Comparing the performance of several tool coatings in turning of commercially pure titanium grade 4

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Abstract
The increasing use of titanium and its alloys in the manufacture of implants results from the simultaneous presence of excellent biocompatibility, relatively low density, high mechanical properties, and corrosion resistance. Unlike the excellent application characteristics, titanium is classified as a difficult-to-machine material. Therefore, one constant challenge for implant manufacturers is to correctly choose turning tools for each application. This work aims to compare the useful life of the uncoated insert with other three types of coatings on carbide tools, titanium aluminum nitride (TiAlN), aluminum chromium nitride (AlCrN), and titanium nitride/titanium carbonitride multilayer coating (TiN + TiCN). Turning experiments were performed using grade 4 commercially pure titanium (typically used in dental implants), testing two cutting speeds for each tool used. The tests were carried out in a CNC rotary head lathe, using cutting fluid in abundance. The results showed that the uncoated insert achieved the shortest life due to its worst properties (lower surface hardness, higher friction coefficient, and lower maximum working temperature), even with its supposedly higher chemical stability with titanium. On the other hand, the tool with the TiN + TiCN multilayer coating obtained the longest tool life among the four tested inserts. The main novelty of this work is that the tool that showed the longest life (TiN + TiCN coating) did not have the best properties among the tested coatings. In fact, it had both the lowest hardness and working temperature. However, this tool has a low coefficient of friction and a multilayer structure coating, which increases its resistance against the wear mechanism that occurred predominantly in this application, which was attrition. Even with the increased cutting speed, this coating also achieved the best result. Therefore, during the machining of titanium, the most important characteristics of the tool are low coefficient of friction and resistance against the pull out of particles.

Keywords Titanium · Carbide · Turning · Coating · Tool life · Wear · Attrition

1 Introduction
Titanium alloys are among the best materials for applications in the aeronautical, petrochemical, medical, and power generation industries due to their inherent properties such as high strength/weight ratio, high fatigue and flow resistance, resistance to high temperatures, biocompatibility, and corrosion resistance [1].

However, the same physical and chemical properties that make this material desirable for a variety of applications also compromise its machinability. Due to the high hardness and strength, high temperatures are generated during machining. As these alloys have low thermal conductivity, the heat generated is mainly dissipated by the tool, causing its premature failure [2]. Its low modulus of elasticity causes large deflections in the part, which can result in tool vibrations and poor quality of the machined surface [3–6].

According to Machado et al. [7], the difficulty in machining titanium is directly proportional to the increase of the content of alloying elements and of the β-phase dispersed in the material matrix. Other characteristic which impairs its machining is its high chemical affinity with various materials causing rapid tool wear [8, 9].

Due to the growing use of this modern material in industry, the machinability of titanium has become a subject of
great interest to the industries that manufacture it. At the same time, the manufacture of dental implants has also been growing in the world market. Titanium is one of the few materials that are inert to corrosion by all body fluids and tissues, one of the greatest requirements for implantation in the human body. In the orthopedic area, titanium is commonly applied in maxillofacial, knee, hip, and skull prostheses and, in orthodontics, in dental implants, in which titanium screws are inserted into the maxillary bone for osseointegration, constituting “artificial roots” for fixation of dental prostheses [10].

Currently, commercially pure titanium (cp-Ti) and Ti-6Al-4V alloy are frequently used in the production of prostheses and dental devices, due to their low modulus of elasticity, high resistance to corrosion, and biocompatibility [11]. Given this scenario, it is important to study ways to improve the machinability of titanium.

In titanium machining, the cutting region may reach temperatures of approximately 1000 °C, even for moderate cutting speeds [4]. These high temperatures, together with the material’s low thermal conductivity [12], result in what is called adiabatic shearing of the chip, which causes a cyclical force variation and, consequently, a high dimensional inaccuracy of the part [13]. All these characteristics mentioned above can result in a shorter tool life [14]. In this scope, it is important to carry out research on carbide tool coatings for their machining, so that longer tool life may be possible and/or the titanium may be machined at higher speeds.

