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A Predictive Method for Cumulative Tool Wear in Variable Cutting Speed Turning Operations

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Abstract

This study investigates cumulative tool wear in turning operations, focusing on the machining of AISI 1045 steel. Tool wear is a critical factor in determining the overall efficiency of machining processes. While current standards such as ISO 3685 provide guidelines for constant cutting speed, real industrial applications frequently involve variable cutting speeds, which leads to cumulative tool wear. The aim of this research is to develop a robust method for predicting tool-life when using variable cutting speeds. The proposed method is based on conducting tool-life tests at constant speeds, followed by the plotting of empirical tool-wear curves for each speed. These curves are then combined to build a cumulative tool-wear model that accounts for variations in cutting speed throughout a machining cycle. Experimental tests were conducted using coated carbide tools, and the wear was monitored using flank wear width (VB) as the primary criterion. Results show that nonlinear effects, which are often presumed to complicate tool-life prediction under variable speeds, have a marginal impact on tool wear progression. The proposed method effectively predicts the useful tool-life by combining the wear curves from different cutting speeds, making it suitable for practical industrial applications. Validation through variable cutting speed tests confirmed the accuracy of this method, as the predicted tool-life closely matched the experimental results. This approach provides a reliable alternative for estimating tool-life in complex machining operations with varying cutting conditions.

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Keywords: cumulative tool wear, turning, AISI 1045, useful tool-life, tool substitution policy.

1. Introduction

Tool wear is a complex phenomenon with significant implications for tool management in the industry. Accurate estimation and maximization of tool life are critical for

enhancing the efficiency and sustainability of machining operations [1]. The wear progression of a tool affects the dimensional accuracy, surface integrity, and overall quality of machined parts [2]. Tool wear monitoring in turning, a time-consuming task governed by international standards ISO

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3685:1993 [3], requires periodic interruptions to measure geometric changes caused by wear. Key parameters like flank wear width (VB) and crater wear geometry on the rake surface are frequently used to assess wear in cemented carbide cutting tools. According to ISO standards, wear is monitored over time in Constant Cutting Speed (CCS) tests, producing a wear-versus-time plot divided into three phases: an initial high-wear "break-in" period (Z1), a steady-wear phase (Z2), and an accelerated wear phase (Z3), each impacting tool life.

Studies show that cutting speed significantly influences tool wear rates [4], with variable cutting speeds (VCS) commonly used in industrial settings due to tool and workpiece design constraints. However, cumulative wear effects caused by these speed variations cannot be accurately predicted using existing ISO standards designed for constant speeds. Early theoretical work on cumulative tool wear linearity, proposed by Miner [5], hypothesized that fatigue-related wear could be described through linear models. Subsequent researches, including Palmi [6][7][8], provided experimental evidence on the effects of cutting speed changes on wear, but findings indicated deviations from linearity. Tests conducted using two-speed VCS settings showed that real tool wear diverged from predictions based on simple linear models, resulting in inconsistencies between actual and calculated tool life.

Further studies [9][10][11] explored the hypothesis of linearity with various approaches, including neural network models and statistical methods, to enhance wear predictions. Researches with specific materials and tool types, such as TiC-TiN coated carbide, suggests that linearity may depend on tool coatings and sequence of process parameters, though findings remain inconclusive due to experimental variability [12]. Moreover, limited testing in Z3 (accelerated wear) introduces uncertainty [13], which calls for a more robust statistical approach to assess non-linear effects thoroughly. A correct modeling of tool wear in this complex variable cutting speed condition is essential to assess numerical model useful to predict tool wear without performing expensive and time-consuming tests [14].

This paper aims to address these gaps by verifying whether non-linear effects significantly impact tool wear evolution and by proposing an innovative procedure for determining tool life under variable speed conditions. The method was tested on AISI 1045 steel with coated carbide tools. To adopt a statistically robust approach, the material was characterized by checking the microstructure and the hardness, and subsequently CCS tests at three different speeds were repeated three times for statistical accuracy. Finally, three VCS tests were designed combining the velocities tested in CCS tests, and a comparison of the tool wear was performed considering the empirical and the actual values.

