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ORIGINAL ARTICLE

Analysis of the life of cemented carbide drills with modified surfaces

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Abstract The performance of cemented carbide cutting tools during machining is influenced not only by the mechanical properties of the coating and substrate but also by the topographies of their surfaces. A tool with good coating and substrate properties but unsuitable topographies may exhibit accelerated wear and, consequently, impaired performance. In this work, drills coated using physical vapor deposition (PVD) were produced with different substrate textures, which in turn generated different coating textures. The surface roughness values of the coated drills were measured together with the residual stress at the interface between substrate and coating. Drilling tests were performed and tool wear was measured during the machining process. Two different tool coatings were studied: TiAlN and TiAlCrSiN. The goal was to study how the characteristics of the substrate and coating (material, surface topography, and residual stress) influence tool life. Tool life experiments were carried out using drilling tests in AISI 1548 steel, which is often used in crankshafts. The primary tool wear mechanism was attrition in all the drills. The main conclusion of this work is that the tool with the lowest roughness and a TiAlCrSiN coating had the best performance in the conditions tested here.

Keywords Cutting tools · PVD coatings · Roughness · Residual stress · Tool wear

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1 Introduction

Substrate, coating, coating topography, the environment between coating and counter material, and the formation of tribofilms are some of the parameters that can determine whether a coated cutting tool or mechanical component functions successfully throughout its expected lifetime [1]. Recently, some studies have proposed modifications to the cemented carbide surface used in tools in order to alter the roughness, residual stress, and composition of the substrate and so improve tool life [2–8]. Tensile residual stresses enable crack formation and propagation when additional external tensile loads are present, while compressive residual stresses are known to slow down crack growth and thus increase tool life [5]. Modification of substrate roughness and composition can improve adhesion between substrate and coating and, consequently, increase tool life [8].

An ideal cemented carbide surface with suitable roughness, residual stress, and carbide composition has not yet been found, but coatings with compositions for specific cutting materials have been produced and used with positive results [3, 9].

Different elements (dopants) have been successfully used in nitride-based coatings to improve cutting-tool performance. The addition of aluminum to the TiN base composition (the first commercial physical vapor deposition, or PVD, coatings) provided not only higher hardness but also a remarkable improvement in high-temperature strength and inertness. The hardness of AlCrN coatings (aluminum added to the

CrN base composition) is similar to that of TiAlN coatings, but what makes the former outstanding is their high adhesion due to their high Cr content, as well as their high oxidation resistance up to 1,200 °C. A new approach that has been adopted in an attempt to improve tool temperature resistance is the inclusion of Si in the coating. AlCrSiN-based coatings have been successfully applied to hobbing, drilling, and milling tools, where coating oxidation resistance and high-temperature resistance are required. From the material point of view, the alloying of TiAlN coatings with dopants provides almost unlimited opportunities; for example, TiAlCrN, TiAlCrSiN, and TiAlCrYSiN coatings have been reported by several researchers, and there are even reports of Zr, V, B, and O having been added to coatings [10, 11].

Another way to improve tool life is to modify the substrate surface by mechanical, thermal, or chemical processes or combinations of these. The cutting performance of coated cemented carbide tools and the properties of their substrates can be affected by microblasting and lapping or a combination of these. Microblasting of ground or lapped substrates results in improved coating adhesion and cutting performance. To achieve sufficient embedding of the carbide in the Co-binder, the surface microroughness after microblasting has to be less than the radius of the WC grains. This can be achieved by microblasting the polished surfaces of the insert. In contrast, substrate polishing before film deposition worsens the substrate's adhesive properties as well as the tool's cutting performance [2].

Removal of feed marks present in the as-ground WC–Co substrates in order to achieve a uniform surface texture and the depth of the layer of cobalt removed are key factors to achieve an adherent diamond coating when chemical etching methods are used. Diamond coatings with a WC-Co substrate modified by chemical etching and a CrN/Cr interlayer were studied in dry machining experiments on silicon aluminum alloys. Three chemical etching methods were used to modify the substrate: Murakami ultrasound bath in (1:1:10 $KOH+K_3[Fe(CN)_6]+H_2O$), method E-1 (Murakami ultrasound bath in 10 % HNO_3+90 % H_2O_2) and method E-2 (Murakami ultrasound bath in a solution of 3 mL of H_2SO_4 and 88 mL of H_2O_2). The results showed that samples treated by the E-1 method, although exhibiting higher crack-length values after Rockwell indentation under 100 and 150 kg loads, displayed the best dry machining performance [12].

Studies in the literature have shown that laser substrate treatment is effective in improving the adhesion of chemical vapor deposition (CVD)-deposited diamond coatings on cemented carbide substrates [13–15], PVD-deposited AlTiN coatings on cemented carbide substrates [16], and PVD-deposited TiN coatings on high-speed steel (HSS) twist drills. Moreover, the tool life of laser-treated drills used to drill steel was much longer than that of commercial HSS drills [17].

Several works measured some output variables of the drilling process like spindle torque [18], thrust force [19], cutting power, feed force, and tool temperature [20] in order to detect tool wear, burr formation, and the impact of the process parameters in the output variables. Rivero et al. [20] carried out dry drilling experiments using uncoated drills and two different PVD-coated drills (the first was a multilayer coating that combines the resistance at high temperatures of a TiAlN layer with the low friction properties of a WC/C layer and the second was an amorphous diamond-like carbon coating) to verify the feasibility of using these coatings in dry drilling of aluminum. In these experiments, they measured torque, power, feed force, and temperature along the experiments. Among their conclusions, it could be cited that the use of the multilayer coating eliminates the increase of torque at the end of the hole, reduces burr size and power consumption, and increases tool life when dry drilling.

In light of these findings, this work, which is a part of a broader research project, sought to establish how modifications to the surface of the cemented carbide substrate influence the surface of a tool after coating and, consequently, its performance in machining. Drills with two types of surfaces with different roughness parameters (referred to as *modified 1* and *modified 2*) were produced and coated with TiAlN and TiAlCrSiN by PVD. These coatings were selected because they are recommended for steel drilling operations by the company that supplied the drills. The roughness and residual stresses of the *modified 1* and *modified 2* surfaces were compared with those of tools whose surfaces had not been modified (referred to as *commercial*). Finally, based on tool life experiments involving the drilling of AISI 1548 steel, the tool life, wear profile, and tool wear mechanisms of drills with the modified surfaces were compared with those of the commercial tools.

2 Materials, methods, and experimental procedures

The substrate of the cemented carbide drill used in this work has an average grain size of 5 μm and is composed of approximately 9 % cobalt binder, 1 % chromium, and 90 % tungsten carbide. The tool coatings, which consisted of either TiAlN or TiAlCrSiN, were PVD deposited to a thickness of between 3 and 5 μm. This drill is classified as ISO grade P20–40. Table 1 shows the main characteristics of these coatings.

