Experimental investigation about abrasion wear of microtools through direct and indirect measurements.

Alessandro Metelli[1,a], Andrea Abeni[1,b*] and Aldo Attanasio[1,c]

[1]Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze 38, 25123 Brescia, Italy

[a]alessandro.metelli@unibs.it, [b]andrea.abeni@unibs.it, [c]aldo.attanasio@unibs.it

Keywords: Tool Wear, Micromachining, Cutting Force, Lead-Free Brass, Surface Integrity, Milling

Abstract. In the industrial context, tool wear has a strong impact on productivity, manufacturing costs, surface integrity and surface roughness. The most common approach on tool wear monitoring requires the estimation of the tool life by performing specific tests according to ISO international standards. A huge number of tests must be performed due to the strong correlation between tool life and process parameters, i.e. cutting speed, feed rate, depth of cut, lubrication. In micro-machining, the size downscaling related issues reduces the tool life. Furthermore, the direct measurement of tool wear requires more accurate instruments at higher magnification than conventional size machining; the tool wear standards do not cover the specific case of micro-machining, so no references exist about, for example, the limit of the width of the flank wear land. The cost in terms of money and time of the wear tests frequently resulted in an un-optimized approach, with a more frequent than necessary substitution of the tools. The development of systems of indirect measurement to monitor tool wear in high-speed micro-machining appears a valuable objective. In this work, an experimental setup was designed by constraining a sheet workpiece on a triaxial piezoelectric loadcell to record the force signals during the machining. The material of the workpiece is CuNi18Zn20, a lead-free hard-to-cut material employed to manufacture micro-products in several industrial sectors, such as jewelry, horology, electronics and biomedical. A flat-end micro-mill with a nominal diameter of 0.8 mm was utilized to machine the upper surface. The machining was periodically interrupted to check the wear on the tool by measuring some geometrical features with a 3D multifocal optical microscope. Moreover, the surface integrity of the machined workpiece was investigated by measuring its roughness. The three force components were elaborated to compute some parameters to research their correlation with the tool wear. The experimental setup was successfully tested, and it can be employed to perform new machining with different materials, tools and process parameters. The procedure allows to monitor online the effects of the wear on the tool on the machining. The data analysis allowed to define a correlation between the force components and the tool wear and a correlation between surface finishing and tool wear.

Introduction

Tool wear monitoring is a critical aspect of machining processes, particularly in micro-milling, where tool dimensions are below the millimeter scale. Tool wear significantly impacts surface quality, dimensional accuracy, and operational efficiency. The challenges in micro-machining are heightened due to the small size of tools, which accelerate wear and necessitates innovative monitoring techniques to maintain both productivity and quality [1, 2]. Optical microscopy has been the primary method for measuring tool wear [3]. The ISO 8688-1:1998 standard specifies recommended procedures for tool life testing during milling operations. It provides a structured framework for evaluating wear progression under controlled conditions, ensuring the repeatability and reliability of results. This direct inspection method allows detailed analysis of the cutting

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

edges, including parameters such as flank wear width (VB). Optical systems offer highly accurate measurements and remain the best technique for assessing wear progression [1, 4]. However, optical inspections have significant limitations. They require interrupting the machining process to examine the tool, increasing downtime and operational costs. Typically, tools are removed after machining a predefined number of parts, and their edges are analyzed under high magnification. Although reliable, this approach is labor-intensive and unsuitable for the industrial applications [5]. Moreover, for small tools, the application becomes more challenging compared to larger tools because it demands higher-resolution and higher-magnification equipment, as well as greater operator skill to achieve accurate and consistent measurements. To address these issues, alternative methods have been developed to monitor tool wear indirectly through real-time data acquisition. These approaches aim to reduce dependence on optical inspections by providing continuous insights into wear progression [2, 6]. Accelerometers, acoustic emission (AE) [7] and load cells are the main alternative systems that can be used in the monitoring of the tool wear. Accelerometers measure vibrations along multiple axes, which can indicate tool instability or wear. AE systems detect high-frequency sound waves generated during machining, with changes in amplitude or frequency patterns providing insights into wear progression [6, 8], but one of the most promising alternatives to optical methods is the use of cutting force signals to monitor tool wear. Load cells measure the forces on the tool during machining, which change as the tool wears. By analyzing these signals, it is possible to infer the state of the tool and predict the useful tool life without halting operations [4, 5]. Force-based methods offer the advantage of continuous, real-time monitoring, making them particularly suitable for industrial applications. Studies in literature about conventional size machining have shown that the increase of the flank wear is strongly correlates with the increase of the cutting forces, especially as worn cutting edges encounter greater resistance [6, 9]. Experimental studies are often conducted to validate force-based monitoring as a replacement for optical inspections. In these experiments, tools are tested under controlled conditions, and both force signals and wear measurements are collected.

