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ORIGINAL ARTICLE

Tool wear analysis in the machining of hardened steels

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Abstract The machinability of a material can be assessed using many output parameters of the machining process, tool life being undoubtedly the most common. Tool life depends mainly on the tool wear rate, which in turn is very dependent on the prevailing wear mechanisms. It is therefore very important to study and analyze correctly the possible wear mechanisms on the rake and flank faces of the tool. When machining materials with high hardness, usually over 35 HRC, the difficulties are enormous because of the high cutting forces and heat generated, causing rapid tool wear and short tool life. When the hardness exceeds 45 HRC, the difficulties are even worse because the chips change from continuous to serrated types formed by localized shearing, increasing forces and temperatures even further. To tackle these adversities, ceramic and ultra-hard (CBN) tool materials are normally used, although other materials are also suitable. In interrupted cutting, for example, cemented carbides are frequently used. Wear mechanism analysis in hard machining is thus of particular importance. This article analyzes the tool wear mechanisms that occur in the machining of several hardened steels during continuous and interrupted cutting. All the analyses were performed after the tools have reached the stipulated end of the tool life criteria. Different types of tool material, such as cubic boron nitride, ceramics, and PVD-coated carbide inserts applied in turning and milling operations had their wear mechanisms analyzed. The main goal of this work was not to compare the tool lives of the conditions tried but to provide a greater understanding of tool wear phenomena and thus contribute to the development of tools with improved properties. Most of the worn tools had their wear region analyzed using a scanning electronic microscope (SEM) with the help of energy dispersive spectroscopy (EDS) technique. The wear analysis performed using the pictures taken in the SEM/EDS system was based on the main literature of this field of knowledge.

Keywords Machining of hardened steels · Tool wear mechanisms · Continuous and interrupted cuttings · CBN, ceramic, and cemented carbide tools

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1 Introduction

Cutting tools usually wear because they are in contact with the chip and workpiece. They can also suffer damages to the cutting edges. The main wear/damage mechanisms are attrition, diffusion, abrasion, chipping, cracks, and breakage caused by shocks between workpiece and tool cutting edge and thermal and mechanical variations at the tool tip [1].

Attrition wear can be defined as the cyclical adhesion of workpiece/chip material to, and removal of particles from, the tool. During this process, microscopic tool particles are torn from the tool and dragged along with the flow of the work material. According to Trent and Wright [2], attrition usually occurs at low cutting speeds, but Diniz et al. [3] observed attrition when machining AISI 1045 steel even at high cutting speeds (490 and 570 m/min). Other conditions for attrition to occur are irregular material flow on the tool face and intermittent contact between workpiece/chip and tool. These conditions are common in interrupted cutting and in operations with depth of cut variation, with a sliding zone between chip and tool and where vibration between tool and workpiece occurs. Attrition is also an important wear mechanism when machining with a built-up edge (BUE) [2]. When attrition is responsible for tool wear, the worn area has a rough appearance [1, 2, 4].

Diffusion wear in machining involves the transfer of atoms between tool and chip/workpiece [4]. It depends on the cutting temperature (it is unlikely to occur at low cutting speeds), chemical affinity between the elements involved in the shear zones, and contact time [5]. Although tool and chip/workpiece are normally in contact for only a short time, making diffusion unlikely, seizure can occur on the rake face between chip and tool and sometimes between workpiece and tool on the flank face. This seizure increases the contact time and temperature (because of material shearing in the seizure zone). Diffusion can therefore in fact become the most important wear mechanism at high cutting speeds. As the seizure zone is renewed periodically, constant diffusive flow is guaranteed.

The main mechanism responsible for crater wear is diffusion, as it is on the tool rake face that seizure is more prone to occur. However, although the cutting pressure on the tool flank face is not high, seizure can also occur on this face after some wear has occurred. Diffusion can therefore also contribute to tool flank wear. As diffusion wear is dependent on tool temperature, it increases with increasing cutting speed. Because it occurs at the atomic level, the worn areas have a smooth appearance [1, 2, 4, 6].

Abrasion is caused by scratching of a hard particle against a surface and is therefore stimulated when the workpiece material contains particles, such as carbides, nitrides, and oxides [2]. It can cause flank and crater wear but has a greater influence on the former as the tool flank face rubs against the rigid workpiece, while the rake face rubs against the flexible chips. An adhesion zone usually forms on the rake face, and the absence of relative movement between chip and tool prevents abrasion [7]. However, when abrasion cannot be avoided, a very hard tool must be used in order to minimize its action. The wear land when abrasion is present generally has scratches or ridges parallel to the cutting direction [1].

The cyclical variation in temperature commonly found in interrupted cutting generates thermal stresses, which may develop thermal cracks. These in turn can cause tool fracture if the tool material has low toughness [7]. Milling is an interrupted cutting operation and consequently subjects the tool to thermal shocks in each revolution. The fast heating when the tool is cutting and fast cooling when it is idle in each revolution can cause large and variable temperature differences between the surface and the bulk of the insert. This variation in temperature inside the tool causes alternating expansion and contraction of the surface layers of the tool, leading to thermal fatigue, which results in cracks perpendicular to the cutting edge [2]. If the number of these cracks increases, the cutting edge may chip or occasionally break away [7]. This is why dry cutting is used in milling, as if a water-based cutting fluid were used, the variation in temperature would increase, stimulating the formation of thermal cracks.

As the tool cutting edge enters and exits the workpiece in each revolution, it is subjected to frequent mechanical shocks, which are another cause of cracks, chipping, and cutting-edge breakage in milling operations. Milling tools must therefore be sufficiently tough and have a rigid cutting edge. Moreover, the tool position in relation to the workpiece must be chosen to make these shocks less damaging to the tool [6]. As the shocks generated when milling hardened material are very intense and can cause substantial damage, it is important to increase the tool's resistance to these shocks. This can be done by using double-negative tool geometry (negative axial and radial angles), although a positive-negative geometry (positive axial angle and negative radial angle) can also be used [8].

Chipping of the cutting edge in milling operations can also occur when the insert leaves the cut in each revolution. Pekelharing [9] observed that the primary shear plane rotates and becomes negative as the insert approaches the exit edge of the workpiece in each revolution. This phenomenon causes a change in chip velocity and produces stresses along the contact length between the tool rake face and the chip. Consequently, the stress condition in the tool alternates frequently between compressive and tensile stress. This phenomenon leads to tool chipping and breakage when the tool is not sufficiently tough. To minimize this, the angle between the cutting edge and workpiece when the edge is leaving the cut must be correctly chosen. Large negative (Fig. 1a) and positive (Fig. 1c) exit angles help avoiding edge chipping. Exit angles of around 0° (Fig. 1c) promote unfavorable stresses in the cutting edge, as the chip is thick when the tool exits the workpiece.

When machining hardened steels the wear is critical because it progresses fast and condemns the tool very rapid, regardless the tool material used. Wang et al. [10] investigated the wear and damage of cemented carbide tools PVD-coated with TiAlN and TiSiN during high-speed milling of two hardened steels (SKD11/HRC62 and S136/HRC51). They found

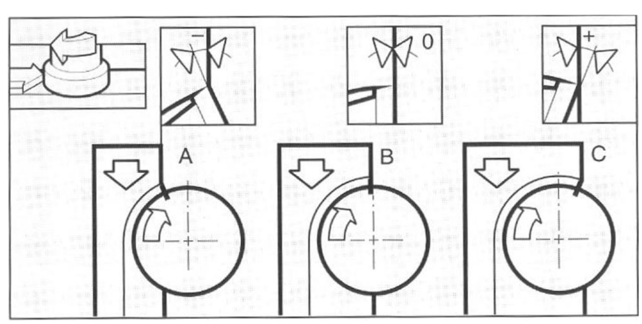


Fig. 1 Relative positions of the cutting edge and workpiece during the exit from the cut [8]

that flank wear, crater wear, breakage, and microchipping were the dominating damaging process that condemned the tools. The breakage process found were coating peeling, chipping, and tip breakage and the main wear mechanism involved in the rake and flank faces was abrasion. The tool coated with TiSiN presented higher resistance to this wear mechanism than TiAlN.

Bronszewski et al. [11] tested Al_2O_3 ceramic tools with addition of Mo (up to 20%) in dry machining of 145CR6steel hardened steel (50HRC). Their main conclusion was that the formation of MoO_3, with structure similar to graphite, helped to lubricate the chip-tool interface and avoid cracking and chipping of the tool.