Two questions which are usually made in companies that manufacture titanium are: To use or not to use coating on the tool? If coating is used, may it contain or not titanium in its composition? Some authors [12, 15, 16] claim that uncoated carbide (which would supposedly be more resistant to the diffusive tool wear process when machining titanium) is the primary tool material when machining titanium. Other authors [17, 18] affirm that coated carbide must be used (coating examples: TiAlN, TiN, Al2O3, and AlCrN), because coating becomes important for wear reduction and, consequently, for increasing tool life. Pervaiz et al. [19] emphasize that uncoated carbide can only be used for processing Ti at low cutting speeds, since the high temperatures generated at high speeds cause thermal softening of the tool and promote rapid diffusion, greatly reducing its life. Therefore, according to these authors, coated carbide tools have surpassed uncoated tools in terms of performance when machining Ti alloys due to the advantages offered by the coating, which was also attested by Revuru et al. [5].

Several studies have considered different coatings to improve the efficiency during the machining of titanium, including AlTiN and CrN [20], TiAlN [21], Ti(C, N)+Al2O3+TiN and (Ti, Al)N+TiN [22], (Ti,Al)N-TiN [23, 24], TiN and ZrN [25], and Zr-ZrN-(Zr,Al,Si)N and Ti-TiN-(Ti,Cr,Al)N multilayer [25].

Li et al. [23] investigated the wear mechanisms during the dry face milling of Ti-6Al-4V alloy using PVD (Ti,Al) N-TiN-coated carbide tools. They observed that the main wear mechanisms were a combination of abrasion, adhesion, coating delamination, and oxidation. Ibrahim Sadik and Isakson [24] studied the wear mechanisms for PVD-(Ti,Al) N-TiN coating and uncoated tools during the face milling of Ti-6Al-4V under cryogenic and wet conditions. For cutting speeds between 60 and 100 m/min, the main occurrence which caused the end of tool life was the chipping of the cutting edge. In this case, both coated and uncoated inserts presented the same occurrence; therefore, the coating did not improve the tool life.

Ren et al. [21] investigated the wear mechanisms for CVD TiAlN-coated carbide and uncoated tools during the dry turning of Ti-6Al-0.6Cr-0.4Fe-0.4Si-0.01B alloy. Results showed better wear resistance and tool life for the coated tool, and adhesion was one of the main wear mechanisms for both tools. An et al. [22] evaluated the wear performance of CVD Ti(C, N)+Al2O3+TiN and PVD (Ti, Al)N+TiN-coated and uncoated tools during face milling of Ti-6242S and Ti-555. The PVD (Ti, Al)N+TiN-coated tool presented the longest tool life, with increased wear resistance and fracture resistance. The main wear mechanisms were adhesion, diffusion, and micro-chipping of the coating.

Vereschaka et al. [25] analyzed the tool life for TiN and ZrN coatings, multilayer Zr-ZrN-(Zr,Al,Si)N and Ti-TiN-(Ti,Cr,Al)N coatings, and uncoated tools during the face milling of VT20 titanium alloy. The multilayer coating achieved the best results, improving tool life by 4 and 4.5 times when compared to the uncoated one. According to Vereschaka et al. [25], the use of multilayer tools with nanostructured coatings reduces the chipping and brittle fracture and at the same time guarantees a more predictable wear pattern.

Chowdury et al. [20] compared AlTiN and CrN hard coatings with uncoated carbide tools during high-speed turning of Ti-6Al-4V. Tool life was shortened due to severe cratering, caused by diffusive wear. The best result was achieved by the CrN-coated tool, opposing the AlTiN-coated tool, which had the worst results regarding tool life. The AlTiN presented a higher hardness but a lower plasticity index, failing in a more brittle way. Also, it had a much higher coefficient of friction, which contributes to its worse tribological properties. With the CrN-coated tool, a Cr2O3 tribofilm was formed, significantly reducing the crater wear.

According to these studies, adhesion is one of the main wear mechanisms during the machining of titanium [21–23, 25]. Therefore, it is fundamental to reduce the coefficient of friction between chip and tool, avoiding coating detachment [20].

The experiments presented below aim to contribute to the improvement of the machining of commercially pure...
titanium (cp-Ti) grade 4, used in dental implant screws, and to answer the questions cited above, through a study on the behavior of different types of tools applied in the turning of this material. For this, the lives of the uncoated carbide tool and also of coated tools with different coating layers were evaluated through the analysis of the tool wear and its mechanisms during the external turning of titanium samples. Therefore, this work intends to find the most satisfactory tool in terms of tool life and to explain the reasons for its better performance.

2 Materials and methods

The experiments of this work were carried out in a company of the dental medical sector specialized in manufacture of dental implants. The material machined in the experiments was the commercially pure titanium according to ASTM F67 grade 4. The workpieces were cylindrical bars with diameters ranging from 4.76 to 6.35 mm from cold drawn process, with h9 diameter dimensional tolerance.

