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Tool life estimation in micro-milling through cumulative wear modeling using direct and indirect methods

Alessandro Metelli[a], Andrea Abeni[a,*], Cristian Cappellini[b], Aldo Attanasio[a]

[a]*Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Via Branze 38, Brescia, 25123, Italy*
[b]*Department of Management, Information and Production Engineering, Università degli Studi di Bergamo, Via Pasubio 7b, Dalmine (BG), 24044, Itay*

* Corresponding author. Tel.: +39 0303715538; fax: +39 0303715538. *E-mail address:* andrea.abeni@unibs.it

Abstract

Tool wear prediction is a critical issue in micro-milling since it has a direct effect on productivity, costs, and the quality of the surface. At the microscale, tool dimensions below one millimeter result in a challenge related to the monitoring of the wear, and indirect methods of measurement are considerable topics of research. The literature underscores also a significant reliance of wear evolution on cutting parameters, especially cutting speed; however, current ISO standards provide guidelines only for constant cutting conditions. Consequently, a reliable estimation of tool life under realistic variable speed cycles remains an open challenge in micro-machining.

This study addresses this gap by testing the tool life of 0.8 mm micro-end mills at a wide range of cutting speeds and collecting cutting force data. Standard wear curves obtained at constant cutting speeds are combined to construct theoretical cumulative wear curves, following a methodology recently validated in conventional size turning. Dedicated micro-milling tests are then carried out by alternating cutting speeds, enabling a direct comparison between predicted and experimental cumulative wear. Cutting forces are measured and correlated to wear in constant cutting speed and variable cutting speed tests both.

The objective is to investigate whether cumulative wear behavior can still be assumed linear —as observed in conventional size machining— also at the microscale or whether nonlinear effects become significant and must be accounted for in predictive models. The proposed approach provides new insights into the mechanisms of cumulative wear in micro-tools.

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Keywords: Cumulative tool wear; Micromilling; Sensor-based monitoring; Micromachining; Cutting forces.

1. Introduction

Tool wear is a central challenge in micro-milling because it directly affects productivity, cost, and the surface quality of small components. Micro-end mills with diameters lower then 1 mm tend to wear faster than bigger tools and produce lower-amplitude process signals [1], but modern high-bandwidth sensors and tailored signal processing make reliable online monitoring [2]. Optical microscopy is one of the most reliable methods used to quantify wear, for example flank wear land width and edge rounding. It requires interrupting machining and becomes more challenging as tool size decreases. For these reasons, online sensor-based monitoring that infers wear from cutting forces, vibrations, or acoustic emission is an important and practical alternative [3].

Cutting speed is one of the process parameters that most strongly influences wear progression in machining [4]. International standards for tool-life testing are based on constant cutting-speed experiments and define typical wear zones and life criteria [5-6]. In industrial practice, however,

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machining cycles often include changes in cutting speed because of tool paths, feature geometry, or spindle control strategies. Adapting predictive methods to these realistic cycles is therefore necessary for effective tool management in micro-manufacturing.

Miner [7] firstly proposed cumulative damage using a linear model for fatigue. Palmai [8] extended this to tool wear in conventional size turning operations. Linearity was expressed with Equation (1), later validated in turning tests on AISI 1045 steel [9]. Two groups of tests were performed: constant cutting speed (CCS) to determine tool life at different speeds, and variable cutting speed (VCS) to study non-linearity. During VCS tests, Δt_i is the interval of time corresponding to the i-th cutting speed, while T_i is the tool life related to the i-th cutting speed estimated through CCS test.

$$\sum_{i=1}^{N} \frac{\Delta ti}{Ti} \cong 1 \qquad (1)$$

Results showed summations of equation (1) ranging between 0.77 and 1.26, indicating deviations from linearity. Further VCS tests [10] confirmed similar outcomes: equivalent cutting speed v_{ce} and equivalent tool life T_e calculated according to Taylor's law in the hypothesis of linearity, offered predictions which differed from the experimental results.