2. Material and Methods

The ISO 3685 standard provides guidelines for estimating tool-life, but as stated in the previous section, it is based on constant-speed conditions, which often do not match actual industrial practices where cutting speeds vary to machine different features on the same part. To address this need, a tool-life estimation procedure was developed, combining the ISO 3685 guidelines with the industrial practice of using varied cutting speeds. This procedure relies on cumulative wear, which considers the wear effect generated across multiple successive phases, and it consists of these four main steps:

1. *Tool-Life Tests According to ISO 3685.* The first step involves conducting tool wear tests according to the ISO 3685 guidelines using a constant cutting speed. The tools and process parameters are chosen to closely match the actual working conditions of the industrial process. The tools undergo repeated tests at selected cutting speeds that represent the tool's working cycle in production. Each test is repeated at least three times to gather reliable statistical data and accurately represent tool wear in specific conditions.
2. *Definition of Standard Tool-Wear Curves.* In the second step, the wear data collected from the tests are processed to build standard tool-wear curves for each cutting speed. The wear curves are created by averaging the wear curves obtained in the tool-life tests, ensuring the curves accurately represent the wear behavior of the tool under the selected speeds. These standard curves are essential for building the cumulative wear curve in the following step.
3. *Construction of the Cumulative Tool-Wear Curve.* The third step involves creating an empirical curve representing the cumulative wear of the tool by combining the standard wear curves obtained in the previous step. This cumulative curve accounts for the work cycle, which in this case is divided into several phases, each with a different cutting speed. A typical machining cycle might consist of three phases:
 - Phase 1: machining a feature at a higher cutting speed (v_{cC}) for a certain time interval $\Delta t_1 = (t_1 - t_0)$, generating initial cumulative wear $\Delta TW_1 = TW_1$.
 - Phase 2: moving to an intermediate cutting speed (v_{cB}) to machine a second feature, for an interval of time $\Delta t_2 = (t_2 - t_1)$, accumulating additional wear $\Delta TW_2 = (TW_2 - TW_1)$.
 - Phase 3: applying a lower cutting speed (v_{cA}) to machine a third feature, for an interval of time $\Delta t_3 = (t_3 - t_2)$ further increasing wear $\Delta TW_3 = (TW_3 - TW_2)$.

Each section of the cumulative curve is created by translating segments of the standard wear curves along the time axis and incrementally summing the wear. In this way, the cumulative curve accurately reflects the actual wear of the tool during a work cycle that involves multiple cutting phases. Fig. 1 shows how the cumulative tool wear curve is built starting from standard tool-wear curves.

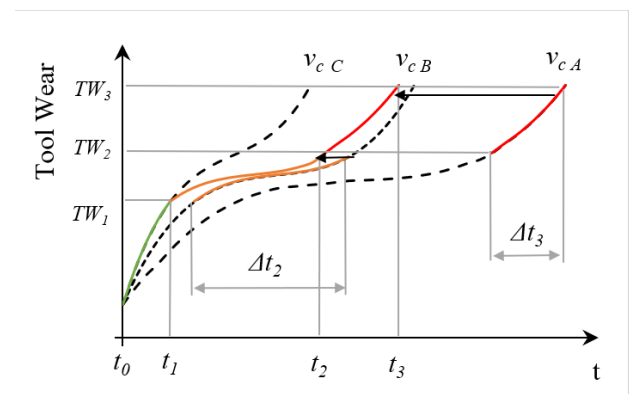


Fig.1. Procedure for the building of the empirical cumulative tool-wear curve.

4. *Estimation of Useful Tool-Life for Cumulative Wear.* The fourth step calculates the useful life based on the cumulative wear curve, adopting a pre-selected tool-life criterion, such as a wear limit on the flank. Using the empirical cumulative wear curve, it is possible to determine when wear reaches the set limit, thus estimating the effective life of the tool.