Initially, optical inspections are still performed to measure wear parameters such as VB. Simultaneously, load cells record cutting forces in real time. By correlating the force signals with the VB measurements, it is possible to develop predictive models capable of estimating tool wear based only on force data [2, 6]. Therefore, this dual approach serves two purposes: it provides accurate benchmarks for calibrating force-based models and offers continuous data to analyze wear trends. For example, as flank wear widens, cutting forces increase, and this relationship can be used to develop algorithms for real-time monitoring [5, 10].

The adoption of these techniques can result in substantial cost savings. By minimizing reliance on traditional optical inspections and avoiding premature tool replacements, manufacturers can optimize resource utilization and reduce production expenses. The key advantage of force-based monitoring is its predictive capability. This allows to schedule maintenance with precision, optimizing operational efficiency and extending tool life. Tool wear monitoring in micro-milling is evolving towards sensor-based approaches. In micro-machining, the study of tool wear becomes even more strategic due to the small size of the cutting tool, the associated high costs, and the need to optimize the process. This makes machine tool sensorization, indirect wear measurement, and predictive maintenance essential. However, the micro scale also introduces significant challenges that complicate their implementation. For example, force, acceleration, and sound signals have lower amplitudes, making them more susceptible to external noise. Additionally, higher spindle speeds (RPMs) in micro-machining result in higher signal frequencies, requiring sensors with greater dynamic response. Conventional sensors may not have enough bandwidth, leading to inaccurate readings, so piezoelectric sensors are necessary to ensure accurate signal capture and process monitoring. A further novelty of this work is the material considered, since there are few studies in the literature addressing this topic. CuNi18Zn20 is a lead-free brass alloy with superior mechanical properties and corrosion resistance compared to conventional brasses, due to the presence of nickel. This element makes it more challenging to machine, resulting in higher wear rates than standard brasses. Additionally, while there are many studies on macro-milling, research on micro-milling is more limited, and only a few of these studies utilize load cells as a measurement system.

This research work is focused on experimental micro-milling tests to evaluate tool wear considering the innovative force-based monitoring technique. A load cell is used to record cutting forces during machining, enabling real-time data collection. In parallel, optical microscopy is used to measure tool wear, specifically the flank wear width (VB), in accordance with the ISO 8688-1:1998 standards procedures. This method ensures precise benchmarking for the force-based approach and helps establish a correlation between cutting forces and tool wear in order to develop predictive models that link force signal patterns to tool wear, enabling efficient and accurate real-time monitoring.

Material and methods

The machining tests were conducted on CuNi18Zn20, a copper-nickel alloy widely used in the high watchmaking industry due to its properties. This alloy is characterized by high mechanical strength, excellent elasticity, superior corrosion resistance, an attractive brightness, and good machinability, making it a preferred choice for precision applications. The raw material for these tests was initially prepared in the form of 3.5 mm thick sheets. These sheets were then cut into plates measuring 90 × 150 × 3.5 mm through laser cutting, ensuring uniform dimensions and surface quality. These prepared plates served as the workpieces for subsequent micro-milling experiments.

The micro-milling operations were carried out using a KERN Pyramid Nano, a high-precision CNC machining center renowned for its suitability in industries demanding extreme accuracy, such as horology. This CNC machine features a spindle capable of delivering a torque of 1.5 Nm and achieving a maximum rotational speed of 50,000 rpm, necessary in order to cut the material with micro-tools. Moreover, it has a structure capable of ensuring high stability during the machining process, reducing vibrations that are highly critical for micro-tools.

For the machining process, a RIME FORM 2000 HM79/08D08Z2 micro-end mills were used. These tools, with a diameter of 0.8 mm and two cutting edges, are made by uncoated tungsten carbide bars. The micro-end mill was mounted on a Big Kaiser HSK-F63-MEGA6N-90 collet chuck. This particular chuck ensures a runout of less than 3 μm, even with tool overhangs up to three times the tool diameter. This level of stability is crucial for high-speed operations, because also this component minimizes vibrations and tool deflection, ensuring machining accuracy and consistency.

