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Use of Longitudinal Roughness Measurements as Tool End-of-Life Indicator in AISI 1045 Dry Longitudinal Turning

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Abstract. The important portion of machining costs associated with cutting inserts and scraps induces the search for better effectiveness in turning. This paper presents the results of an exploratory study on the influence of tool flank wear on roughness indicators (arithmetic average roughness, root mean square roughness and maximum height of the roughness profile). The objective is to determine which of these indicators is best correlated with the cutting tool flank wear. In order to do this, specimens of AISI 1045 are machined until the end of life of a cutting insert. Significant, strong and positive correlations are found between all three roughness indicators and the tool flank wear. The most significant correlation is found with the arithmetic average roughness and the root mean square roughness of the profile. The choice of the end-of-life criteria for cutting inserts in industrial contexts is also discussed.

Introduction

The manufacturing industry undergoes strong competition that leads to a permanent search for cost effectiveness. The reduction of costs includes the aim for the quality improvement of produced goods and the standardization of manufacturing processes. In the case of turning, the quality of workpieces is evaluated through the respect of specifications such as dimensional and geometrical tolerances, or surface roughness.

Flank wear of cutting inserts, and in particular its progression, is crucial to the deviations that may occur with respect to those specifications [1], the moment of tool replacement is therefore crucial, as it may lead to important losses [2]. Simultaneously, the replacement of cutting inserts also represents a costly aspect of machine-tool maintenance, because of the unavailability of the machine and the cost of the insert itself.

The ISO 3685:1993 standard [3] states that the end of useful lifetime of cutting inserts is defined as the duration after which the tool ceases to produce workpieces of the desired dimensions and surface quality. In workshops, tests are performed in order to determine an average tool useful life, that becomes the standard for the considered operations. This procedure must then be reproduced after switching tool manufacturers, as processes evolve, or as coating and tool material change throughout time.

The ISO 3685:1993 standard defines a procedure for such life-testing. Relating to machining with sintered carbide tools, it provides two end-of-life flank wear measurements, depending on the wear land being regularly worn or not: $\mathrm{VB_B}$ is the average width of the flank wear land on the tool flank face zone B, and is used for regularly worn tools; $\mathrm{VB_B max}$ is the maximal width of the same wear land, and is used in the case of irregular wear. The flank wear zone B is defined by ISO 3685:1993 as comprised between zones A and C, with C being the curved part of the cutting edge, and A the quarter of the worn cutting edge farthest away from the tool corner (see Figure 1-2).

These criteria are shown on a worn tool flank face in Figure *2*. The end-of-life thresholds, which are described in this standard as “most commonly used” are respectively: $\mathrm{VB_B} = 0.3$ mm, or $\mathrm{VB_B max} = 0.6$ mm. Yet, various other values for these criteria are also widely used in the literature.

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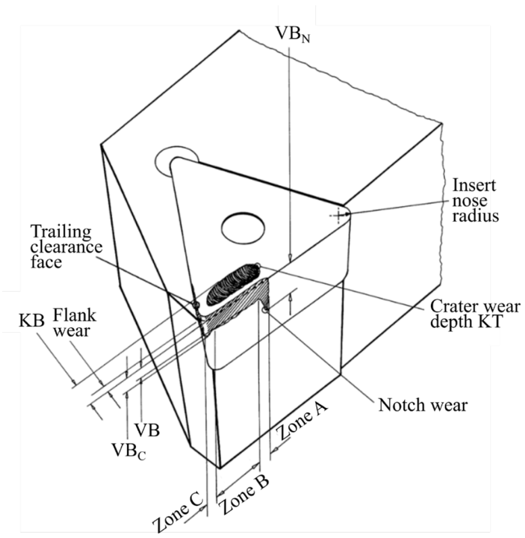

Figure 1. Geometry of the tool wear patterns, including the division between A, B and C zones of the flank wear. Figure adapted from [4, ch.7].