To validate the described tool-life estimation procedure, turning tests on AISI 1045 steel samples were executed. The experimental tests consisted of longitudinal turning operations performed at constant cutting speeds while maintaining a constant feed, following the ISO 3685:1993 standard. Specifically, three cutting speeds were selected to ensure a tool-life of no less than 5 minutes at the highest speed. Cutting parameters and sample characteristics were carefully inspected to obtain representative and reproducible results. The samples used in the experiments were manufactured from a batch of AISI 1045 steel bars provided by Ascométal France Holding SAS. The material characterization of the workpiece included the following phases:

- **Chemical Composition:** Analyzed using a Horiba Jobin Yvon JY3 spectrometer, previously calibrated with an SS407 steel reference sample. Each measurement was repeated on randomly collected samples from the batch to ensure homogeneity.
- **Brinell Hardness (HB):** Hardness tests were conducted with a load of 187.5 kg using a Brinell hardness tester. The same samples used for the chemical analysis were used for hardness testing.
- **Metallographic Analysis:** Conducted to evaluate grain size and microstructure distribution, and to detect any internal defects. The samples were polished and etched with a 4% Nital solution, then observed under an optical microscope to detect inclusions or microcracks.

The tests were performed on two different CNC lathes: a Sonim T9 and an OCN-PPL Olympus, located respectively at LaBoMaP Laboratory (Cluny Campus, Art et Métiers Institute of Technology) and at Technology and Manufacturing Systems Laboratory (Department of Industrial and Mechanical Engineering, University of Brescia). The usage of two different machines allowed to verify if their characteristics influence the tool wear. Sandvik VBMT 160404 PM4325 inserts were used, mounted on a Kennametal SVJBR 2020K16 tool holder with a normal rake angle of 5° , an inclination angle of 0° , and a cutting edge radius of 0.040 ± 0.003 mm. The insert, made from coated tungsten carbide, features a multi-layer CVD coating (TiCN-Al₂O₃-TiN) to increase tool life and improve surface quality. Each test was executed with a new insert, which was previously inspected with an optical microscope to assess the actual cutting edge radius. Table 1 lists the values of the depth of cut, the feed per tooth and the cutting speed used to machine the samples.

Table 1. Process parameters.

Process parameter			
Depth of cut <i>DOC</i> [mm]	1	1	1
Feed rate [mm/rev]	0.1	0.1	0.1
Cutting speed <i>V_c</i> [m/min]	300	350	400

The cutting fluid used was a mixture with 5% Zubora 65 M oil in water, applied with a pressure of 0.8 bar and a flow rate of

75 l/min. Each CCS test was repeated three times to statistically validate the procedure. Tool wear was monitored using high-resolution digital multi-focus microscopes, Keyence VHX-1000 and Hirox RH2000. A tool-life criterion of 0.3 mm flank wear width (VB) was used, since the crater wear on the rake surface resulted neglectable. Wear was measured at three points along the tool flank to consider the possible effect of the cutting edge curvature on wear (close to the end of the tool nose radius *VB_A*, one along the inclined zone *VB_B*, one along the straight zone *VB_C*), according to Figure 2. The points were identified at a constant distance from the tool point (i.e. the intersection between primary and secondary cutting edges).

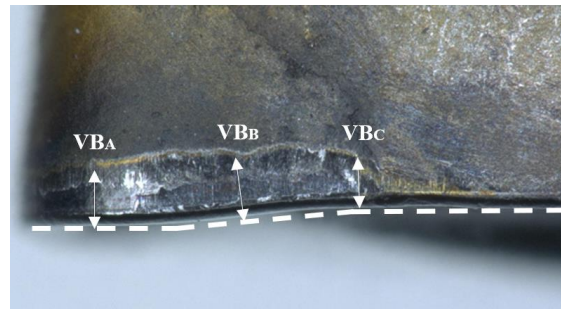


Fig.2. Example of worn profile, with three measurements *VB_A*, *VB_B*, *VB_C*.

The wear curve was plotted against machining time, with an increase of the measure frequency during the decelerated and accelerated wear periods (Z1 and Z3) to ensure higher accuracy. The procedure summarized in Fig. 1 was utilized to build three different VCS tests, which were performed in the same conditions of CCS tests.

3. Results

The results of the validation are presented by dividing the results of the material characterization, the results of CCS tests and finally the outputs of the VCS tests.

Material Characterization. Spectrometric analysis confirmed the steel standard composition, which is summarized in Table 2.

Table 2. Chemical composition of the tested material.

