TOOL WEAR ANALYSIS OF THE PVD-TIALN COATED FINE-GRAIN CEMENTED CARBIDE TOOLS IN THE HARD TURNING OF AISI 4340 STEEL

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Abstract. *The hard turning processes are usually performed using PCBN or ceramic tools because they have suitable properties to withstand the tribological conditions imposed in the tool-chip-workpiece interface. This research aims to evaluate the performance of the PVD-TiAlN coated fine-grain cemented carbide tools in the turning of AISI 4340 with 55 HRC, considering different cutting conditions: continuous cutting; interrupted cutting; and adopting a machining strategy with recoil (woodpecker). Finishing hard turning experiments were performed with industrial cutting parameters applied in PCBN/ceramic tools. The tool wear progression was analyzed using focus variation microscopy (FVM) applying the volumetric wear parameter W_{RM} (volume of removed material from the tool) and the traditional VB_B according to ISO 3685:1993. In the three cutting conditions tested, the tool collapses soon after the exposure of the substrate. Thus, the tool life limit should be the time of the coating layer deterioration. Since the volumetric wear parameter (WRM) is sensitive to identify the wear rate over the coating layer, this parameter is suitable to determine the tool life. For the three cutting conditions applied, after the coating deterioration occurs a sudden modification of the tool geometry by a generation of the crater wear formed by the diffusion wear mechanism.*

Keywords: *hard turning; coated cemented carbide tools; PVD coating; tool life; volumetric wear parameters.*

1. INTRODUCTION

The turning of hardened steels has been studied and industrially applied since the 1980s as finishing and semi-finishing operations, making it a viable alternative to the grinding process. Regarding its characteristics, hard turning has advantages regarding process flexibility, material removal rates, setup time, environmental compatibility, and it is mainly applied in the machining of complex geometry or multi-body components. For the manufacture of critical components that require high wear resistance and high dimensional quality, such as gears, bearings, transmission shafts, the hardened steel turning process is being adopted as a replacement or in combination with the grinding process (Klocke et al, 2005; Astakov, 2011; Tönshoff, 2000).

The hard turning processes are usually performed using PCBN or ceramic tools because they withstand the process' tribological conditions imposed by the machined material (Tönshoff, 2000). According to Boing, 2016, the main limitations for the use of cemented carbide in hard turning are the high hardness, mechanical strength, and the presence of primary carbides in the machined material microstructure, which promote restrictions on cutting conditions, such as cutting speed. However, the ultra-fine grain technology in the cemented carbides grades coupled with the coating techniques provide the properties required for the application of the cemented carbides in the turning of hardened steels (Chinchanikar and Choudhury, 2013; Fang et al., 2009).

The ultra-fine grain technology provides an increase in the cutting edge resistance, in the mechanical strength, and the resistance of the abrasion wear mechanism (Klocke, 2011). In addition to improvements in tool strength, reduction of grain size reduces the thermal conductivity of the tool, disfavoring the chemical affinity promoting better resistance against the diffusion and adhesion tool wear mechanisms (Klocke, 2011; Gille et al., 2002).

In the turning of steel AISI H13 with a hardness of 50 HRC, Xiong et al., 2013, showed a longer tool life of WC–5TiC–10Co ultrafine cemented carbide grade (α and β phase grain size 0.2-0.5 μm) than the conventional cemented carbide grade (α phase grain size 1.8-2.4 μm; β phase grain size <1.5 μm). Considering the end of tool life VB_B = 0.3

mm, the tool life of ultrafine WC–5TiC–10Co tool increased 22% in v_c = 120 m/min, 27% in v_c = 152 m/min and 66% in v_c = 176 m/min in relation to the conventional grade.

