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Turning of interrupted and continuous hardened steel surfaces using ceramic and CBN cutting tools

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ABSTRACT

In the machining of hardened steel surfaces, turning instead of grinding has been employed increasingly due to several advantages it offers, such as flexibility and the possibility of dry cutting. The main tool materials used for this purpose are CBN and ceramic due to their high hardness and, in the case of some grades of these materials, high chemical stability with iron. However, when interrupted surfaces are turned, the tool requires not only these properties but also sufficient toughness to resist impacts against workpiece interruptions. Therefore, the main goal of this work is to compare CBN and ceramic tools in continuous and interrupted cutting. To this end, several turning experiments were carried out on continuous surfaces (in this case, CBN with an added ceramic phase and a mixed ceramic were compared, due to their high chemical stability and hardness) and on interrupted surfaces (here, a high CBN content and a SiC-reinforced ceramic were compared due to their good ability to withstand impacts), applying different cutting speeds. The main conclusions of this work were that in both continuous and interrupted cutting, the CBN tools exhibited a much better performance with respect to both tool life and workpiece surface roughness than the ceramic tools.

1. Introduction

Turning of hardened steels has been used increasingly to replace grinding operations due to the development of very hard tool materials (ceramics and CBN) and very rigid machine tools, which can ensure the same accurate geometrical and dimensional tolerances. In recent years, continual improvements have been made in hard turning insofar as surface roughness and IT standards are concerned. Klocke et al. (2005) compared grinding and hard turning with PCBN tool in the finishing operation of a transmission gear shaft. Some of the conclusions of this comparison were: (a) the material removal rates were, depending on the surface of the shaft, sometimes higher in grinding, sometimes in turning, but, in the average, turning presented a higher removal rate and, consequently, a shorter cutting time; (b) in terms of surface roughness, the same occurred, i.e., in some surfaces grinding reached a smaller roughness and, in others, turning was better. However, in both, turning and grinding, surface roughness values were between 0.1 and 0.8 μm (Ra); (c) concerning the shape and position tolerances, the requirements were met more accurately in hard turning than in grinding. Additionally, these authors also stated that turning provides higher flexibility (it is possible to carry out internal, external and face turning in just one fixation of the workpiece, what is rarely possible in grinding) and even the possibility of dry machining (fluid in grinding is a big problem, because the wet small chips becomes a kind of mud, difficult to be handled and recycled). In terms of costs of the operations, turning lathes are usually cheaper than grinding machines, but the cost of the tool per machined part is usually higher in turning. However, with the development of new tool materials and strategies to turn hardened steel aiming the increase of tool life, the cost of the tool per machined part tends to decrease.

Abrasive wear resistance and chemical stability are the most important properties for a tool material intended for hardened steel turning. The hardened workpiece surface has an abrasive effect on the tool material, and the high temperature at the cutting edge causes diffusion between tool and chip. Moreover, if the surface has any kind of interruption, toughness is an additional necessary property of the tool material to prolong the tool life (Wellein and Fabry, 1998).

Ceramics and CBNs are the best tool materials for this type of operation, due to their high hot hardness and wear resistance. Their hardness and chemical stability enable them to withstand the high thermal and mechanical loads of such machining operations. CBN has a higher hardness than ceramic tools at both low and high temperatures. Other CBN properties such as high thermal conductivity and low thermal expansion coefficient are also important when

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Table 1
Properties of ceramics and CBNs (adapted from Abrão, 1995; ASM International, 1995).

Properties	Mixed ceramic	Whisker reinforced ceramic	High CBN content material	Low CBN content material
Hardness at room temperature (HV)	1900	2000	4000	2850
Hardness at 1000 °C (HV)	800	900	~1800	–
Fracture toughness (MPa m$^{1/2}$)	3.3	8	10	3.7
Thermal conductivity (W/m °C)	12–18	32	100	44
Young's Modulus (kN/mm^2)	420	390	680	587
Coefficient of thermal expansion ($\times 10^6$/K)	8	4.5	4.9	4.7

using such tools in hardened steel turning. Some average properties of these materials are shown in Table 1 (Abrão, 1995; ASM International, 1995).

Ceramic also has good properties for use in hardened steel turning, such as hot hardness, wear resistance, and excellent chemical stability—higher than CBN. Childs et al. (2000) classified the chemical or adhesive interaction between carbon steel and mixed ceramic as "none", between carbon steel and whisker reinforced ceramic as "moderate" and between carbon steels and PCBN as "weak". Pure ceramic tools have found limited success in hard turning due to their poor thermal shock resistance and fracture strength. Such characteristics make them unsuitable as tool materials in hardened steel turning of interrupted surfaces (Luo et al., 1999). Microchipping and fracturing, which are common occurrences when using this tool material, are caused by hard inclusions in work material, high cutting forces, vibrations, thermal shock and improper entry or exit of the tool in the cutting operation. However, the fracture and thermal shock resistance of alumina tools can be increased by adding ZrO_2, TiC, TiN or SiC whiskers. Under these conditions, SiC whisker-reinforced tools are recommended for interrupted cutting operations.

CBN tools are usually classified in two grades: high CBN content (around 90%), called CBN-H and low CBN content (around 60%), called CBN-L, with a ceramic phase added to the material, usually titanium nitride. CBN-H tools exhibit higher toughness than tools with an added ceramic phase (CBN-L). Therefore, CBN-H tools are usually recommended for turning interrupted surfaces of hardened steels. Moreover, the high CBN content of these tools makes them harder than those with a lower amount of CBN. The CBN grade that has part of the CBN replaced by a ceramic phase loses in hardness and toughness, but gains in chemical stability. This is important for the finish turning of continuous surfaces, in which high temperature is reached and diffusive wear must be avoided (Sandvik Coromant, 1994).