C %	Cr %	Cu %	Mn %	Ni %	S %	Si %	Fe %
0,479	0,153	0,078	0,720	0,051	0,034	0,037	Rest

Hardness measurements ranged between 168 HB and 190 HB, with an average of 179 HB, showing minimal scatter across the bar's longitudinal and transversal sections [13]. A slight reduction in hardness close to the centre of the bars was attributed to the effects of continuous casting and hot rolling processes, which influence material solidification and cooling dynamics. Microstructural analysis revealed equiaxed grains of ferrite and lamellar pearlite, transitioning in size radially from the edge (12.5 μ m) to the centre (24.3 μ m) [13]. The hot rolling process induced elongated grains along the rolling direction. To minimize variability in cutting tests, only sections with a minimum diameter of 40 mm were tested, maintaining cutting speeds within equipment limits. Metallographic examination detected small, uniformly distributed inclusions (0.5–5 μ m),

which had negligible impact on cutting performance since the chip section is considerably higher. Overall, the material displayed consistent hardness, microstructure, and inclusion distribution, affirming its homogeneity and reliability for machining applications.

The results of CCS tests. Figure 3 shows an example (first repetition of the test at $v_c = 300$ m/min) of the progression of wear on the tool by distinguishing Z1 (Fig. 3a), Z2 (Fig. 3b) and Z3 (Fig. 3c). Analogue trends were observed in the other CCS tests, regardless the velocity. Abrasion resulted the dominant wear mechanism, although in Z3 the rounding of cutting edge due to the remarkable tool wear determines also the adhesion of the workpiece material on the tool. In fact, it determines negative actual rake angles, fostering built up edge phenomena.

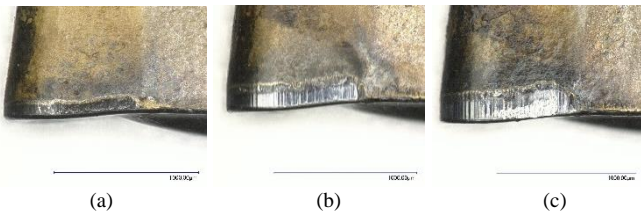


Fig.3. An example of the evolution of the wear on tool flank for the first repetition of the test performed at $v_c = 300$ m/min after 4 min (a), 18.5 min (b) and 30 min (c).

To model the evolution of tool wear in time as function of the cutting speed, the parameter VB_B was selected because it firstly reaches the limit of VB in each test. The first repetition of each CCS test was conducted on the Sonim T9 lathe; it showed no significant deviation compared to subsequent tests performed on the OCN-PPL Olympus lathe, irrespective of the cutting speed. Consequently, the lathe features did not influence tool wear, allowing for statistical analysis of the data independently of the machine used as an aggregated dataset.

The piecewise function expressed by Equation 1 was used as a fitting model for the experimental value of VB (in mm) depending on time (in minutes).

$$\begin{cases} VB = a_1 t^2 + b_1 t + c_1 & \text{when } t < t_1 \\ VB = b_2 t + c_2 & \text{when } t_1 < t < t_2 \\ VB = a_3 t^2 + b_3 t + c_3 & \text{when } t > t_2 \end{cases} \quad \text{Eq. 1}$$

It fits the Z1 with a second order polynomial, the Z2 with a first order polynomial and finally Z3 with a second order polynomial. This approach overcomes the limitations of fitting the data with a unique third order polynomial function [13], since it considers a constant wear rate in Z2, as well established in literature. The second order polynomial functions used for Z1 and Z2 allow to fit, respectively, the decrease and increase of tool wear rate typical of these zones. A criterium was adopted to compute the time domain of each section of the function with the purpose to standardize the identification of the transitions from Z1 to Z2 (at t_1) and from Z2 to Z3 (at t_2). The incremental ratio (IR_{VB}) of VB on time, between two consecutive measurements, was computed by using the Equation 2:

$$IR_{VB} = \frac{VB_i - VB_{i-1}}{t_i - t_{i-1}} \quad \text{Eq. 2}$$

Figure 4 represents the trend of IR_{VB} as function of time for

cutting speed equal to 300 m/min, but analogue trend was achieved for the other cutting speed. During the decelerated wear zone Z1, it decreases until reaching a plateau during the constant wear rate zone Z2. Finally, it increases in the accelerated wear zone Z3.