The development of coatings technologies as the grain and crystals orientation technologies in the coating layers, allow the cemented carbides to withstand the severe tribological conditions imposed in the hard turning process, properties typically achieved by PCBN or ceramic oxide tool materials. Since the 1980s, TiN, TiCN and Al_2O_3 coatings began to be deposited by the CVD method. In the present time, these coatings are the most frequently used by the CVD method (Ginting, 2018; Bouzakis, 2012). The Al_2O_3, when used as an intermediate layer of coating, has the function of improving the transfer of heat to the chip; and TiC or TiCN are used to improve the wear resistance (Boing, 2016; Klocke, 2011). The grain orientation of the Al_2O_3 coating layer, i.e., layer with epitaxial grains, appears as an innovation in the coating field. The technology, performed by the chemical deposition process (CVD), orients the crystals of Al_2O unidirectionally, raising the hardness of the coating layer and aiding in heat dissipation (Bouzakis, 2012; Sandvik-coromant, 2018).

The PVD processes are characterized by the creation of material vapors (evaporation or sputtering, for example) and their posterior condensation onto a substrate to form the film (Bunshah, 2011). These processes can control thicknesses coating on the edges (~2-5 µm), guaranteeing a sharp coated edge. Usually, TiAlN is used as coating cemented carbide due to its high-temperature stability and wear resistance (Klocke, 2011).

Chinchanikar and Choudhury, 2014, studied the effect of cutting parameters and coating type on tool-chip interface temperature. The authors indicate the temperature is higher for the CVD coated multilayer tool compared to single-layer TiAlN. Also, the tool-chip interface temperature is affected mainly by the cutting speed.

Chinchanikar and Choudhury (2013; 2014) analyzed the flank wear progression on coated cemented carbide tools with single-layer PVD TiAlN, and multi-layer CVD MT-TiCN/Al_2O_3/TiN during dry turning of hardened AISI 4340 steel (35 HRC). The PVD coated single-layer TiAlN carbide tools showed a lower wear rate. However, the wear rate increases quickly after the removal of the thin layer of the coating due to the deterioration of the cutting edge. On the other hand, because of the thicker coating, the CVD coated multi-layer TiCN/Al_2O_3/TiN tool presented better results for tool life. The dominant wear mechanisms observed were adhesion and abrasion, for both coated tools. However, the diffusion wear too was observed in the PVD coated tool.

Boing et al., 2018, evaluated the limiting conditions of the application of coated cemented carbide tools in the turning of three grades of hardened steels (AISI 4340, AISI 52100 and AISI D2) – a function of the volume fraction of primary carbides in the steel's microstructure. The cutting parameters adopted were cutting speed (v_c) = 150 m/min, depth of cut (a_p) = 0.2 mm, feed (f) = 0.08 mm and dry cutting. The coated cemented carbides feasibility of application were stipulated as a tool life longer than 15 min. With the mentioned cutting parameters, the limiting conditions found by the authors were: steel AISI 4340 – 55 HRC – TiAlN PVD coated cemented carbide; steel AISI 52100 – 50 HRC – MT CVD TiCN/Al_2O_3/TiN; and steel AISI D2 – 45 HRC – MT CVD. TiCN/Al_2O_3/TiN. The steels without carbides in the microstructure, such as AISI 4340, promoted better tool life results because there are no impacts of primary carbides against the cutting edge, which means a high stability cutting process.

In this context, this experiment aims to evaluate the performance of the PVD-TiAlN coated fine-grain cemented carbide tools in the turning of AISI 4340 with 55 HRC, considering different cutting conditions: continuous cutting; interrupted cutting; and adopting a machining strategy with recoil (woodpecker) intent to promote a thermal relief along the cutting length.

2. EXPERIMENTAL PROCEDURES

The turning tests were carried out in a turning center manufacturer by Romi, model GL 240, with 15 kW of power in the spindle motor and a maximum speed rotation of 4500 rpm. The workpieces were manufactured with steel AISI 4340, quenched and tempered, with a hardness of 55 ± 1 HRC. Two workpiece geometries were produced, with both an internal diameter of 32 mm and an external diameter of 120 mm. One of the geometries has no channels to simulate continuous cutting (Fig. 1a), and another, to promote the interrupted cutting has channels machined at 45º (Fig. 1b).