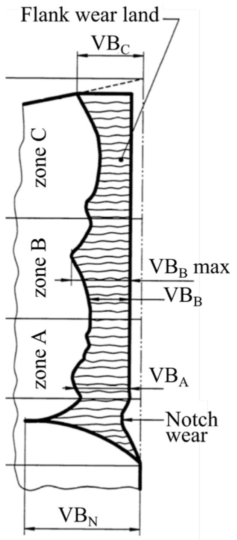

Figure 2. Flank face of a worn tool, and standardized tool-life testing end-of-life criterion measurements (VB_B, VB_B max). Figure from [3].

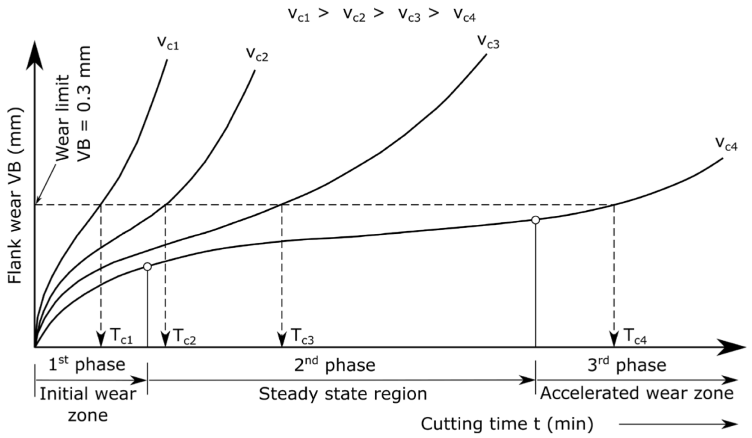

Figure 3. Usual evolution of the flank wear measurement of cutting tools. Figure adapted from [5, p. 60].

Flank wear usually follows an evolution that may be divided into three parts (see Figure 3). A first quick wear part is followed by a steady-state period, which later leads to an accelerated wear. The increase of cutting speed (v_c) leads to steeper behaviors, but the same qualitative evolution is met regardless the cutting parameters. Industrial practice may tend to avoid this third phase, due to its quick evolution and less predictable tendencies [6].

On a more physical point of view, the degradation in surface quality of workpieces is linked with the progressive wear of the cutting insert [7]–[9, ch. 10], the progressive wear of the cutting edge induces a drift in machined dimensions. The machined workpiece variability is increased by the tool flank wear, leading to inconsistency in the quality of production [4, ch. 7].

Efforts have been made on the reverse problem, that is predicting the evolution of the surface roughness from other variables including tool wear. Machine learning techniques may use condition monitoring data as inputs for this prediction [10]. The cutting parameters also have important effects on the surface roughness and tool life [11]. More advanced techniques, such as machine learning and in particular neural networks may take tool wear as a variable for roughness prediction, mainly for inducing uncertainty [12]. It has also been suggested to predict both the tool wear and the surface roughness from the cutting parameters and learning data [13].

In a broader framework, statistical approaches include the modeling of tool degradation, for example through degradation modeling such as stochastic [14] or Markov approaches [15]. Another proposed way of assessing the progression of tool wear is to evaluate the total amount of energy that was conveyed by the cutting insert [16].

Condition monitoring approaches include direct methods, that require off-line measurements (tool geometry, optical measurements, etc.) or indirect methods, that may be applied on-line (cutting forces, vibratory measurements, acoustic properties, etc.) [17]. In particular, a correlation was shown between force signals and surface state in Inconel 718 turning, but more interestingly that surface defects may occur even at early stages of machining, when the tool does not present worn characteristics [18].

Yet, the roughness monitoring approach to the cutting tool replacement problem is essential in two key aspects. First, quality sampling is already a common procedure in most productions, some of which control the entirety of production. Therefore, it does not necessitate additional sensors, and it relies on procedures that are known and mastered. Second, the variable that is monitored, and that may induce a maintenance action, is a key quality indicator and represents the value of the workpiece to be delivered to the customer. The maintenance, the production and the customer are therefore focused on a common variable. The time required by a systematic inspection of the entire production would, however, constitute the main drawback to this method.

A particular study stands out in the literature [19]. In dry longitudinal turning of AISI 4140 steel, using an uncoated cemented carbide tool, the authors remarked that despite the roughness increasing with tool wear at first, it seems to diminish near the traditional tool end-of-life criterion, before increasing again after severe wear.