The machine tool used to carry out the tests was a CNC Lathe (Swiss type), typically used for turning small and precision parts. This machine has automatic bar feeder and clamping system of the workpiece by gripper and guide bush. As this process is carried out continuously, always with the same clamping force, the system is considered rigid for the turning process.

The tool holder used was the PDACL 1010 M-07S. It has a 91° of cutting edge angle ($\kappa_r$), insert in neutral position, that is, with no inclination in the holder, but the insert has a 20° rake angle in its own geometry derived from the chosen chipbreaker. Thus, the tool as a whole is positive in 20°. The insert for the application was the DCGT 070,202 AS-IC20. It is an uncoated insert with a positive geometry, with 2 edges. Figure 1 shows the rake and clearance angles of the tool, measured on a confocal microscope AliconaTM.

Subsequently, other 3 types of identical inserts were coated by physical vapor deposition (PVD) method, but with different compositions and microstructure. The coatings were TiAlN, AlCrN, and TiN+TiCN. The cemented carbide used as substrate for all tools tried was the same, with microhardness of 1650 (HV 0.05) and average grain size of 1.8 µm. The uncoated insert has a reference cost of BRL 60.22. Each type of coating has a different cost per unit, due to its type of processing, TiAlN costs BRL 2.92, AlCrN costs BRL 5.05, and TiN+TiCN costs BRL 3.88. Table 1 shows a summary with all the information collected about the tools and coatings used in this work.

In order to observe the coating structure, a ball-cratering test was performed for all coated tools using a tribometer CSEM Calotest. Figure 2 shows the (a) TiAlN, (b) AlCrN, and (c) TiN+TiCN coating layers.

The turning operation performed in the tests is considered medium machining on the outer diameter of the part sketched in Fig. 3, with a length that can vary between 8.5 and 15.0 mm (dimension B). The machining is done in such a way as to leave on the part of the dimensions previous to the threading operation, starting from a diameter of either 6.35 or 4.76 mm, which are the bar diameters (dimension D). Implant diameter and entry angle dimension (dimensions A and C) depend on the implant model to be machined.

Initially, the cutting parameters used were those recommended by the tool manufacturer, that is, cutting speed ($v_c$) = 55 m/min and feed ($f$) = 0.06 mm/r. Then, the experiments were also carried out with $v_c = 66$ m/min (20% higher than the initial one). The workpiece turning was performed with only one pass of the tool, that is, the cutting depth ($a_p$) varied according to the model of the

| Tool configurations for each test |
|-----------------------------------|
| Coating structure | Uncoated | TiAlN | AlCrN | TiN+TiCN |
| Coating thickness (µm) | - | 2–4 | 2–4 | 2–4 |
| Surface microhardness (HV 0.05) | 1670 | 3300 | 3800 | 2950 |
| Friction coefficient against dry steel | 0.30 | 0.15 | 0.30 | 0.17 |
| Maximum working temperature (°C) | 500 | 900 | 1100 | 800 |
| PVD process temperature (°C) | - | 450 | 450 | 400 |
implant. The machined length per tool and the volume of chip removed per tool also varied depending on the model of the implant to be machined. Machining was done with abundant external coolant for all the tests. The cutting fluid used was an integral fluid based on vegetable esters, not miscible in water, with a kinematic viscosity of $10 \text{ mm}^2/\text{s}$ ($40 \degree\text{C}$).

Each test performed was replicated once, that is, 16 tests were performed in total. The output variable used for comparison between the tools used in this work was the total machined length measured in the feed direction (what can be called feed length) of each tool when the workpiece reached roughness equal to $0.8 \mu\text{m Ra}$. This was the criterion used by the company to replace the cutting edges in this operation once roughness increases as tool wear increases.

To fully understand the wear mechanism generated in the tested inserts, a scanning electronic microscope (SEM) Zeiss EVO MA15 with Smart SEM software was used to analyze the worn cutting edges. The energy dispersive spectroscopy (EDS) technique was used in order to observe chemical elements present on the tool surface.