After the coating process, some of the drills were polished using a process with alumina grains. The agitation of these grains caused by the polishing machine produces the polishing effect on the tools. More details about the polishing process could not be obtained due to confidentiality issues. Two groups of drills were analyzed; the first group consisted of a commercial drill and two different experimental drills, none of which were polished; while the second consisted of a

Table 1 Main characteristics of the coatings used in this work (manufacturer's data)

Characteristics	TiAlN	TiAlCrSiN
Material	TiAlN	AlCrN
Microhardness (HV 0.05)	3,300	3,000
Compressive residual stress (GPa)	−2.0	−3.0
Maximum service temperature (ºC)	900	1,100
Coating temperature (ºC)	<500	<500
Coating structure	nano	multilayer
Coating thickness (μm)	4	3.5

commercial drill and two experimental drills, all of which were polished. Three different substrate surfaces were used on the drills: the unmodified substrate on drills as supplied by the tool manufacturer (referred to as *commercial*) and the substrate on drills as supplied by the tool manufacturer and subsequently subjected to two different types of modification (referred to as *modified 1* and *modified 2*).

To measure residual stress at the substrate–coating interface, a diffractometer was used in continuous-scan mode with an angular range (2θ) of 20–120° in Bragg–Brentano geometry, a scan step of 0.02° and a scan time of 1 s. The maximum voltage variation in the tests was 40 kV, and the maximum current variation 40 mA. The diffractometer had a copper X-ray tube and a laser beam depth of up to 10 μm. To analyze tool coating and substrate roughness parameters (average roughness and Abbott curve parameters) an optical profilometer equipped with Vision software was used.

For machining tests, drilling operations were carried out in a vertical CNC machining center with spindle motor power of 22 kW and a rotation frequency of 50–12,000 rpm. As illustrated in Fig. 1, a cemented carbide drill with a diameter of 11.44 mm, point angle of 140°, and helix angle of 30° was used. The length of 18 mm in the figure indicates the modified part of the experimental surface. The drills were ground by the manufacturer and each drill was used just once (they were not reground). All the drills were ground in the same batch, in order to attain a good repeatability of geometry.

Two cutting speeds (v_c) were used in the experiments: 114 and 137 m min^{-1}. The polished and unpolished drills were tested at v_c=137 m min^{-1} and v_c=114 m min^{-1}, respectively. These cutting speeds were higher than those used in a local crankshaft manufacturer—the steel used in the tests is typically used in crankshafts—and were chosen to determine whether they could be used on the shop floor, thereby decreasing the cutting time of a machine that is frequently the bottleneck in a production line.

Cutting fluid was injected through the drill at high pressure (70 bars), and the feed rate used (f) was fixed at 0.34 mm rev^{-1}. A drilling experiment was considered to have finished when the tool life criterion was reached (flank wear $VB_B \cong 0.3$ mm) or when the drill had machined 70 m of feed length. Each drilling experiment was carried out at least twice (at least two replicas). When the difference of the results of either flank wear or tool life at the end of each replica of an experiment was larger than 20 %, another replica was carried out. Figures 7 and 8, which present the flank wear results, were built with the average values obtained in the replicas. Due to the high pressure injection of the fluid, the chips never clogged the helix channels of the drill. Moreover, no other unexpected occurrence happened. The worn flank surfaces were monitored throughout the tests using a stereoscopic microscope with a digital camera connected to a computer with image processing software. After machining, the morphology of the worn edges was characterized using a scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy analysis (EDX), which was also used to detect chemical elements on the worn surfaces of the tool.

The workpiece used in the drilling experiments consisted of several 140×140×80 mm blocks of AISI 1548 steel, which is frequently used in crankshafts. Its main properties are average hardness 240 HB, tensile strength 800 MPa, yield strength from 450 to 500 MPa (values supplied by the manufacturer).

3 Results and discussion

3.1 Roughness parameters

The surfaces were analyzed for average roughness (Ra) and three parameters of the Abbott curve: core roughness depth (Rk), reduced peak height (Rpk), and reduced valley depth (Rvk). The parameter Rk is defined in ISO 13565-2 (1996) as

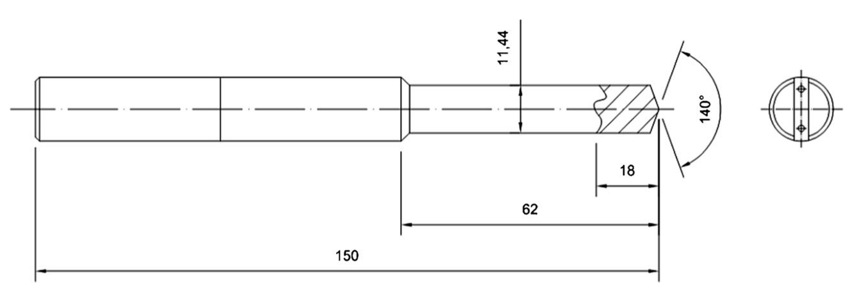

Fig. 1 Drill used in the machining experiments

the depth of the roughness core profile. It characterizes the long-term running surface that will influence the performance and life of the surface. The parameter Rpk is the reduced peak height and is defined in ISO 13565-2 (1996) as the average height of the protruding peaks above the roughness core profile. It represents the top portion of the surface, which is the first to be worn away. The parameter Rvk is the reduced valley depth and is defined in ISO 13565-2 (1996) as the average depth of the profile valleys projecting through the roughness core profile. It characterizes the oil-retaining capacity of the surface provided by the deep valleys [21].

Figures 2, 3, 4, 5 show the values of the roughness parameters for the tool substrates and coatings. Analyzing the unpolished tools, it can be seen that the coating produced a small increase in roughness values (Figs. 2b, 3, 4, and 5b). Most of the substrates coated with TiAlCrSiN had lower roughness parameters (particularly Rpk and Rvk) than those coated with TiAlN. This difference is probably due to defects generated during coating deposition, such as peaks, craters, asperities, microscratches, inclusions, impurities, and particles that remain on the surface after the cleaning procedure [22]. The *modified 2* tools generally had the highest roughness parameters before and after coating, with the TiAlN coatings having higher roughness values than the TiAlCrSiN coatings.