Chou and Evans (1999) conducted experiments to identify CBN tool wear characteristics in interrupted cutting, turning a workpiece made of M50 steel with 62–64 HRC using a CBN-L tool and a CBN-H tool at different cutting speeds. The tool life of CBN-H tools decreased as cutting speed increased. However, the life of CBN-L tools increased when the cutting speed was increased from 2 to 4 m/s, and then decreased as it increased from 4 to 7.8 m/s. In the experiment at a cutting speed of 2 m/s, the CBN-H tool exhibited the longest life, but at 4 m/s, CBN-L proved to be the best tool material. The typical types of wear of these tools were flank and crater wear. No cutting edge chipping and cracking was observed, proving that tool impact against the interruptions of the turned surface was not an important factor in shortening the tool life. The predominant factor in shortening the tool life of the CBN-H tool was rising temperature caused by increased cutting speed. The increase in the life of the CBN-L tool when cutting speed changed from 2 to 4 m/s resulted from workpiece softening around the cutting region, which facilitated chip removal. However, when cutting speed increased from 4 to 7.8 m/s, cutting edge softening due to higher temperatures had a greater effect than workpiece softening, leading to a shorter life.

Diniz et al. (2009) performed experiments with a whisker-reinforced ceramic tool (recommended for hard turning of interrupted surfaces – Sandvik Coromant (2006)) and a low CBN content tool (CBN-L) with an added ceramic phase (recommended for hard turning of continuous surfaces – Sandvik Coromant (2006)) on interrupted and continuous surfaces, in order to evaluate tool life and wear. At a constant cutting speed, the CBN-L tool presented much longer lives than ceramic in continuous cutting, what was expected, since CBN-L is recommended for this kind of operation. In interrupted cutting, the performance of both tool materials in terms of tool life was similar, what was not expected, since the whisker reinforced ceramic is recommended for this kind of operation and, therefore, was supposed to perform better.

Diniz and Oliveira (2008) also carried out hard turning experiments using a high CBN content tool (CBN-H) and a CBN-L tool with an added ceramic phase, with chamfered and rounded edges and on continuous, semi-interrupted and interrupted surfaces. Again, these experiments were carried out at only one cutting speed. The chamfered geometry was the best choice for all kinds of surfaces while the rounded geometry produced good results on interrupted surfaces. As expected, this work has shown that, on continuous and semi-interrupted surfaces, the CBN-L tool with added ceramic phase provided the longest life, since it is recommended for continuous cutting. However, contrary to expectations, on interrupted surfaces, the CBN-H tool with higher fracture strength than the CBN-L content tool and, consequently, recommended for turning of interrupted surfaces, presented the same tool life as the latter, proving that the fracture strength of the low CBN content tool suffices to perform interrupted cutting.

This work is a continuation of the last two studies mentioned earlier. Its main purpose is to evaluate the behavior of two types of hard turning tools – ceramic and CBN tools – at different cutting speeds and on two distinct surfaces: interrupted and continuous. One difference between this work and the other two is that the tools recommended in the literature for each type of surface were used. In the first work cited (Diniz et al., 2009), a tool recommended for continuous cutting (CBN-L) was tested against another tool recommended for interrupted cutting (whisker reinforced ceramic), in both continuous and interrupted cutting. In the second work cited (Diniz and Oliveira, 2008) two CBNs were tested, one with higher toughness (CBN-H) and, consequently, recommended for interrupted cutting and other with higher chemical stability (CBN-L) and, consequently, recommended for continuous cutting. In the present work, a whisker-reinforced ceramic tool and a CBN-H tool were used to turn interrupted surfaces (both tools presented high toughness and, therefore, are recommended for interrupted turning), while mixed ceramic and CBN-L content tools were employed to turn continuous surfaces (both tools recommended for continuous cutting due to their high chemical stability). Another difference from this work and the other two cited was that the cutting speed also varied, depending on the machined surface. The cutting speeds recommended for both tools were applied in the experiments with each tool to turn both interrupted and continuous surfaces. In the other two works cited cutting speed was the same for all the experiments. The main goal of these experiments was to determine the

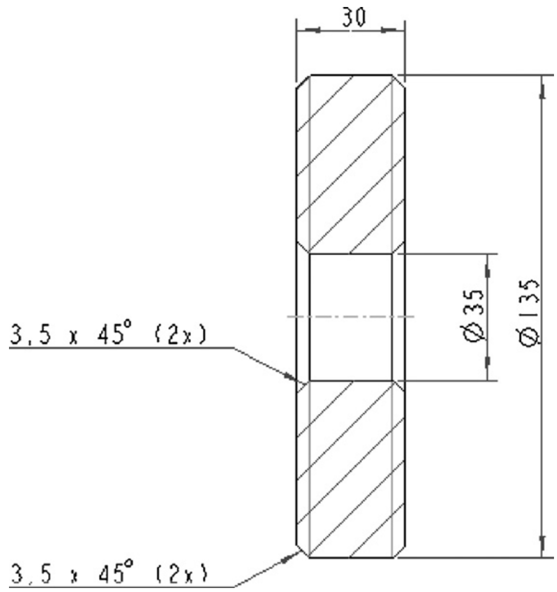


Fig. 1. Continuous cutting.

best tool and optimal cutting speed for continuous and interrupted turning of hardened steel from the standpoint of tool wear, tool life and workpiece surface roughness.

2. Experimental procedure

The experiments were carried out on a CNC lathe with 15 kW of power in the spindle motor.

The workpiece material was made of AISI 4340 steel with 56 HRC of hardness. Two types of workpieces were used, as shown in Figs. 1 and 2. These workpieces were designed for continuous and interrupted cutting during radial turning.