### 3 Results and discussion

Figure 4 shows the tool life in terms of machined feed length for each type of insert tested. Since there are two different cutting speeds, it is more convenient to analyze the tool’s performance in terms of length machined than cutting time. Doing like this, if two tools have the same life in minutes, the one with the highest speed is more efficient. It can be seen that the insert coated with TiN + TiCN presented the longest tool life for both cutting speeds ($v_e$) tested. It is also observed that the higher the cutting speed, the shorter the tool life, according to what is well established in the literature [26]. It is worth noting that the insert coated with TiAlN was the one that obtained the greatest difference in terms of tool life, between $v_e = 55 \text{ m/min}$ and $v_e = 66 \text{ m/min}$. The tool
life was 54% lower, that is, it was the most harmed insert with the increase of tool temperature caused by the increase of cutting speed.

For the insert coated with TiN + TiCN, the difference in life between \( v_c = 55 \) and 66 m/min was the smallest one when compared to the others tested, 9% lower for 66 m/min. That is, this coating material was the one with the highest resistance to the increase in cutting temperature caused by the increase in cutting speed.

It is also noted that for \( v_c = 55 \) m/min, the insert coated with TiN + TiCN was the one which reached the longest tool life, with 68 m of machined length. TiAIN had the second position for tool life. For \( v_c = 66 \) m/min, the TiN + TiCN obtained a much higher result when compared to the others in this cutting speed, 196% higher when compared to AlCrN, 148% higher than TiAIN, and 265% higher than the uncoated one.

An attempt must be made to explain the behavior of tool materials in terms of life. The first attempt to do this is using their properties shown in Table 1. The tool with the worst performance in terms of life was the uncoated one. This was due to the fact that it has the lowest micro-hardness and the lowest working temperature among all materials tested. Therefore, the supposedly greater chemical stability of the uncoated carbide elements [12, 15] in relation to titanium and aluminum present in the coating layers was not enough to make this material to have a superior performance in terms of tool life. Moreover, as it will be seen ahead in this work, a low friction coefficient of the tool material is a very important property for the tool to turn a titanium material, since the main tool wear mechanism is attrition, which includes the adhesion of the material being machined on the tool. As it can be seen in Table 1, the uncoated tool presents a 0.30 friction coefficient (the highest value among all the tested tools), while this value is 0.17 for the TiN + TiCN-coated tool and 0.15 for the TiAlN-coated tool. Therefore, the tool coating is necessary not just to increase the tool hardness and its working temperature, but also to decrease its coefficient of friction.

The tool which obtained the longest life (TiN + TiCN-coated carbide) did not have the best properties, at least among those mentioned in Table 1. It can be seen in the table that this material has the lowest hardness, the second lowest friction coefficient and the lowest working temperature among the tested coatings. So, these properties cannot be used to explain the good results of this material. Later in this work, the tool wear mechanisms will be studied, in order to understand the reasons which made this material the most suitable for turning pure titanium grade 4 among the materials tested.

For all applications, the tool life criterion was the maximum surface roughness of 0.8 \( \mu m \) Ra on the turned surface of the part, i.e., there was no evaluation of tool conditions or measurement of flank wear during the process. After completion of the tests, the inserts were evaluated to verify the type of wear and flank wear (\( V_B \)) values. Figure 5 shows the flank wear value at the end of tool life found on each tool used in the tests (measurements made using the scanning electronic microscope (SEM)). \( V_B \) ranged between 0.10 and 0.50 mm at the time \( R_a \) was 0.8 \( \mu m \). Thus, it can be stated that flank wear did not have a direct influence on the increase of roughness but, rather, some other type of tool wear. It can be also seen in Fig. 5 that the tool with TiN + TiCN coating presented the smallest value of \( V_B \) when \( R_a \) was 0.8 \( \mu m \). Therefore, it can be concluded that, if the tool life criterion was not surface roughness but the value of flank wear itself, this tool could present an even longer tool life, indicating that it is the most suitable tool for turning this material among those tested.
The roughness of the turned part depends on the shape of the tool nose in general. Thus, the deformation of its nose (variation of the nose shape in relation to the initial shape) is the type of wear that must influence the increase of surface roughness of the part along tool life and this wear is not directly related to the tool flank wear. In order to analyze the tool wear mechanisms, the worn cutting edges were analyzed in a scanning electronic microscope (SEM) with energy dispersive spectroscopy (EDS). Figures 6, 7, 8 and 9 show these pictures.

It is possible to observe in Fig. 6 that the flank wear was 0.45 mm. It can be seen that the tool edge was significantly deformed and lost a lot of particles; besides that, a lot of material was adhered to the tool faces, as can be seen in points 2, 3, 5, and 7. Point 5 seems to indicate that a built-up edge was formed during the process, since, at this point, a titanium abscess can be observed on the rake face of the tool.