As shown in Fig. 2, although the *modified 1* substrate had a higher Ra value than the commercial substrate, the Ra values were statistically equal when both substrates were coated with TiAlN. Before and after coating with TiAlCrSiN, the *modified 1* substrate had a higher roughness value (Ra) than the commercial substrate. After the commercial and *modified 1* tools had been polished, their Ra values were statistically equal for both coatings and similar to—and sometimes even lower than—the values for the precoating surface (substrate). The *modified 2* surface had the highest Ra values of all the surfaces, and the tool coated with TiAlN had an even higher Ra value than the tool coated with TiAlCrSiN. In other words, polishing was able to decrease the roughness of the *modified 1* and commercial coatings to the same value as that of their substrates, but although it was able to decrease the roughness of the *modified 2* coating to a value below that of the substrate, it was not able to reduce the roughness to the same value as that of the commercial and *modified 1* coatings.

The following observations can be made in relation to the parameters of the Abbott curve (Figs. 3–5):

1. Again, the *modified 2* substrate had the highest value for all parameters (Rk, Rvk, and Rpk) regardless of whether the tool was coated or not. The only exception was the TiAlN-coated tool, for which the *modified 1* and *modified 2* substrates had statistically equaled Rvk values because of the high dispersion of the *modified 1* tool;
2. For the unpolished tools, the Abbott parameters of the *modified 1* tool with or without a coating were generally higher than the corresponding parameters for the commercial tools. An exception to this was the TiAlCrSiN-coated tool, which had Rpk and Rvk values that were statistically equal to those of the *modified 1* and commercial tools;
3. Again, polishing caused all the Abbot parameters to decrease and also caused the values for *modified 1* and commercial tools to fall to the same values as, or below, those of their substrates. However, although polishing decreased the *modified 2* parameters to below the corresponding figures for the substrate, it was not able to reduce them to the same levels as the parameters of the *modified 1* and commercial tools.

3.2 Residual stress

Residual stress was measured at the coating–substrate interface. As illustrated in Fig. 6, the modified surfaces contained

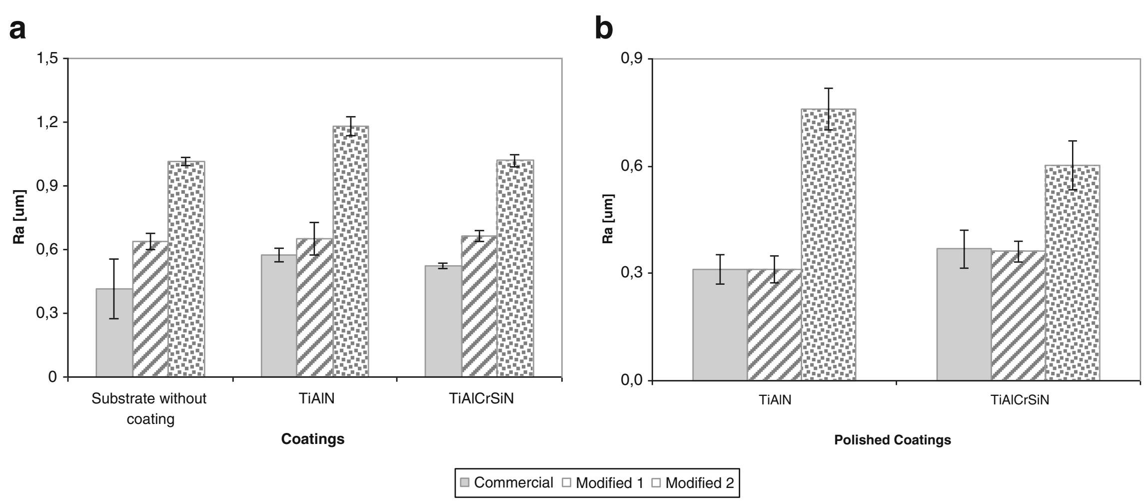

Fig. 2 Average roughness (Ra) of unpolished (**a**) and polished (**b**) surfaces

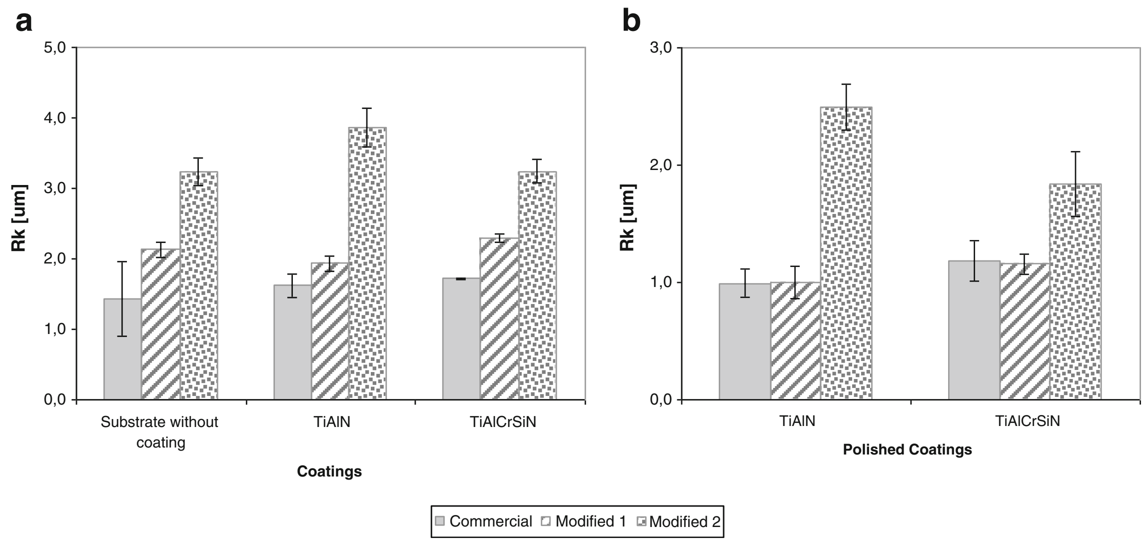

Fig. 3 Core roughness depth (Rk) of unpolished (**a**) and polished (**b**) surfaces

tensile residual stresses and the commercial surfaces, compressive stresses. In the commercial and *modified 1* surfaces, the stress was greater in the TiAlCrSiN coating. In the *modified 2* surface, the stress was statistically equal for both coatings.

Polishing caused the residual stress to decrease for the commercial substrate coated with TiAlCrSiN and for the *modified* 1 surfaces with both coatings. For the other tools, polishing did not change significantly residual stress. Therefore, the influence of the polishing process on the residual stress of the substrate–coating interface could not be established, since no tendency could be seen in the results.

According to Denkena et al. [5], compressive residual stress increases tool life. Therefore, based on the residual stress analysis, it is reasonable to suppose that the commercial TiAlCrSiN-coated drill would have the longest tool life because of its high compressive stress and that the modified surfaces would not perform well because of the tensile stresses they contain.