Two CBN grades were used for the tools: 7015 and 7025. According to the tool supplier (Sandvik Coromant, 2006), the CBN7015 grade (CBN-L) is a material with low CBN content and an added ceramic phase, while the CBN7025 grade has a high CBN content (CBN-H). Two types of ceramics were also used: CC670 and CC650. According to Sandvik Coromant (2006), the CC650 grade is an alumina-based mixed ceramic (Al_2O_3 + TiN) while the CC670 grade is a SiC whisker-reinforced ceramic. Both (CBN and ceramic) are recommended for the machining of hardened steel and cast iron in finishing operations. CBN-H and SiC whiskers ceramic are recommended for interrupted cutting, while CBN-L and mixed ceramic are recommended for continuous cutting.

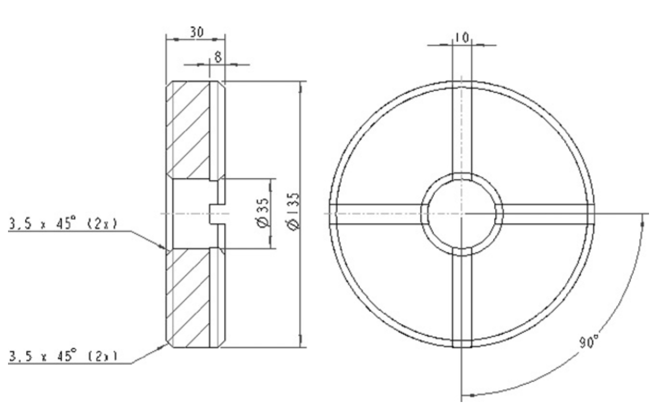


Fig. 2. Interrupted cutting.

Table 2
Cutting speeds recommended by the manufacturer.

CBN-L	270 m/min
CBN-H	195 m/min
CC650	150 m/min
CC670	150 m/min

The ISO code of the tool holder was DSBNR2525M12 and those of the inserts were SNGA120412S01030A (CBN-L), SNGN120412S01030A (CBN-H), SNGA120412T01020 (mixed ceramic) and SNGN120412T01020 (SiC whisker-reinforced ceramic). All the tools were geometrically identical except for the tool chamfer. The CBN tools had a 0.3 mm × 20° chamfer slightly rounded at the tip, while the ceramic tools had a 0.2 mm × 20° chamfer without rounding. Since all the tools had the same chamfer angle and the chamfer length was larger than the chip thickness, this difference is not supposed to influence the results.

The cutting conditions used were: depth of cut a_p = 0.15 mm and feed f = 0.08 mm/rev. This depth of cut was chosen because it is an usual value of material stock removed in a grinding operation (operation that hard turning is supposed to replace). To use a value smaller than this would make the tool nose radius much larger than the depth of cut, what could have caused vibration problems. To use a larger value than this is really not usual in grinding operations of workpieces with this size. The feed value was chosen aiming to obtain surface roughness values close to those obtained in grinding. To use a value smaller than this would cause the chip thickness to be very small and, consequently, specific cutting force to be very large. To use a larger value than this would harm surface roughness. The cutting speeds recommended by the tool supplier for each tool to cut hardened steel are given in Table 2.

The experiments were carried out at the cutting speeds recommended by the manufacturer and also at the speed recommended by the manufacturer for the "concurrent" insert in the same type of cutting. For example: the CBN-L was tested at its own speed (270 m/min) and at the speed recommended for the CC650 (150 m/min) – the concurrent ceramic in continuous cutting. Table 3 lists the cutting speeds used in all the experiments.

Throughout the tool life, flank wear was inspected with an optical microscope. Tool life was considered ended when flank wear reached VB_B = 0.20 mm. The experiment was also terminated if, after 100 min of cutting time, this flank wear value had not been reached. At the end of tool life (or the end of the experiment), worn inserts were examined under a scanning electronic microscope coupled to an EDS system.

One experiment consisted of successive radial turning passes of one of the surfaces shown in Figs. 1 and 2 with the same cutting edge until the moment when either the tool reached the end of its life, or the cutting time reached 100 min. Each experiment was carried out three times. During each experiment, ten measurements of the workpiece surface roughness were taken at different moments of tool life. Roughness was measured at three points of each surface.

Table 3
Surfaces, tools and cutting speeds.

Continuous cutting		
CBN-L	v_c = 270 m/min	Experiment 1
	v_c = 150 m/min	Experiment 2
CC650	v_c = 150 m/min	Experiment 3
	v_c = 270 m/min	Experiment 4
Interrupted cutting		
CBN-H	v_c = 195 m/min	Experiment 5
	v_c = 150 m/min	Experiment 6
CC670	v_c = 150 m/min	Experiment 7
	v_c = 195 m/min	Experiment 8

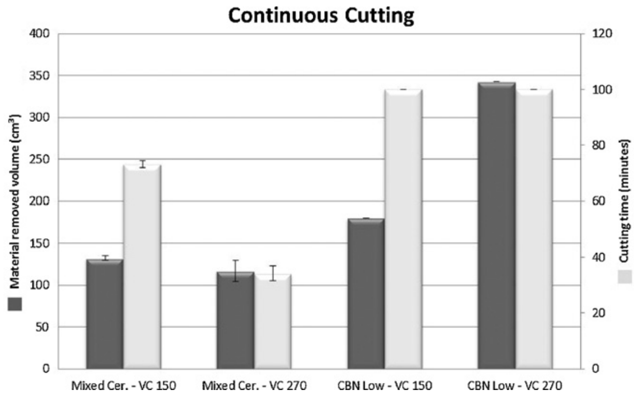


Fig. 3. Tool life (or end of experiment for CBN tool) as a function of cutting time and chip removal volume on continuous surfaces.

3. Results and discussion

The results will be presented in two parts according to the type of cut: continuous and interrupted.