The main limitation of these studies concerns the difficulty in distinguishing non-linearity effects from the intrinsic variability of the wear phenomenon. Later studies [11–12] gave mixed conclusions: some found negligible non-linearity, others significant effects depending on tool coatings or process parameters. Overall, literature highlights uncertainty, suggesting robust statistical approaches are needed to distinguish non-linear effects from variability. In [13], cumulative tool wear in turning was experimentally investigated. Non-linearity effects were quantified through VCS tests and by assessing them by considering wear variations in CCS tests. A subsequent study refined the analytical interpolation of experimental CCS data to construct wear curves using piecewise-defined functions [14]. As a conclusion of these studies, in conventional-scale machining the non-linear effects associated with variations in cutting speed were shown to have a marginal impact when statistically describing tool wear evolution. This confirms the reliability of the proposed approach under different operating conditions. The negligibility of non-linear effects cannot be automatically extended to different combinations of tools, workpiece materials, and process conditions. In micromachining, the size effect [15] and the development of specific cutting regimes, such as ploughing [16], introduce distinct wear mechanisms. In the literature, there is a lack of studies addressing cumulative tool wear in micromachining.

This study builds on previous micro-milling experiments in which constant-speed tests were performed while recording cutting forces and progressively measuring wear [17]. Those tests produced standard wear-versus-time curves at selected cutting speeds and revealed correlations between the width of flank wear land (VB), corner chamfer rounding, and surface roughness. In this paper, those constant-speed results are used as the starting point to construct theoretical cumulative wear curves for 0.8 mm micro-end mills. The predictive capability of the cumulative-wear procedure described in [13] was tested.

Constant-speed micro-milling tests provide empirical wear models, later combined into theoretical VCS wear curve. These are validated through experiments with variable cutting speeds.

The following sections describe the experimental setup and measurement procedures, the construction of cumulative wear curves, the results of variable-speed tests, and the implications for predictive monitoring and tool-life estimation in micro-milling.

2. Material and Methods

The ISO 8688 standard provides guidelines for estimating tool life in milling, but it is based on constant-speed conditions. However, it should be noted that ISO 8688 specifically addresses conventional macro-scale milling operations and does not apply to micro-milling processes. To address this gap, a cumulative-wear procedure that combines CCS tests with an empirical method to build cumulative wear curves was adopted.

The procedure begins with tool-life tests carried out according to ISO 8688. These tests are performed at CCS by selecting speeds that well-represent the typical working cycle of the tool. The width of the land on flank (VB) was periodically measured, and the experimental data were used to fit empirical model computing the related confidence intervals.

From these standard curves, a cumulative tool-wear curve is constructed as similarly done in [14]. This curve is obtained by combining portions of the standard curves according to the chosen work cycle. Each phase of the cycle, corresponding to a different cutting speed, adds an incremental contribution to VB. These segments are shifted along the time axis and added together to form the overall cumulative wear trajectory, and Fig. 1 shows an example of the procedure.

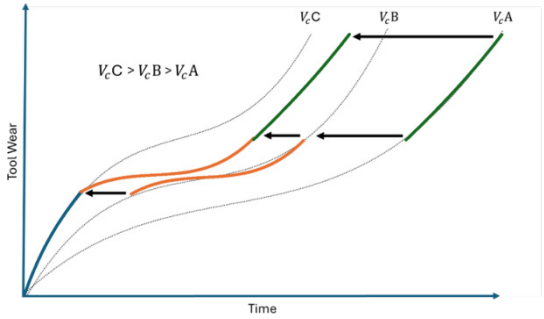


Fig.1 Example of the procedure for the building of the empirical cumulative tool-wear curve.

Finally, the useful tool life under the VCS cycle is estimated considering a pre-selected wear criterion, such as a flank wear land limit. In this work the procedure was tested on micro-milling on workpiece material CuNi18Zn20 (lead-free brass), commonly used in precision micro-components. Raw sheets (90 × 150 × 3.5 mm) were cut by using laser machining and treated via ultrasonic cleaning bath. Micro-milling tests were carried out on a KERN Pyramid Nano high-precision CNC machine with a spindle with a maximum speed of 50 000 rpm. The cutting tool was a RIME HM79/08 flat-end micro-mill (diameter 0.8 mm, two flutes, uncoated tungsten carbide), visible in Fig.2.

