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THE IMPACT OF TIN COATING ON THE PERFORMANCE OF AL_2O_3-TIC CERAMIC TOOLS IN HARD TURNING

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Abstract. *Ceramic tools are widely applied in machining processes due to their high level of hardness, chemical stability, and wear resistance. However, ceramic tools have low resistance to thermal shock, thus turning with these tools is usually carried out without cutting fluid. To limit the drawbacks of dry turning, the use of coated tools is typically adopted, but there is no consensus on the impact of coatings on mixed-ceramic tools. Although coatings on ceramic tools can improve the machining process, the cost is high and is usually not justified by the result because of the weak adhesion between the coating material and the ceramic substrate. In this context, this study investigates the impacts of TiN coating on the performance of* Al_2O_3*-TiC ceramic tools applied in dry turning of the hardened steel AISI 4340 (55 HRC). Radial turning experiments were performed with (*v_c*) = 150 m/min, feed (f) = 0.08 mm/rev, and depth of cut (*a_p*) = 0.20 mm. Machining forces, tool wear and surface roughness in turning with coated and uncoated mixed-ceramic tools were evaluated. The TiN-coated ceramic tool has a higher edge radius, which caused higher cutting force and passive force than the uncoated tool. On the other hand, the TiN coating provides higher toughness to the tool, leading to lower notch wear in coated tool. The flank and notch wear were the main forms of wear in the uncoated tool, while in the coated tool was formed a crater that contributed intensely to the volume of material removed from the tool (*W_{RM}*). The value of the* W_{RM} *for the coated tool was approximately 22% higher than for the uncoated tool. Despite this, the lower notch wear in the coated tool was decisive for the quality of the machined surface. When using the TiN-coated tool a decrease around 40%, 44%, and 47% in the roughness* S_z*,* S_a *and* S_q *occurred, respectively.*

Keywords: *ceramic tool; coated tool; TiN coating; hard turning; AISI 4340 steel*

1. INTRODUCTION

Hard turning – the turning of materials with a hardness exceeding 45 HRC (Klocke, 2011) - has been industrially employed since the 1980s as a finishing or semi-finishing operation to replace, or in conjunction with, the grinding process (Klocke *et al.*, 2008; Davim, 2011; Patel *et al.*, 2020). The most used cutting tools for hard turning are polycrystalline cubic boron nitrides (PcBN) due to their high hot hardness, thermal stability, and chemical stability (Bartarya and Choudhury, 2012). However, mixed-ceramic tools are a more economical alternative. Mixed-ceramic tools combined with appropriate machining parameters can result in a surface roughness (R_a <0.8 µm) corresponding to high dimensional precision (IT <7 mechanic precision construction), eliminating the necessity of cylindrical grinding operations (Davim and Figueira, 2007).

In turning of hardened steels the predominant wear mechanism in mixed-ceramic tools is abrasion, which is controlled mainly by its hardness and toughness. However, the hardness of mixed ceramic tools is strongly impacted by temperature (Kumar *et al.*, 2003). For instance, at 20 °C the hardness of an Al_2O_3-TiC tool is 1900 HV and in 1000 °C the hardness is only 800 HV (Abrão *et al.*, 1993). In hard turning with mixed-ceramic tools, the heat generated in cutting is not effectively dissipated due to the low thermal conductivity of this tool material, leading to great temperature gradients and concentrated tool wear (Davim, 2011). To limit the shortcomings and negative impacts of high temperature in machining, the most traditional technique is the use of cutting fluids (Klocke, 2011; Kuram *et al.*, 2013). However, ceramic tools have low resistance to thermal shock, and they must be kept hot throughout the operation, therefore, is commonly used dry machining with these tools (More *et al.*, 2006; Davim, 2011). Although dry machining offers environmental and economic advantages (Kuram *et al.*, 2013; Patel *et al.*, 2020), frictional and adhesive problems can take place between the tool and the workpiece (Klocke, 2011). To solve the issues related to dry cutting an alternative is the use of coated tools.