3.1. Continuous cutting (workpiece shown in Fig. 1)

3.1.1. Tool life

Fig. 3 shows the results of tool life in continuous cutting experiments. As can be seen, the CBN-L tool lasted longer than the mixed ceramic tool (CC650) at the ceramic's recommended speed (150 m/min) and CBN-L's recommended speed (270 m/min). The difference in life between CBN-L and mixed ceramic tools was more than 1.3-fold at the lowest speed and more than 3-fold at the highest. It was written "more than" because at both cutting speeds, the CBN-L tool did not reach the wear criterion adopted for the end of tool life ($V_B = 0.2\ \mu$m); therefore, the experiments with this tool were interrupted when they reached 100 min of cutting time. The real tool life was therefore even longer than the duration of the experiments. Since it was impossible to compare CBN and ceramic tool lives due to the end of CBN experiments with 100 min of cutting time, Fig. 4 presents the curves of tool flank wear against volume of chip removed, to show a better view of the different performances of CBN and ceramic tools. One pass of the tool on the workpiece removed 2 cm^3 of chip. Therefore, for example, in the experiment with CBN-L tool using $v_c = 150$ m/min, where the experiment was interrupted after 180 cm^3 of material removed, the tool had passed 90 times on the workpiece, i.e., 90 layers of 0.15 mm of thickness ($a_p = 0.15$ mm) had been removed from the workpiece.

It can be seen in Fig. 4 that when the cutting speed was 270 m/min, the CBN-L tool had almost reached the end of tool life, i.e., had almost reached flank wear of 0.2 mm when the experiment was interrupted with cutting time of 100 min (volume of material removed of 342 cm^3). In the other hand, when the cutting speed was 150 m/min, when the experiment finished (cutting time of 100 min, volume of material removed of 180 cm^3), tool flank wear was around 0.1 mm, very far from the limit for tool life. Therefore, rewriting the phrase just written, it can be said that "the difference in life between CBN-L and mixed ceramic tools was *much more than 1.3-fold* at the lowest speed and *around 3-fold* at the highest".

Alumina is chemically stable at temperatures of up to 1200 °C and often has a low or zero tendency for diffusion wear when machining steels, as cited in Section 1. However, the CBN-L tool showed longer life due to less thermal softening. In continuous hard turning, the temperature in the cutting region is high, reducing tool hardness. As can be seen in Table 1, CBN-L tools show hardness of 2850 HV at room temperature, while the hardness of mixed ceramic tool is 1900 HV. Ueda et al. (1999) measured flank face temperature using a CBN tool in continuous turning of hardened steel and recorded values of 800 °C and 950 °C at 100 m/min

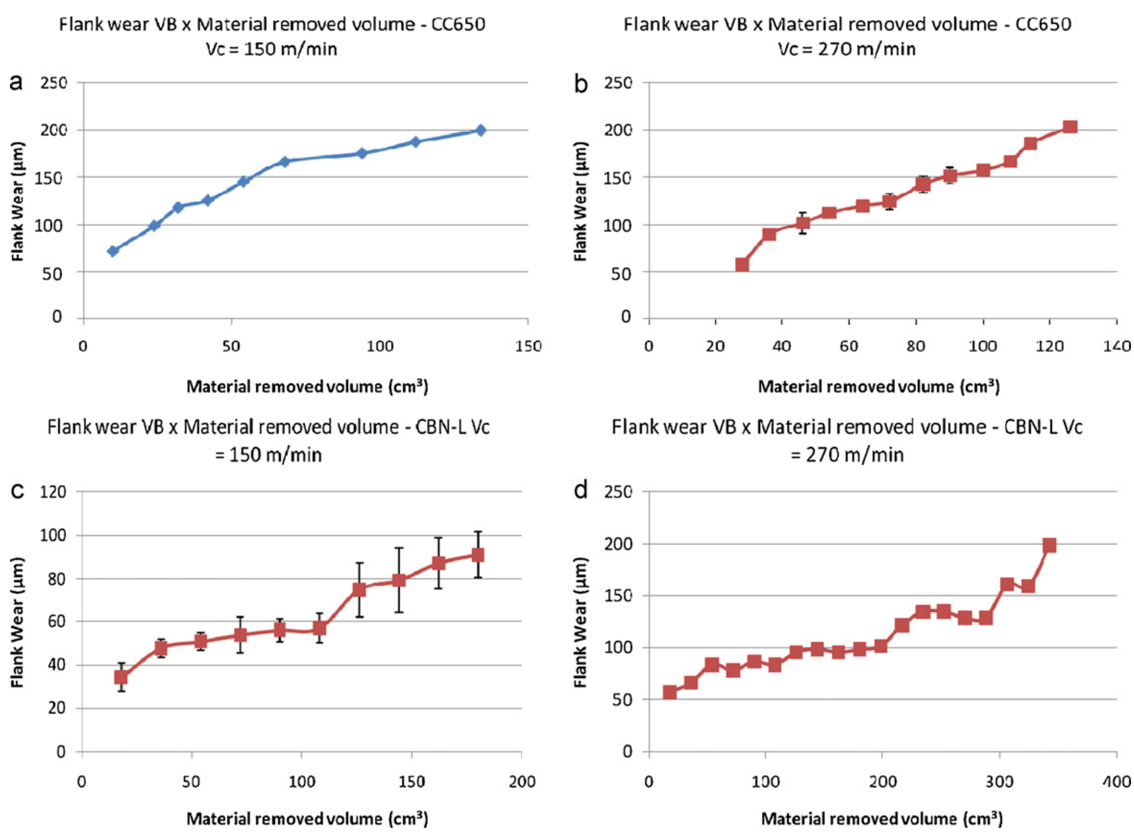


Fig. 4. Flank wear against volume of material removed for the continuous cutting experiments.