The difference between the residual stress in TiAlN and TiAlCrSiN coatings can be attributed to the time required for the coating process, which is longer for TiAlN coatings. Studies have shown that the temperature required for PVD coating may lead to a decrease in compressive stress because tempering reduces or even removes residual stresses [23].

3.3 Tool wear behavior

It can be seen in Fig. 7 that with v_c=114 m min^{-1} (unpolished drills), the tool with the best performance when a TiAlN coating was used (Fig. 7a) was the commercial drill and that both modified surfaces produced very similar performances. When a TiAlCrSiN coating was used (Fig. 7b), both the commercial and *modified 1* surfaces had the best performance.

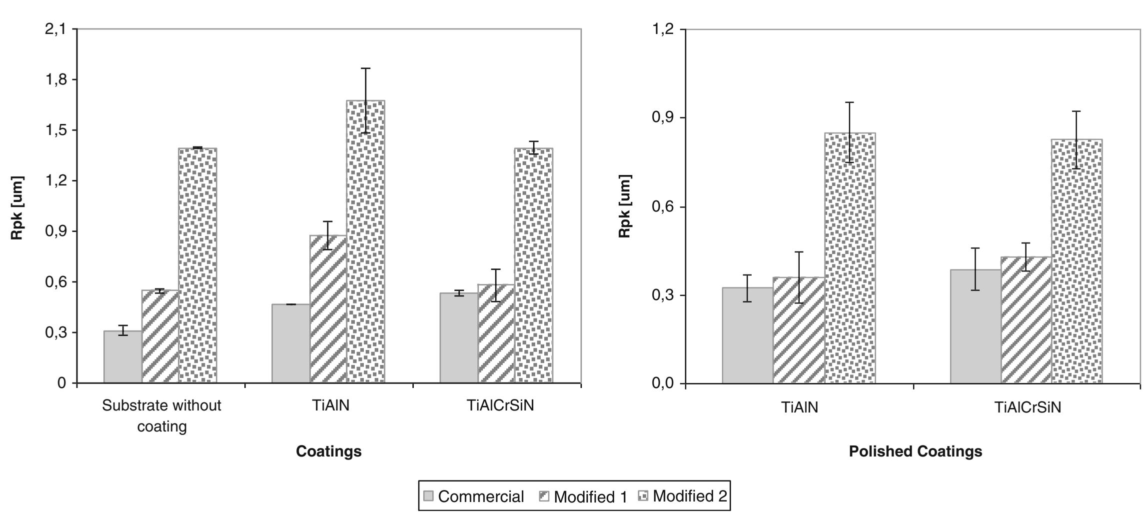

Fig. 4 Reduced peak height (Rpk) of unpolished (**a**) and polished (**b**) surfaces

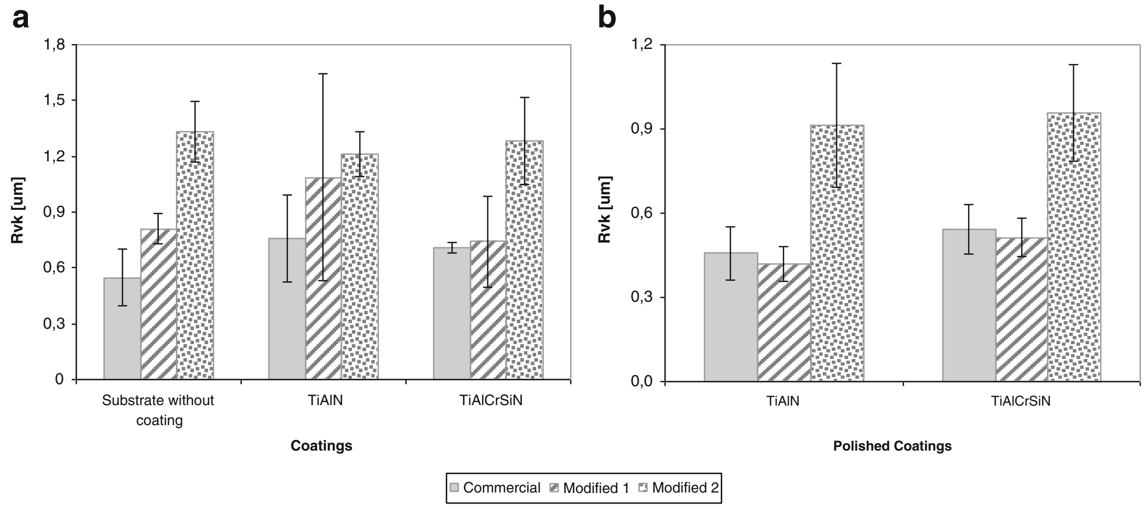

Fig. 5 Reduced valley depth (Rvk) of unpolished (**a**) and polished (**b**) surfaces

TiAlCrSiN-coated tools with *modified 1* and commercial surfaces had the best wear performance as after 70 m of cutting their flank wear values were still below 0.2 mm.

In drilling tests, using a cutting speed of 137 m min^{-1} (polished drills), drills with a commercial TiAlCrSiN-coated surface reached the highest machined length for flank wear equal to 0.3 mm, as shown in Fig. 8. For both coatings the *modified 1* and commercial surfaces exhibited similar behavior (their flank wear curves were very close), while the *modified 2* surfaces always had the worst performance. With a TiAlN coating, the *modified 1* drill reached the end of its life a little later than the commercial one, while the opposite occurred with the TiAlCrSiN coating. Again, drill life was longer with a TiAlCrSiN coating than with a TiAlN coating (compare Fig. 8a and b).

Later in this work a connection will be established between surface roughness, residual stress, and tool wear in an attempt to conclude which surface results in the longest tool life. However, one point must be addressed now: the TiAlN coating has a higher hardness than the TiAlCrSin coating (3,300 HV 0.05 for TiAlN and 3,300 HV 0.05 for TiAlCrSiN) and lower maximum service temperature (900 ° C for TiAlN and 1,100 ° C for TiAlCrSiN), as shown in Table 1. It is therefore important to investigate how these properties are connected to surface characteristics in order to produce a tool with a very long life.

3.4 Tool wear mechanisms

The photographs of the tool wear lands shown here were taken at the end of the tests and therefore allow the wear mechanisms that may have occurred during cutting to be evaluated.

