannot move their defective equipment to rehabilitate it. One activity exists to overcome these issues: On-site machining. It consists of carrying out a wide range of machining operations to repair and restore immovable parts, right in the industrial plants, using portable machines.

However, due to the lightweight of these portable machines, significant faults can occur, especially chatter [1] [2] [3], machine failure [4] or abnormal machining conditions [5] [6] [7]. To study those defaults, we focus on the sound produced while machining and especially with on-site machining, which is a fundamental source of information. Indeed, microphones are very suitable for chatter and default detection in milling because their sensitivity to the onset of chatter is comparable to that of expensive sensors such as plate dynamometers, displacement probes and accelerometers [8]. In addition, the sensors used to acquire the sound signals are relatively cost-effective. Thus, the use of audible signals is necessary for on-site machining condition monitoring [9].

The authors aim to present our results on the acoustic monitoring of dynamic behaviour during on-site milling. More specifically, we will focus on the health of the machining inserts during our operation. For this purpose, we have implemented a dual-microphone analysis to suppress industrial noise. Indeed, the latter is very present and strongly degrades our acoustic measurements. Secondly, we are studying an experimental approach to detect the gradual degradation of the milling inserts and their consequences on the surface roughness. We will confront these results with our customer specifications.

2 Methods

Experiments were carried out using a lightweight milling machine frequently used on on-site machining. A set-up was then specifically designed to evaluate the effectiveness of our on-site dynamic machining behaviour through the acoustic field. Shown in Figure 1 is the lightweight milling machine with a machined sample S235JR fixed by six welding points on a common plate. This machine is equipped with three dovetail slides (X, Y and Z axis) of lengths 1250, 300 and 300 mm, respectively. The X-axis is equipped with a demountable electric power feed ALGS-AL310S. The Y and Z-axis each have a manual drive. The milling head was fixed on the Z-axis dovetail slide. This head was powered by an OMP100 hydraulic motor that drives a milling cutter SA40. The cut was made with five Kennametal KC725M (TiAlN-PVD coated carbide) machining inserts, reference [ISO SEPT1404AEENGB2]. To be sure of the cutting experimental conditions, we adjusted the position of each light milling machine component with a Faro laser tracker [10].

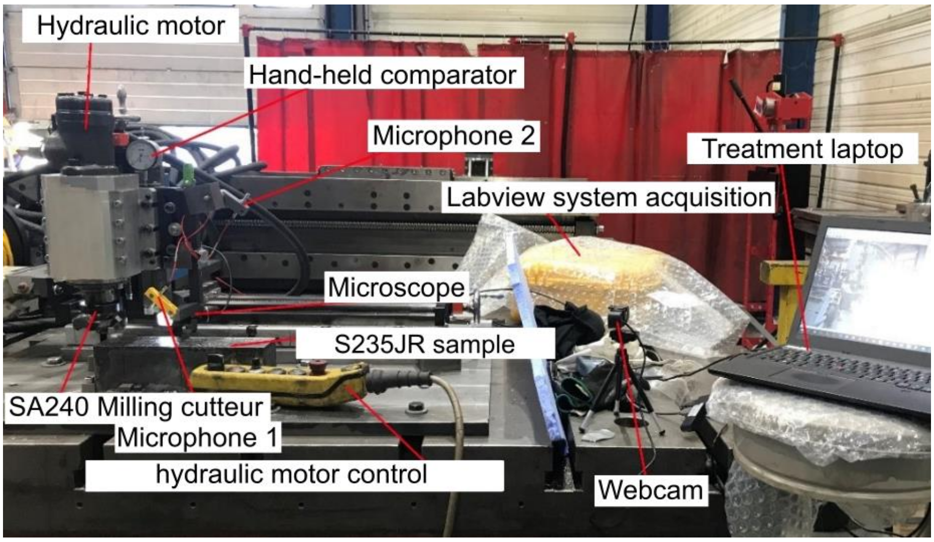


Figure 1: The experimental setup for the acoustic dynamic behaviour of the on-site milling machine.

To carry out the acoustic acquisitions, we use a GRAS microphone, reference [40BE]. It is an omnidirectional microphone of 1/4" size. It has a useful operating range of between 4 Hz and 100 kHz. This covers infrasound, audible and ultrasonic frequencies. The dynamic range of the microphone is between 30 and 168 dB(A) (160 dB with a CCP pre-amp). The microphone has a sensitivity of 4 mV/Pa and an electrical capacitance of 5 pF. An important feature of this microphone is its frequency response. There is a strong dependence between the response of the microphone and its incidence's angle with the acoustic source. This should be considered when positioning our microphones.