To improve the machining performance of mixed ceramic tools, several coatings such as TiN, AlCrN, AlTiN, TiAlN and TiAlSiN have been proposed (Kumar and Patel, 2018). Nitride coatings are the most used because of their excellent properties such as good thermal conductivity, hardness, high melting point, chemical stability, and toughness (Deng *et al.*, 2012; Santecchia *et al.*, 2015). Kumar and Patel (2018a) reported that AlTiN coating on mixed-ceramic tools exhibits superior anti-oxidation, anti-adhesion, and anti-abrasive properties as compared to AlCrN coating and uncoated tools. Besides, the lower compressive residual stresses of AlTiN prevent the flaking of the coating, unlike the AlCrN coating. Karpuschewski *et al.* (2014) indicated that TiN coating provides thermal protection to the mixed-ceramic tools, leading to tool life 5,9% and 10% higher in coated tool than in uncoated tool when f = 0.2 and 0.1 mm/rev, respectively. However, Kumar and Patel (2018b) observed the AlTiN coating spalling in mixed-ceramic tools at high feed rates (> 0.20 mm/rev) and cutting speeds (> 150 m/min) due to the poor adhesion of the coating to the substrate when the coating thickness is 2 µm. Likewise, Kumar *et al.* (2020) describes that the performance of DLC and WC/C coated mixed-ceramic tools converges towards uncoated tools as the feed rate and cutting speed are increased.

According to Aslantas *et al.* (2012), in uncoated mixed-ceramic tools occur more frequently fracture and chipping damages, whereas in TiN-coated tools the more common type of wear is crater. TiN-coated tools are less affected by vibrations and shock loads due to the high toughness of TiN. Nevertheless, TiN-coated tools react with steels at high temperatures since the TiN coating is less chemically stable than Al_2O_3 ceramics. Bensouilah *et al.* (2016) reported in turning of AISI D3 steel (63 HRC) higher tool life and better surface quality for TiN-coated Al_2O_3-TiC tools than for uncoated tools ($T_{coated}/T_{uncoated} = 1.27$ at $v_c = 150$ m/min, $a_p = 0.20$ mm and f = 0.08 mm/rev). Conversely, Khellaf *et al.* (2017) mentioned that in turning of AISI H11 steel (50 HRC) the tool life of TiN-coated Al_2O_3-TiC tool is only 28 min while for an uncoated tool is 49 min ($v_c = 150$ m/min, $a_p = 0.30$ mm and f = 0.08 mm/rev). Likewise, the uncoated tool generated better surface quality: R_a(uncoated)/R_a(coated) = 0.89 and R_t(uncoated)/R_t(coated) = 0.85.

As exposed, there is no consensus on the impact of coatings on mixed-ceramic tools applied in hard turning. Davim (2008) quotes that coatings on ceramic tools can improve the machining process, however, the cost is high and usually does not justify the end result because of weak adhesion between the coating materials and ceramic substrate. In this context, the aim of this study was the investigation of the effects of the TiN coating on Al_2O_3-TiC mixed ceramic cutting tools in the dry turning of the hardened steel AISI 4340 (55 HRC).

2. EXPERIMENTAL PROCEDURES

The mixed-ceramic tools (Fig. 1) were an uncoated Al_2O_3-TiC tool (code SNGA 120408T01020, grade 650), and a TiN-coated Al_2O_3-TiC tool (coating thickness ≈ 2 µm, code SNGA 120408T01525, grade 6050), both manufactured by Sandvik Coromant. The workpieces (AISI 430 steel - 55 HRC) were disk-shaped with an external diameter of 125 mm, a central diameter of 25 mm, and external and internal chamfers of 1.5 mm x 45° to minimize the tool shocks. The workpiece steel had a predominant martensitic microstructure with low content of bainite and austenite, which resulted in ultimate strength = 1962 MPa, yield strength = 1295 MPa and maximum strain = 11.6%.

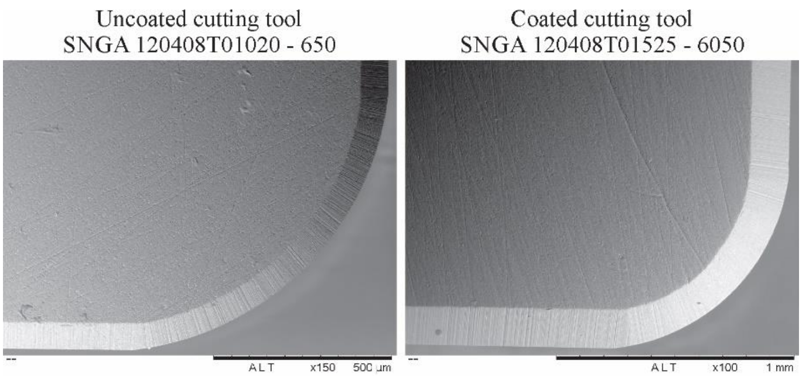

Figure 1. Cutting tools used in turning experiments.