As illustrated in Fig. 9, for a cutting speed v_c=114 m min^{-1}, adhered work material and exposed substrate were observed on the flank wear land for all three surfaces coated with TiAlN. The photographs in Fig. 9 indicate that attrition was the main wear mechanism for these tools. The high normal pressure on the tool rake face, together with vibration that may

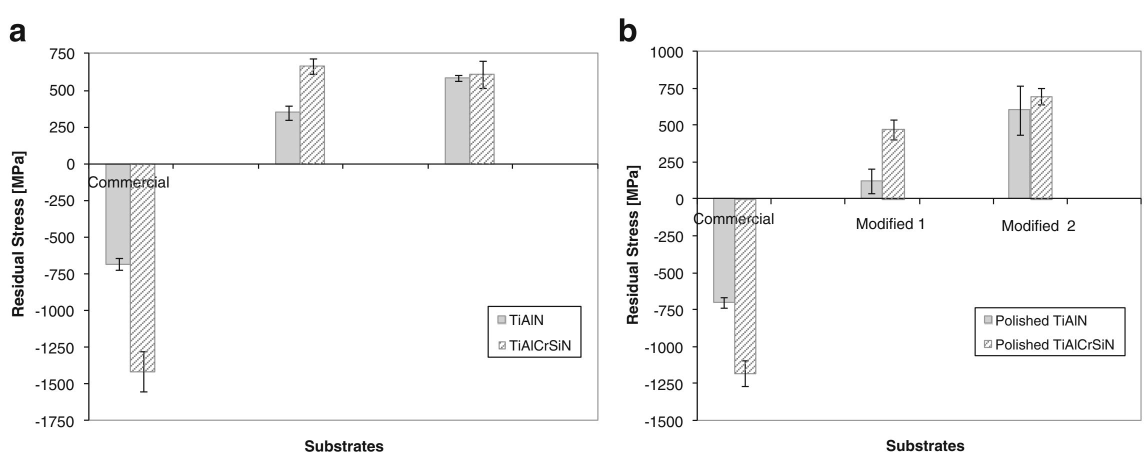

Fig. 6 Residual stress at the coating–substrate interface of unpolished (**a**) and polished (**b**) surfaces

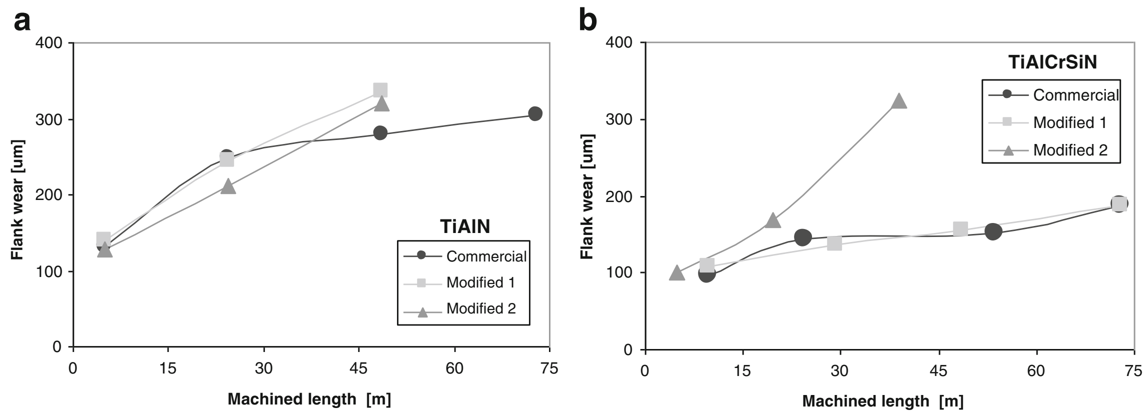

Fig. 7 Flank wear and machined length for the three surfaces coated with TiAlN (**a**) and TiAlCrSiN (**b**) without polishing and with v_c=114 m min^{-1}

have occurred in the tool, meant that chips were extruded between the cutting edge and workpiece, causing work material to adhere to the worn area of the tool flank. Because of the relative movement between chip and tool and between workpiece and tool, a stick–slip process occurred, causing large particles to be removed from the tool (in a mechanism typical of attrition) and the edge to be weakened because of wear, with a consequent increase in tool chipping. This process occurred on all three surfaces shown in Fig. 9 but was more pronounced (faster) for the modified substrates.

In the drills coated with TiAlCrSiN, the main wear mechanism was also attrition (Fig. 10), and the wear performance (Fig. 7) confirmed the roughness results (Figs. 2a, 3, 4, and 5a). For this kind of coating, the slowest tool wear rate was achieved with the commercial and *modified 1* tools. As already mentioned, these tools had lower roughness parameters than the *modified 2* tool. Comparing the parameters of both tools (commercial and *modified 1*), it can be seen that they had similar Rpk and Rvk values and that the commercial drill had lower Ra and Rk values than the *modified 1* surface. It seems, again, that the low Rpk values of these surfaces reduced the impact of attrition as the removal of tool particles caused by the stick-slip phenomenon becomes more difficult when the surface has fewer peaks to be removed. Moreover, it can be seen in Fig. 6a that residual stresses did not play an important role in tool wear evolution as the two best-performing tools (commercial and *modified 1*) had opposite residual stresses (compressive for the former and tensile for the latter).

For the experiments carried out with a cutting speed v_c= 137 m min^{-1} (polished drills), the main wear mechanism was again attrition on the three surfaces coated with TiAlN, as illustrated in Fig. 11. Chipping of the edge was greatest in the drill with the *modified 1* substrate and, because of its extent, may have developed before the end of the tool life. During cutting, the workpiece material stuck and slipped in the wear region several times, which contributed to the increase in spalling. Because of the higher cutting speed, the delamination of the coating may have occurred intensely in the initial stages of the cut, as a result of which the surface would have been exposed to the attrition mechanism for longer.

It can be seen in Fig. 8a that the tool with the *modified 2* substrate had the highest tool wear rate and that the wear rates for the commercial and *modified 1* surfaces were similar. As can be seen in Figs. 2b, 3, 4, and 5b, all the roughness parameters for these two tools (commercial and *modified 1* coated with TiAlN) are very similar and lower than the

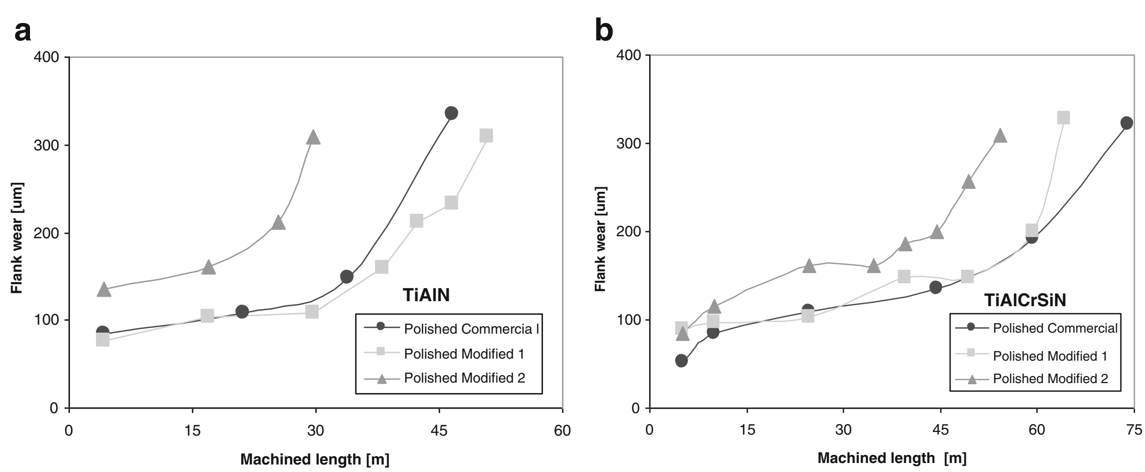

Fig. 8 Flank wear and machined length for the three surfaces coated with TiAlN (**a**) and TiAlCrSiN (**b**) with polishing and with v_c=137 m min^{-1}