To study the cutting phenomena and the dynamic behaviour of the milling machine, we will locate our microphone as close as possible to the cut. The microphones holder was therefore built to attach them onto the milling head and direct it towards the cutting inserts. The acoustic responses of the system are acquired and processed using a compact NI cDAQ-9174 DAQ chassis, a 9122 module and a LabView module dedicated to sound and vibration analysis.

The first microphone will be located as close as possible to the cup. The second microphone is oriented symmetrically to the first microphone to pick up ambient noise. We have then located it at the top of the milling head. This will allow the signals to be processed using a 'dual microphone' technique introduced by Joshi [11] to reduce the ambient noise significantly.

Several experiments are required to study the gradual deterioration of cutting inserts during our on-site machining operations and especially on-site milling. We will present here our results for a set of cutting parameters illustrating all the phenomena observed by our experiments. For this test, we set a cutting speed of 200 tr.min^{-1}, a feed rate of 240 mm.min^{-1}, and a depth of cut of 0.4 mm for a machined sample length of 300 mm.

2.1 Implementation of the dual microphone processing to reduce industrial noise in our sound measurements

In our on-site machining operations, we are exposed to considerable industrial noise. We must therefore prevent this by implementing a signal processing technique explained by Joshi et al. (2013). This processing becomes a priority to ensure a clean and reliable measurement. It consists in removing the ambient noise by following the process shown in Figure 2.

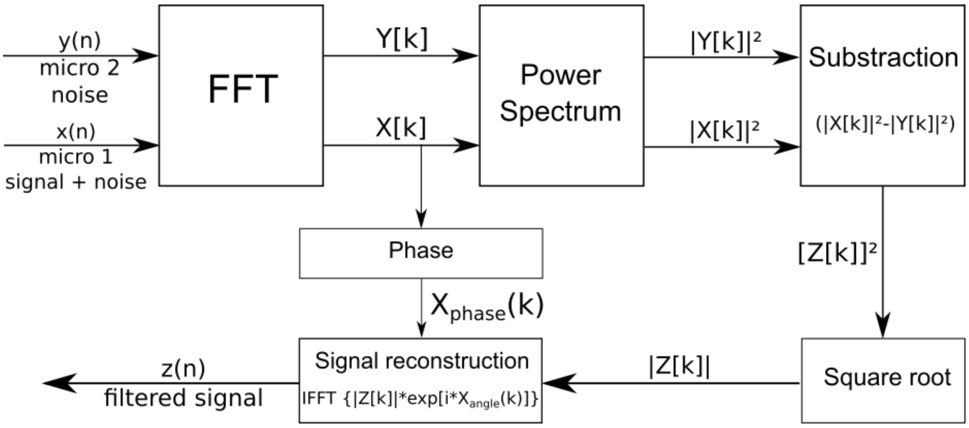


Figure 2 : Schematic representation of the dual microphone processing.

Two acoustic signals should be recorded. The first microphone x(n) receives the machining signal (the signal generated by the machine including the environmental noise). The second microphone y(n) receives only the environmental noise.

After an FFT of these signals, we obtain the spectra X[k] and Y[k]. We then solve for the phase of X[k]: $X_{angle}(k)$. In parallel, we calculate the root of the previously squared spectra:

$$|Z[k]| = \sqrt{|X[k]|^2 - |Y[k]|^2} \tag{1}$$

We can finally reconstruct the filtered signal using the phase of X[k]:

$$z(x) = IFFT\left\{Z[k] * exp\left(i * X_{phase}(k)\right)\right\} \tag{2}$$

2.2 Process verification and extraction of the useful machining signal

To assess the relevance of this noise filtering method, we investigate the signal envelope. We then represented on the same graph (Figure 3) the signal from the microphone close to the cut (orange), the signal capturing only the ambient noise (blue) and the subtracted signal (green).

We observe that the amplitude of the ambient noise corresponds to the lowest values. The highest values are those recorded with the microphone positioned close to the cutting part. The green curve representing the noise signal has a lower amplitude than the signal from the microphone near the cutter. This is also confirmed by listening to the audio of the denoised signal. We can therefore state that we have successfully implemented this denoising.