Radial turning experiments (facing) were carried out with cutting speed (v_c) = 150 m/min, feed (f) = 0.08 mm/rev, depth of cut (a_p) = 0.20 mm, and dry cutting in a horizontal turning center (Heyligendstaedt, model Heynumat 10U), with a spindle motor power of 75 kW, speed rotation maximum of 4500 rpm and clamping system with three-jaw chuck with a maximum chucking pressure of 45 bar. Each machining test consisted of four radial passes on the workpiece surface from the largest to the smallest diameter (machining time = 3.6 min), using a variation in the spindle rotation to maintain a constant cutting speed.

Figure 2 shows the setup system used for the machining experiments. The machining force components were monitored during the turning process using a system coupled to the turning center. The force system consisted of a piezoelectric platform (Kistler Instrument AG, model 9257) with three acquisition channels and capacity to identify force components up to 5 kN (x and y) and 10 kN (z); three amplifiers by Kistler Instrument AG model 5011 (cutting force and thrust force) and 5006 (feed force), and an acquisition board with 10 kHz acquisition rate by National Instrument, model NI USB 6218.

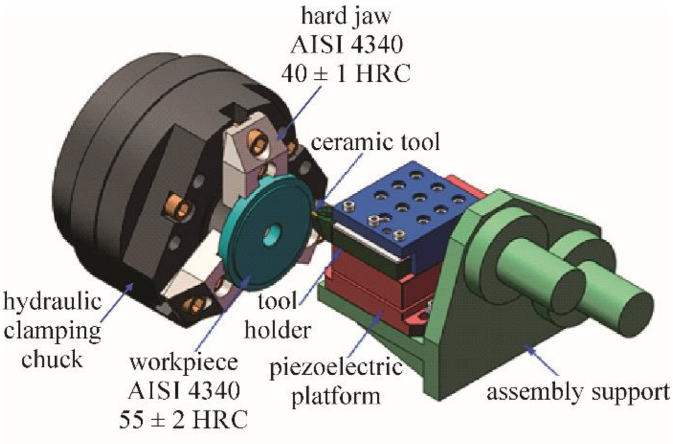

Figure 2. Setup system.

The tool wear was assessed using scanning electron microscopy (SEM) coupled with X-ray spectroscopy, HITACHI, model TM3030, and using focus variation microscopy (FVM), ALICONA, model Infinite Focus G5. FVM was applied to measure the three-dimensional tool wear parameter W_{RM} (volume of material removed from the tool) using the methodology previously reported by Danzl *et al.* (2009) and Boing *et al.* (2018). The traditional wear parameters VB_B (average flank wear) and VB_C (notch wear) were determined as described in ISO 3685:1993. The surface roughness of the machined workpieces was obtained by a white light interferometer (Zygo NewviewTM 7300) using the software MetroPro and MoutainsMap. The three-dimensional roughness parameters were obtained according to ISO 16610-71.

3. RESULTS AND DISCUSSION

3.1 Forces

The cutting force F_c and passive force F_p in cutting with the coated tool are approximately 6% and 12% higher than with the uncoated tool, respectively (Fig. 3). Although the TiN coating promotes lower friction between the tool and the workpiece (according to the results found by Karpuschewski *et al.* (2014)), the coated tool has a higher cutting-edge radius. The higher cutting-edge radius causes higher efforts in the machining process due to the higher contact between the cutting edge and the workpiece, which promotes higher deformation of the machined material in front of the cutting edge [27,28]. Regarding the feed force F_f, is not possible to state that there is a statistical difference between the two tools (p-value = 0.20).

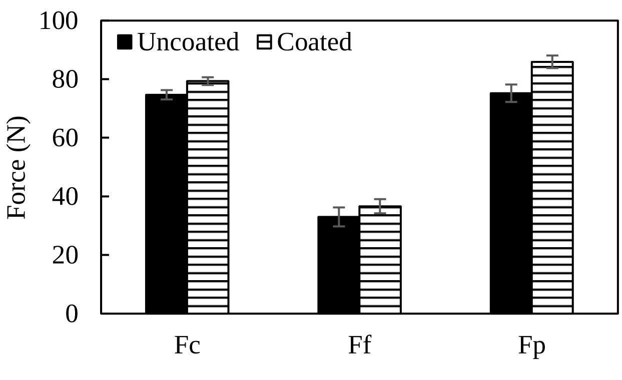

Figure 3. Cutting force (F_c), feed force (F_f) and passive force (F_p) during turning experiments with the uncoated and coated tools (turning of AISI 4340 – 55 HRC, v_c = 150 m/min, f = 0.08 mm/rev, a_p = 0.20 mm, machining time = 3.6 min).