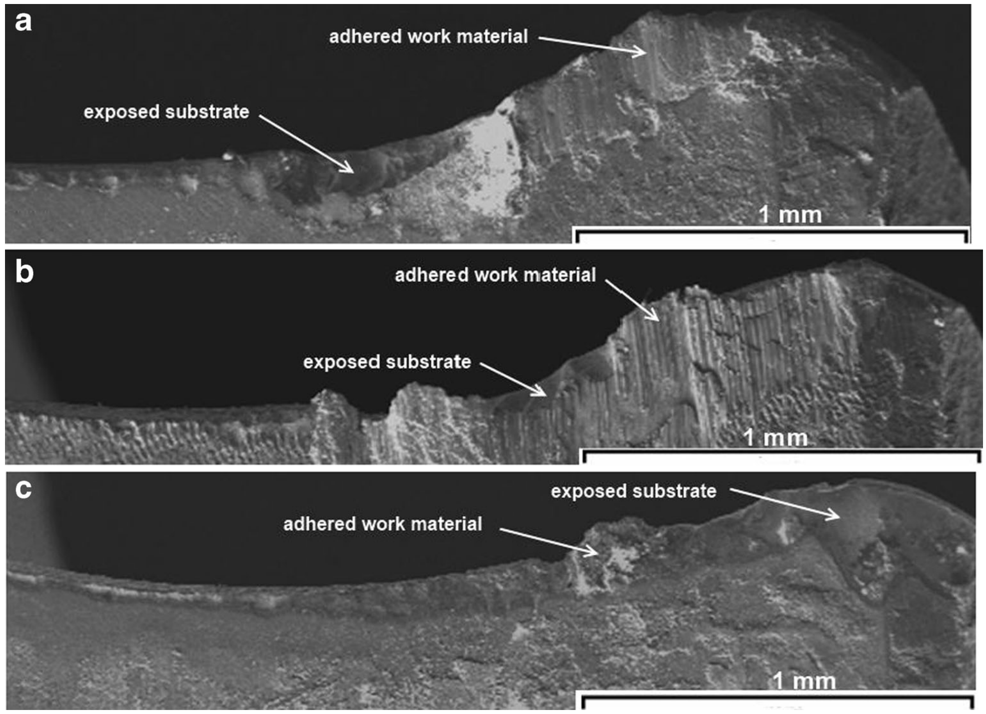

Fig. 9 Flank wear of commercial (**a**), *modified 1* (**b**), and *modified 2* (**c**) surfaces coated with TiAlN and used with v_c=114 m min^{-1}

parameters for the *modified 2* surfaces. This result indicates that the tool surface has to have low roughness values to achieve a long tool life. Again, the residual stress values of the coating–substrate interface proved that the stress at this interface is not a good indicator of tool wear performance as the two best-performing tools had opposite residual stresses (see Fig. 6b).

In the drills coated with TiAlCrSiN, both adhered work material and exposed substrate were observed on the three surfaces (Fig. 12). On the commercial and *modified 2* surfaces, chipping was identified at the end of the test. The results obtained with this kind of tool (polished and TiAlCrSiN-coated) corroborate the findings of the tests with the other tools, i.e., that the tool surface must have low roughness

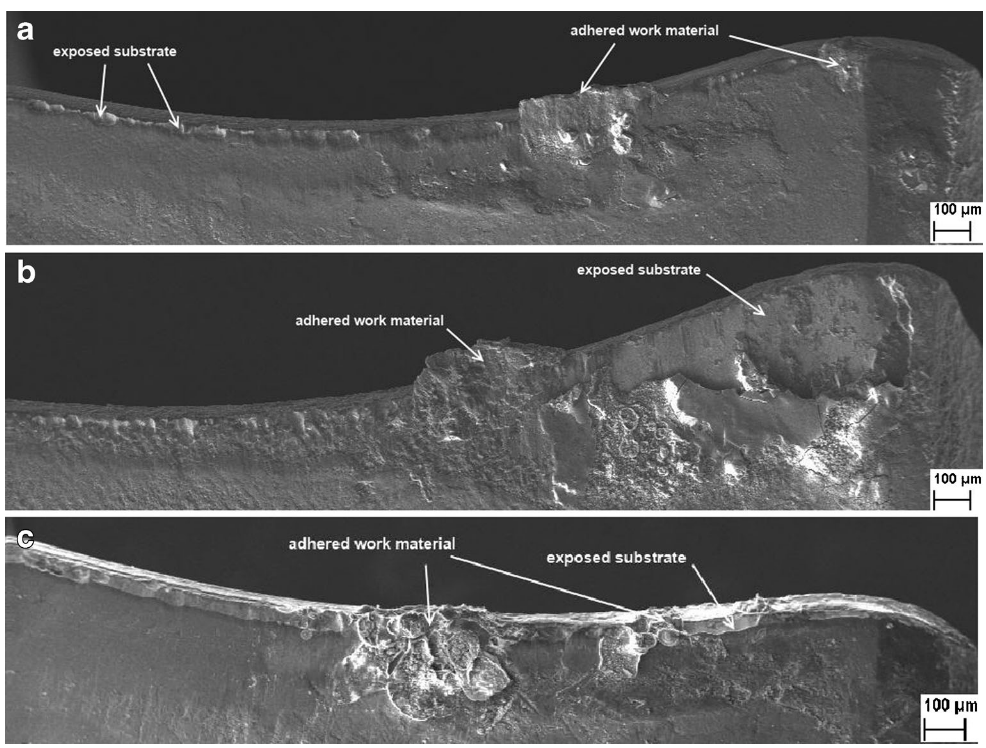

Fig. 10 Flank wear of commercial (**a**), *modified 1* (**b**), and *modified 2* (**c**) surfaces coated with TiAlCrSiN and used with v_c=114 m min^{-1}