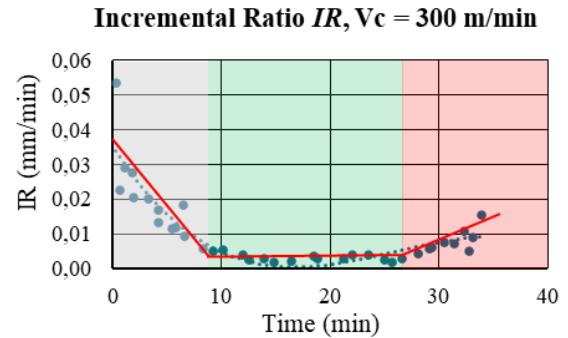


Fig.4. Incremental Ratio IR as a function of the time for the cutting speed of 300 m/min

Upper and lower bounds for the empirical model were determined by adding and subtracting twice the standard deviation from the average value of VB. These bounds were subsequently modeled using piecewise functions to empirically define the confidence intervals of the experimental data. The transition instants for lower and upper bounds were assumed equal to the values determined for the average VB. The upper and lower bounds of the accelerated wear zone (Z3) were fitted with a linear model instead of a second order polynomial because it better model the actual behaviour of the computed upper and lower limits.

The fitting process was executed by imposing the continuity of the functions (average, upper and lower bounds) along their entire domains of time. The fitting of the experimental data was performed by using the least square method. Table 3 reports the coefficients of Equation 1 for $v_c = 300$ m/min, $v_c = 350$ m/min, and $v_c = 400$ m/min, respectively.

Table 3. List of the coefficients of Eq. 1 for the three velocities.

Vc (mm/min)	300	350	400
a_1	-0,0019	-0,0031	-0,0045
b_1	0,0325	0,0386	0,0499
c_1	0,0400	0,0400	0,0400
b_2	0,0036	0,0049	0,0073
c_2	0,1506	0,1281	0,1414
a_3	0,0009	0,0016	0,0041
b_3	-0,0447	-0,0535	-0,0886
c_3	0,8270	0,6795	0,6939

Figure 5 illustrates the average experimental values of VB (triangles for Z1, circles for Z2 and rhombuses for Z3) the fitted model defined by Equation 1 (the continuous black line), along with the upper and lower bounds (the red and blue dotted lines) for each tool-life test condition. All wear curves exhibit the characteristic behavior described in the introduction, highlighting the three distinct wear zones. Notably, these curves do not originate from the axis origin, which is attributable to the cutting edge radius of 0.04 mm on the unused

insert. According to ISO 3685, the nominal cutting edge serves as the reference for flank wear measurements, providing a more consistent basis for measurements than the shifting flank surface caused by wear. The position of the nominal cutting-edge remains constant throughout the machining process, ensuring a reliable reference for measuring the width of the land.