Barry and Byrne [12] investigated the wear mechanism of mixed ceramic (Al_2O_3 + TiC) in the machining of five heats of BS 817M40 steel (AISI 4340) hardened steel (52 HRC). They found that abrasion was the dominant wear mechanisms developed by different processes. In machining steels containing Ca-bearing mixed oxide inclusions, a reaction of them with the alumina phase of the tool was responsible for the rapid tool wear. In machining steels containing very low levels of Ca, superficial plastic deformation of the tool surface was responsible for the wear in a process very dependent on the amount of carbide content of the work material. These authors also tested CBN/TiC tools in the machining of three heat of the same work material [13]. In this case, they found that the dominant wear mechanism had chemical nature and the amount of Al and S in the workpiece material is related to the wear rate.

This article presents analyses of the wear mechanisms that occur in the machining of different hardened steels. The designed tests, including the machining parameters used, are common situation encountered in the shop floors of mold and die manufacturers. The analyses were always conducted after the tools have reached the stipulated end of tool life criteria in each test. It seeks to provide a greater understanding of tool wear, thus contributing to the development of new tools with improved properties to tackle the challenge of machining hardened steels.

2 Analysis of tool wear mechanisms

The analyses of tool wear mechanisms that will be presented in this paper are compilation of several tests carried out by the authors in their respective universities in the last decade. They are machinability tests and most of them consider tool lives, cutting forces, cutting temperature, power consumption, surface roughness, and chip morphology. Full details of these research works can be found in the references cited when each analysis is described.

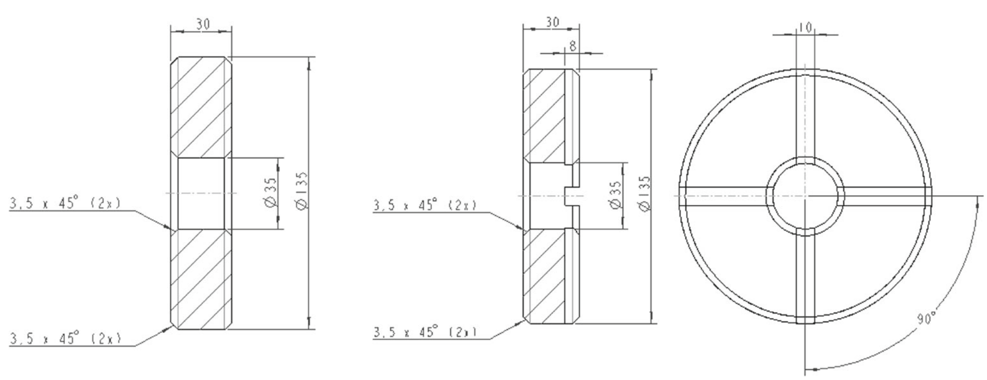
2.1 Turning of hardened steels

Turning is frequently used instead of grinding because of, among other factors, the availability of very hard tool materials such as cubic boron nitride (CBN) and ceramics [14]. These materials are very suitable for turning hardened steels as they have higher hot hardness and wear resistance than the coated cemented carbide tools generally used for turning unquenched and untempered steels. Therefore, they can resist the high thermal and mechanical loads generated in these machining operations.

The key properties of CBN are (i) high hardness at low and high temperatures, (ii) high thermal conductivity, and (iii) low thermal expansion coefficient. The properties of ceramic tools that make them suitable for turning hardened steel are (i) high hot hardness (although not as high as that of CBN), (ii) good wear resistance, and (ii) high chemical stability in the presence of iron (higher than that of CBN) [15].

De Godoy and Diniz [16] carried out turning experiments on 56 HRC AISI 4340 steel using two types of workpieces designed for continuous (Fig. 2a) and interrupted (Fig. 2b) cutting during radial turning.

Two kinds of CBNs and two kinds of ceramics were used as tool materials. The first was a grade with low CBN content and an added ceramic phase (called CBN-L). The second was a grade with higher CBN content and no added ceramic phase, referred to as CBN-H [17]. The third tool material was an alumina-based mixed ceramic (Al_2O_3 + TiN) and the fourth a SiC whisker-reinforced ceramic. All these tool materials are



(a) (b)

Fig. 2 Workpiece for **a** Continuous cutting; **b** Interrupted cutting recommended for machining hardened steel in finishing operations. Two of them (CBN-H and the SiC whisker ceramic) are recommended for interrupted cutting and were therefore used in the experiments with the workpiece shown in Fig. 2b, while the other two (CBN-L and the mixed ceramic) are recommended for continuous cutting and were used in the experiments with the workpiece shown in Fig. 2a. Depth of cut (a_p) and feed rate (f) were kept constant in all experiments (a_p = 0.15 mm and f = 0.08 mm/rev). Cutting speed was 150 and 270 m/min for the continuous cutting experiments and 150 and 195 m/min for interrupted cutting.

Figure 3 shows photos of the worn edges of the tools used in the continuous cutting operations.

The main wear mechanism in the ceramic tool at both cutting speeds was abrasion, indicated by the thin scratches parallel to the cutting direction in Fig. 3a, c. The high chemical stability of the ceramics prevented the occurrence of diffusion, and the lower hot hardness of the mixed ceramic made abrasion possible. EDS (energy dispersive spectroscopy) analysis failed to reveal iron atoms in the ceramic wear lands, indicating that the diffusion and attrition did not occur. The scratches seen in the figures were caused by abrasion. Possible explanations for the abrasion were (i) it was caused by hard workpiece particles being scratched with the tool and (ii) the friction between the tool and workpiece removed the binder from the tool (which is much softer than the ceramic phase), and consequently, the hard particles were removed and abraded the tool, producing the scratches.

When the CBN-L tool was used with a cutting speed of 150 m/min (Fig. 3b), abrasive scratches occurred together with some smooth regions, indicating that the wear also occurred because of diffusion. The CBN-L tool was made of CBN and an added ceramic phase that decreases the material's thermal conductivity and increases its chemical stability in the presence of Fe. At low cutting speeds, abrasion was the main wear mechanism although diffusion also occurred. However, when the cutting speed was increased to 270 m/min, the tool temperature also increased and the diffusion resistance of the tool was consequently insufficient to avoid flank wear caused by this mechanism. The severe crater wear shown in Fig. 3d is another hint that diffusion occurred, as this phenomenon is often the main cause of wear on the tool rake face. These findings can be observed in Fig. 3d, where the smooth flank and rake wear lands suggest diffusion. EDS analysis of several points on the wear land showed small amounts of Fe (maximum 12%), which was only present in the workpiece, indicating that it had reached the tool in a diffusive process. If more Fe together with layers of workpiece material were present on the tool, adhesion of the workpiece/chip material would very likely have occurred, but this was not the case. Therefore, it can be concluded that the presence of Fe on the tool indicates that diffusion was the main wear mechanism for this tool.

The only experiment where pull-out of macroscopic particles (Fig. 3d) occurred was the one in which a cutting speed of 270 m/min and the CBN-L tool were used. At this speed, the tool reaches higher temperatures, which probably caused the decrease in the tool binder resistance and consequent loss of cohesion between the binder and the CBN, allowing the large amount of tool material shown in Fig. 3d to be removed. However, abrasive scratches that could be caused by friction of these removed macroparticles against the workpiece cannot be observed in Fig. 3d. This can be explained by the fact that

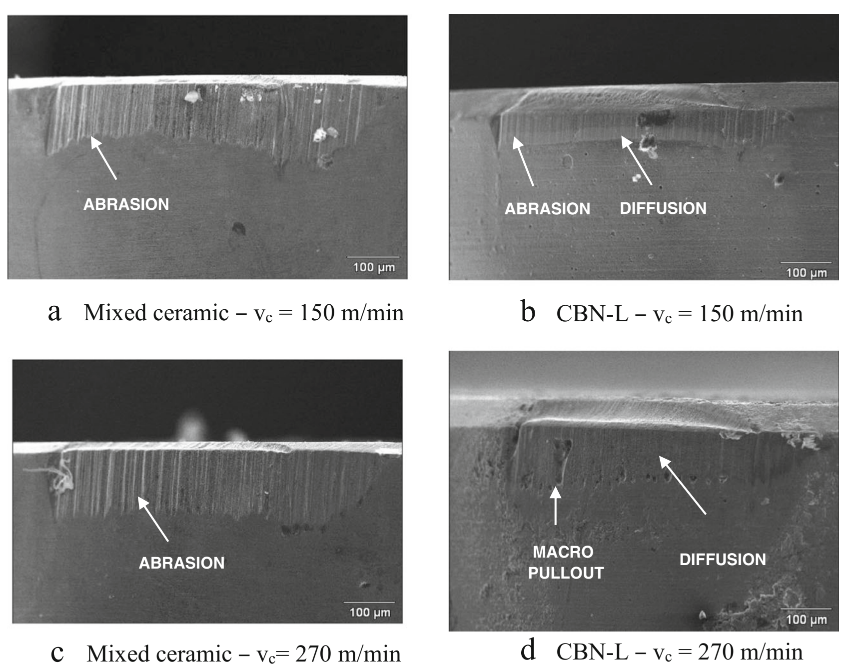


Fig. 3 **a**–**d** Scanning electron microscope images of the worn tool flank faces used in the continuous cutting experiments