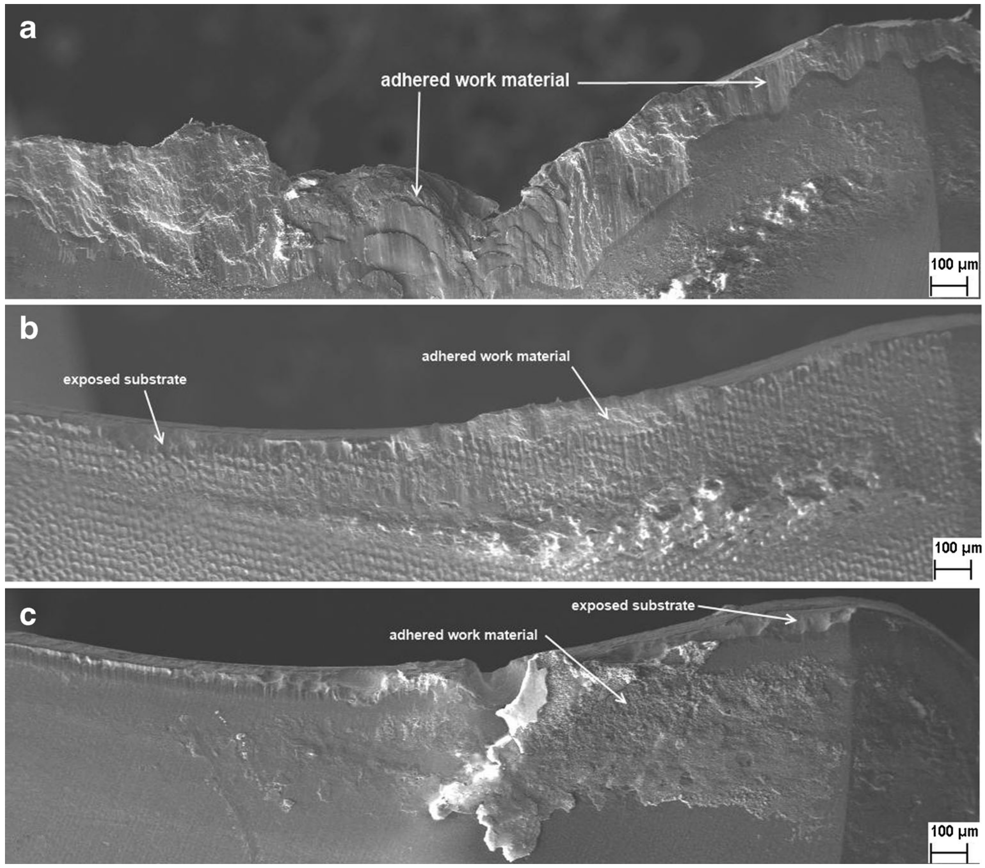

Fig. 11 Flank wear of commercial (**a**), *modified 1* (**b**), and *modified 2* (**c**) surfaces coated with TiAlN and used with v_c= 137 m min^{-1}

values and that the residual stress condition is not important for wear to occur.

Based on these results it can be concluded that residual stress does not provide exact information about tool performance during a cutting test. According to Denkena et al. [5], compressive residual stress supposedly provides longer tool life. Our results prove that this is not true as good wear performance was observed in tools with compressive residual stress (commercial) and in those with tensile stress (*modified 1*). It is clear from the results that the surface roughness parameters of these tools cannot be as high as those of the *modified 2* surface as this tool always had the worst wear performance. For good wear performance, the surface of the tool must be smooth, which equates to a low Rpk.

One question remains to be answered: why do tools with TiAlCrSiN coatings have longer lives than TiAlN-coated tools? As TiAlN is harder than TiAlCrSiN and TiAlCrSiN resists higher temperatures than TiAlN (higher maximum service temperature), the question arises as to which property is more important for tool performance and whether there is any other surface characteristic that could also influence tool wear. In an attempt to answer these questions, we first carry out an analysis of the residual stress. This parameter does not depend on the kind of coating used as compressive stress and tensile stress were observed at the coating–substrate interface of TiAlCrSiN and TiAlN coatings (Fig. 6). Instead, as already mentioned, residual stress actually depends on the characteristics of the substrate surface. Looking at the roughness parameters, it can be seen that they are not affected by the type of coating. Depending on the parameter used, the TiAlCrSiN coating can sometimes be smoother and at other times rougher. This is also true for the Rpk parameter, which was identified as the most important parameter to reduce the impact of the attrition mechanism. Therefore, it must be assumed that TiAlCrSiN coatings resulted in longer tool lives than TiAlN coatings because of their higher maximum service temperature, which helps these tools to keep their characteristics at higher temperatures and, consequently, to slow down the removal of particles typical of attrition.

3.5 Analysis of the interaction between the results

Many studies of coating behavior have been carried out in an attempt to understand the wear performance of coatings [3, 6, 7, 9, 24]. The formation of oxides during service is one issue that has been studied in recent times [9, 24, 25]. The thermal stability of tribofilms is highly dependent on deposition method and parameters that affect their crystallinity, composition, stoichiometry, thickness, surface roughness, grain size, and orientation [24].