Micro-milling operations demand carefully selected process parameters to achieve a balance between machining efficiency and tool wear. In these experiments, the following parameters were used:

- Cutting speeds: 70 m/min, and 80 m/min.
- Feed rate: 0.005 mm/rev*tooth.
- Depth of cut: 0.2 mm.
- Overlap: 5%.

These parameters were selected based on prior studies and preliminary tests to establish conditions that would provide optimal results in terms of tool performance and material removal efficiency. Furthermore, these parameters are recommended by the tool manufacturer. Cutting speeds that are too low cannot be used, as they would lead to the formation of built-up edge, while excessively high cutting speeds result in rapid wear rates, compromising the quality of the results. Before running the primary milling operations, roughing passes were conducted using a 6 mm diameter end mill. These passes leveled the surface of the workpiece, ensuring uniform material thickness and consistent machining conditions across all tests.

Minimal Quantity Lubrication (MQL) was employed for the test as it is ideal for micromachining as it efficiently reduces friction and operating temperatures, ensuring optimal performance, while reducing the overall cost and environmental footprint. Tool wear analysis is a primary focus of the study, with particular attention on measuring flank wear width (VB), a critical indicator of tool life and machining performance.

A Hirox RH-2000 microscope was used to examine the worn edges of the tools. Flank wear was analyzed at a magnification of 400×, while edge rounding was observed at 1000×. This high-resolution microscope, with an accuracy of 0.8 μm, allowed for detailed examination of the wear features. Each measurement was repeated three times to ensure statistical reliability and consistency in the results. The wear analysis follows the ISO standards, which defines parameters such as VB_{max} and VB_{ave} to analyze tool degradation. These parameters were monitored over time to gain insights into the progression of wear mechanisms.

In addition to flank wear, the tool nose radius, and secondary flank wear were also evaluated. These geometrical changes were correlated with cutting forces and material removal rates to establish a comprehensive understanding of tool performance under varying process conditions.

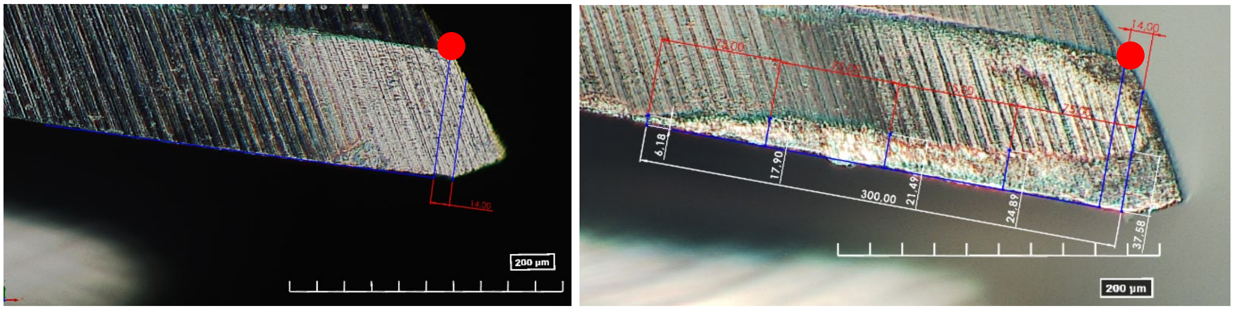


Figure 1 – (a) references point and lines; (b) lines pattern used to measure the tool wear.