The face turning tests were realized in the radial direction, from larger to smaller diameter using a variation in the spindle rotation to maintain the cutting speed constant. Figure 2 shows the two strategies adopted for the experiments. In conventional turning (Fig. 2 (a)) the tool moves from point P1 to point P2 through rapid positioning (G0). From point P2 the tool moves forward to point P3 machining the workpiece (G1), then moving away to the point P4. When turning with recoil (woodpecker machining strategy), the tool moves closer to the workpiece (P1 to P2) through the rapid positioning (G0), after starting machining through the programmed feed (G1), the tool machines 5 mm of the material and then performs the deviation through the circular movement in the counter-clockwise (G3) as shown in Fig. 2 (b). The recoil is carried out until the entire length of the material has been machined, and it was realized to promote a thermal relief in the cutting edge. To summarize, three cutting conditions were applied in the experiments: i) continuous cutting with conventional turning; ii) interrupted cutting with conventional turning; iii) woodpecker machining strategy (in continuous cutting).

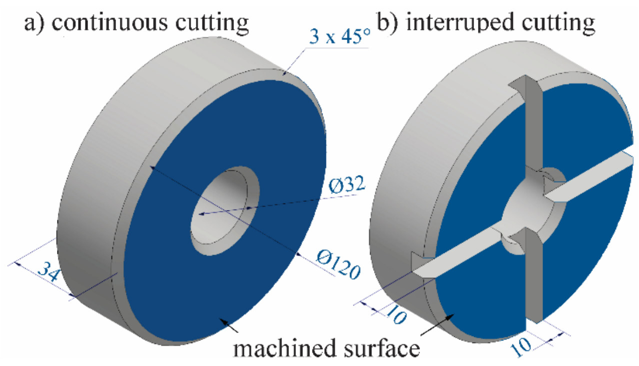

Figure 1. The geometries of the workpiece

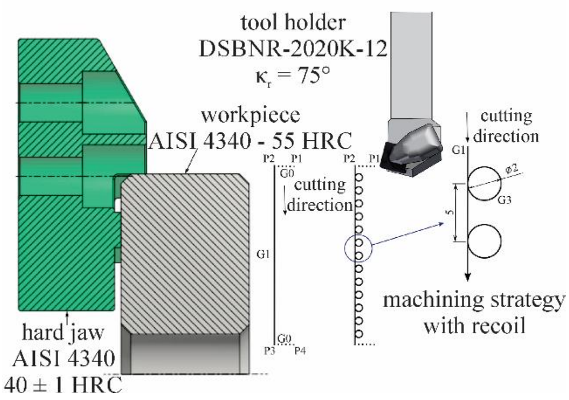

Figure 2. (a) Conventional turning; (b) turning with recoil (woodpecker machining strategy).

Sandvik Coromant® manufactured the coated cemented carbide tools used on the tests. The ISO code of the inserts was SNMG 120408, grade 1105 (ISO S15). This tool has fine-grain cemented carbide grain sizes (0.8 – 1.3 µm), and it presents monolayer TiAlN deposited by the PVD technique with a thickness of approximately 2 - 4 µm. The TiAlN coating is used in turning with high thermal requests. To fix the tool, a specific tool holder for turning (DSBNL 2020K 12) was used, which allows the cutting angle (χ) = 75º, exit angle (γ) = -6º and inclination angle (λ) = - 6º.

The cutting parameters adopted were: cutting speed (v_c) = 150 m/min, feed (f) = 0.08 mm, depth of cut (a_p) = 0.2 mm, and dry cutting. The experiments consisted of serial face turning passes on machined surfaces, until the moment that the tool reached the end of its life. The tool life was considered ended when the flank wear reached VB_B = 0.3 mm, or a catastrophic failure occurred. The tests were carried out three times for each condition.

In addition to the wear parameters described in ISO 3685:1993, three-dimensional (volumetric) wear parameters described by Boing et al., 2018, were investigated. The parameter W_{RM} is defined as the volume of removed material from the tool. A focus variation microscope (FVM) was used to perform the tool wear evaluation, model Infinite Focus G5 manufactured by Alicona®. Figure 3 illustrates the methodology. Firstly, each cutting edge was measured to create a reference geometry. In each machining test interval, the cutting edges were remeasured. With the data collected, the surfaces were overlapped, indicating the difference between the fresh and worn cutting edge (Boing et al., 2018).