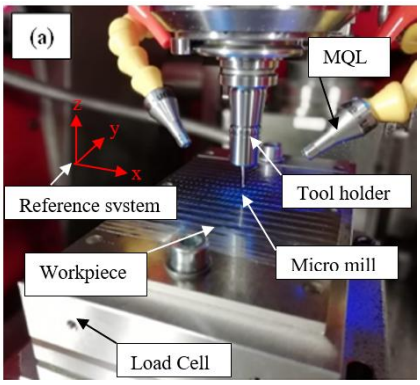
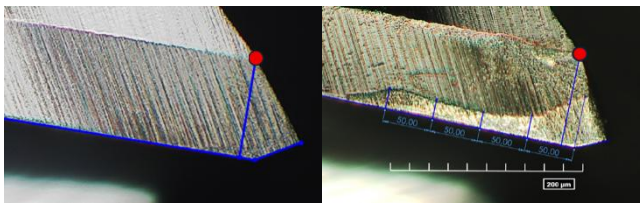


Fig.2 Experimental configuration.

Tools were mounted on a Big Kaiser HSK-F63 collet chuck; the assembly guarantees runout below 3 µm for the selected overhang. Each test (CCS and VCS) used a new tool to surface-mill the sheet by consecutive passes in x-direction. The tool trajectories determine an overlapping in y-direction equal to 5% of the tool diameter and alternating a climb milling pass with a up milling pass. Once the surface of the sheet was completely machined, a roughing pass with 6 mm mill was executed to resurface the sample preparing it for further micro-milling tests. Constant depth of cut (a_p) of 0.2 mm and feed per tooth per revolution (f_z) of 5 µm/rev*tooth were selected after preliminary experiments, while cutting speeds were equal to 70, 80 and 90 m/min. Therefore, feed rate corresponds to 278 mm/min, 318 mm/min and 358 mm/min. Minimal Quantity Lubrication (MQL) was used throughout the experiments.

Tool flank wear width (VB) was measured from high-resolution x400 zoomed images captured with a Hirox RH-2000 multifocal microscope by periodically interrupting the micro-machining. An image of the new tool was imported into SolidWorks and used as the baseline geometry, as shown in Fig. 3(a). As the tool wears, the cutting-edge geometry changes, so a fixed reference point is defined to keep all measurements consistent. After setting this reference point, a 200 µm reference line is drawn along the cutting edge. The ISO 8688 standard states that the average width of the flank land should be measured in the section where it is constant. However, experimental tests showed that the width of the wear land is not constant in a wide section, as visible in Fig. 3(b). Therefore, at each time step, five measurements of VB were acquired at a relative distance of 50 µm, from the beginning of the original cutting edge. In contrast to [17], where the maximum values VB_{max} were considered, in this work the average values VB_{mean} were computed to achieve a more reliable computation of the extension of the land on the flank.



(a) (b)

Fig.3 A new tool with the relative reference of the unworn cutting edge (a) and a worn tool with the position of the five points in which the width of flank land was measured (b).

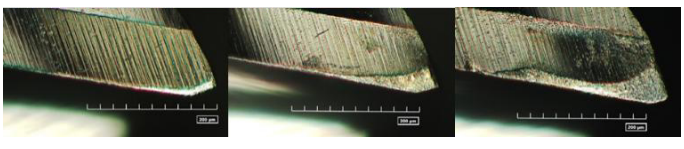
This method provides a systematic and repeatable way to measure tool wear and capture how it develops along the cutting edge. Initially, the measurements were carried out at intervals of 150 s to correctly model the initial slow down phase. From the instant 900 s, the interval of measurements was increased to 300 s until the end of the tests.

Cutting forces were recorded using a Kistler 9257BA triaxial piezoelectric load cell on which the sheet metal was fastened using two M10 screws. The loadcell has a wide bandwidth (≈5 kHz) and a sensitivity of 10.0 mV/N on the X–Y axes and 5.0 mV/N on the Z axis. Signals were acquired with a National Instruments NI-9205 DAQ (sampling frequency 50 kHz, 16-bit). Cutting force were acquired for time interval equal to 30 s after each machining restart following an interruption to perform the VB measurement. Raw signals were preprocessed in LabVIEW: a 15 Hz high-pass filter removed low-frequency drift, and a 1500 Hz low-pass filter removed high-frequency noise. Further post elaboration of the signals consists in processing randomly selected window corresponding to 30 spindle revolutions and combining the three force components into the resultant cutting force (F_c) for further analysis.