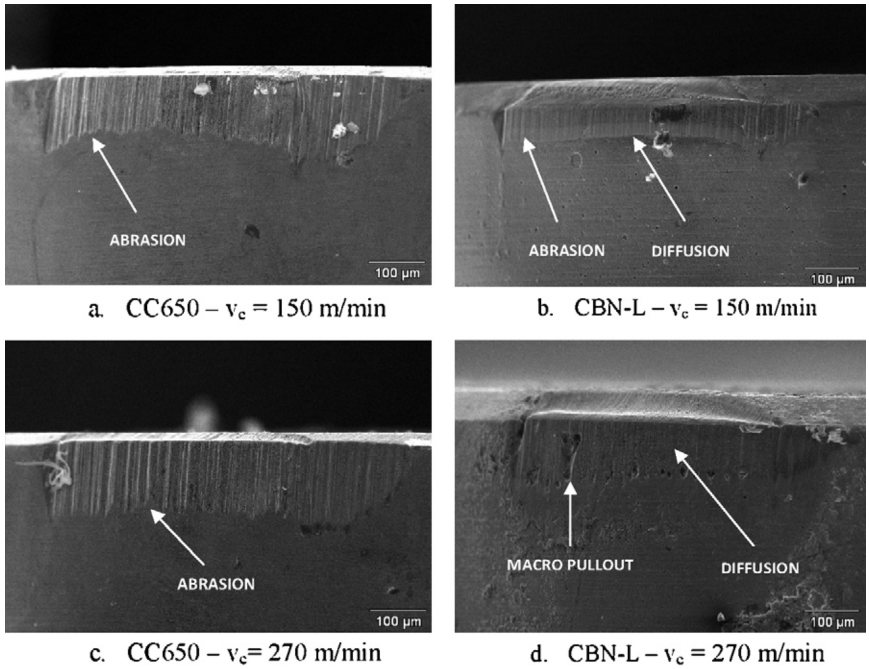


Fig. 5. SEM images of the worn tool flank faces used in continuous cutting experiments.

and 300 m/min, respectively. Furthermore, even at 700 °C, CBN and alumina ceramic showed a similar decrease in hardness as the temperature increased. Also in Table 1 it can be seen that, at 1000 °C, the hardness of mixed ceramic is 800 HV (decrease of 1100 HV compared to the room temperature hardness). The same table does not contain the CBN-L hot hardness, but it can be supposed that, as Ueda et al. (1999) concluded, the decrease in the CBN-L tool hardness caused by the temperature was close to the ceramic tool decrease and, therefore, mixed ceramic was less hard than CBN when cutting the continuous surfaces of this work.

Moreover, the mixed ceramic is less thermally conductive than the CBN as can be seen in Table 1. According to Stephenson and Agapiou (1996), the higher thermal conductivity reduces cutting temperatures near the tool edge. In other words, tool materials with higher thermal conductivity allow the heat to flow out of the cutting region. This lower thermal conductivity in mixed ceramic tools than in CBN tools contributed even further to tool thermal softening and increased the abrasive wear rate, which was the main wear mechanism in continuous cutting, as will be shown in the discussion of wear mechanisms.

With regard to the influence of cutting speed on tool life, Fig. 3 indicates that the life of the ceramic tool measured in cutting time dropped sharply when cutting speed was increased, but remained almost unchanged when measured in terms of chip removed volume. It should be kept in mind that, as the cutting speed increases, the tool's temperature rises, causing it to lose hardness. As it will be seen in Section 3.1.2, abrasion was the main wear mechanism of the ceramic cutting edge. Abrasive wear is typically caused by sliding hard particles against the cutting tool. The hard particles come from either the work material's microstructure, or are broken away from the cutting edge. Abrasive wear reduces, the harder is the tool relative to the particles and generally depends on the distance cut (Childs et al., 2000). Therefore, the loss of the hardness caused by the increase in the tool temperature decreased the relative hardness between tool and workpiece particles and stimulated the wear process. However, the workpiece material close to the cutting zone also loses hardness, facilitating chip removal, particularly with a material as hard as the one used here. The sum of these two factors, one with a negative and the other with a positive effect on tool life, resulted in the tool's life remaining almost constant when measured in chip removed volume. In the case of the CBN-L tool, life measured in cutting time remained almost constant when cutting speed increased, thus increasing considerably when measured in volume of chip removed. This was due to the fact that even in high temperature, CBN hardness is still high (see Table 1). In this case, therefore, there was only the positive effect of softening of the workpiece material close to the cutting zone, when the increase of cutting speed caused cutting temperature growth.

3.1.2. Tool wear mechanisms

Fig. 5 shows scanning electronic microscope images of the worn edges used in continuous cutting. No chipping or breakage was visible on the cutting edges, indicating that the cutting parameters were adequate and the stiffness of the workpiece and tool fixture systems was suitable for the operation. Fig. 6 shows the results of EDS analysis made on the wear lands.

Due to the high chemical stability of ceramics and also to the not so high hot hardness of the mixed ceramic (see Table 1), the main wear mechanism on the ceramic tool at both cutting speeds was abrasion, indicated by the thin scratches parallel to the cutting direction depicted in Fig. 5. As no iron atoms were found (see Fig. 6b and d) in EDS inspection (energy dispersive X-ray spectroscopy), the scratches were caused by abrasion from one of two possible sources: it was caused either directly by contact of hard workpiece particles with the tool, or friction with the workpiece led to the removal of one phase present in the tool, removing some of its hard particles, which rubbed against the tool, producing the scratches.