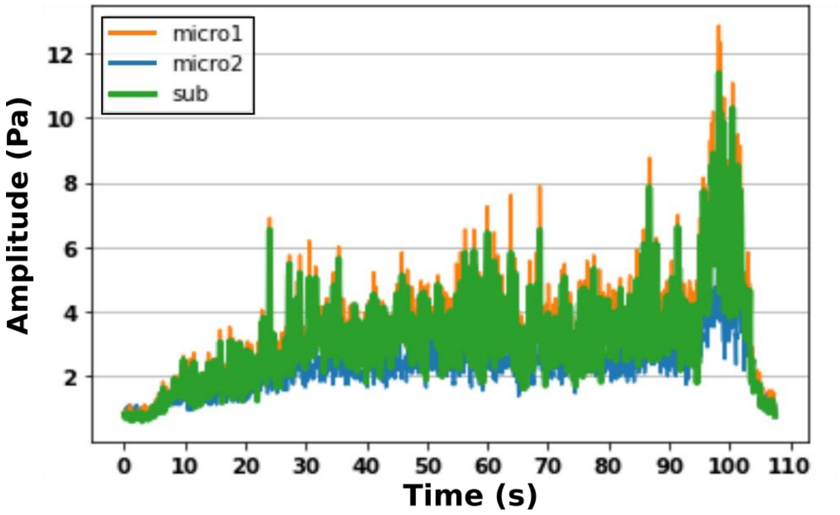


Figure 3 : Signal envelopes of the microphone 1 (orange), the microphone 2 (blue) and the filtered signal (green).

To record the complete machining signal, we start and stop the recording a few seconds before and after the machining. Our recording signal then contains irrelevant data. To extract only the valuable part of the sound signal, we use the RMS value to identify the general pattern. With this method, we can easily detect the start and end of the machining process and extract the desired data as shown in Figure 4.

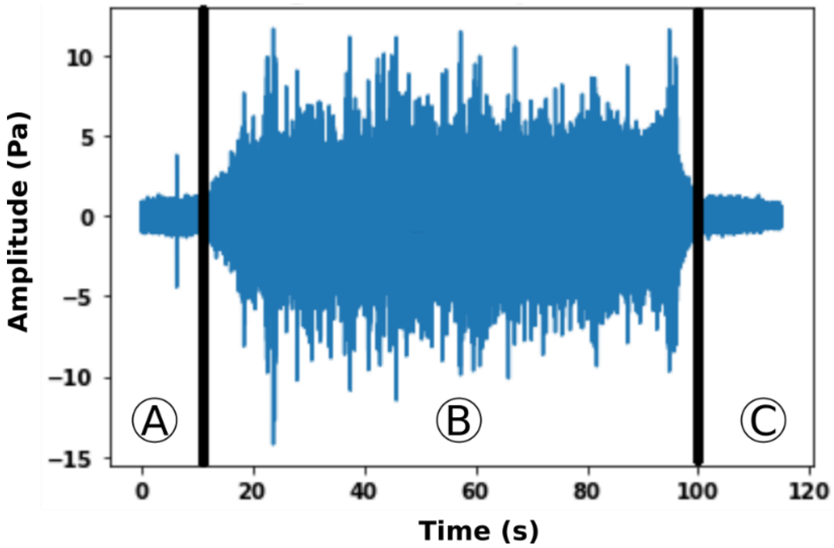


Figure 4: Representation of a relevant sound sequence corresponding only to the milling operation. (A) corresponds to the start of the milling machine, (B) corresponds to the machining of our material and (C) corresponds to the end of the process without machining.

2.3 Estimation of the degradation rate of the cutting inserts

During these tests, we were particularly interested in the visual appearance of our cutting inserts. We then observed a continuous degradation as the machining time passed. For example, Figure 5 shows the visual evolution of insert number 3. Gradual degradation of the cutting edge can be seen from test number 32 to test number 38. In Figure 5 test 33, a greyish spot can be seen caused by the melting of the chips on the cutting edge. This phenomenon is due to extremely high temperatures during machining. In the following test, the material is torn away from the cutting edge. This phenomenon, which is perpetually repeated in subsequent tests, is responsible for the progressive and complete degradation of the cutting insert.