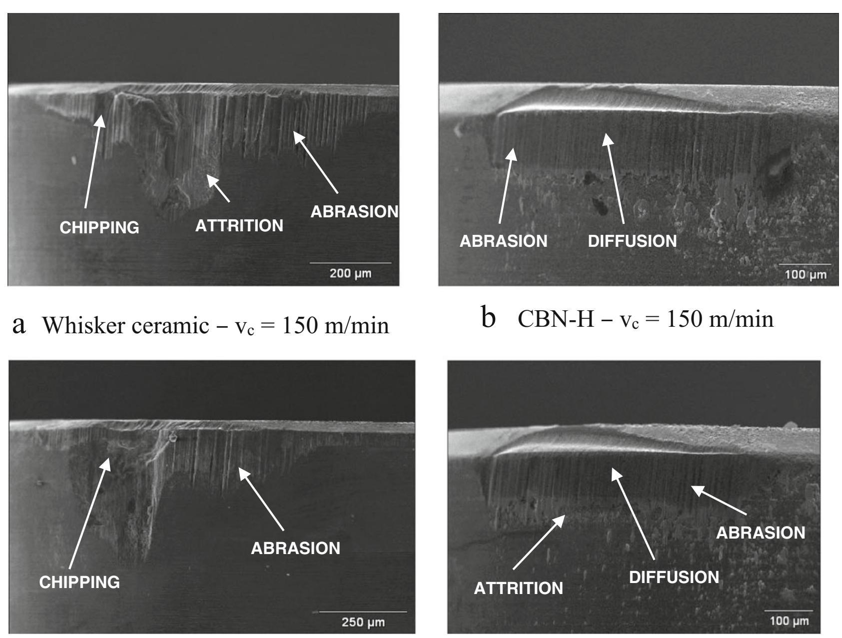
these particles were removed close to the end of the worn area, i.e., close to the end of the tool-workpiece contact.

Interestingly, the tools made with CBN-L had longer lives for both cutting speeds tested. This fact indicates that with this material both, the abrasive wear at low cutting speeds and diffusion wear at high cutting speeds involved slower mechanisms than the abrasive wear when the mixed ceramic was used. Based on these results, it can be concluded that, in order to improve even more the suitability of using CBN-L material in the turning of hardened steel of continuous surfaces, it is necessary to improve its chemical stability with iron (in order to either avoid or minimize diffusion [2]) and increase the tool binder resistance at high temperature.

Many turned surfaces in real industrial applications require interrupted cutting, which could cause tool chipping and breakage when materials with high hardness are machined. De Godoy and Diniz [16] therefore also carried out turning experiments on interrupted surfaces, as cited before.

Figure 4 shows images of the edges used in the interrupted cutting experiments. The images show that the whisker-reinforced ceramic tool exhibited chipping of the cutting edge in all the experiments (Fig. 4a, c). Abrasive scratches were also present on the worn lands of the ceramic tools used. When the cutting speed was 195 m/min (Fig. 4c), the EDS analysis failed to reveal any Fe from the chip/workpiece material outside the chipped region, indicating that attrition did not occur and was therefore not the cause of chipping. Figure 4c also shows that the chipping of the cutting edge was not caused by thermal stress, as there are no cracks perpendicular to the cutting edge, a typical feature of this type of failure. All the cutting was performed on the curved portion of the cutting edge since the depth of cut was smaller than the tool nose radius. Consequently, the chip thickness varied from zero at the tool tip to the maximum value at the end of the depth of cut. As can be seen in Fig. 4a, c, chipping occurred in the region of the tool where the chip was thickest, leading to the conclusion that the chipping was probably caused by mechanical shocks against the workpiece. The abrasive scratches seen in Fig. 4c (cutting speed of 195 m/min) again may have two causes: (i) scratching of the tool flank face by hard workpiece particles; (ii) removal of the tool binder as a result of friction of the workpiece against the tool, causing hard particles to be removed from and rub against the tool and so producing abrasive wear. The first hypothesis is more likely, since the cutting interruptions did not allow the tool temperature to increase to the point that the binder resistance was affected, thus avoiding hard particles being removed from the tool.

When the cutting speed was 150 m/min (Fig. 4a), EDS analysis revealed the presence of Fe inside the abrasive scratches in the ceramic tool, indicating that attrition was the main cause of this abrasion process. Attrition removed tool particles, which were then pushed by the movement between workpiece and tool, generating friction in the process, unlike what occurred when the cutting speed was 195 m/min. According to Trent and Wright [2], attrition occurs more easily at moderate cutting speeds. The fact that attrition is involved in flank wear when turning workpieces with high hardness proves that even a material without high ductility can be extruded between cutting edge and workpiece surface and sticks to the flank face. However, this happens without a thick layer of adhered material forming, as usually occurs when machining soft steels [3].



a Whisker ceramic – v_c = 150 m/min

b CBN-H – v_c = 150 m/min

c Whisker ceramic – v_c = 195 m/min

d CBN -H – v_c = 195 m/min

Fig. 4 **a**–**d** Scanning electronic microscope images of the cutting edges used in interrupted cutting

When the CBN-H tools were used (Fig. 4b, d), the tool rake face was smooth, indicating that diffusion was the cause of crater wear at both cutting speeds. The whisker-reinforced ceramic tool had higher chemical stability in the presence of iron than its CBN-H counterpart and therefore exhibited less crater wear than it (visual inspection). When the CBN-H tool was used, EDS analysis showed the presence of Fe in the lower edge of the flank wear region at both cutting speeds, indicating that attrition was the main wear mechanism in these experiments. Removal of hard particles from the tool by attrition probably caused abrasion, which can be seen by the abrasive scratches in Fig. 4b, d. Attrition in turn may have been stimulated by the low cohesion between CBN and its binder. Diffusion also played an important role in this wear, since some wear regions had a smooth appearance.

No chipping occurred on the CBN-H cutting edges even after 100 min of cutting, and consequently, this proves that CBN-H is sufficiently tough and can be used in a tool designed for this kind of cutting. Again, the CBN-H tools had longer tool lives than the whisker-reinforced ceramic tools (more than twice as long at both cutting speeds), proving that the wear mechanisms in the former (attrition and diffusion) were slower than the chipping process and wear mechanisms (abrasion and attrition) in the latter. Based on these results, it can be concluded that, in order to improve even more the suitability of using CBN-H material in the turning of hardened steel of interrupted surfaces, it is necessary to improve its chemical stability with iron (in order to either avoid or minimize diffusion) and to decrease the friction coefficient of the material (in order to minimize the adhesion of the material on the tool which precedes attrition) [2].

Oliveira and Diniz [18] also carried out turning experiments with hardened steel (56 HRC AISI 4340 steel) in continuous, semi-interrupted, and interrupted cutting. What they called continuous and semi-interrupted cutting was radial turning of workpieces with geometries like those shown in Fig. 5. The workpiece geometry for what they called interrupted cutting is shown in Fig. 6. They compared two grades of CBN: CBN-L [low-CBN-content material with a ceramic binder (TiN)] and CBN-H (high-CBN-content material). Tools made with the latter exhibited higher toughness than those with an added ceramic phase (CBN-L) and are, therefore, usually recommended for turning hardened steels with interrupted surfaces. Furthermore, the high CBN content of these tools makes them harder than those with a low CBN content. Essentially, the addition of a ceramic phase to CBN (as in the grade with a low CBN content) reduces its hardness and toughness but increases its chemical stability. This is important in finishing operations on continuous surfaces, where a high temperature is reached and diffusion wear must be avoided [8]. The cutting conditions recommended by the tool manufacturer were cutting speed v_c = 150 m/min, feed f = 0.08 mm/rev, and depth of cut a_p = 0.15 mm.