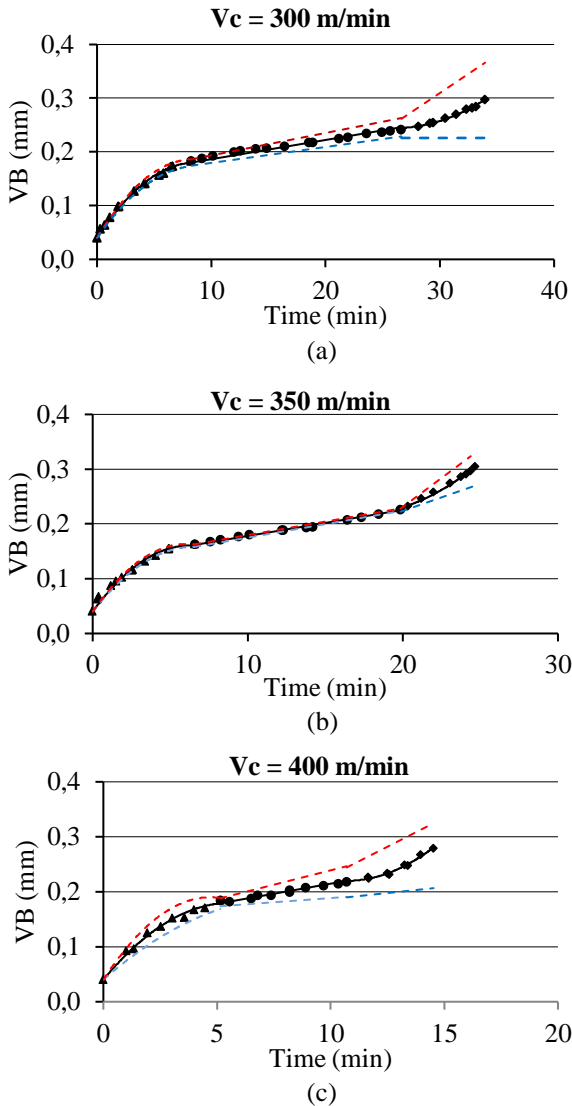


Fig.5. Tool wear curves, average values of VB and representation of the model and interval of confidence for $v_c = 300$ m/min (a), $v_c = 350$ m/min (b), $v_c = 400$ m/min (c),

Using a tool-life criterion of 0.300 mm, tool life was estimated as 34.1 minutes for 300 m/min, 24.4 minutes for 350 m/min, and 15.1 minutes for 400 m/min. As expected, higher cutting speeds correspond to reduced tool life. Low data scattering was observed in wear zones I and II, while zone III exhibited greater variability due to unstable tool degradation. This phenomenon determines highest and increasing standard deviations among the VB values in Z3. As consequence, the values of upper and lower limits, which depends on standard deviation, resulted better fitted by linear functions instead of 2nd order polynomials, as previously anticipated. Furthermore, the tests performed at 350 m/min exhibits minimum standard deviation and consequently the interval of confidence resulted less extensive than the cases of 300 m/min and 400 m/min. A possible explanation is that 350 m/min represents the best cutting speed, according to the tool manufacturer, and it

resulted in a more stable and repeatable process.

The results of VCS tests. Table 4 summarizes the three VCS tests, achieved by combining the different speeds in different orders. It provides also the estimated useful tool-life.

Table 4. Cumulative tool wear data.

Test ID	Vc (m/min)	Interval time (min)	Starting value of VB (mm)	Final value of VB (mm)	Estimated useful tool-life (min)
A	400	6min 15s	0.000	0.190	21.75
	300	10min 15s	0.190	0.220	
	350	End of TL	0.220	> 0.300	
B	300	4min 15s	0.000	0.130	21.75
	350	8min 45s	0.130	0.195	
	400	End of TL	0.195	0.300	
C	400	4min 30s	0.000	0.175	28.50
	350	11min 30s	0.175	0.220	
	300	End of TL	0.220	>0.300	

Figure 6 shows the results of the procedure, by comparing empirical cumulative wear models with experimental measurements.