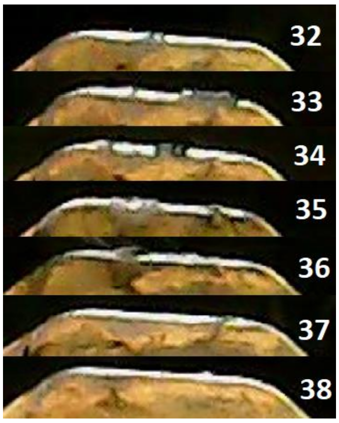
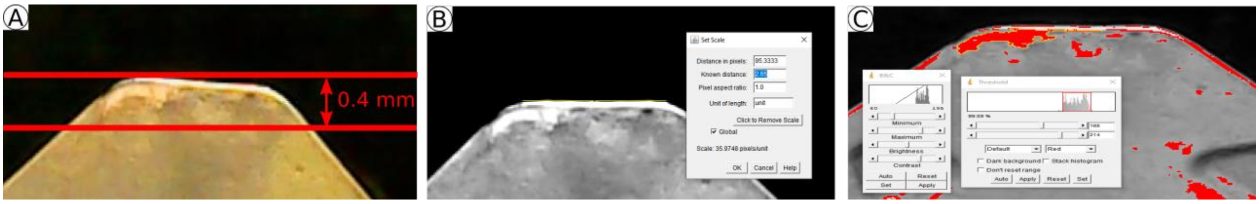


Figure 5 : Cutting edge picture of insert n°3 from test 32 to 38.

To acquire a quantitative indicator of cutting insert degradation, we use a purely visual indicator. To do this, we took photographs at each machining pass. We then post-processed our images with the "Image J" software. The first step was to convert the frames into 8-bit black and white ones. The insert's slope was modified to have a horizontal edge and thus obtain a scale factor. Knowing the exact distance of the camera and the resolution, we then define a scale factor (see Figure 6). To highlight the wear details, we also adjusted the brightness.



Distance in pixels: 95.3333
Known distance: 2.65
Pixel aspect ratio: 1.0
Unit of length: unit
☑ Global
Scale: 35.9748 pixels/unit

Default Red
☐ Dark background ☐ Stack histogram
☐ Don't reset range

Figure 6: (a) initial picture (b) 8 bit black and white picture with a horizontal edge (c) highlighting of the degradation area.

To determine the degradation of our cutting inserts, we have distinguished two area. The first is the zone between the tip of the cutting insert and the limit given by the chosen cutting depth (here 0.4 mm). The second is the area after the selected cutting depth. Two degradation rates are defined inside and outside the 0.4 mm height limit as follows:

$$\tau_{<0.4} = \frac{A_{d\ |<0.4}}{A_{tot}} \qquad and \qquad \tau_{>0.4} = \frac{A_{d\ |>0.4}}{A_{tot}} \tag{3}$$

$A_{(d\ |<0.4)}$ the area damaged by the machining inside the 0.4 mm height limit, $A_{(d\ |>0.4)}$ the area damaged by the machining outside the 0.4 mm height limit and A_{tot} the total area of the insert inside the 0.4 mm height limit.

3 Results

These two indicators are shown in Figure 7. On the left, the evolution of the degradation rate inside the 0.4 mm height limit of the machining insert can be seen. The degradation rate profile as a function of machining time is different for each insert. Indeed, we observe an increased degradation of insert n°2. Its total wear occurs after 15 minutes. After the third machining pass (trial 3), insert number 3 started to degrade following the same profile as insert n°2 (see curve orange and green Figure 7). After trial 8, the rate of insert 3 stagnates. It can be seen that degradation is taking place on insert n°5. After the rate on insert n°5 has exceeded 80%, it is again the turn of insert n°3 to degrade. In the same test, the wear on pad n°4 increased significantly. Finally, the degradation rate of insert n°1 deteriorated linearly.