Preprocessed data were exported to MATLAB for advanced processing. An eighth-order Fourier fit was applied to the resultant signal to smooth it and avoid local maxima caused by multiple frequency components. Peaks were then detected on the fitted waveform by using an algorithm; since a two-flutes micro-mill was employed, a corresponding number of cutting force maxima are detected for each tool rotation (F_{c_PEAK1} F_{c_PEAK2}) [18]. The peaks related to different flutes are not equal, since tool run-out phenomena determines an unbalanced cutting condition between flutes [19]. The cutting force maximum were averaged considering the 30 spindle rotations, achieving a final average force peak $F_{c_PEAK_AV}$ for each interval of measurements.

3. Results

The results of the work are shown by firstly presenting the CCS VB_{mean} curves and then the elaboration regarding the VCS test. The Fig. 4 shows an example of tool wear progression during the tests with CCS equal to 80 m/min, highlighting three instants: 600 s (Fig. 4a), 3000 s (Fig. 4b), and 8000 s (Fig. 4c). Starting from 6000 s, the progression of VB_{mean} becomes negligible because a dominant wear mechanism develops at the tool corner chamfer, involving the bottom cutting edge. As a result, the VB_{mean} abruptly increases and immediately after it remains constant even though the overall tool wear increases significantly. For this reason, the rise of the wear rate typically seen in the final part of the test (Z3 region) cannot be observed.



(a) (b) (c)

Fig.4 Example of the evolution of the wear land width for the CCS test at 80 m/min after 600 s (a), 3000 s (b), and 8000 s (c)

The experimental curves were interrupted before the developing of the different wear mechanism, since they compromise the chip formation mechanism. Similar results were obtained at cutting speeds of 70 and 90 m/min, as well as in the VCS test. The piecewise function in Equation (2) was used as the fitting model for the experimental VB_{mean} values (in µm) as a function of time (in seconds), accordingly to the modelling proposed for turning at conventional scale [14].

$$\begin{aligned} &Z1: VB = a_1 t^2 + b_1 t && \text{when } t < t_1 \\ &Z2: VB = b_2 t + c_2 && \text{when } t > t_1 \end{aligned} \quad (2)$$

In the experimental tests, no significant Z3 region was observed, so the fitting model was adjusted for micro-milling by considering only the Z1 and Z2 zones; Z1 is fitted with a second-order polynomial and Z2 with a first-order polynomial. This method avoids the limitations of using a single third-order polynomial [13], because it accounts for the constant wear rate in Z2, as reported in the literature. The second-order polynomials used for Z1 make it possible to capture the typical decrease in wear rate observed in this zone; the constant term is equal to zero since VB is null in new tools.

A criterion was used to define the time range of each section of the function, so the transition from Z1 to Z2 at t_1 could be identified in a consistent way. The incremental ratio (IR_{VB}) of VB over time, calculated between two consecutive measurements, was obtained using Equation (3). The transition between Z1 and Z2 occurs since the IR_{VB} stops decreasing, becoming constant in time as visible in Fig. 5.

$$IR_{VB} = \frac{VB_i - VB_{i-1}}{t_i - t_{i-1}} \quad (3)$$

Table 1 lists the coefficients of Equation 2 for cutting speeds of 70, 80, and 90 m/min. The fitting process was done by using the least square method, ensuring the continuity of the function in t_1. Furthermore, it collects also the values of the coefficient of determination R^2 for the each piecewise of the models. Regardless of the cutting speed, the R^2 resulted higher than 0.98 demonstrating as the model well describe the correlation between VB_{mean} and time. Fig. 5 show the VB_{mean} evolution for each CCS test. The experimental measurements and the model prediction are both visible for CCS equal to 70 m/min (Fig. 5(a)), 80 m/min (Fig. 5(b)) and 90 m/min (Fig. 5(c)). An interval of confidence of the model was built considering a normal distribution of the data and a level of confidence equal to 95%, ensuring a robust statistical approach about describing the evolution of wear through the empirical model.