The CBN-L tool working at 150 m/min (Fig. 5b) showed several abrasive scratches and some smooth regions, suggesting that the wear occurred also by diffusion (Trent and Wright, 2000). As mentioned previously, the CBN-L tool is made of CBN plus an added ceramic phase. The ceramic phase decreases the thermal conductivity (compare the thermal conductivity of CBN-H and CBN-L in Table 1) and increases the chemical stability with Fe. At low cutting speeds, diffusion occurred, but abrasion was the main wear mechanism. However, at high speeds the tool reached higher temperatures, and the diffusion resistance was insufficient to prevent flank wear. Furthermore, this was the tool with the most severe

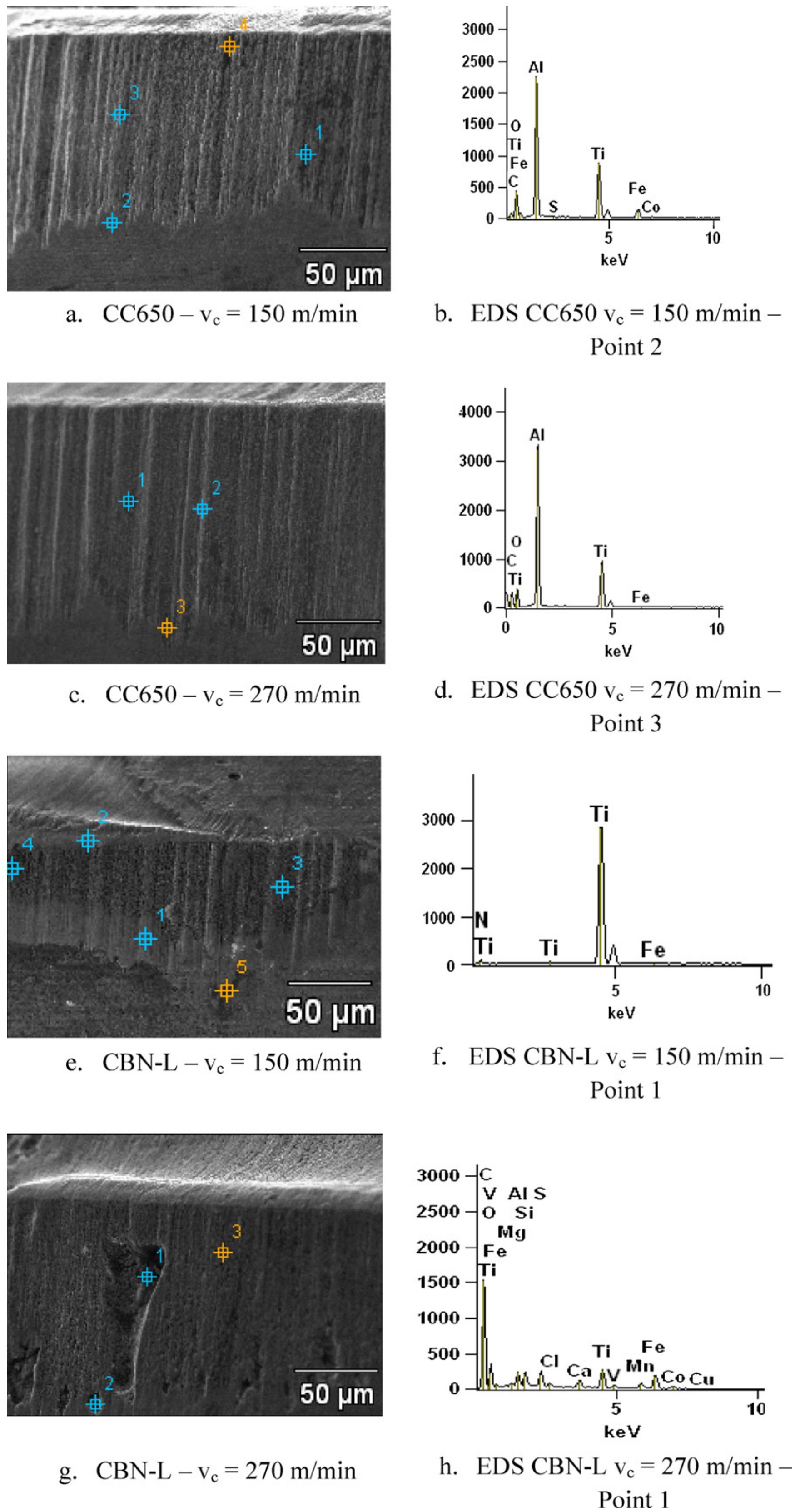


Fig. 6. EDS of mixed ceramic tool (CC650) and CBN tool plus an added ceramic phase (CBN-L).

rake face wear, which is often caused by diffusion. These findings can be observed in Fig. 5d, where the smooth aspect of the flank and rake wear land suggests diffusion. Moreover, the EDS analysis of many points on the wear land (Fig. 6h) shows the presence of small amounts of Fe (maximum 12%) from the workpiece. Because the amount of this element in the worn area is small, it must have reached the tool in a diffusive process. Had the amount of Fe been quite large and the images shown layers of workpiece material

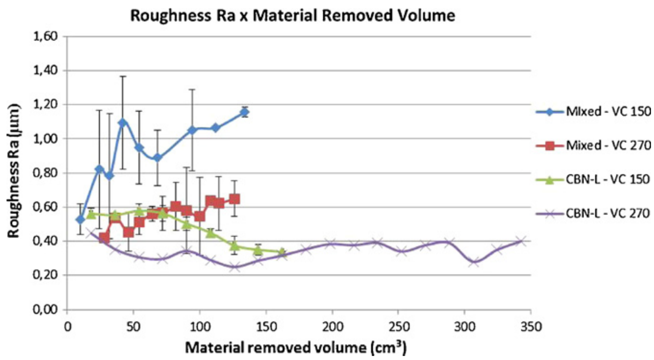


Fig. 7. Roughness Ra versus volume of removed material in continuous cutting.