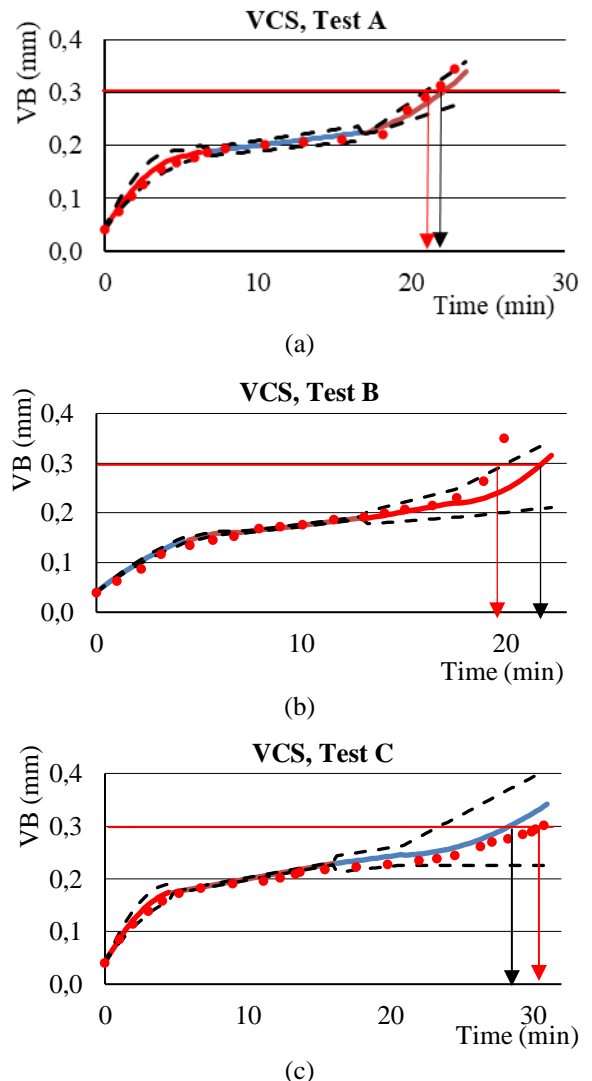


Fig.6. Empirical cumulative tool-wear curves and VCS experimental values.

Colored lines represent model predictions (based on Eq. 1 and the coefficient of Table 3, while red dots indicate the measured values. Upper and lower bounds, shown as dashed lines, are the same bounds represented in Fig. 5 and they were modified as the cutting changes. The model robustness is demonstrated since the majority of the red dots belong to the interval of confidence. Also in wear Z3, where adhesion increase the uncertainty of the wear, the data always fit the interval of confidence (with the exception of the last point of Test B). It means that the proposed procedure ensures a strong predictive accuracy. The new method of data fitting significantly improves the statistical robustness of the procedure if compared to the work presented in [13]. In fact, with the previous model, the prediction capability in Z3 resulted lower and the negligibility of non-linear effect resulted in doubt. With the new methodology, it was demonstrated that the procedure is reliable also in this wear region. Furthermore, with the previous method, some experimental points were out of the interval of confidence, while now every experimental data belong to the interval. The unique data which are external to the interval of confidence miss the bounds for few micrometers, and they all are related to cutting 350 m/min. As previously explained, at this speed the standard deviation of the experimental data is extremely low and the wide of the interval of consequence is minimum as consequence. This new approach demonstrate as the variation of VB during VCS from the empirical prediction is determined only by the intrinsic variability of the phenomenon of wear, and it is not the results of a change of cutting speed during the process. The actual tool life were 21.26 min for Test A (the empirical visible in Table 4 is 21.75 min), 19.35 min for Test B (the empirical is 21.75 min), 31.63 min for Test C (the empirical is 28.50 min). The maximum difference is 3.13 minutes and it belongs to the interval of confidence of the phenomenon.

4. Conclusion

This study provides a robust foundation for predicting cumulative tool wear in variable cutting speed (VCS) turning operations. By employing empirical data from constant cutting speed (CCS) tests, this work develops a predictive model that accurately represents tool wear progression machining operations. The experimental validation demonstrated high predictive accuracy, with empirical tool-life estimates closely matching empirical observations. Furthermore, the nonlinear effects of variable speeds were shown to have a marginal impact when statistically describing the evolution of the tool wear. This confirms the reliability of the proposed approach under diverse operational conditions, although the negligibility of non-linear effect can not be automatically extended to different combinations of tools, workpiece materials and process conditions. Moreover, the innovative contribution of this research lies in the methodology for constructing cumulative tool-wear curves. By combining wear curves from different cutting speeds into a single empirical model, the study provides a practical and statistically validated procedure for predicting tool life in industrial context. This method not only simplifies the assessment of tool wear but also bridges a critical gap between ISO 3685 guidelines and industrial machining practices. Furthermore, the use of a robust statistical approach

to define confidence intervals enhances the reliability of the predictions, offering an improvement over prior models. Future work should focus on extending the application of this methodology to a wider range of workpiece materials and tools. Incorporating additional variables, such as cutting fluid characteristics, tool geometry variations, and workpiece material characteristics, could further refine the model's accuracy. Additionally, integrating real-time sensor data with the predictive model could enable the usage of adaptive control systems, optimizing tool management during machining. Exploring machine learning techniques to analyse data may also unlock new possibilities for enhancing predictive capabilities. The integration of such advancements could solidify this framework as a cornerstone for sustainable and efficient manufacturing practices.

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