Figure 7 shows pictures of the worn edges taken in a scanning electronic microscope (SEM). It can be seen in this figure that no chipping or breakage occurred on the cutting edges even when interrupted surfaces were turned, proving that all the tools had sufficient toughness to resist the impacts inherent to the cutting of interrupted surfaces, regardless the tool material used.

Abrasion scratches can be seen in the secondary cutting edge (left side of each image) in almost all the images in

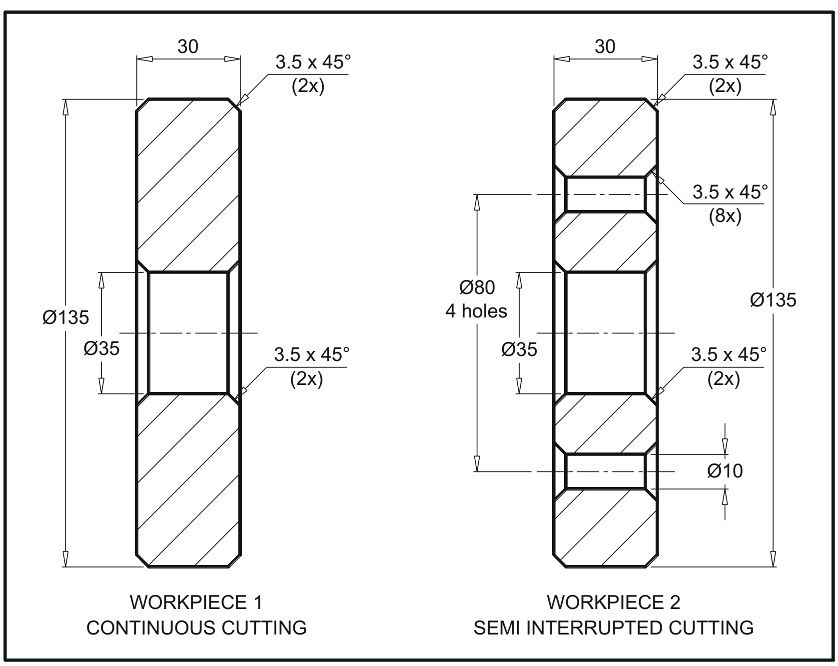


Fig. 5 Workpieces used for continuous and semi-interrupted cutting

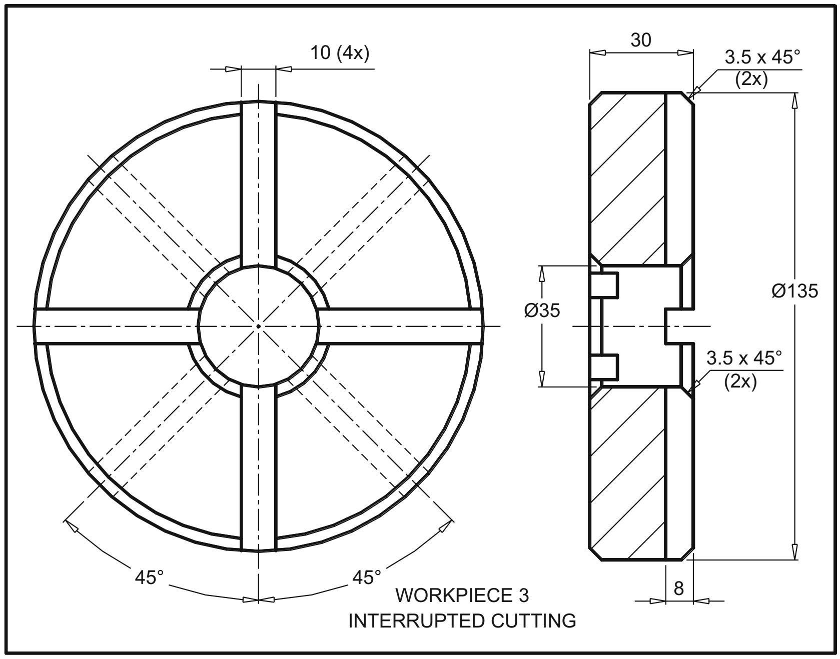


Fig. 6 Workpiece used for interrupted cutting

Fig. 7. This was attributed to the very low chip thickness in the region, which caused chip side-flow and further increased the specific cutting force in that point.

Figure 7 also reveals that abrasive scratches were present not just in the secondary cutting edge but also along all the wear regions when CBN-L tools were used, regardless the workpiece shape. Furthermore, crater wear in CBN-L tools was always smaller than in CBN-H tools. When the latter were used, the abrasive wear mechanism was only important in the interrupted cutting experiments. When continuous and semi-continuous surfaces were turned, the small abrasive scratches were not so clear, and there was substantial crater wear.

As mentioned earlier, the CBN-L tool was made of CBN plus a ceramic phase. This decreases the material's thermal conductivity and increases its chemical stability in the presence of Fe, increasing the tool's resistance to diffusion. As also mentioned earlier, diffusion is the main mechanism responsible for crater wear. In this work, even when continuous surfaces were being turned, resulting in high tool temperatures, crater wear was always small. On the other hand, since the hardness of CBN-L is lower than that of CBN-H, abrasion was the most important wear phenomenon when CBN-L tools were used.

When CBN-H tools were used to turn continuous and semi-interrupted surfaces, the abrasive scratches on the flank face occurred only on the secondary cutting edge (tool tip). On the flank face (the kind of tool wear which led the tools to the end of their lives) just below the main cutting edge the wear was caused by diffusion, as the wear region had a smooth appearance. The low chemical stability and high thermal conductivity of the CBN-H grade made diffusion possible, as the tool temperature was higher and resistance to diffusion lower than in CBN-L tools. Since for the turning of continuous and semi-interrupted surfaces CBN-H life was much shorter than CBN-L life (as it was expected), it is not necessary to make any efforts to improve its properties in order to cut these kind of surfaces. The results reinforced what is recommended by the tool manufacturer—CBN-H cannot be used to cut continuous (and even semi-interrupted) surfaces.

When interrupted surfaces were machined using CBN-H tools, abrasive scratches could be seen in all the wear regions, but these were deeper in the secondary edge region because of the low chip thickness in this region. Diffusion also contributed to flank wear on the main cutting edge. This result shows that, even for interrupted cutting (condition in which CBN-H performed better than CBN-L in terms of tool life), when the tool temperature is not so high, diffusion is important, as it was cited before in this work. Therefore, it is necessary to find a way to increase the CBN-H chemical resistance (as already cited before), without harming its toughness, which is so important to resist to the frequent shocks of this kind of machining [7]. Other point to increase even more the wear resistance would be to increase of CBN-H hot hardness, in order to minimize the occurrence of abrasion, again, without harming toughness.

A comparison of Figs. 3b and 7b, both of which are pictures of CBN-L tools used in continuous cutting of hardened steel at v_c = 150 m/min but are extracted from two different works ([16] and [18]), shows that abrasion is present in both tools but that the abrasive scratches are deeper in the tool used in [18]. Similarly, a comparison of Figs. 4b and 7e, both of which are pictures of CBN-H tools used in interrupted cutting of hardened steel at v_c = 150 m/min but are extracted from the same two different works ([16] and [18]), shows that abrasive