To evaluate the coating wear rate (WR_{RM}) was used the model proposed by Castro et al., 2018, described in Eq. 1. The parameter W_{RMi} quantifies the volume of removed material from the tool in each time interval $t_{i,}$ and n is the number of collected wear values.

$$WR_{RM} = \frac{\sum\left(t_i * W_{RM\,i}\right) - \frac{\sum W_{RMi} \cdot \sum t_i}{n}}{\sum t_i^2 - \frac{\left(\sum t_i\right)^2}{n}} \cdot \frac{1}{60} \qquad (1)$$

3. RESULTS AND DISCUSSIONS

Figure 4 shows the tool life for the experiments. The results were obtained by the average of tests and their replicates with a 95% confidence interval. It is important to note that the cutting speed value adopted (v_c = 150 m/min) was at the same level as the industrial hard turning application of the ceramic and PCBN tools.

Analyzing the results in Fig. 4, the continuous turning reached the highest value for tool life ($\overline{T}$ = 31.2 min). The interrupted turning and turning with recoil (woodpecker) reached lower values for tool life in comparison to continuous turning, a reduction of approximately 55%. Through the analysis of variance, the interrupted turning and turning with recoil (woodpecker) had no significant difference from each other (P-value = 0.486). The lower tool life for the interrupted cutting condition is a clear indicator that the mechanical shocks promoted the channels in the workpiece (Fig. 1b) accelerate the deterioration of the tool coating leading to the lower tool life.

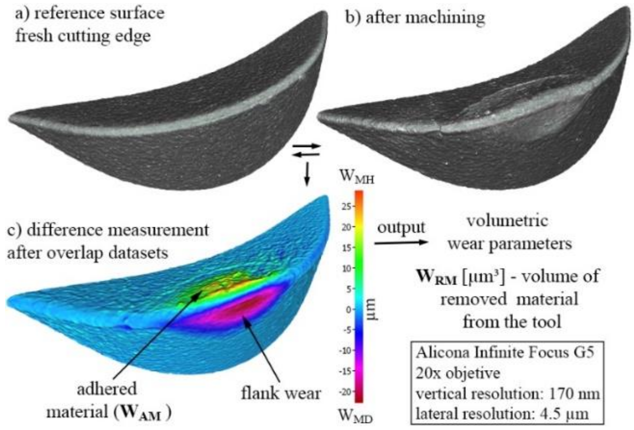

Figure 3. The methodology of output three-dimensional (volumetric) wear parameters according to Boing *et al.* [18].

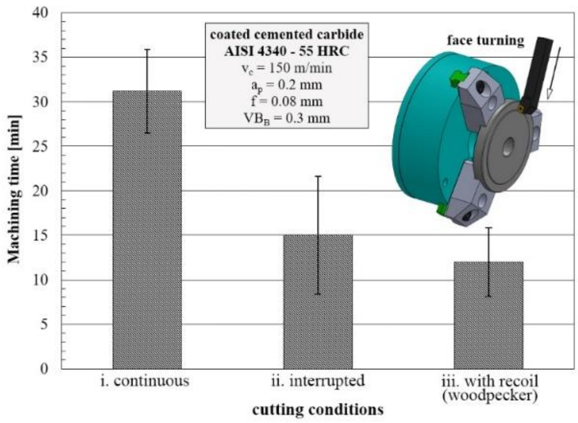

Figure 4. Tool life for experiments with PVD-TiAlN coated cemented carbide in the hard turning of the AISI 4340 steel with 55 HRC.