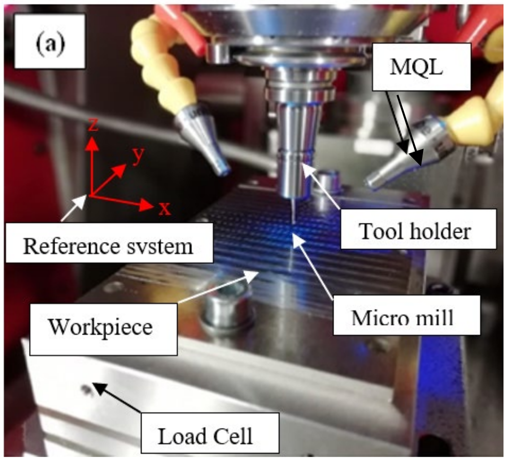
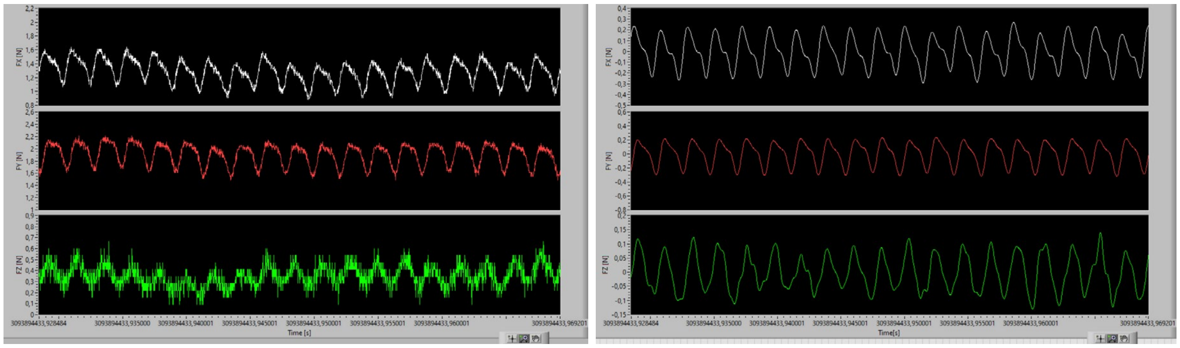


Figure 2 – The experimental setup.

The measurement of tool flank wear width (VB) in micro-machining is performed through procedure that involves both microscopic imaging and analysis by using SolidWorks software. The process begins with capturing a high-resolution image of the new cutting tool using a microscope. This image is then imported into SolidWorks to serve as the baseline geometry of the tool. As tool wear progresses over time, the geometry of the cutting edge changes, making it essential to establish a fixed reference point that remains constant throughout the measurement process. This reference point (red point in Fig. 1.a) ensures consistency in all subsequent measurements. Once the reference point is established, a reference line is drawn along the cutting edge of the tool, measuring 300 microns in length. From this reference line, five perpendicular lines are drawn. The lengths of these perpendicular lines change depending on the geometry of the wear land. The VB measurement is then executed at five distinct points along the perpendicular lines, each spaced 75 microns apart (as shown in Fig. 1.b). The VB value considered for analysis is the average of these five measurements. This method, used for each step of each test, ensures a systematic and repeatable approach to measuring tool wear, capturing the wear distribution along the cutting edge with precision.

Parallel to the microscope measurements, the forces generated during the machining process were measured using a Kistler 9257BA triaxial piezoelectric load cell (Fig. 2). It allows to create a correlation between the forces developed during machining and the tool wear. The load cell is designed for high rigidity, which provides a wide measurement bandwidth and enables the detection of minimum variations in cutting forces that are 10,0 mV/N for X-Y axes and 5 mV/N for the Z axes. The data acquisition system used to study the forces is based on a National Instruments NI 9205 DAQ module. This module supports a sampling rate of up to 50 kHz and a resolution of 16 bits. Before initiating the experiments, a calibration phase was conducted to verify the sensitivity and linearity of the sensor, ensuring accurate and reliable force measurements throughout the study. Between two consecutive stops to measure the tool wear, the cutting forces were acquired at the beginning, at the end and in the middle of the machining by using an acquisition period of 30 seconds.

The raw data collected from the load cell underwent preprocessing in LabVIEW, where noise filters were applied to enhance signal clarity. Therefore, the processing of each force component involved filtering with a high-pass filter with a cut-off frequency of 15 Hz and a low-pass filter with a cut-off frequency of 1500 Hz. Once the signal was filtered, a window of 30 cycles, equivalent to 30 rotations, corresponding to 0.075 seconds, was considered. Fig. 3 shows the force signal acquired with LabVIEW before (a) and after (b) filtering.



(a) (b)

Figure 3 – (a) Signal before filtering; (b) Signal after filtering.

The three cutting forces components were combined to compute the resultant cutting force which was employed for the subsequent elaborations. After preprocessing, the data was exported to MATLAB for advanced analysis. Custom scripts were developed to execute algorithms based on an eighth-order Fourier series, allowing the detection of periodic fluctuations, the calculation of average force values, and the identification of peaks in the resulting force. It should be noted that the force values corresponding to the two peaks are different due to the tool run-out.