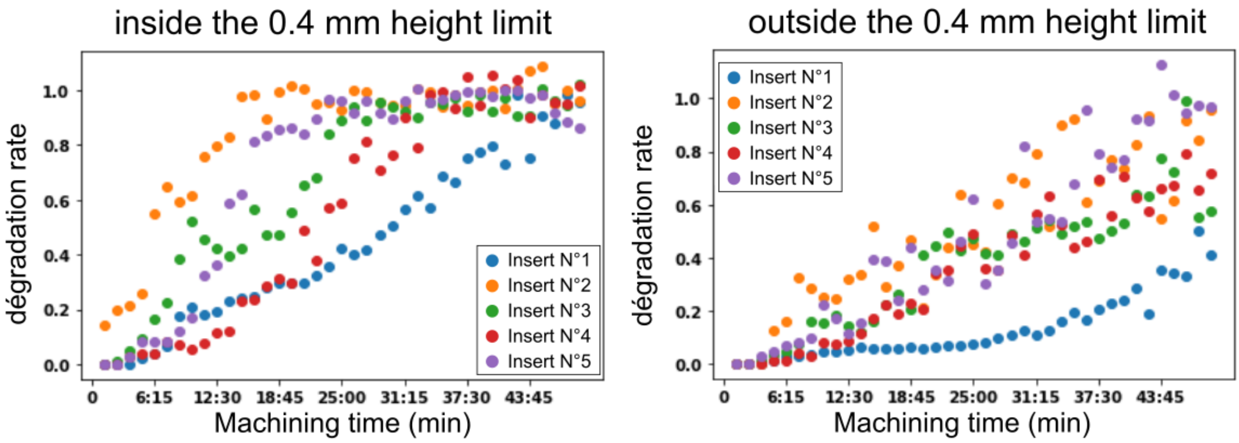


Figure 7 : degradation rate inside and outside the 0.4 mm height limit in function of the machining time.

The presence of the second indicator is due to the chip rolling up until it reaches the deflector. Its primary function is to break up the chip and remove it from the cutting area. Hence, it is necessary to observe outside of the cutting depth. The impact of this phenomenon is quantified by the degradation rate outside the 0.4 mm height limit (Figure 7). we observe that the wear rate increases steadily and linearly during the tests. However, the slope of these trends is unique for each insert. The steepness of the curve slope follows the order of degradation observed for the innerwear of the cutting inserts. Indeed, inserts 2 and 5 have high slopes of external wear degradation and are also the first to have 100% internal wear. The following inserts are 3 and 4. Finally, insert 1 has the lower inside and outside degradation rate.

These results are supplemented by those obtained from the microphones. The mean sound level (in dB) was shown as a function of the machining time (Figure 8). The sound level obtained was previously processed using the dual microphone technique. The result is a non-trivial evolution of the sound level. Indeed, "jumps" can be observed after the first test but also after tests 11 and 32. The minimum and maximum values of the sound level are respectively: 87.7 dB and 98 dB. The standard deviation of the sound level increases steadily with each test, except for two of them (tests 17 and 34).

We also measured the roughness at three different locations of the machine material during each test. Figure 8 shows the average roughness value for these three points as a function of the tests carried out. A relatively linear evolution of the roughness can be observed. The minimum roughness is evaluated at 2.7 µm and the maximum at 9.3 µm. However, several roughness peaks are observed after tests 7, 16, 23, 29 and 35.

When measuring the average sound level, we were also able to measure the mean frequency barycentre for each test (Figure 9). This ranged from 2450 Hz to 1600 Hz. It gradually decreases during the tests until the "critical" test 11. From this test onwards, this parameter starts to decrease sharply until it reaches a relatively constant value of 1600 Hz. The standard deviation of the frequency barycentre remains globally constant throughout the tests. An exception is test 8, where the standard deviation increases drastically.

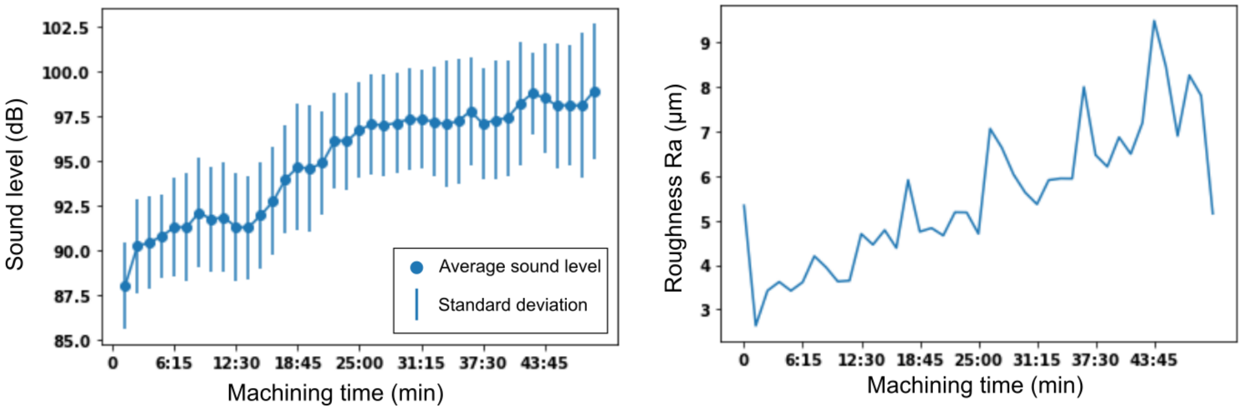


Figure 8 : Mean sound level and roughness in function of the machining time.