The temperature achieved by the hard turning process in the tool-chip interface typically is higher than the austenitization temperature of the steel alloy (König et al., 1993; Klocke et al., 2005; Astakhov, 2011), which is a temperature level that reduces approximatively four times the cemented carbide hot hardness (from ~1700 HV_{30} at environmental temperature to ~450 at 900°C) (Gille et al., 2002). Its combination is the main explanation that when the cemented carbide tool is applied in the hard turning process, the coating is mandatory, as discussed by Boing et al., 2018. The application of the machining strategy with recoil (woodpecker) intent to promote a thermal relief in the cutting edge. However, considering the tool life results shown in Fig. 4, the machining strategy woodpecker, was not effective, which also accelerate the tool wear in comparison to continuous cutting. To better understand cutting tool wear progress, the discussion ahead promotes the detailed evaluation of the one representative wear curve for each cutting condition studied.

Figure 5 shows the tool wear progression in continuous turning. It is verified that the parameter W_{RM} (volume of removed material from the tool) has behavior similar to the parameter VB_B, remaining stable throughout the process until a sudden increase at the end of life. According to the parameters of the wear curves and the images shown in Fig. 5, at the point "a" (t = 25.2 min) the substrate of the tool is partially exposed. After two machining passes (t = 27.9 min), the tool suddenly fails, forming intense crater wear, point "b". The results in Fig. 5 indicate that the tool substrate even with fine-grain sizes does not upstand the tribological conditions imposed by the hard turning process studied.

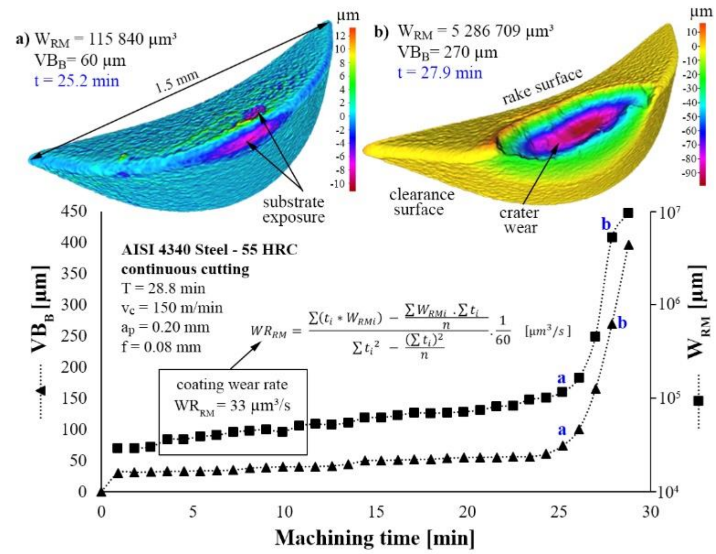

Figure 5. Evolution wear of the coated cemented carbide tool wear for continuous cutting.

The slope of the W_{RM} wear curve is more intense when compared to the VB_B wear curve (Fig. 5), indicating that the volumetric evaluation of the tool wear is more sensitive to detect a lower level of wear – as the wear over the tool coating. As discussed by Boing et al., 2018, it is possible to apply the W_{RM} as a parameter to define the tool life limit. In the case of the wear curve shown in Fig. 5, the tool life limit should be the point "a" and not the VB_B = 0.3 mm. Furthermore, as suggested by Boing et al., 2018a, based on the technology available to measure the tool wear, i.e., optical focus variation technology, and the evolution of the machining process, i.e., tool material, coating material/process, tool geometries, advanced machined materials, integration with industry 4.0; the three-dimensional (volumetric) wear parameters should be included in the ISO 3685:1993 [18] or similar.

The wear curve in Fig. 5 shows that the tool fails at the moment of the coating deterioration. Considering this situation, the coating ceramic material (TiAlN) is the "tool" in the hard turning process applied, and the original tool substrate can be considered as a "tool holder". Analyzing the wear curve in Fig. 5, the wear progression until the point "a" represents the wear over the PVD coating layer (TiAlN). With it is possible to calculate the tool wear rate using the model proposed by Castro et al., 2018, Fig. 5, which is important information to develop and evaluate the coating wear resistance to a specific tool-workpiece pair.