Table 1. List of the coefficients of Eq. 2 for the three cutting speeds.

v_c (m/min)	70	80	90
a_1	-7.15E-06	-1.50E-05	-2.42E-06
b_1	1.89E-02	2.95E-02	1.69E-02
R^2	0.9936	0.9888	0.98715
b_2	3.70E-03	4.24E-03	5.86E-03
c_2	7.98	10.54	8.07
R^2	0.9919	0.9786	0.9819

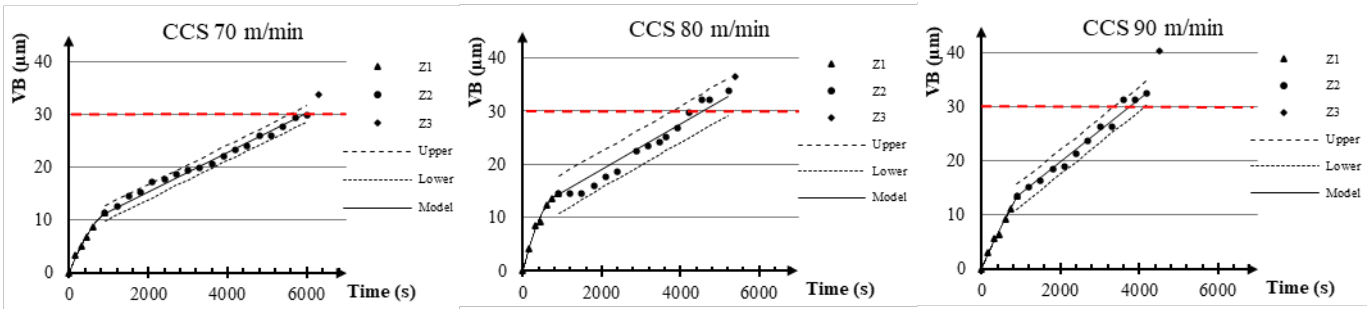
A tool life criterion was defined considering a VB_{mean_limit} = 30 µm, since the Z2 section stops in correspondence of a value of VB_{mean} slightly higher than it (30.0 µm for 70 m/min, 32.7 µm for 80 m/min, 32.4 µm for 90 m/min). The tool life criterion was adopted to compute the useful tool life, which resulted 5950 s at 70 m/min, 4586 s at 80 m/min and 3741 s at 90 m/min, considering the model described by Eq. 2 and coefficients in Table 1. As the cutting speed increases, a reduction in useful tool life is determined as expected.

The procedure described in Section 2 was employed to plan a VCS test, using the cutting speeds indicated in Table 2. It provides also the estimated useful life as a linear combination of the five cumulative tool wear contributions, which resulted equal to 4770 s.

Table 2. Cumulative tool wear data related to VCS test.

Vc (m/min)	Interval time (s)	Starting value of VB (µm)	Final value of VB (µm)	Estimated useful tool-life (s)
90	750	0.00	10.9	
80	1350	10.9	18.4	
70	1050	18.4	22.2	4770
90	750	22.2	26.4	
80	End of TL	26.4	> 30	

Fig. 6 illustrates the results of the experimental VCS test (the red dots), allowing to compare them with the empirical cumulative wear model derived from CCS tests (the coloured confidence intervals individuated by the continuous lines and the dashed line representing the lower and upper bounds).



(a) (b) (c)

Fig.5 Tool wear VB curves for CCS test at 70 m/min (a), 80 m/min (b), and 90 m/min (c).

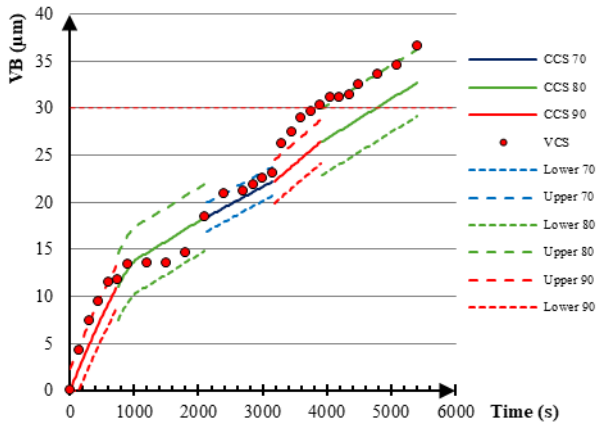


Fig. 6 Comparison between the experimental VB measured during VCS, and the prediction of the empirical model.