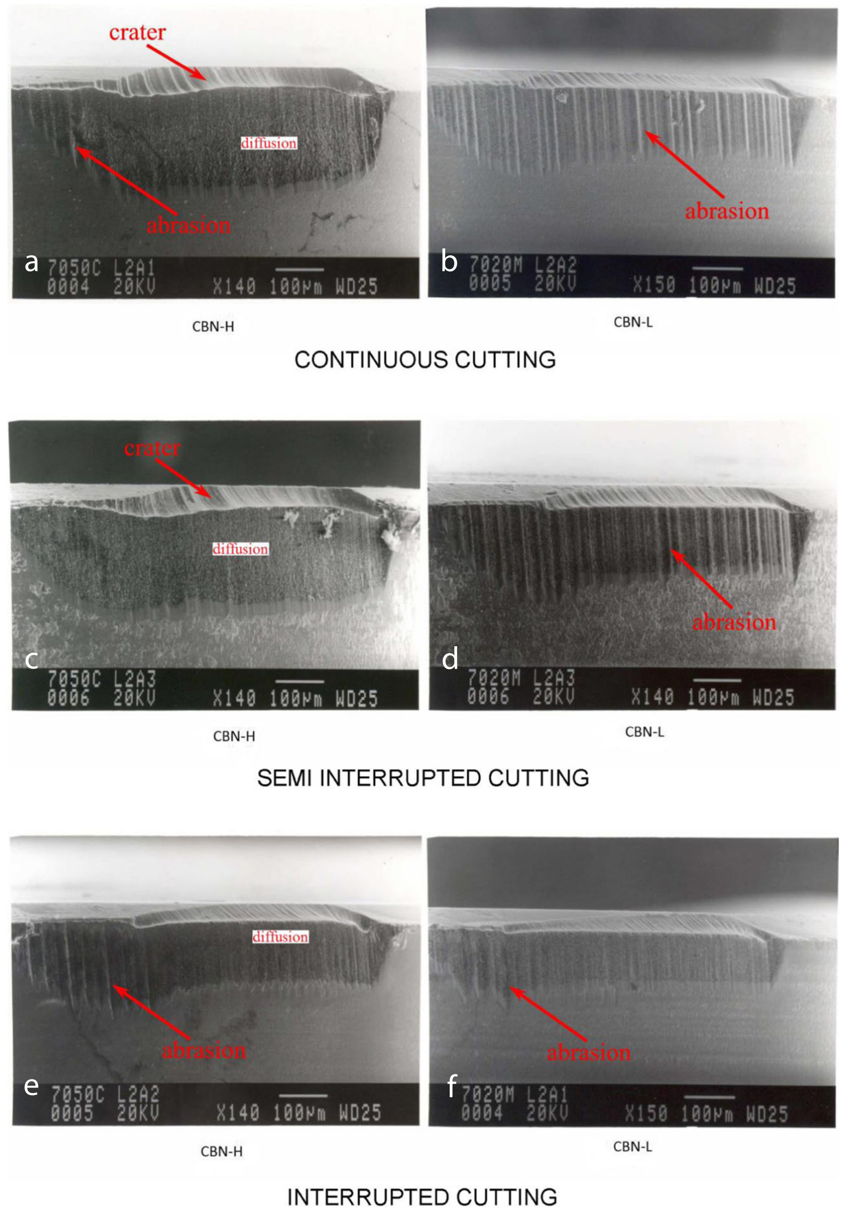


Fig. 7 **a**–**f** View of the worn flank face of the CBN tools

scratches are present in both tools. In the first work [16], since the authors found traces of Fe in the scratches, they supposed that these were caused by attrition. In both works, diffusion also played an important role in tool flank and crater wear when CBN-H was used. Based on the results of these two works, it can be stated for the turning of hardened steels that (a) CBN performed better than ceramic tools (tool life was longer and there was no chipping of the edge even in interrupted cutting); (b) abrasion and diffusion were important wear mechanisms when CBN-L tools were used and so it is necessary to find a way to improve chemical stability and hot hardness of this tool material, as already cited in this work; and (c) diffusion was the most important wear mechanism when CBN-H tools were used in both interrupted and semi-interrupted cutting, but abrasion was also present.

Camargo et al. [19] used polycrystalline boron nitride (PCBN) tools with a low CBN content (50%—CBN-L) and a ceramic binder (TiCN + Al_2O_3) coated with a thin layer of TiN (this coating contrasts with the substrate and helps identify the wear land) in dry machining of AISI D6 hardened steel (60 HRC) under several cutting conditions. They found that the main wear mechanism on the flank face of the tool (this kind of wear determined the end of tool life) was abrasion and on the rake face, attrition. Figure 8 shows the overall view of the worn area of a PCBN tool as an example of what occurred in all the tools tested. On the rake face, workpiece material can be seen to have adhered to the tool, and the rough appearance of the worn area indicates that attrition is the dominant wear mechanism. On the flank surface, the parallel ridges are a clear indication of abrasion. This result reinforces what was already

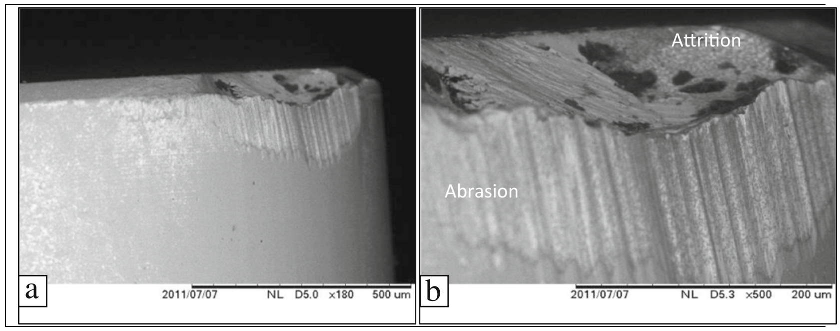


Fig. 8 **a** General view and **b** higher magnification of the worn area of a PCBN tool after machining of AISI D6 steel at v_c = 250 m/min, f = 0.15 mm/rev, and a_p = 0.05 mm

stated in this work: to improve even more performance of CBN-L in the turning of continuous surfaces of hardened steel, it is necessary, among other steps, to increase the tool hot hardness. Moreover, the use of the TiN coating on the CBN material that, besides helping to identify the wear land, could decrease the tool friction coefficient and, consequently, minimize adhesion, in this case it was not efficient enough because adhesion/attrition was an important wear mechanism.

Bonfá [20] used the same workpiece material and cutting tool as Camargo et al. [19] to study the effect of the application of cutting fluid using the minimum quantity of lubrication (MQL) technique. The cutting fluid sprayed was Accu-Lube LB2000, a synthetic plant-based oil manufactured by Rocol – ITW Chemical Products Ltd. A flow rate of 60 mL/h was used. The air jet that conveyed the mist was adjusted to a pressure of 6 bar. The MQL nozzle was directed separately in three different positions (the MQL nozzle was positioned so as to deliver lubricant): (i) overhead, (ii) between the flank face of the tool and the workpiece, and (iii) between the secondary flank face of the tool and the workpiece. The results were compared with those obtained by Camargo et al. [19], which were based on dry cutting. Bonfá [20] showed that the abrasive wear clearly seen on the flank face of tools used in the dry condition (Fig. 8) was significantly reduced when cutting with MQL, regardless the cutting conditions and direction in which the mist was applied. Figure 9 is an example of the wear pattern found in all the tools tested. A large amount of adhered workpiece material can be seen on the tool rake and flank faces. The overall rough appearance of the worn area is an indication that attrition is taking place and dominating the wear. A few parallel ridges are also faintly visible, showing that abrasion was not totally suppressed. In practically all the tool cutting edges chipping can be seen at the end of the tool life, as depicted in Fig. 9.

Following the work carried out by Camargo et al. [19] and Bonfá [20], another (unpublished) study was performed at LEPU (The Machining Research and Teaching Laboratory) at the Federal University of Uberlândia. In this new study, the same work material (60 HRC AISI D6 steel) was turned using the same tool material [PCBN tools with a low CBN content (50%) and a ceramic binder (TiCN + Al_2O_3) coated with a thin layer of TiN, manufactured by Sandvik]. Solid lubricant (MoS_2) dispersed in neat oil and delivered using MQL was tested and compared with the dry condition and pure neat oil also using MQL. The MQL system delivered the oil in spray form through two nozzles, one at the tool rake face (from overhead) and the other at the tool flank face, at a flow rate of 60 mL/h (30 mL/h each nozzle). The air pressure was set at 0.5 MPa (5 bar). The neat oil used was LB2000. A 3^K factorial design was adopted, where, in addition to the three lubrication/cooling conditions (dry, MQL and MQL with solid lubricant), the feed rate (0.05, 0.10, and 0.15 mm/rev) and cutting speed (150, 225, and 300 m/min) were varied between three values. The depth of cut was kept constant at 0.2 mm. Cutting forces, surface roughness, and tool life were the parameters controlled. At the end of the tool life tests, the tools were observed in an SEM to analyze the tool wear mechanisms. Under the least severe cutting conditions (v_c = 150 m/min and f = 0.05 mm/rev), MQL produced the best values of tool life. Pure neat oil resulted in a tool life 29% longer than dry cutting, and neat oil mixed with MoS_2 produced an even longer tool life (18 min), 37% higher than dry cutting.