Figure 6 shows the behavior of the W_{RM} and VB_B parameters over the machining time for the interrupted cutting. In point "a", as well as in continuous cutting, the tool substrate is partially exposed (t = 11.7 min) and in point "b" (t = 13.5 min) the tool failure occurs. The higher value found for the WR_{RM} (tool wear rate) in the interrupted cut condition can be explained by the combination of the alternating mechanical and thermal loads (promoted by the channels in the workpiece face) that the tool was subjected to, which associated with the low toughness of the TiAlN coating promote the shorter tool life.

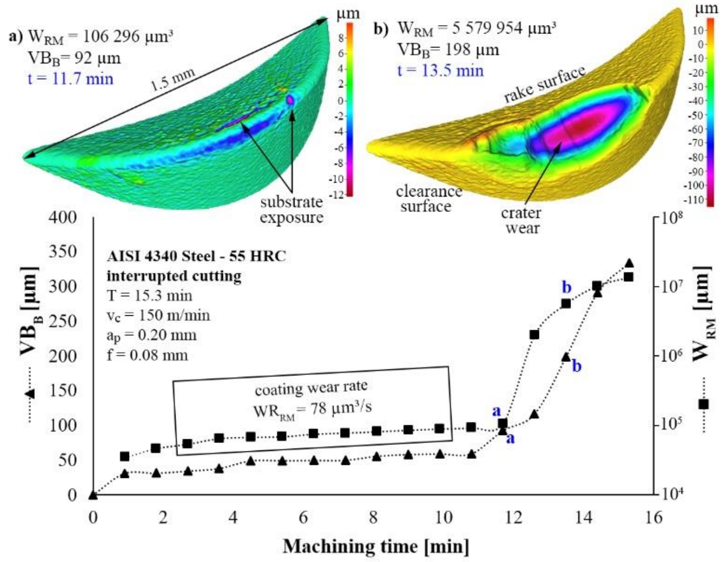

Figure 6. Evolution wear of the coated cemented carbide tool wear for interrupted cutting.

The results in Fig. 6 demonstrated that the coating is mandatory in the cemented carbide tools even in interrupted cutting. On the other hand, the tool substrate has fundamental relevance to avoid direct tool breakage. If the tool was built just with the TiAlN material, one small crack generated on the coating-free surface could propagate throughout the tool leading the catastrophic failure. The cemented carbide substrate breaks the crack propagation and the tool still feasible. Although the lower tool life compared to continuous cutting, the results present in this research to interrupted and woodpecker cutting strategy indicates the potential of the hard coatings applications in machining process with the severe alternating mechanical and thermal loads.

Figure 7 shows the behavior of the W_{RM} and VB_B wear parameters along the machining time for the cutting with recoil (woodpecker machining strategy). As the other two conditions discussed, at point "a" (Fig. 7), the tool substrate begins to be exposed (t = 9.9 min), after that, at the point "b" the tool fails (t = 13.5 min).

The woodpecker machining strategy promotes similar results as compared to the interrupted cutting. The alternating mechanical and thermal stresses generated by the trajectory with recoil (woodpecker) can cause mechanical shocks between the tool and the workpiece, promoting the coating edge damage, and in consequence the tool failure. Considering that the ceramic coating is the active material of the tool, the oscillation in the mechanical and thermal loads can reduce the performance of the tool, as happens in the ceramic tools when applied in the hard machining process. Furthermore, in the woodpecker machining strategy, the circular entry of the tool into the workpiece promotes a variation in the effective chip thickness, which can increase the specific machining force in the secondary cutting edge, contributing to the coating tool deterioration.

Figure 8 shows the wear morphology of the cemented carbide tool applied in interrupted cutting obtained by SEM (scanning electron microscope) and FVM (focus variation microscope). When the tool achieves the end of tool life (VB_B = 0.3 mm), the main wear mechanism is diffusion. From the moment the coating has deteriorated, the thermal protection of the substrate is gone, and occurs the free interaction of the tool substrate elements with the chip, which is activated by the high temperature achieved in the hard turning process, promoting the crater wear as shown in Fig. 8.