A fitting approach was chosen instead of identifying the peaks directly in the original signal because, as the signal is composed of multiple frequencies, there are peaks of negligible intensity that could distort the data by generating local maxima. Once the peaks were identified, the software classified them into two groups: those generated by tooth 1 and those by tooth 2 and calculated the average force for each group. This process produced three output values: the average force of the peaks generated by the first tooth, the average force of the peaks generated by the second tooth, and the combined average force of both.

Results and Discussion

In this section, the experimental results are summarized and discussed by analyzing how the cutting forces recorded by the load cell vary during the experimental tests considering the changes of tool flank wear width (VB), tool diameter and the cutter nose radius. Additionally, the relation between surface roughness and tool wear is stated.

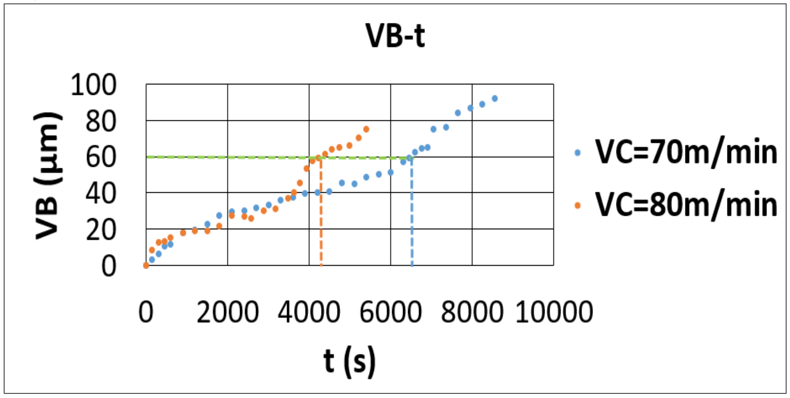


Figure 4 – Tool flank width variation over time.

Fig. 4 illustrates how tool flank wear width (VB) changes over time with different cutting speeds. It can be observed that increasing the cutting speed reduces the tool life. For example, when VB reaches 60 microns, this value is attained after approximately 4300 seconds at a cutting speed equal to 80m/min, compared to about 6500 seconds at VC=70 m/min. These results are consistent with existing literature, which shows that higher cutting speeds decrease tool life.

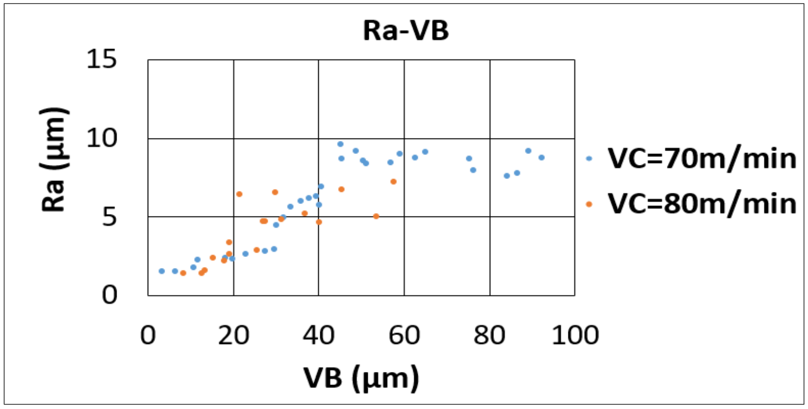
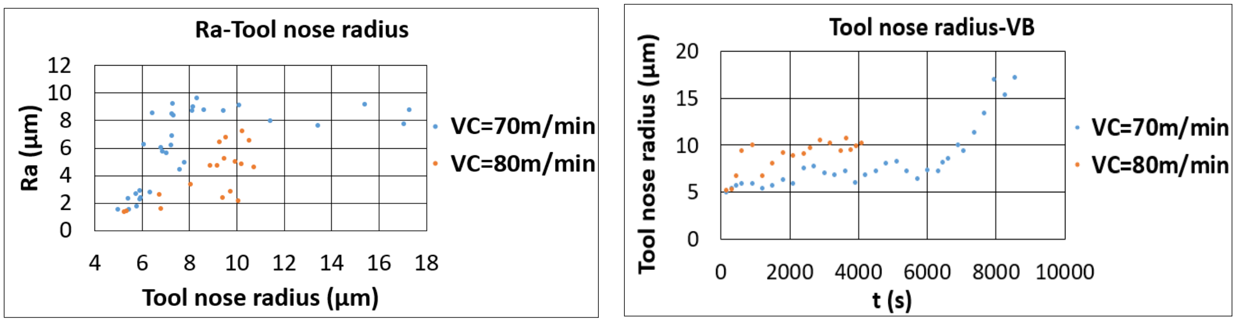


Figure 5 – Roughness variation with the width of the worn flank.