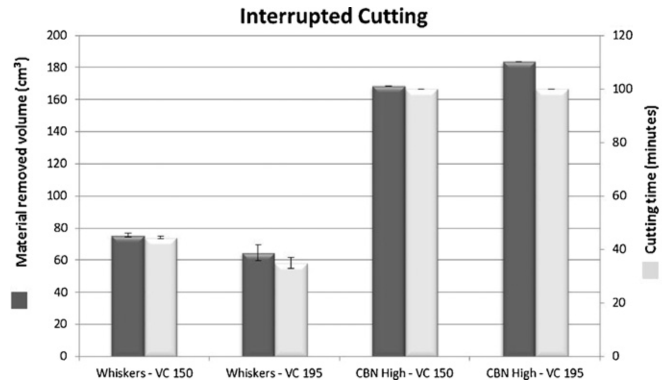


Fig. 9. Tool life (or end of experiment for CBN tool) in interrupted cutting.

on the tool, workpiece material adhesion would very likely have occurred, which was not the case. Therefore, this small amount of Fe on the tool indicates the presence of diffusion.

The pullout of macroscopic particles (Fig. 5d) occurred only at 270 m/min with the CBN-L tool because, in this condition, the tool reaches higher temperatures. The high temperature probably caused the binder resistance to drop, resulting in loss of cohesion with CBN, facilitating the removal of a large volume of tool material. However, there were no noticeable abrasive scratches caused by the friction of these removed macroparticles against the workpiece, which can be explained by the fact that these pullouts occurred next to the end of the worn area – at the end of the tool flank face-workpiece contact.

3.1.3. *Workpiece surface roughness*

Surface characteristics are responsible for the component's mechanical functioning and fatigue strength. Surface roughness is one of the important indicators of the surface integrity of machine components. Tool nose geometry and feed rate strongly affect surface roughness values in the turning process. Alterations in roughness values as tool wear progresses are related mainly with changes in tool topography as a function of wear rate, which tend to be transferred to the workpiece surface, especially changes in the shape of the secondary cutting edge. Thus, the behavior of workpiece roughness and the worn tool shape may be directly correlated. The feed rate and tool nose radius were kept constant (0.08 mm/rev and 1.2 mm, respectively) in all the experiments of this work. Fig. 7 shows the results of roughness behavior during the continuous cutting experiments.

As can be seen in this figure, the roughness obtained with the ceramic tool and a cutting speed of 150 m/min increased greatly during the tool's life, almost reaching the value of 1.20 μm – the highest value attained in the continuous cutting experiments, while the roughness obtained with CBN-L tool at 270 m/min did not exceed 0.45 μm and remained almost constant throughout the tool's life. It should also be noted that roughness increased along the tool life whenever ceramic tools were used and, at least for one condition (v_c = 150 m/min), overcame by far the value usually demanded for a ground surface (below Ra = 0.8 μm). However, when CBN-L tools were used, roughness remained constant or even decreased over time, remaining consistently within the range of suitable values for a process intended to replace the grinding process (below Ra = 0.8 μm).

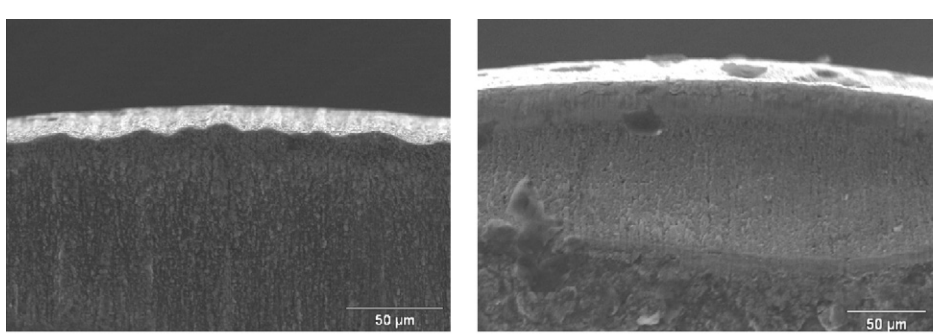
These results are related to the worn tool nose shape, as illustrated in Fig. 8. There was a clearly visible difference between the two noses: while the CC650 tool showed a rippled shape on the secondary cutting edge, the CBN-L tool preserved a shape very similar to the original one, contributing to the stability of roughness values. Another fact that has to be explained is the decrease of roughness as the volume of material removed increased for the surface machined with CBN-L. It is very likely that, while the shape of the tool nose did not change as the wear progressed, the edge may had become sharper as the cutting went by (a fresh tool has a very negative chamfer), causing the decrease of surface roughness.

However, before being influenced by the wear, the initial roughness values were similar in all the experiments, ranging from 0.42 to 0.55 μm regardless of the type of tool used.

3.2. *Interrupted cutting*

3.2.1. *Tool life*

Fig. 9 shows the results of tool life in interrupted cutting experiments. As can be seen, the CBN-H tool attained longer lives than the whisker-reinforced ceramic tool (CC670) at both, the speed recommended for the ceramic (150 m/min) and for the CBN-H (195 m/min) tools. The difference in life between these tools was more than 2.2-fold at the lowest speed and more than 2.8-fold



a. Tool nose shape CC650 – v_c = 150 b. Tool nose shape CBN-L – v_c = 270

Fig. 8. CBN-L and CC650 worn tool nose shape in continuous cutting.