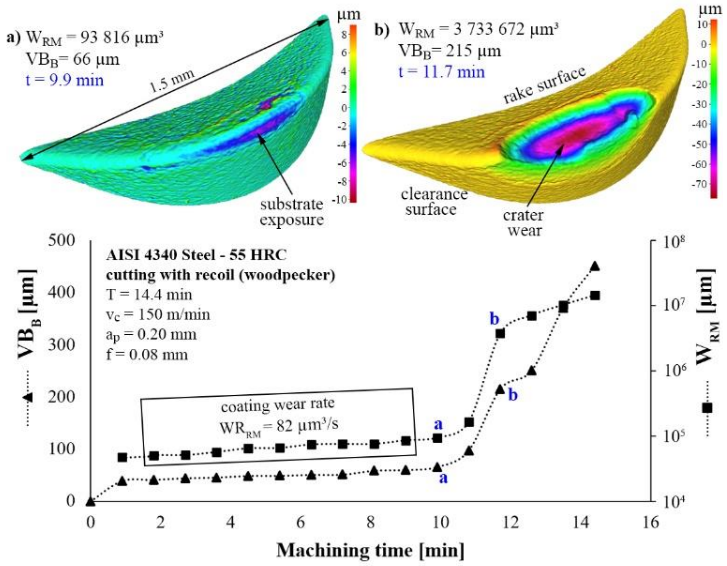

Figure 7. Evolution wear of the coated cemented carbide tool wear for woodpecker machining strategy.

The sudden modification in the tool geometry in the function of the crater wear development (as shown in Figs. 5-7: point “a” to “b”) associated with the increase in the tool-chip contact area can also promote the chipping in the cutting tools, as shown in Fig. 8a. In the industrial environment, the sudden modification in the tool geometry can impact the dimensional and geometric tolerance in the machined part. Thus, the limit of the tool life should be the time the tool substrate begins to be exposed, points “a”, Fig. 5-7.

Analyzing Fig. 8, the abrasion wear mechanism is clear just in the small transition region between the clearance surface and the crater wear, Fig. 8a. Which reinforced that when the coating deteriorates, the diffusion is the main wear mechanism – based on the intense crater wear formation. To evaluate the active tool wear mechanism over the coating (from the beginning of the tool life until the point “a”, Figs. 5-7), it is necessary to perform SEM evaluation along the specific region. On the other side, adopting the three-dimensional (volumetric) wear parameter W_{RM}, it is possible to calculate the tool wear rate (WR_{RM}) over the coating, as shown in Figs. 5-7.

Figure 8 shows the tool wear morphology based on two methods: Fig. 8a, the traditional scanning electron microscope (SEM); and 8b the focus variation microscope (FVM). The techniques are complementary to evaluate the tool wear. While Fig. 8a (SEM) provides morphological information making it possible to evaluate the tool wear mechanism, Fig. 8b (FVM) provides volumetric information about the tool wear (also it is possible to measure the tool wear parameters according to ISO 3685:1993, which promote more detailed and precise measurement to optimize and develop the machining processes.

The highest value for tool life ($\overline{T}$= 31.2 min; continuous cutting) achieved in this research is lower than the values achieved when the PCBN or mixed ceramic tools are applied in the hard turning of the same steel alloy with similar cutting conditions, as shown in Oliveira et al., 2009, the PCBN had better performance in continuous cutting ($\overline{T}$ ~ 60 min) when compared to alumina-based ceramic reinforced with silicon carbide ($\overline{T}$ ~ 22 min). In interrupted cutting, both cutting tools showed similar results, and the tool life was approximately three times longer ($\overline{T}$ ~ 170 min). Comparing the actual market price, the PCBN can tool cost 20 times more than mixed ceramic tools, and 25 times more than coated cemented carbide tools. The results in this research showed that the coated cemented carbide tools can be an alternative to PCBN tools in the hard turning of steels with free of primary carbides in the microstructure, as also discussed by Boing et al., 2018.

Figure 9 shows the representative curves of the surface roughness along the tool life for the three cutting conditions evaluated. The surface roughness of the continuous cutting and the woodpecker machining strategy increases along the tool life. At the end of tool life for the continuous cutting, occurs a significant reduction in the surface roughness, which is related to the sudden tool geometry modification in function of the wear. The interrupted cutting achieved the lowest value of the surface roughness.