3.2 Tool wear

The tool wear morphology and the VB_B, VB_C and W_{RM} tool wear parameters for the uncoated and coated tools are shown in Fig. 4. Both tools exhibited abrasive marks (grooves parallel to the cutting direction) in the flank and rake face. The values of flank wear VB_B can be considered statistically equal for the two tools.

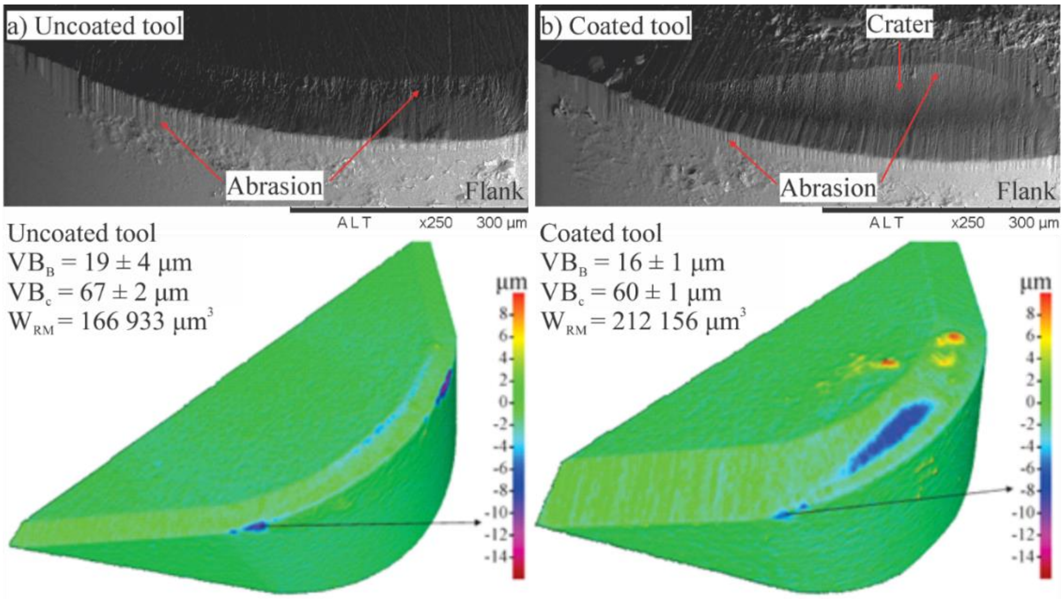

Figure 4. Tool wear morphology and tool wear parameters (VB_B, VB_C and W_{RM}) of the uncoated and coated tools applied in turning of AISI 4340 - 55 HRC (v_c = 150 m/min, f = 0.08 mm/rev, a_p = 0.20 mm, machining time = 3.6 min).

In addition to material removal due to the abrasive wear, both tools showed notch wear on the secondary flank (VB_C) (Fig. 5). Notch wear commonly occurs in ceramic tools because of the low toughness of the ceramic material. Notching in Al_2O_3-based ceramic tools applied in hard turning is also reported by Kumar *et al.* (2003), Grzesik (2008), Oliveira *et al.* (2009), and Kumar *et al.* (2018). It is clear from Fig. 5 that the greater notching occurred on the uncoated tool. Tian *et al.* (2017) reported that the increase in fracture toughness promoted by TiN additions in Al_2O_3-TiC tools improves the tool resistance to thermal and mechanical stress, leading to lower notch wear.