Figure 10 shows images of the tools used for the least severe cutting conditions tested. Although the tools were

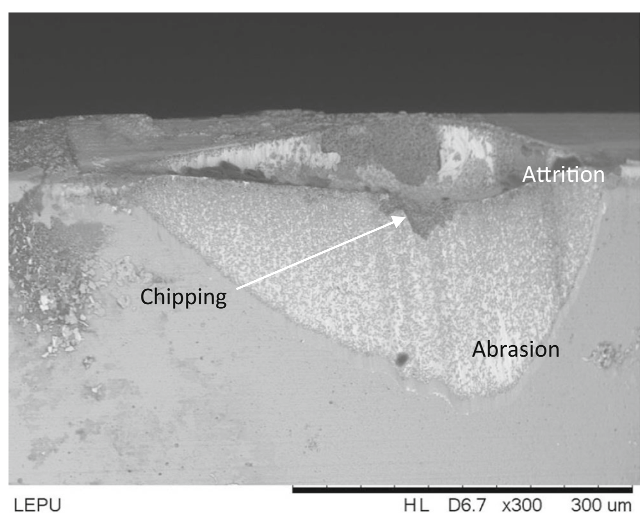


Fig. 9 Tool cutting edge after application of lubricant from an overhead position using MQL; v_c = 340 m/min, f = 0.05 mm/rev, a_p = 0.05 mm

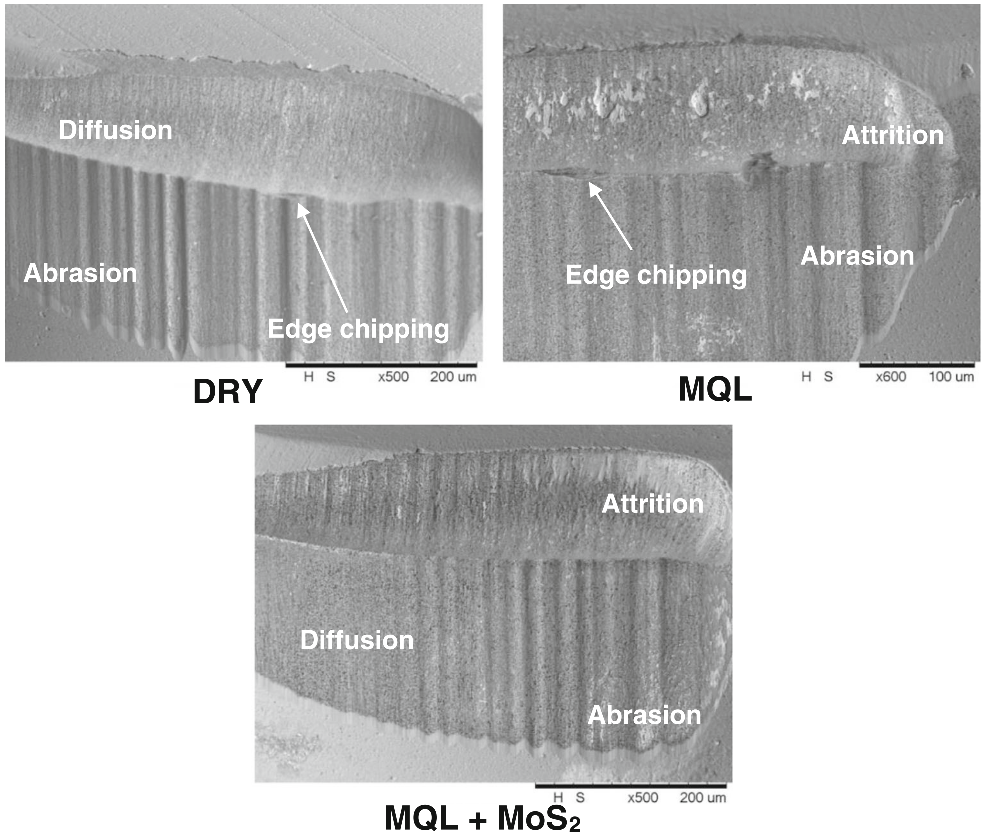


Fig. 10 Tool wear after turning of AISI D6 steel under different lubrication/cooling conditions (v_c = 150 m/min, f = 0.05 mm/rev, a_p = 0.2 mm)

washed in a solution of HNO_3 for 5 min to remove adhered work material from the tool surfaces, this seems not to have been sufficiently long, because there is still some work material adhering to the surface. Crater and flank wear occurred under all lubrication/cooling conditions. On the rake face of the tools, a line can be observed close to the edges of the craters in all the figures. This is because the PVD TiN coating was removed beyond the edge of the crater by the movement of the chip. On the flank, in contrast, the coating wore out smoothly together with the substrate. The presence of adhered work material on the tool surface and the rough appearance of the worn area leads to the conclusion that the crater wear is dominated by attrition when MQL and dry conditions were used. In addition to attrition, diffusion also took place, as some smooth areas can also be observed. Abrasive wear is not discarded, although parallel ridges are only faintly visible. On the flank face the predominant wear mechanism was abrasion, regardless the lubrication/cooling conditions used. However, smooth surfaces were present, indicating that diffusion has also occurred. Diffusion wear is a strongly temperature-dependent mechanism, and when hardened steel is being machined, the temperature is high enough for this wear mechanism to occur, even with MQL. Microchipping can be observed at the cutting edge under dry and MQL conditions, but has been suppressed by the MoS_2 solid lubricant.

Tests at the highest cutting speed of 300 m/min resulted in very short tool lives (maximum 4 min with the smallest feed rate of 0.05 mm/rev using MQL + MoS_2) because the accelerated tool wear always involved microchipping at the tool cutting edge. Figure 11 shows the damage to the tools using a cutting speed of 300 m/min and feed rate of 0.10 mm/rev. This cutting speed is higher than the maximum recommended by the manufacturer (250 m/min).

Results of the research on machining of AISI D6 hardened steel with CBN tools indicate that in addition of improving tool qualities, the application of a lubricating oil by MQL technique (either neat or with addition of solid lubricants—MoS_2) is a positive measure to improve productivity when processing this difficult-to-machine material.

2.2 Milling of hardened steels

Oliveira and Diniz [21] milled inclined surfaces of hardened 50 HRC AISI H13 steel (typically used in the production of dies and molds) under cutting conditions recommended for semi-finishing operations. The experiments were performed under different cutting conditions and with different inclinations between the machined surface and the tool axis. The tool used was a toroidal mill with two circular inserts made of cemented carbide (H15 grade) coated with multiple layers of

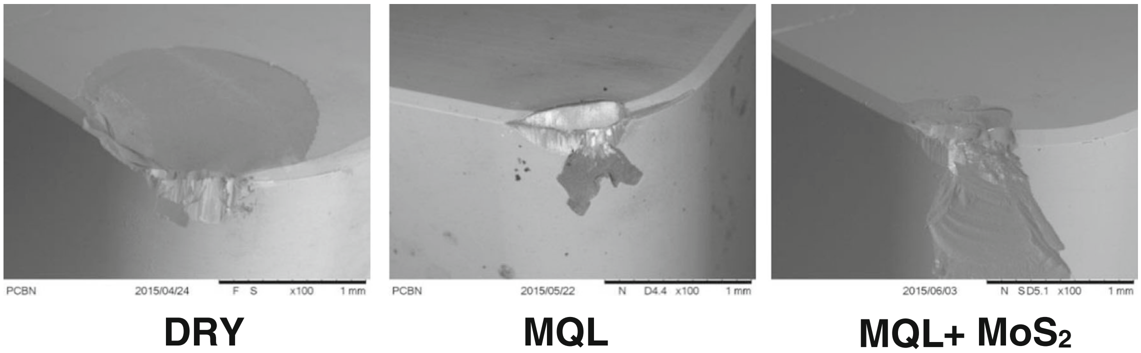


Fig. 11 Damage to the tools tested using a high cutting speed (v_c = 300 m/min, f = 0.10 mm/rev, a_p = 0.5 mm)

TiCN and TiN deposited by PVD. Figure 12 is included as an example of the various images in the work. It shows SEM micrographs of the tool used in the experiment with the following parameters: angle of inclination between the tool axis and a line perpendicular to the machined surface $\alpha = 45°$; feed per tooth, f_z = 0.25 mm; radial depth of cut, a_e = 0.40 mm; cutting speed, v_c = 300 m/min; and axial depth of cut, a_p = 0.25 mm. The image on the right shows the results of an EDS analysis of several points on the flank face.