Contrary to observations reported for conventional-scale turning operations [13], the present study shows a significant deviation between experimental data and model prediction: a first discrepancy occurs around 1200s, when VB_{mean} does not increase as rapidly as expected. A further deviation corresponds to the increase from 70 to 90 m/min at 3150 s, resulting in a significant degradation of the tool. The VB_{mean} becomes higher than the upper limit of the confidence interval, demonstrating that the hypothesis of linearity is not valid. Furthermore, VB_{mean} reaches the VB_{mean_limit} = 30 µm before 3900 s of machining. The deviation with respect to the tool life predicted by the empirical model is therefore equal to 870 s, corresponding to 18.2% of the theoretically predicted tool life. This difference cannot be considered negligible; consequently, non-linear wear phenomena have a meaningful impact in the context of micromachining operations.

The study of cutting forces enables a deeper investigation of non-linearity and further validates the results derived from the VB computation. The average force peaks $F_{c_PEAK_AV}$ corresponding to each machining restart during CCS tests are visible in Fig. 7, plotted as function of VB_{mean} to investigate a correlation between wear and forces. The bandpass filter applied on cutting force data allows the constant component of the force to be neglected, focusing exclusively on the variation over one spindle revolution, represented by $F_{c_PEAK_AV}$ shown in the graph. Interestingly, it is observed that, in general, as the cutting speed increases, the $F_{c_PEAK_AV}$ become more contained for a given tool wear condition. This indicates greater cutting efficiency at 90 m/min, which therefore represents the optimal condition among those tested. At lower speeds, it can be hypothesized that the tool–workpiece interaction is not sufficiently dynamic, hindering chip formation.

In general, an increase in force peaks is observed as flank wear becomes more pronounced, although this load increase is not constant across different cutting speeds. To quantify the variation of cutting force with tool wear across the different cutting speeds, the data were fitted with a linear model, expressed by the Equation 4:

$$F_{c_PEAK_AV} = m * VB + q \qquad (4)$$

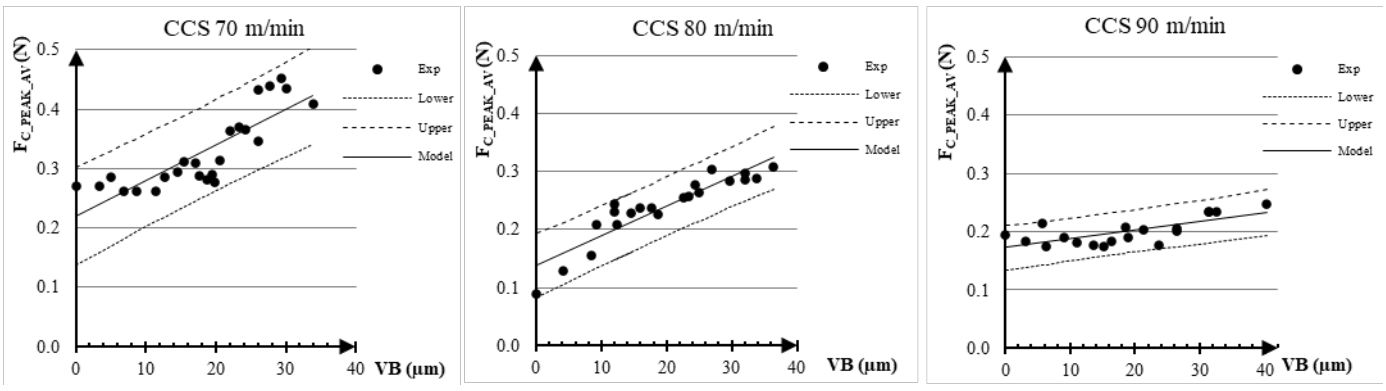
Table 3 lists the model parameters and the coefficient of determination R^2 of the fitting executed with least square method. Fig. 7 represents also the interval of confidence corresponding to a confidence level of 95%.