The current study is an exploratory work that aims at a first production of roughness data in machining of AISI 1045 steel. The objective of the study is to machine workpieces at constant cutting parameters, follow the evolution of the wear criteria and evaluate the evolution of the roughness parameters: arithmetic average roughness R_a, root mean square roughness R_q, and the maximum height of the roughness profile R_t. These measurements are done in order to determine and compare their relevance for determining the tool end of life when compared to the ISO 3685:1993 criteria.

Experimental Design and Equipment

In this study, the objective is to measure three roughness parameters (arithmetic average roughness, root mean square roughness and maximum height of the roughness profile) and the wear of the cutting insert in order to evaluate their evolution over machining time in semi-finishing of AISI 1045 steel in dry longitudinal turning. A single cutting insert was used for this study.

The experimental workpieces are cylindrical bars of AISI 1045 (1.0503 steel), 250 mm long. The machined length is, however, limited to 175 mm in order to avoid interaction between the chuck jaws and the cutting tool. The initial diameter of the bars is 58 mm, after preparation (removal of the mill scale, as suggested by ISO 3685:1993). The workpieces also underwent an annealing heat treatment (8 hours above 850 °C and slow cooling). The Vickers hardness after the heat treatment is measured at 154 HV_{30}, and it is homogeneous throughout the section of the bar. AISI 1045 is the recommended alloy for tool life testing as per ISO 3685 specifications.

The insert and the toolholder are selected for AISI 1045 dry longitudinal turning. The retained tool is a coated cemented carbide tool (Seco Tools CNMG120408-MF5, TP2500 grade). The TP2500 coating belongs to the P 10 ISO group. A compatible toolholder (DCLN L/R 2020K12-M) is used.

The CNC lathe used for this experiment is a Weiler E35 horizontal lathe. For reasons unrelated to this study, the cutting tool was mounted on a triaxial force sensor (Kistler 9257B). This particular mounting required to flip the tool holder (facing downwards). The workpiece mounted on the lathe is shown in Figure 4. In this figure, the cutting insert is highlighted by a circle, and the arrow shows the rotational direction of the lathe. In order to prevent vibratory effects due to the slenderness of the bar at its final diameter, the bar is supported by the tailstock center.

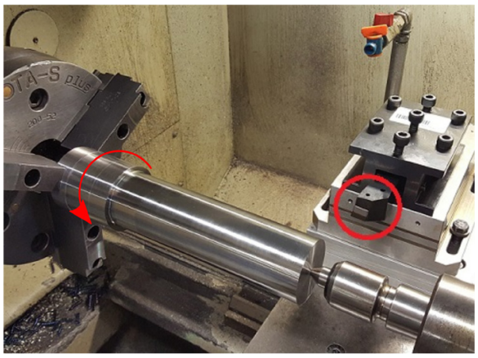

Figure 4. Experimental setup: a C45 sample is set on the lathe with a tailstock center for support.

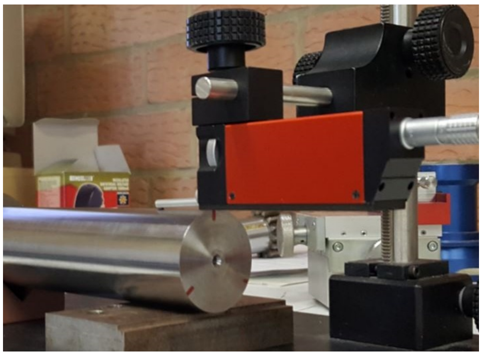

Figure 5. Diavite DH-6 roughometer and a machined workpiece. The lines drawn on the workpiece indicate the localization of the measured surfaces on the cylinder.

The cutting conditions are given in Table 1. The recommended cutting conditions, as provided by the tool manufacturer, are respected. The initial diameter of each bar is 58 mm, and the bar final state is reached after ten passes, at a diameter of 44 mm. Sixteen bars are necessary to reach the end-of-life criterion following the ISO 3685:1993. The wear of the cutting insert and the roughness of the workpiece are evaluated throughout the experiment, following the measurement sequences given in Table 2.