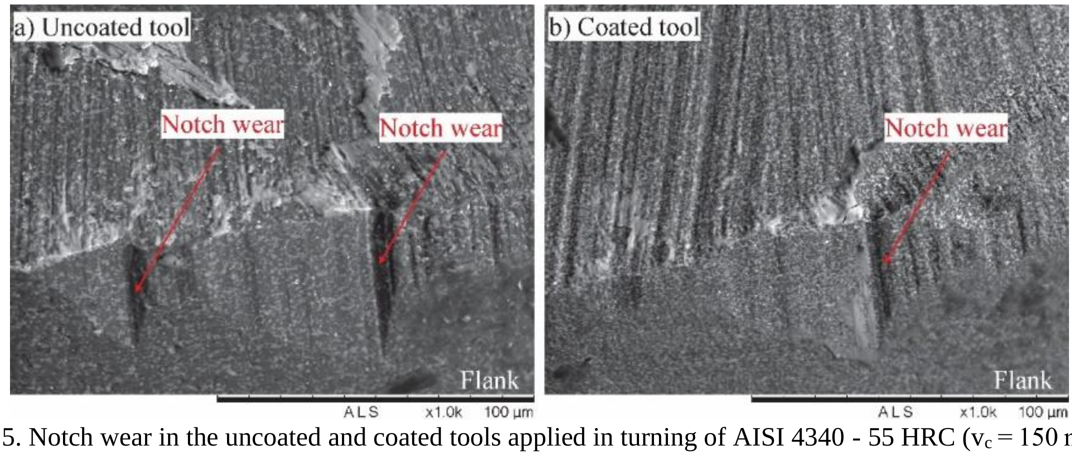

Figure 5. Notch wear in the uncoated and coated tools applied in turning of AISI 4340 - 55 HRC (v_c = 150 m/min, f = 0.08 mm/rev, a_p = 0.20 mm, machining time = 3.6 min).

The flank and notch wear are the main forms of wear in the uncoated tool, while in the coated tool was formed a crater that contributed intensely to the volume of material removed from the tool (W_{RM}). The W_{RM} for the coated tool is approximately 22% higher than for the uncoated tool.

Traditionally, crater wear is associated with the diffusion wear mechanism. Since TiN has higher chemical affinity with the workpiece steel than the Al_2O_3 (Kumar *et al.*, 2003; Aslantas *et al.*, 2012), the TiN coating may have reacted with the Fe in the workpiece during the cutting and formed the crater, whereas in the uncoated tool due to the higher chemical resistance of the Al_2O_3 this phenomenon was less intense. Despite the EDS analysis on crater region in the coated tool (Fig. 6) indicates the presence of both tool elements (Ti, C, Al, and O) and steel elements (Fe and C), this is insufficient to confirm that diffuse wear has occurred, as the content of Fe in the crater is substantially lower than the content of the tool elements. On the other hand, the abrasive marks on the crater in the same direction as the abrasive marks on the flank indicates the action of abrasion wear mechanisms. Furthermore, the presence of Al and O in the crater region of this tool revealed that abrasion led to the removal of the TiN coating. Shalaby *et al.* (2014) reported that the lower hot-hardness of TiN than Al_2O_3 and TiC causes higher tool wear in TiN-coated tools (PcBN tools) than in uncoated mixed-ceramic tools (Al_2O_3-TiC tools).