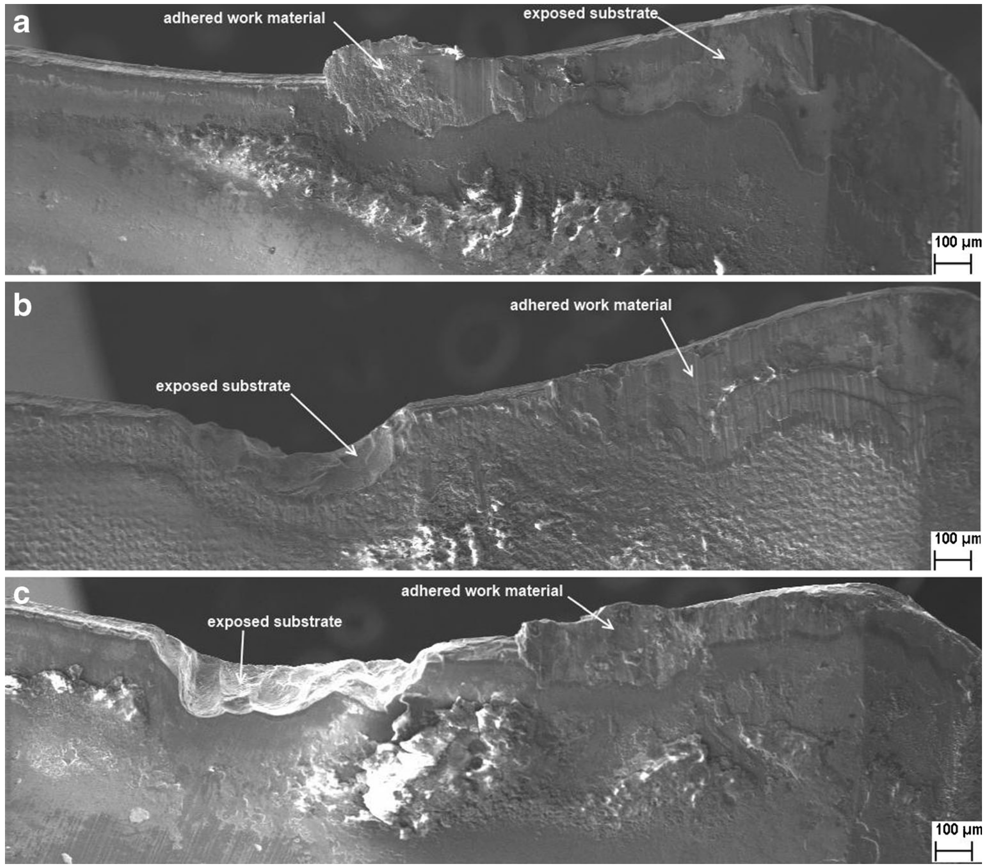

Fig. 12 Flank wear of commercial (**a**), *modified 1* (**b**), and *modified 2* (**c**) surfaces coated with TiAlCrSiN and used with v_c=137 m min^{-1} (polished drills)

Studies of TiAlCrSiN coatings have shown that this type of film oxidizes faster than CrN films, mainly because of the presence of Ti, and oxidizes more slowly than TiN films because of the presence of Al, Cr, and Si. It has also been reported that Al, Cr, and Si form Cr_2O_3, Al_2O_3, and SiO_2, respectively, which are extremely protective, while Ti forms semi-protective TiO_2 [24, 26].

One work that brought together the results of studies into the formation of oxides on tools during the machining of difficult-to-cut materials showed that depending on the type of coating and cutting conditions, various types of oxides can be formed [25]. In coatings such as TiAlCrSiYN/TiAlCrN and TiAlCrSiN, refractory compounds like sapphire (Al_2O_3) and mullite (Al–Si–O) can form simultaneously, affording excellent protection of the surface under severe frictional conditions (with increasing cutting speeds). Both materials, especially sapphire, have an excellent ability to accumulate energy from external impact, which leads to reduced entropy production during friction. Being chemically stable materials, they reduce adhesive interactions at the workpiece/tool interface and, therefore, heat generation during cutting. This could shift the friction to a much milder mode, significantly reducing the wear rate. If the tribological conditions are not very severe (moderate cutting speed) then a less protective alpha-alumina phase is formed on the friction surface instead of sapphire [25].

Based on the literature and the results of the present study, it is reasonable to suppose that the longer life of the TiAlCrSiN-coated drill is probably due to the formation of oxides. The substrate coated with TiAlCrSiN has a tendency to form protective (Cr_2O_3, Al_2O_3, and SiO_2) and semi-protective (TiO_2) oxides and consequently may have lower friction, reducing the wear rate. In contrast, TiAlN films form more TiO_2 than Al_2O_3, which, because of its high stoichiometry, grows very slowly [24]. In other words, the higher maximum service temperature already cited in this work may be related to the temperature at which these oxides are formed. It is very likely that at the temperatures the tools reached in this work, the TiAlCrSiN coating formed protective oxides, while the oxides formed on the TiAlN coatings were not as protective.

Surface roughness also affects the formation of the films. If the oxide forms but the surface does not provide the necessary conditions for it to grow and adhere, the oxide will not protect the surface. This is probably what happened in the *modified 2* substrate as it had the highest roughness parameters, impairing the adhesion and growth of oxides on the worn surface. The high peaks in the roughness profiles of the tools with this substrate are easily removed by the relative movement of the tool and workpiece even if protective oxides are present.

When cutting speed of 114 m min^{-1} and TiAlN coating were used, the commercial drill had the best performance.

This may be associated with the lower Rpk value for the commercial drill, as already mentioned. The worse performance of the modified drills under these conditions can be attributed to two factors: the Rpk value and the way the wear occurs in the TiAlN films. A study comparing the tribological behaviors of AlCrN and TiAlN coatings showed that when TiAlN coatings were tested in reciprocating sliding tests, a large area of debris layer was formed, which was the main degradation phenomenon. Furthermore, it was difficult to remove this debris from the wear land [27]. In the modified drills, this debris probably formed in greater quantities because of the higher Rpk value. In these drills the wear occurred quickly in the first stages of the experiments. However, the performance of the *modified 1* and *modified 2* tools coated with TiAlCrSiN for v_c=114 m min^{-1} was not the same (the commercial and *modified 1* tools had the best performance), probably because of the different way the wear occurred and the Rpk value of the *modified 1* drill. The Rpk values for the commercial and *modified 1* tools were similar and about half the corresponding figure for the *modified 2* drill.

With regard to the residual stress, the substrate with compressive residual stress did not always have the best performance. While the commercial substrate coated with TiAlCrSiN had the highest compressive residual stress and the longest life, the *modified 1* drill coated with the same coating presented tensile residual stress and the same tool life for a cutting speed v_c=114 m min^{-1}. Similarly, the TiAlN-coated *modified 1* substrate (tensile residual stress) had a similar tool life to that of the commercial substrate coated with the same material (compressive residual stress) for a cutting speed v_c=137 m min^{-1}. From these results, it can be concluded that tensile residual stress does not always decrease tool life. Instead, the type of coating and the roughness of both substrate and coating can be more important than residual stress for tool wear performance.

4 Conclusions

The use of coatings with different roughness parameters can give tools different performance characteristics. In this study, surfaces with a low Rpk generally had a longer tool life than those with a high Rpk. Tools on which the coating formed adherent, protective oxides also had a longer tool life. Hence, for a tool surface to have good performance during machining, it must have a low Rpk to provide the necessary conditions for the formation of oxides and delay the attrition wear mechanism, thereby prolonging tool life.

Tools with TiAlCrSiN coating presented longer tool lives than those with TiAlN coating due to the protective oxides formed on those tools which allow it to support higher service temperatures during the cutting. High surface roughness parameters of the coatings impair the adhesion and growth of oxides on the worn surface and, consequently, contributes to decrease tool life.

Tool life was not influenced by residual stress at the coating–substrate interface. Long tool lives were obtained with both, compressive and tensile residual stresses.

Attrition was the main wear mechanism for the tools used in the experiments of this work.

Based on our findings, the most appropriate surface for machining forged AISI 1548 steel is the commercial substrate coated with TiAlCrSiN, which had the best performance with and without polishing of the coated surface.

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