Table 1. Cutting conditions of the experiment.

Radial depth of cut	a_p	0.7 mm
Feed	f_n	0.4 mm/rev
Cutting speed	v_c	365 m/min

Table 2. Measurement sequences of tool wear and roughness.

	Tool wear	Roughness
Bars 1 to 3	Every 5 passes	Every 10 passes
Bars 4 to 13	Every 10 passes	Every 10 passes
Bars 13 to 16	Every 5 passes	Every 10 passes

The expected lifetime of the cutting insert may be computed using Taylor's formula (Eq. 1) [20] from data given in the manufacturer's catalog [21]. Indeed, a tool life $\mathrm{T_1}$ of 15 min is estimated by the manufacturer at $\mathrm{v_{c1}} = 410\ \mathrm{m/min}$ in the same material, for the same feed and depth of cut. Using $\mathrm{k} = -5$ for the case of a cemented carbide tool [22], the lifetime of the tool can be computed at $\mathrm{v_{c2}} = 365\ \mathrm{m/min}$ through Eq. 1:

$$\mathrm{T_2} = \mathrm{T_1}\left(\frac{\mathrm{v_{c2}}}{\mathrm{v_{c1}}}\right)^{\mathrm{k}} = 15\left(\frac{365}{410}\right)^{-5} = 26.8\ \mathrm{min}. \tag{1}$$

A Diavite DH-6 roughometer (see Figure 5) is used to measure the roughness parameters. They are computed by the Diasoft Standard Software. A Gaussian filter is applied in compliance with the ISO 16610 standard in order to dampen undesirable roughness profile waves. Pictures (640x480 pixels) are taken with a 800x magnification microscope for estimating the wear.

The wear measurement is made through two pictures taken at each measurement step. One allows evaluating the evolution of the flank and the other the crater wear. The crater wear is not the subject of this study, but its evolution is monitored in order to ensure that it does not constitute a cause for tool end-of-life (as given by ISO 3685:1993 criteria). The scale is printed on the image and the measurement of the flank wear land length $\mathrm{VB_B}$ is made through the Mesurim software. Ten lengths are evaluated on the flank wear length in order to determine a mean $\mathrm{VB_B}$ value, and its standard deviation. Likewise, three measurements of the $\mathrm{VB_B}$max are performed. Three measurements are made on each bar after the end of the machining on the corresponding bar. The measurements are made on the cylindrical external surface, along the cylinder axis. They are separated by 120° (see

Figure 5). From these measurements, the three roughness parameters (R_a, R_t, R_q) are computed for each bar.

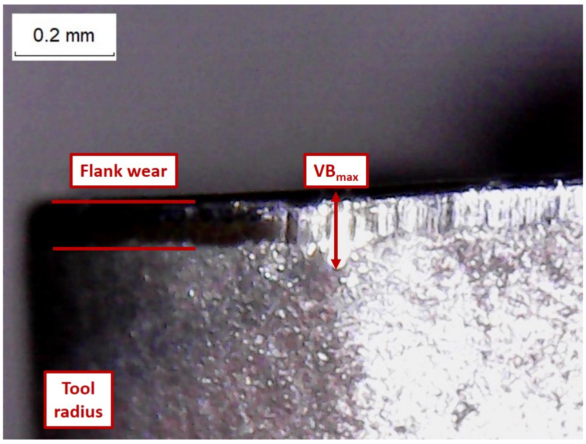

Figure 6. Flank face at machining time 1.92 min.

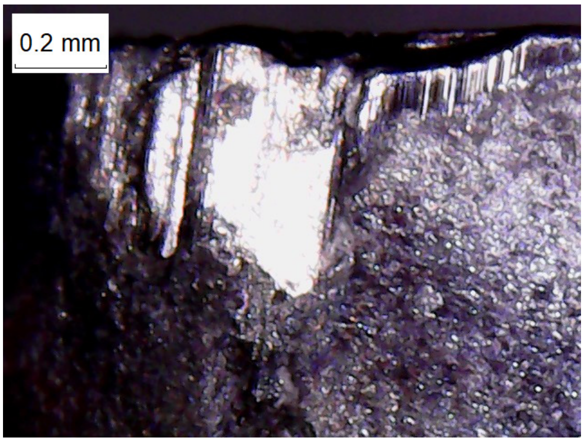

Figure 7. Flank face of the worn tool (final state).