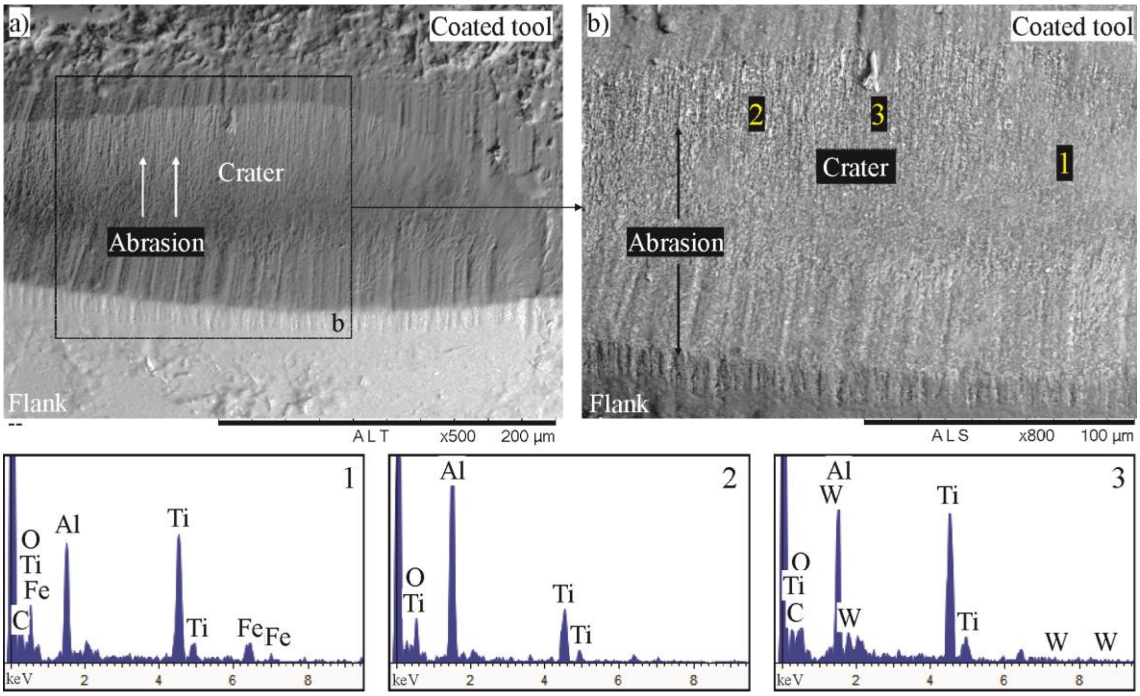

Figure 6. Crater wear in the coated tool applied in turning of AISI 4340 - 55 HRC (v_c = 150 m/min, f = 0.08 mm/rev, a_p = 0.20 mm, machining time = 3.6 min).

3.3 Surface roughness

The amplitude roughness parameters S_z, S_a and S_q of the machined surfaces obtained with the uncoated and coated ceramic tool are shown in Fig. 7. As found for the notch wear, the coated tool performed best than the uncoated tool. When using the TiN-coated tool occurred a decrease of approximately 40%, 44%, and 47% in the roughness S_z, S_a and S_q, respectively. The coated tool generated a surface class N6 and the uncoated tool a surface class N7 (ISO 1302:2002).

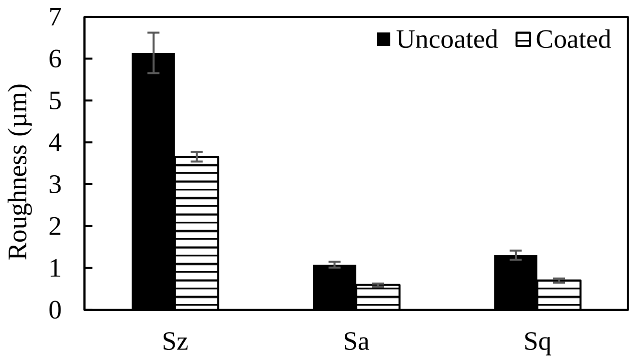

Figure 7. Roughness of the machined surfaces obtained with the uncoated and coated tools (turning of AISI 4340 – 55 HRC, v_c = 150 m/min, f = 0.08 mm/rev, a_p = 0.20 mm, machining time = 3.6 min).

The lower surface quality obtained by the uncoated tool occurred due to its higher notch wear. The surface roughness is generated by the tool secondary cutting edge, i.e., by the tool region where the notching occurs. The notching transforms the blunt irregular initial peaks into final sharp individual peaks since the machined surface copy the notch grooves (Grzesik, 2008). This phenom in ceramic tools, named profile sharpening effect, is described by Grzesik (2008) and Grzesik and Wanat (2006).

4. CONCLUSIONS

Based on the results obtained in the turning experiments of AISI 4340 (55 HRC) with uncoated and TiN-coated mixed-ceramic tools, the following conclusions can be drawn:

• The coated tool caused cutting force (F_c) and passive force (F_p) approximately 6% and 12% higher than the uncoated tool, respectively. These results occurred due to the higher cutting-edge radius of the coated tool.

• Abrasion was the main wear mechanism for both tools. In addition to abrasion on the flank and rake face, both tools presented notch wear in the secondary flank (VB_C). The higher notch wear occurred on the uncoated tool.

• The flank and notch wear were the main forms of wear on the uncoated tool, while on the coated tool was formed a crater (caused by abrasion) that contributed intensely to the volume of material removed from the tool (W_{RM}). The W_{RM} for the coated tool is approximately 22% higher than for the uncoated tool. Moreover, the EDS analysis in the crater region of the coated tool indicated the removal of the TiN coating.

• The larger notch on the uncoated tool negatively impacted the machined surface. The coated tool generated surfaces with roughness approximately 40% (S_z), 44% (S_a), and 47% (S_q) lower than the uncoated tool.

5. ACKNOWLEDGEMENTS

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