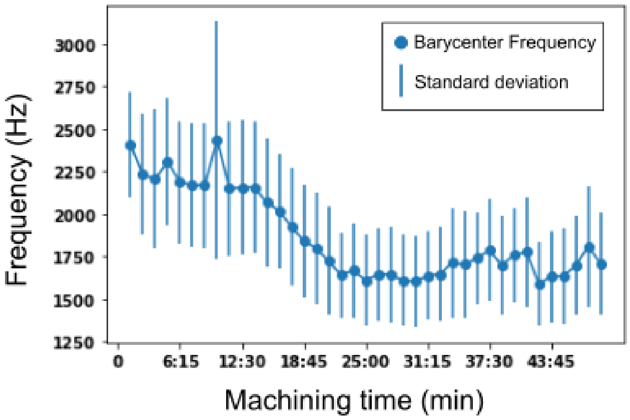


Figure 9 : Average barycentre and its standard deviation according to each test performed.

4 Discussion

From these tests, we can establish direct relationships between the acoustics and our on-site machining processes. Hence, we can link the roughness, noise level, insert condition and frequency barycentre. In this way, we can correlate the tolerances requested by the customer, the health of the machine and the machining performed.

Before starting the discussion, it is necessary to distinguish two types of operation in on-site machining: the usual cutting and the finishing process. In the first case, we roughly machine the material without worrying about the surface finish obtained. The objective of this operation is to go as fast as possible even if vibrations and chatter occur that lead to an unstable cut. After the usual machining follows the finishing operation. Thanks to conservative cutting parameters, this operation allows the customer's tolerances and the required surface finish to be respected. A distinction must be made between these two operating phases. Another relevant aspect is the delimitation of these results, which are then dependent on our imposed cutting limit conditions. They will therefore be different from other cutting parameters.

Initially, the "dual-microphone" treatment seems to be effective in the laboratory. It then remains to carry out tests in realistic on-site machining conditions. If the treatment is not as effective as now, it is possible to improve the signal processing by using wavelet processing.

Furthermore, one of the most important aspects for the customer is the roughness obtained after the machining. Our experience with client requests suggests that the roughness required is between 3.2 and 6.4 µm. Bearing that in mind, our results allow us to decide on two points. For a required roughness of 3.2 µm and these experimental conditions, it is necessary to change the cutting inserts for the finishing operation. However, we estimate that a noise level of less than 90 dB under these experimental conditions allows the desired roughness to be achieved.

The second point concerns the required roughness of 6.4 µm maximum. This roughness value is overcome in experiment 14. However, if we look at the linear evolution of this roughness as a function of the tests, we can see that the required roughness is only exceeded from experiment 20 onwards. If we look at the measured sound level, we obtain a value of 96 dB after filtering the sound signal. It means that there was an evolution of about 10 dB before reaching the threshold roughness value requested by the customer. Further experiments are required to validate these results.

Another important comparison should be made between the rate of degradation rate and the noise level generated. First of all, not all insert degradation rate occurs at the same time. We can therefore conclude that the positioning of the insert is not perfectly flat. Furthermore, it is interesting to note that each time an insert starts to degrade significantly, there is a much more pronounced increase in the noise level. This is a behaviour that it would be good to validate by setting up other comparative tests.

5 Conclusion

This paper presents the acoustic characterization of a machining defect. We present our work on cutting tool monitoring through the acquisition of sound signals during on-site machining operations. We implemented a dual-microphone treatment to filter out ambient noise, including industrial noise. Following this, we carried out experimental tests to observe the gradual degradation of the machining inserts. We highlighted two quantitative parameters. They made it possible to emphasize the non-homogeneous degradation of the cutting edges of our platelets. In addition, the study also makes it possible to distinguish between non-homogeneous degressions and different deflectors. The profile of the deflector degradations appears to be linear and related to the degradation of the cutting edge.

Observations have shown the links between the degradation of the cutting plates and the recorded sound signal. Thus, we show that the customer specifications are respected as long as we do not notice a difference of 10 dB in the sound signal.

In addition, it is interesting to note that each time a cutting plate begins to degrade significantly, there is a much more pronounced increase in the noise level. This feature should be validated through further comparative tests. Finally, this approach of default detection through acoustic will play its full role for on-site machining activity once an active control system has been set up based on those results.

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