Results and Analysis

An example of the wear measurement photographs is given in Fig. 5. In this early wear photography, the flank wear is easily noticed and its measurement is not complex, the cutting edge and the end of the flank wear land being clearly noticeable. When the tool is at more advanced wear stages, the limit of the flank wear land is more complex to identify (see Fig. 7), and the wear land itself is also less linear, making the standard deviation of the measurement wider and the overall mean flank wear measurement less precise, and therefore less reliable.

The evolution of the mean tool flank wear over the machining time is given in Figure 8. The ISO 3685:1993 end-of-life criterion was reached at $T = 25.35$ min. This value is very similar to the one computed from Taylor's law (see Eq. 1). The general behavior of the evolution of the wear follows the usual pattern shown in Figure 3. As expected, the uneven wear at advanced stages induce larger standard deviations.

Likewise, a similar graph may be made for the evolution of the maximal value of flank wear. This particular measurement is made easier because of the nature of the maximal flank wear. Its limits are more clearly visible on the micrographs, therefore limiting the errors. With respect to that criterion, the tool end of life is reached at 26.8 min, which corresponds exactly to the estimate made from Eq. 1. Following the criteria of ISO 3685:1993, the first end-of-life criterion to be met determines the tool end of life. In this case, the mean flank wear VB_B criterion was reached first.

The evolution of roughness parameters are depicted in Fig. 9. The comparison of Figs. 8 and 9 shows that the roughness indicators tend to rise with the flank wear. The major advantage of using mean values of the roughness is the limitation of the influence of local discrepancies that strongly affect R_t. In general, the roughness parameters grow as tool wear widens. The relative evolution of the roughness parameters are important between the first and the last measurement:

- 48 % increase of R_a
- 76 % increase of R_t
- 64 % increase of R_q

The evolution of the arithmetic roughness with the tool flank wear is represented in Figure 10. The correlation between the roughness indicators and the flank wear can be evaluated (Table 3).

Discussion

Experiment Results and Experimental Setup. The experiment allowed to reach both criteria of ISO 3685:1993 for tool end-of-life (VB_B and VB_Bmax). Their measurement is made complex by the irregularity of the flank wear land, but the resulting lifetime corresponds to the estimate from Taylor's law. The variability in the estimate of the flank wear for more worn situation is a clear limitation to the manual estimate of the tool flank wear. This variability may be reduced by the use of a more advanced imagery technique, and in particular by better lighting. Further, automated image analysis may be used in order to identify the mean VB_B value.

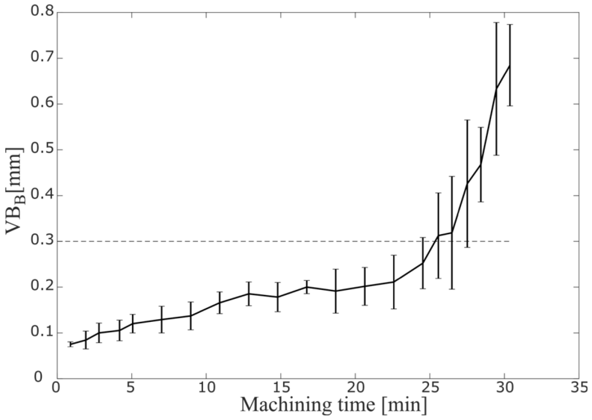

Figure 8. Evolution of the mean tool flank wear over machining time. Error bars represent standard deviation.