Table 3. List of the parameters of Eq. 4 for the three cutting speeds.

v_c (m/min)	70	80	90
m	5.98E-03	5.14E-03	1.46E-03
q	2.20E-01	1.38E-01	1.74E-01
R^2	0.6967	0.8379	0.5026

The low slope m and correlation coefficient R^2 observed at 90 m/min indicate that force peaks increase with tool wear far less than at 70 and 80 m/min. This further corroborates the earlier observation that cutting efficiency at 90 m/min remains high, even under significant wear progression. These results underscore the inherent challenges in monitoring micro-machining tool wear through indirect, online methods—such as cutting force measurements—given the strong dependence of the signals on chip formation mechanics, which can vary markedly even with minor changes in process parameters.

The impact of cumulative tool wear related to the changes about cutting speed was evaluated with an approach similar to that previously adopted for VB monitoring. Fig. 8 compares the cutting force peaks $F_{c_PEAK_AV}$ as function of the width of the land on flank VB_{mean} measured during the VCS test (the red squares) with the interval of confidence of cutting force built with the CCS tests.



(b) (b) (c)

Fig.7 Average force peaks curves for CCS test at 70 m/min (a), 80 m/min (b), and 90 m/min (c).

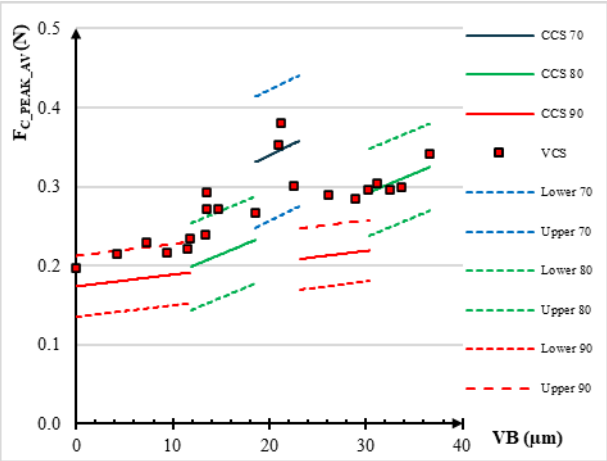


Fig. 8 Comparison between the experimental $F_{c_PEAK_AV}$ during VCS test and the prediction achieved by combining the results of CCS tests.

As already observed in Fig. 6, also the prediction about cutting force resulted inaccurate around 1200s, when a force higher than expected is recorded during VCS test during the section with cutting speed of 80 m/min. An even worse prediction of force starts at 3150s, the instant corresponding to the increase in cutting speed from 70 to 90 m/min. The unexpected degradation of the flank determined by the increase in cutting speed (visible in Fig. 6) leads to greater than predicted cutting force. The model accuracy is restored to an acceptable level in the final portion of the test, corresponding to speed decrease at 80 m/min. The correspondence between the wear and force models under variable cutting speed tests confirms the feasibility of using online-acquired signals, as a reliable indicator of tool wear, even in the presence of speed changes. On the other hand, this highlights the relevance of nonlinear wear phenomena in micromachining, which therefore cannot be neglected.

4. Conclusions

The paper presents a cumulative-wear procedure suitable for VCS in micromachining, demonstrating its applicability and limits for 0.8 mm micro-end mills. The empirical CCS-based model reproduces the overall trend of flank wear, but its main limit is the underestimation of tool wear during cutting speed increasements: the predicted life exceeded the experimental life (≈18.2%), with the largest discrepancy occurring at the 70 → 90 m/min transition. This outcome shows that wear accumulation in micro-milling is not strictly additive in all conditions and that transient microscale mechanisms—likely related to changes in chip formation, localized chipping and tribological transitions—can trigger rapid, non-linear increases in flank wear that the linear cumulative model, validated in conventional size machining, does not capture. Cutting-force peaks resulted correlated with VB and they increase with wear. Also in this case, the sensitivity of the linear cumulative model depends on cutting speed and is markedly reduced at 90 m/min. On this basis, the CCS cumulative empirical approach remains a useful starting point for life estimation. The study is limited to a single workpiece material, one tool geometry and a restricted set of speeds, and it does not fully isolate the microscopic causes of the observed nonlinearity; therefore, extending the experimental matrix and integrating additional sensing modalities (vibration, acoustic emission) are necessary next steps. Hybrid predictive models that combine CCS-derived segments with nonlinear, transition-triggered terms and real-time updating algorithms that assimilate deviations observed during machining appear to be promising strategies to achieve more tool wear predictions for industrial micro-milling applications.

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