Fig. 5 shows how roughness (Ra) varies with tool flank wear width (VB). It can be observed that as tool wear increases during the experimental test, surface roughness (Ra) also increases, resulting in a decrease in the workpiece surface quality. Furthermore, the roughness is not influenced by the cutting speed: roughness values Ra are comparable at the same VB.



(a) (b)

Figure 6 – (a) Roughness variation with tool nose radius; (b) Tool nose radius variation over time.

Fig. 6 (a) analyse how roughness (Ra) changes with the tool nose radius. Due to abrasive phenomena, the tool nose radius tends to increase during the experimental tests as wear progresses. The chart shows that an increase in the tool nose radius corresponds to a deterioration in the surface quality of the workpiece at the beginning of the test. In the final part of the curve with a cutting speed of 70 m/min, it is possible to observe that the surface roughness value remains almost constant as the tool nose radius increases. However, in Graph 6 (b), a significant increase in the tool nose radius over time is evident. This phenomenon can be explained by the fact that the surface quality of the component is more influenced by the tool flank wear width (VB), as illustrated in Fig. 4, rather than by the variation in the tool nose radius.

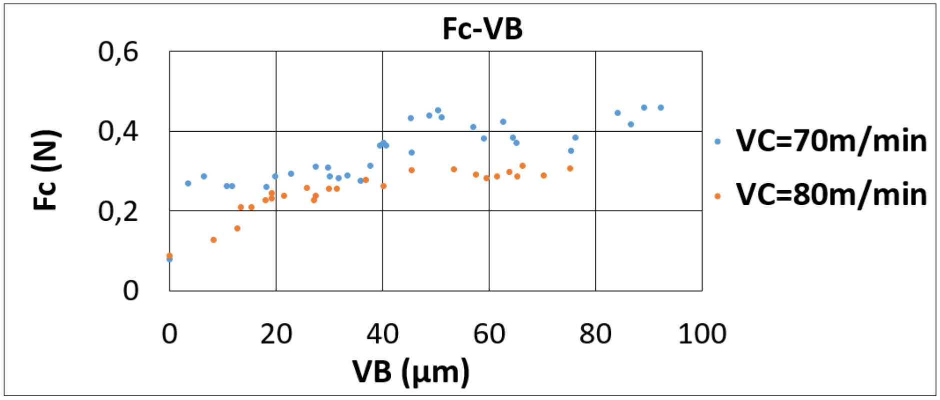


Figure 7 – Cutting forces variation with tool flank wear width.

Fig. 7 correlates the resultant cutting force (Fc) with tool flank wear width (VB). This chart is significant because it provides initial results analyzing how cutting forces vary with tool wear, establishing a relationship between these two factors. It can be observed that as tool flank wear width (VB) increases, the load cell registers an increase in cutting forces. This phenomenon occurs because tool degradation does not allow an optimal removal mechanism of the material. Additionally, increasing the cutting speed leads to a decrease in the forces developed during the tests.

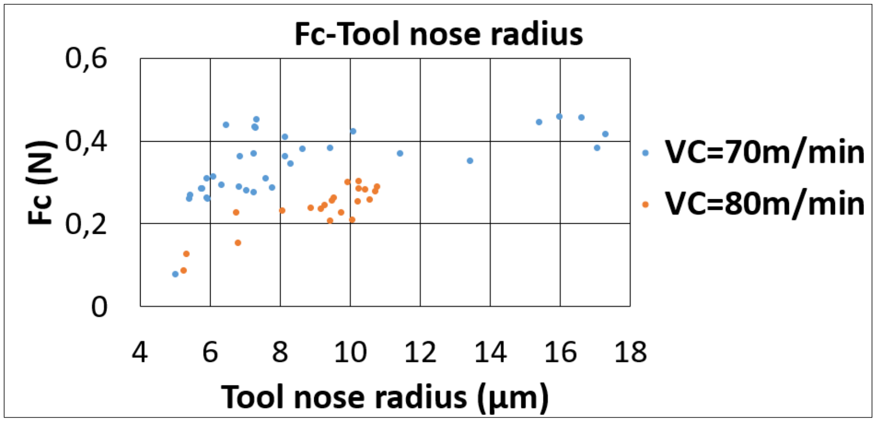


Figure 8 – Cutting forces variation with tool nose radius.