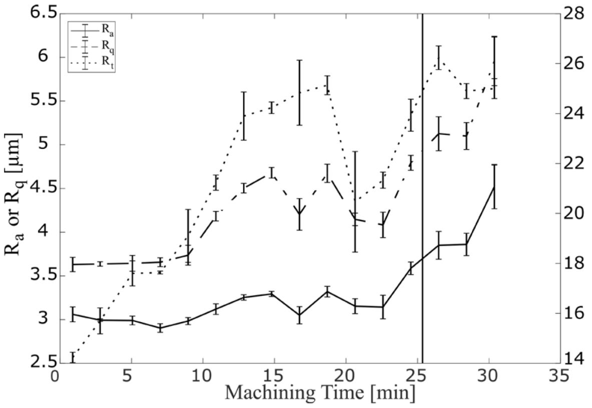

Figure 9. Evolution of the arithmetic average roughness R_a, the root mean square roughness R_q, and the maximum height of the roughness profile R_t over machining time. Error bars represent standard deviation.

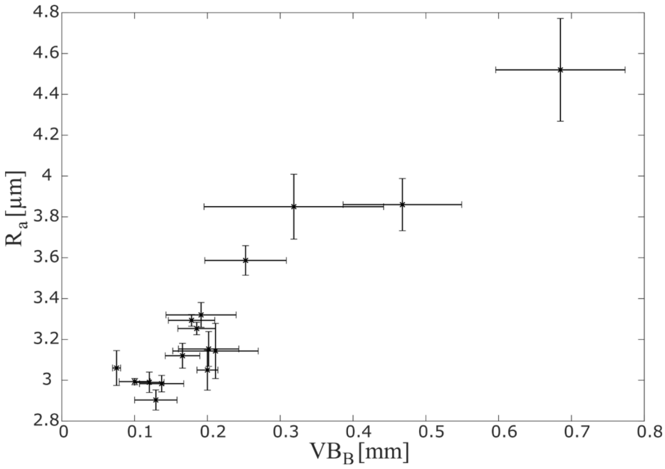

Figure 10. Evolution of arithmetic mean roughness R_a with the mean tool flank wear. Error bars represent standard deviation.

Table 3. Correlation analysis results of the different roughness parameters and the mean tool flank wear (Pearson correlation coefficient).

	Correlation coefficient	95 % confidence interval	p-value
VB_B vs R_a	0.95	[0.86, 0.98]	< 0.001
VB_B vs R_t	0.62	[0.17, 0.85]	0.011
VB_B vs R_q	0.90	[0.72, 0.96]	< 0.001

Similarly, an increased number of roughness measurements may play a role in better identifying the interest of roughness measurements. Further, other quality indicators may play a role in the evaluation of tool wear, such as geometrical specification control (cylindricity, etc.) and dimensional control.

As it is shown in Table 3, and following the tendency that may be seen in Figs 8-9, all three roughness indicators are *significantly* and *strongly* correlated to the flank wear. However, the total roughness seems to be the least significant indicator of the tool flank wear, due to its weaker correlation to flank wear. In particular, the quick rise in both the arithmetic average and the root mean square roughness indicators, near the end of the tool life, may constitute an interesting feature in identifying the tool end of life. Similar conclusions (hinting the interest of searching for positive and locally important increases rather than absolute maximum values) were drawn by Bonifacio and Diniz [23] when using vibratory RMS values for monitoring cutting inserts.

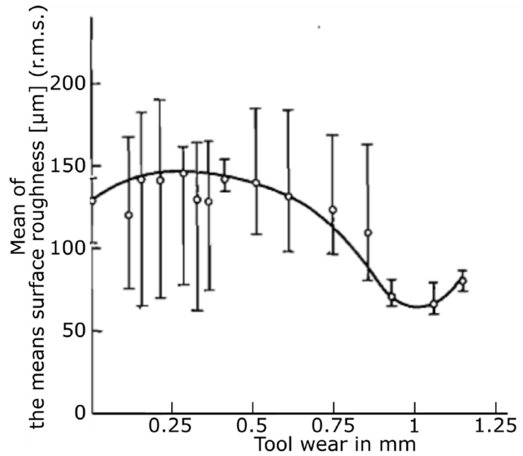

Figure 11. Quadratic roughness mean values as a function of tool wear according to Sundaram and Lambert [19].