Figure 12 shows that microchipping (chipping smaller than the maximum flank wear land) and adhesion of workpiece material caused the cutting edge to fail. The EDS analysis in detail A of Fig. 12a shows the presence of Fe and Si from the workpiece material and W from the tool substrate. Microchipping can be seen along the whole cutting edge. In addition to analyzing tool wear at the end of the tool life, the authors checked tool wear throughout the test. At the end of the tool life, the wear mechanisms were analyzed in an SEM. They found that, at first, abrasion removed the tool coating on the portion of the cutting edge that removed chips that were thinner than the cutting edge radius. On the part of the edge that removed thicker chips than the cutting edge radius, attrition and diffusion caused crater wear. As cutting time increased, so the wear in the region where the tool coating had been removed increased, allowing the workpiece/chip material to adhere to the tool in the flank wear region. The workpiece flow dislodged these adhesions, causing large particles of the tool substrate to be removed. In the region of the cutting edge where crater wear was the result of diffusion and attrition, the increase in crater size weakened the tool edge, leading to microchipping at the cutting edge. The authors concluded that neither mechanical nor thermal fatigue caused microchipping, since no cracks were seen on the cutting edges. They also concluded that the chippings and microchippings seen in Fig. 12 were caused by adhesion/attrition on one side of the cutting edge and by attrition and diffusion on the other. Furthermore, they noted that seemingly unlikely events can occur, including (i) wear caused by diffusion when milling this kind of surface, as the contact angle between cutting edge and workpiece is very small and the contact time in each tool rotation is therefore short; (ii) massive adhesion/attrition when machining material with low ductility such as hardened steel. Based on these results, it can be concluded that it is necessary, for this kind of operation, to use a harder tool, to avoid the early removal of tool coating and, consequently, adhesion/attrition and also with higher chemical stability in order to minimize diffusion. Of course, the improvement of these properties cannot be accompanied by the decrease of toughness, since this property is necessary to withstand the frequent shocks typical of milling operation.

Fig. 12 SEM images of the flank wear land at the end of the tool life (f_z = 0.25 mm, a_e = 0.40 mm, $\alpha = 45°$)

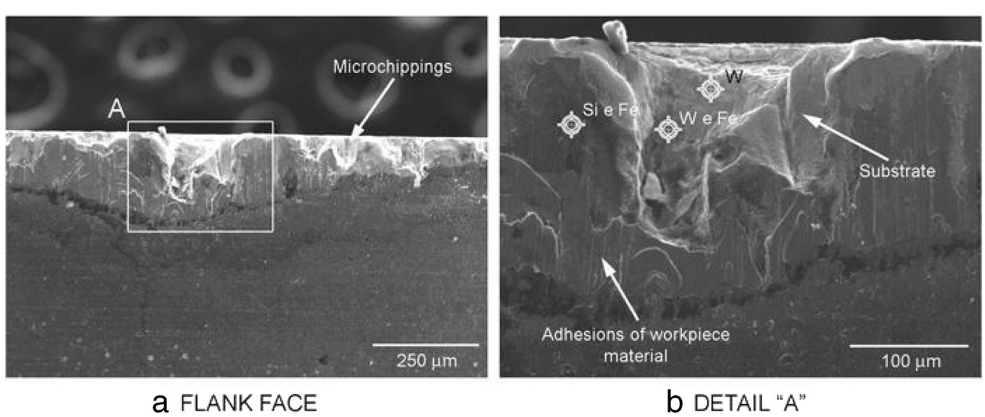


Table 1 Chemical composition of the die steel machined

Material									
N2711M	C	Si	Mn	P	S	Cr	Mo	Ni	V
	0.541	0.348	0.788	0.0094	0.0063	1.030	0.473	1.56	0.0865
	Al	Co	Cu	Nb	Ti	W	Pb	Sn	B
	<0.0005	0.0216	0.0896	0.005	<0.0010	0.0400	<0.0025	0.0035	<0.0003
	Ca	Zr	Bi	As	N	Sb	Fe	CE	
	>0.0003	0.0035	<0.005	0.0031	0.0369	<0.003	94.9	1.102	
VP ATLAS	C	Si	Mn	P	S	Cr	Mo	Ni	V
	0.274	0.291	1.62	0.0241	0.0021	1.79	0.662	0.493	0.0845
	Al	Co	Cu	Nb	Ti	W	Pb	Sn	B
	<0.0005	0.150	0.0323	0.0071	0.0013	0.0405	<0.0025	0.0025	<0.0003
	Ca	Zr	Bi	As	N	Sb	Fe	CE	
	>0.0078	0.0021	<0.005	0.0036	0.0286	<0.003	94.5	1.089	

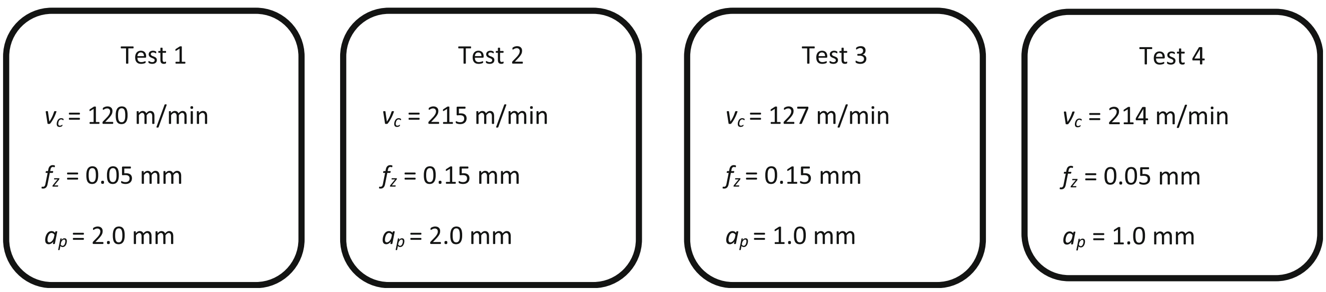


Fig. 13 Cutting conditions used in end milling tests with the N2711M and VP ATLAS steels

Montalvão [22] compared the machinability of two tool steels used to manufacture molds and dies: N2711M (DIN 1.2711), classified as a martensitic steel (38 HRC; UTS = 1217 MPa) and VP ATLAS (no equivalent product in the market), classified as a bainitic steel (38 HRC; UTS = 1250 MPa). The latter is a new material developed by Villares Metals with the objective of launching a less expensive steel with properties similar to those of N2711M on the market. The chemical composition of the steels is shown in Table 1.

The machining characteristics of both steels were determined in tool life tests using an optimization program to calculate the coefficients of the extended Taylor equation [23] for end milling. The milling cutter was the R390D–032A32–11M, which has a diameter of 32 mm. Three new cemented carbide inserts [R390-11T310M–PH, grade 1025, PVD-coated with TiN (3 μm)] were mounted on the cutter in each test. Machining forces, torque, power consumption, surface roughness, and swarf were also studied. According to the method used [23], the first four tests are carried out with the

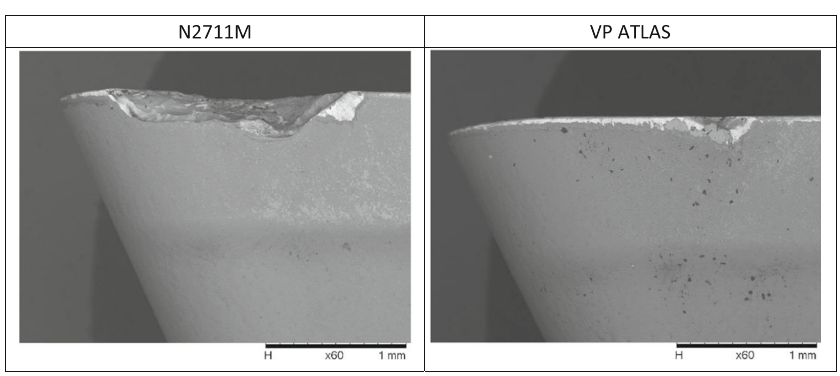


Fig. 14 View of the worn tools after each work material was milled under the cutting conditions of test 1 (v_c = 120 m/min, f_z = 0.05 mm, a_p = 2.0 mm)

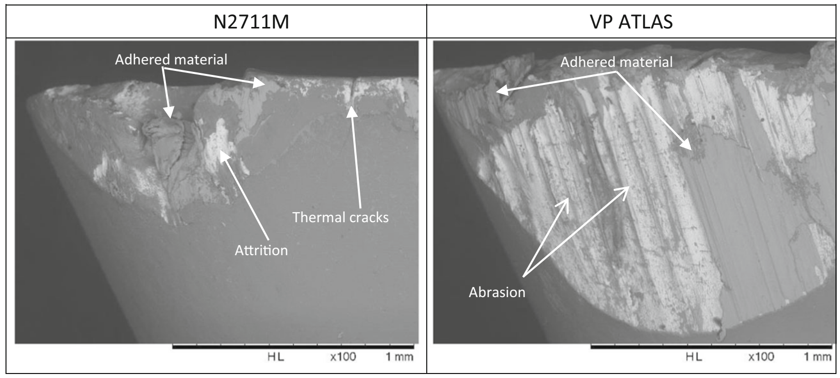


Fig. 15 View of the worn tools after each work material was milled under the cutting conditions of test 2 (v_c = 215 m/min, f_z = 0.15 mm, a_p = 2.0 mm)