Fig. 8 relates the variation in the tool nose radius to the forces developed during the experimental tests. As in the previous case, the progression of tool wear generates abrasion, which leads to tool rounding. Consequently, the tool tip radius tends to increase during machining. For both cutting speeds, it can be observed that cutting forces initially increases with the tool radius since it reaches a plateau at around 8 micrometres, as observed in Fig. 6(a).

Conclusions

This study shows that load cells can be a practical and innovative way to measure tool wear indirectly in micro-machining. By recording and analysing cutting force signals during machining, the research found a clear link between how the forces change and how much the tool wears out. This method provides a useful alternative to traditional optical inspections, which, although accurate, require stopping the process frequently, leading to more downtime and higher costs.

The experiments proved that load cells can monitor tool wear in real-time, making it possible to track wear without interrupting the machining process. The force data collected by the sensors was closely connected to tool wear, such as the width of the worn area (VB). The results confirm that as tools wear down, the cutting forces increase, demonstrating the reliability of this approach.

This work serves as a starting point for using force-based monitoring systems in micro-machining. These systems can make it easier to predict when tools need replacement, improve efficiency, and reduce waste. By addressing the specific challenges of micro-machining, this method offers a simple, cost-effective, and accurate way to measure tool wear without disrupting production. In the future, additional experimental tests will be conducted to increase the available data, which will then be processed using AI. This technology could also potentially provide insights into the influence of individual wear phenomena on cutting forces.

References

[1] L.L. Alhadeff, M.B. Marshall, D.T. Curtis, T. Slatter, Protocol for tool wear measurement in micro-milling, Wear 420 (2019) 54-67. https://doi.org/10.1016/j.wear.2018.11.018

[2] Mohammad Malekian, Simon S. Park, Martin B.G. Jun. (2009) "Tool wear monitoring of micro-milling operations." https://doi.org/10.1016/j.jmatprotec.2009.01.013

[3] Corne, Rafael, Nath, Chandra, El Mansori, Mohamed, and Kurfess, Thomas. (2017) "Study of spindle power data with neural network for predicting real-time tool wear/breakage during inconel drilling." Journal of Manufacturing Systems 43:287–295. https://doi.org/10.1016/j.jmsy.2017.01.004

[4] Klocke, Fritz, Dobbeler, Benjamin, Pullen, Thomas, and Bergs, Thomas. (2019) "Acoustic emission signal source separation for a flank wear estimation of drilling tools." Procedia CIRP 79:57-62. https://doi.org/10.1016/j.procir.2019.02.011

[5] Wang, Jinjian, Xie, Junyao, Zhao, Rui, Zhang, Laibin, and Duan, Lixiang. (2017) “Multisensory fusion based virtual tool wear sensing for ubiquitous manufacturing.” Robotics and Computer-Integrated Manufacturing 45:47–58. https://doi.org/10.1016/j.rcim.2016.05.010

[6] Oberlè, Robin, Schorr, Sebastian, Yi, Li, Glatt, Moritz, Bahre, Dirk, Jan, C., and Aurich. (2020) “A use case implement Machine Learning for Life Time Prediction of Manufacturing Tools.” Procedia Cirp 93:1484-1489. https://doi.org/10.1016/j.procir.2020.04.056

[7] Galipothu Dheeraj, Simon, and Deivanathan, R.. (2019) “Early detection of drilling tool wear by vibration data acquisition and classification.” Manufacturing Letters 21:60–65. https://doi.org/10.1016/j.mfglet.2019.08.006

[8] A. Colpani, A. Fiorentino, E. Ceretti, A. Attanasio, Tool wear analysis in micromilling of titanium alloy, Precision Engineering 57 (2019) 83-94. https://doi.org/10.1016/j.precisioneng.2019.03.011

[9] Ravikumar, S., and Ramachandrana, K.I.. (2018) “Tool Wear Monitoring of Multipoint Cutting Tool using Sound Signal Features Signals with Machine Learning Techniques.” Materials Today: Proceedings 5:25720–25729. https://doi.org/10.1016/j.matpr.2018.11.014

[10] Abeni, Andrea, Cappellini, Cristian, and Attanasio, Aldo. (2021) “Finite element simulation of tool wear in machining of nickel-chromium based superalloy” ESAFORM 2021. 24th International Conference on Material Forming, Liège, Belgique. https://doi.org/10.25518/esaform21.4302