The results in this research showing the potential application of the coated cemented carbide tool in the hard turning of AISI 4340 steel. As discussed, the tool fails suddenly when the tool substrate is exposed. Metalworking fluids can be applied to increase the tool performance, e.g., flooding or minimum quantity lubrication (MQL).

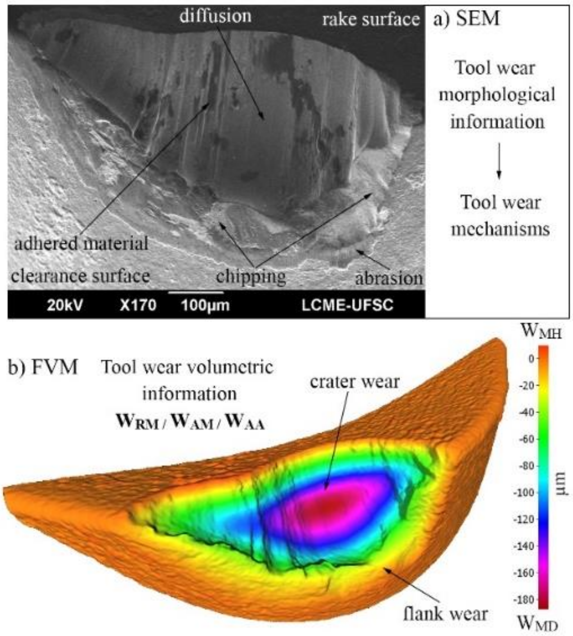

Figure 8. Worn cutting tool applied in interrupted cutting. (a) Tool wear morphological information - SEM (b) Tool wear volumetric information - FVM.

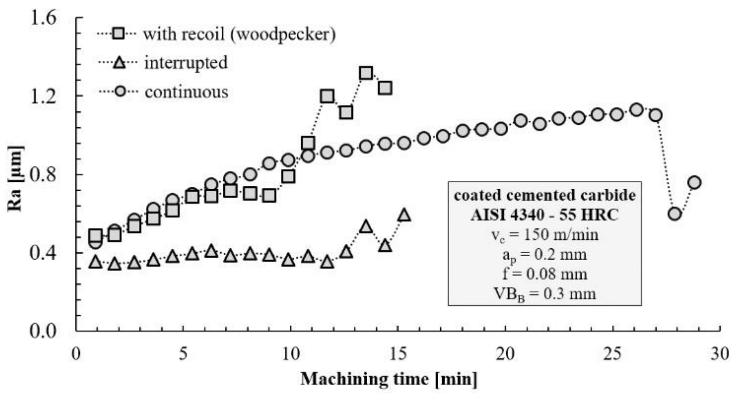

Figure 9. Representative curves of the surface roughness along the tool life.

4. CONCLUSIONS

Based on the results obtained in these experiments it can be concluded that in the turning of AISI 4340 (55 HRC) with PVD-TiAlN coated fine-grain cemented carbide tools:

- The continuous turning reached the highest value for tool life ($\overline{T}$ = 31.2 min). Adopting the interrupted turning and turning with recoil (woodpecker machining strategy) the tool life reduces of approximately 55% in comparison to continuous turning.
- The coating is mandatory for the PVD-TiAlN coated fine-grain cemented carbide tools' performance. For all the cutting conditions tested, the tool collapses soon after exposure to the substrate. Thus, the tool life limit should be the time of the coating layer deterioration.
- The volumetric parameter is more sensitive to detect small values of tool wear, like the wear over the coating, which made it possible to calculate the tool wear rate over the coating.
- After the coating deterioration occurs a sudden modification of the tool geometry by a formation of the crater wear, which is associated with the diffusion wear mechanism.
- The focus variation microscope (FVM) and the scanning electron microscope (SEM) are complementary to evaluate the tool wear, regarding the tool wear mechanism and precise volumetric measurement to the tool wear, respectively.

5. ACKNOWLEDGEMENTS

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