The flank wear (Fig. 6a) also contains titanium from the workpiece material (points 1, 2, and 3 of the EDS analysis), but it also has grooves parallel to the cutting direction. This usually occurs when the adhered material is pulled from the workpiece, and, consequently, tool particles are taken along with this material (attrition). In this case, these particles also caused wear in the region of the tool that rubs against them, causing parallel grooves (abrasion) [27]. Point 4, which is out of the worn region, shows that this carbide tool was...
basically made of cobalt (binder) and tungsten carbides (the carbon content did not appear on this EDS analysis).

It can be also observed that the titanium is adhered also to the flank face of the tool. This occurs by the extrusion of the chip in formation between the cutting edge and the machined surface, generated by the high normal pressure that the chip imposes on the tool and also by some vibration between tool and part, which allowed the generation of spaces for this extruded chip to pass between the tool and the workpiece [27].

Through Fig. 6, it can be seen that the entire worn region on the flank face was full of workpiece/chip material adhered on it. As a built-up cutting edge was formed at the very tip of the tool (point 5 of the EDS analysis), the flank wear region, indicated by arrow 1 in the figure, may have been caused by the continuous breakage of this edge, which also carried particles from the tool. Observing the tool nose radius, there was a lot of deformation, that is, it has a very different shape from its initial condition, which was the cause of the rapid growth of the surface roughness of the part.
The predominant wear mechanism that can be observed was adhesion (attrition), that is, there are indications that there were cyclical movements of adhered material sequenced by pulling out of this adhered material, taking with its particles from the tool. The surface appearance of the tool that undergoes this wear mechanism is a rough and deformed surface due to the subtraction of particles. However, in the regions indicated by arrows 1 and 3, it is also observed that there are parallel scratches in the cutting direction, which means that there was also the abrasion mechanism in this region; that is, hard particles either from the workpiece of the material or from the tool itself may have ripped particles off the tool in the cutting direction, causing this visual aspect to the tool.

Pictures of the worn faces of the uncoated tool from the test made with $v_c = 66 \text{ m/min}$ will not be shown to save space, but it can be said that the same wear mechanisms were present in this condition, i.e., the tool was worn by attrition and abrasion.

Based on these results and on the properties cited in Table 1, a hypothesis can be built to explain the bad performance of the uncoated carbide tool to carry out the turning of this titanium alloy: (a) its friction coefficient is too high, which allowed significant adhesion of workpiece/chip material on both flank and rake faces; (b) its maximum working temperature is too low, which facilitated the tool loss of particles caused by the increase of the tool temperature; (c) its hardness is low, which not just made possible the removal of particles, but also the abrasion scratches seen on the tool flank face. These three properties enabled tool wear to be very fast and, consequently, tool life to be very short. Therefore, even with its supposedly higher chemical stability with titanium, this uncoated carbide tool is not suitable to be used in the turning process of this titanium alloy.

For the experiments made with TiAlN-coated tool, just the faces of the tool used to cut with $v_c = 66 \text{ m/min}$ will be shown (Fig. 7), also to save space. However, it can be said that the wear mechanisms for both cutting speeds were very similar.

Figure 7 shows that the tool flank wear measured after the end of the test is 0.32 mm. Note that there is also workpiece material adhesion on the tool rake face (Figs. 7b, c), but it does not seem that built-up edge occurred. The tool nose radius shape varied greatly from the original shape, which made the tool to reach the roughness value that determined the tool’s end of life.

The predominant wear mechanism that can be observed was adhesion (attrition) since it is possible to detect high levels of workpiece material (Ti) at almost all measured points. In this case, no abrasion wear occurred since there were no abrasive scratches on the tool.

Analyzing the wear of the flank face (Fig. 7a), it can be seen that, at point 1, there were both workpiece material (Ti) and substrate material (W and Co), indicating that, at this moment, this portion of the tool had its coating particles pulled out. Points 2 and 3, on the other hand, show a percentage of Ti greater than that present in the coating, indicating again the presence of Ti adhered to the tool, causing the attrition mechanism.

For the experiments made with AlCrN-coated tool, just the faces of the tool used to cut with $v_c = 55 \text{ m/min}$ will be shown (Fig. 8), also to save space. However, it can be said that the wear mechanisms for both cutting speeds were very similar.
It can be seen in Fig. 8 that the tool wear in the end of tool life was 0.12 mm. Observing the tool nose, there is not much deformation, that is, its shape is similar to its initial condition.