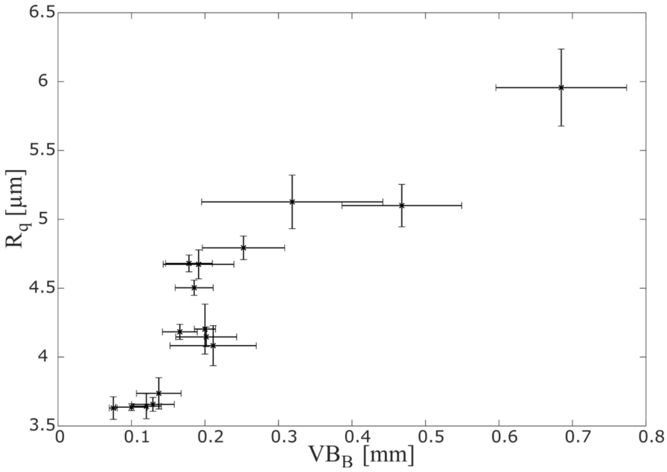

Figure 12. Quadratic roughness mean values as a function of tool wear according to the result of the current study. Error bars represent standard deviation. locally important increases rather than absolute maximum values) were drawn by Bonifacio and Diniz [23] when using vibratory RMS values for monitoring cutting inserts.

The increase of roughness indicators with the evolution of flank wear corresponds to a behavior observed by other authors [7]–[9]. However, as presented in Figs. 11 and 12, while Sundaram and Lambert [19] found the quadratic roughness (R_q) to present a plateau and a decrease after $VB_B =$ 0.25 mm, the observed R_q in the case of this study did not exhibit such a behavior. The reason for this difference may be found in the fact that error bars in Figure 11 are quite large in comparison with Figure 12. Moreover, the maximal flank wear measurement that was reached in the case of this study is roughly 0.7 mm, that is 0.0275 in (about half of the tool wear range shown in Figure 11). In a broader point of view, the plateau observed by Sundaram and Lambert may be explained by the wear of the cutting insert itself. The cutting edge radius may become a chamfer, and in turn, crushing the peaks of the workpiece asperities [23].

The Use of Roughness Measurements as End-of-Life Indicator. The flank wear land is evaluated, according to ISO 3685:1993, on the flank face, because it is the most advisable type of wear, and usually leads to a progressive diminution in the tool quality. However, the nose radius in particular, and to some extent the trailing edge are in direct contact with the machined surface. It may therefore be expected that the wear of those surfaces may bear a more significant influence on the workpiece roughness. The relevance of the standardized criterion regarding tool flank wear could possibly be challenged.

The roughness parameters fail in all cases to account for other quality and machinability properties. The residual stresses in particular could hardly be linked to the surface roughness. Yet, in high added value industry, such properties may be of greater importance than the surface quality.

The major advantage of using the evolution of roughness as a tool replacement indicator is the direct measurement of the quality indicator itself: the potential drift in quality is not evaluated through other variables. In a similar fashion, industrial machining systems already include a compensation for the dimensional drift due to the cutting insert wear evolution.

Conclusions and Perspectives

This research has investigated the wear of a cutting insert in dry longitudinal turning of AISI 1045. No similar data was published in the case of this material, and only few roughness measurements in general. For this purpose, an experimental setup has been identified and used in order to acquire roughness data, which could possibly be used as a tool end-of-life indicator. The conclusions drawn from this work are as follows:

- The maximal height of the roughness profile had the most important relative rise with the cutting tool wear evolution. However, its evolution did not show entirely monotonous, and measured values would not allow to properly identify the tool end of life.
- The RMS roughness value shows less ambiguous results, and its local derivative may prove a valuable indicator for tool end of life.
- The observed RMS roughness tendencies differ widely from a similar literature application. The uncertainty associated with the measurement seems to be lower in this study. The material used in both studies differs.
- Experimental setup weaknesses (mainly in the observation of flank wear and the number of replications of the experiment) have been identified.

The perspectives of this work include:

- Experimental research on the relationship between end-of-life criteria and other on-line monitoring variables such as cutting forces and electrical power measurement.
- Clearer identification of industrial end-of-life criterion, and possible questioning of the relevance of the flank wear measurement with respect to that criterion.
- Statistical methods based on reliability, stochastic modeling and machine learning in general may be pursued.

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