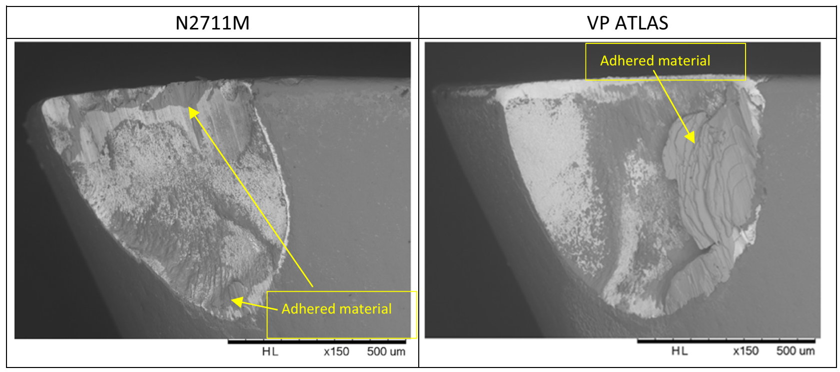


Fig. 16 View of the worn tools after each work material was milled under the cutting conditions of test 3 (v_c = 127 m/min, f_z = 0.15 mm, a_p = 1.0 mm)

same cutting conditions for the two work materials and the conditions in subsequent tests are stipulated by the program based on the results of the first four tests. The cutting conditions used in the first four tests are shown in Fig. 13.

The results allowed comparisons of the machinability of the materials and showed that the N2711M steel had the longest tool life.

After the tests, the tools were placed in an SEM so that the wear mechanisms could be analyzed. The cutting conditions for test 1 were the least severe, and those for test 2 the most severe. The tool damage for each work material after tests 1 and 2 is shown in Figs. 14 and 15, respectively.

Tool wear in test 1 before chipping started to occur was due mainly to attrition, although abrasion was also present. These conclusions were based on observation of the worn areas in the vicinity of the chippings on the flank face of these tools. Parallel grooves, mainly on the tool nose, indicate abrasion wear, while rough areas, mainly at the end of the depth of cut, indicate attrition wear. The life of the tool used to machine the N2711M steel was 40 min, against 10 min for the tool used to machine the VP ATLAS steel. This explains the greater damage in the tool used to machine the N2711M steel, although both tools reached the end of tool life criterion stipulated. A large amount of work material adhered to the worn area, promoting attrition (which was

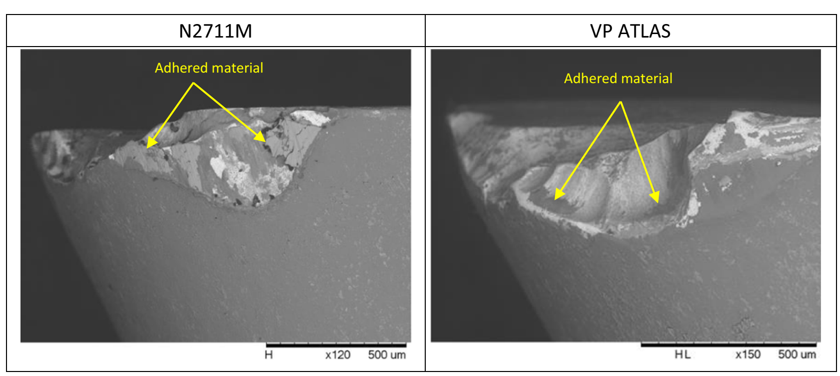


Fig. 17 View of the worn tools after each work material was milled under the cutting conditions of test 4 (v_c = 214 m/min, f_z = 0.05 mm, a_p = 1.0 mm)

confirmed by EDS analysis). As the wear increased, the cutting forces increased proportionally, leading to chipping. This microchipping increased as the cutting progressed, but not to the extent that the tool had to be immediately condemned. Only when the chipping extended over a large wear land and the tool reached the end of tool life criterion (VB = 0.3 mm) was the test stopped. This damage mode is quite common in milling operations and even more common when machining hard materials.

In test 2, which had the most severe cutting conditions, the tool life when machining the N2711M steel was 8.5 min, against only 2.0 min for VP ATLAS. Again, a large amount of workpiece material remained adhered to the scars on the tool (Fig. 15). This adhered material was responsible for the attrition wear mechanism identified on the flank surface of the tool used to machine the N2711M steel. Chipping was also observed in this tool, probably as the result of a mechanism involving thermal and mechanical cracks. A thermal crack is identified in Fig. 15 and, prior to chipping, there were probably other thermal cracks parallel to the one identified, before repeated mechanical shocks during each rotation of the cutter led to the destruction of the cutting edge.

The tool used to machine the VP ATLAS steel also exhibited chipping but to a lesser extent. The very short tool life, a result of the flank wear caused by abrasion, did not allow enough time for the cutting edge to be destroyed because of chipping, as occurred with the N2711M steel.

The tool damage for each work material after tests 3 and 4 is shown in Figs. 16 and 17, respectively. The tool lives were 24.5 and 2.7 min for machining respectively the N2711M and VP ATLAS steels under the cutting conditions of test number 3. Under the cutting condition of test number 4, the tools lives were 34 and 13 min, respectively.

The worn area of the tools used to machine both work materials under the cutting condition of test 3 (Fig. 16) shows the rough aspects on most of the area of the flank wear, which indicate the adhesion/attrition is the dominant wear mechanisms. The adhered work material also corroborates to this conclusion. Closer to the cutting edges, parallel ridges are observed indicating abrasion wear mechanisms. The tool used to machine the N2711M steel presents microchippings on the cutting edge. This is because of the much longer tool life when machining this work material compared to the VP ATLAS, consequently with larger numbers of mechanical shocks.

The tools used to machine both work materials under the cutting condition of test number 4 have experienced large chippings. These chippings occurred after the tools worn typically by adhesion/attrition before as the consequence of adherent work material on the flank surfaces of the tools.

This results prove that, even when cutting a hard material, adhesion/attrition is an important wear mechanism and steps aiming to decrease tool friction coefficient must be taken in order to improve the tool performance. In the presence of chippings, tools presenting high toughness and wear resistance is advisable.

3 Conclusions

The following conclusions can be drawn about the turning operations performed on AISI 4340 hardened steel:

- CBN performed better than ceramic (tools made with CBN had longer tool lives and there was no chipping of the cutting edge even in interrupted cutting).
- Abrasion and diffusion were important wear mechanisms when CBN-L tools were used.
- Diffusion was the most important wear mechanism when CBN-H tools were used in both interrupted and semi-interrupted cutting, but abrasion was also present.

The following conclusions can be drawn about the turning operations performed on AISI D6 hardened steel:

- Attrition and abrasion were the dominant wear mechanisms (attrition in crater wear and abrasion in flank wear). Diffusion was also present but to a lesser extent.
- Application of cutting fluid using MQL extended tool life, particularly when MoS_2 solid lubricant was added, but did not change the wear mechanisms. Addition of MoS_2 solid lubricant, however, did prevent tool microchipping.

The following conclusions can be drawn about the milling operations performed on H13 hardened steel using a PVD-coated cemented carbide tool:

- Abrasion/attrition followed by microchipping of the cutting edge were the wear mechanisms at the portion of the cutting edge that removed thin chips.
- Diffusion and attrition followed by microchipping were the wear mechanisms at the part of the cutting edge that removed thicker chips.

The following conclusions can be drawn about the end milling operations performed on N2711M and VPATLAS mold and die steels with coated carbide tools:

- Under the least severe cutting conditions, attrition was the dominant wear mechanism. As cutting time increased, chipping started to occur and contributed significantly to the destruction of the tool.
- Under the most severe cutting condition, the sequence of wear phenomena was the same. However, the tools used to machine the N2711M steel lasted longer and the dominant wear mechanisms were attrition and thermal and mechanical cracks, leading to severe chipping.
- The tool used to machine the VP ATLAS steel developed rapid flank wear. This was caused primarily by abrasion followed by chipping.

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