Analyzing the wear on the rake surface of the tool (Fig. 8b), it can be seen that, at points 4 and 6, the presence of workpiece material (Ti) was small. This small content of Ti present at these points came from the workpiece, as the coating in this case did not contain this element. Only at point 5 there was a more accentuated presence of Ti, indicating some adhesion of chip material. However, it can be seen that crater wear was not deep, that is, a crater that could harm the tool’s performance and lead to breakage was not characterized.

On the other hand, the analysis of the flank face (Fig. 8a) indicates the presence of the attrition mechanism. Point 3 was made just of workpiece/chip material, and point 1 presented not only elements from the substrate, but also some material of the part adhered. On the other hand, point 2, which was on the edge of the wear region, mainly indicates the presence of material of the tool coating (Al and Cr). No abrasive scratches were seen in this wear region.

For the experiments made with TiN + TiCN-coated tool, just the faces of the tool used to cut with $v_c = 66$ m/min will be shown (Fig. 9), also to save space. However, it can be said that the wear mechanisms for both cutting speeds were very similar.

The flank wear at the end of tool life was 0.12 mm. Again, it can be said that this tool could be used longer if the tool life criterion was not the workpiece surface roughness. Regarding the wear on the tool rake face (Fig. 9b), it can be seen that this wear was shallow, not characterizing a crater. At point 5, there was chip material adhered, without any accumulation of it. At point 6, the Ti found refers to the coating material applied to the tool, as there was no adhesion at this point and the content of this element was very low. At point 4, it can be stated that there was a small accumulation of chip material, but it cannot be affirmed that there was a built-up edge. The tool nose deformed very little, showing that it had a similar shape to the initial wear condition.

Regarding the wear of the flank face (Fig. 9a), at point 1, the tool substrate was quite exposed (W and Co), and the Ti present there may come from the tool coating itself. At point 2, there was a high content of Ti, indicating that the predominant wear mechanism was adhesion (attrition). The rough appearance and signs of grain subtraction from the tool face confirm this wear mechanism. Point 3 was very similar to point 1.

The tool which obtained the longest life (tungsten carbide coated with TiN + TiCN) did not have the best properties, at least among those mentioned in Table 1. It can be seen in Table 1 that this material has the lowest hardness and the lowest working temperature among the tested coatings.

It also had a low friction coefficient, similar to the lowest coefficient obtained among all tools. It remains then to answer the question: why was a tool with lower hardness and temperature resistance the one that presented the longest tool life? This answer can be given by the wear mechanisms analysis just made. It was verified in this analysis that adhesion (attrition) was the main present wear mechanism. This was also attested by several studies in the machining of titanium alloys [21–23, 25]. To resist this mechanism, the tool must have a low coefficient of friction to minimize adhesion. The tool that achieved the longest life of all (the one with TiN + TiCN coating) had a low coefficient of friction, which corroborates the results obtained by Chowdury et al. [20] that achieved the best wear performance with the coating with significantly lower friction (CrN), highlighting the importance of tribological properties during the machining of titanium. In other words, tribological properties are more important than mechanical properties, such as tool hardness.

But this feature alone does not explain everything, as the tool with TiAlN coating (the second better in terms of tool life) has an even lower coefficient of friction. Another important feature for the tool to resist attrition is the resistance of its coating layers to have particles ripped out by the attrition process. Among the properties of the tools/coatings shown in Table 1, there is none that measures this characteristic. However, it can be pointed out that a multilayer tool such as the one with TiN + TiCN coating, which has dozens of alternate layers of TiN and TiCN nanometric thicknesses, resists more to this pullout, due to the small thickness of its layers, which is endorsed by Vereschaka et al. [25] results, that obtained the best tool life and a more predictable wear pattern with the use of multilayer nanostructured coatings.

4 Conclusions

Based on the results of this work, it can be concluded for conditions similar to those tested here that.

- The tool that showed the longest life among all those tested was the one coated with TiN + TiCN. It did not have the best properties among the tested coatings. In fact, it had the lowest hardness and the lowest working temperature. Even so, the tool presented the best performance. This is supposed to have occurred because, due to its low coefficient of friction and the fact that it is multilayered and nanometric coating layers, it was able to resist the main wear mechanism, which included material adhesion to it (low coefficient friction) and pullout of its particles (due to the small thickness of its layers).
- The tool with the highest surface hardness did not obtain the longest life.
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