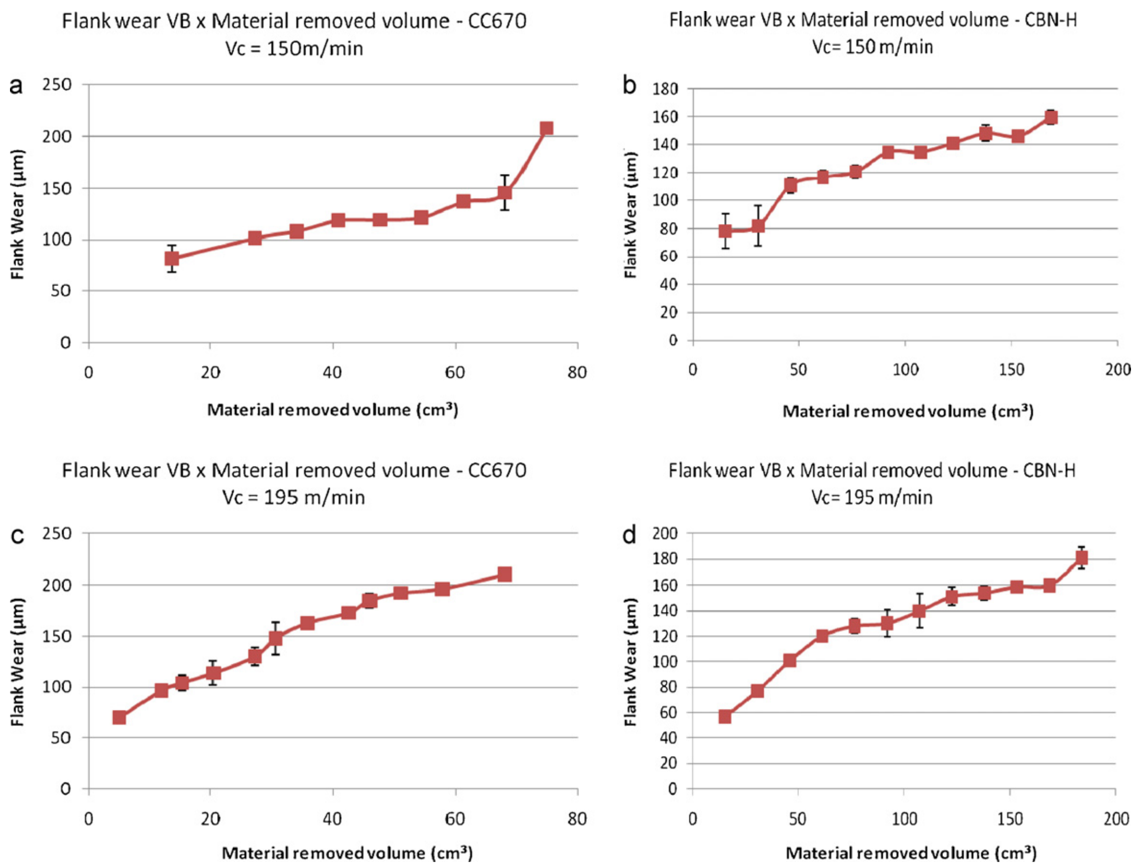


Fig. 10. Flank wear against volume of material removed for the interrupted cutting experiments.

at the highest. It was written "more than" because at the two cutting speeds, the CBN-H tool did not meet the wear criterion adopted ($V_B = 0.2\ \mu m$). Therefore, the experiments with this tool were interrupted when they reached 100 min of cutting time. Thus, the real lives are even longer than the duration of these experiments. Since it was impossible to compare CBN and ceramic tool lives due to the end of CBN experiments with 100 min of cutting time, Fig. 10 presents the curves of tool flank wear against volume of chip removed, to show a better view of the different performances of CBN and ceramic tools. It can be seen in this figure that, when cutting speed was 150 m/min, the CBN-H tool had reached flank wear of 0.16 mm and, when cutting speed was 195 m/min, flank wear for CBN-H tool was 0.18 mm at the end of the experiments. Therefore, both tools could have cut a little longer after the end of the experiments.

The decisive factor for this difference in tool life is the sudden chipping of the whisker-reinforced ceramic tool, as will be discussed later. In interrupted cutting, the tool's fracture strength – which is lower in the ceramic tools (compare the fracture toughness of whisker reinforced ceramic and CBN-H in Table 1) – is more important than its chemical stability and thermal conductivity, since the working temperature is lower than in continuous cutting. Diniz and Oliveira (2008) cited three reasons why tool temperature is lower in interrupted cutting: (a) heat propagation through the workpiece is hindered by interruptions, and the tool reaches a colder part of the workpiece at every 90° (workpieces used in this work); (b) the rotation of the workpiece generates an air flux through the grooves of the interrupted surfaces, helping to keep the workpiece and tool at a lower temperature; and (c) because the tool cuts only a small portion of the workpiece between two grooves, the time is insufficient to build a seizure zone between chip and tool rake face. When this seizure occurs, compressive stresses, strain rate and temperature are high, and particle exchange between chip and tool is enhanced, stimulating tool wear.

3.2.2. Tool wear mechanisms

Fig. 11 shows SEM images of the edges used in the interrupted cutting experiments. As mentioned previously, the whisker-reinforced ceramic tool showed edge chipping in all the experiments. In addition to chipping, abrasive scratches were visible on the worn lands used.

At $v_c = 195$ m/min, traces of Fe from the workpiece were not found outside the chipped region in the EDS analysis (see Fig. 12b). This indicates that attrition did not occur and was therefore not the cause of chipping. Fig. 11a and c also indicates that the source of chipping was not thermal, in view of the absence of cracks which are typical in this type of failure. As this occurred in the region of the tool which faced the largest chip thickness (h) – see Fig. 13, the reason for chipping was the mechanical shocks against the workpiece interruptions.

Abrasion may be caused either directly by friction with hard particles from the workpiece or by removal of binder caused by workpiece friction with the tool, and consequently, pullout of hard particles from the tool. These particles rub against the tool, causing wear. The first hypothesis is more likely, since the tool temperature was lower due to the interruptions, preventing the binder from losing resistance and releasing hard particles from the tool.

At the lowest speed, Fe was found inside the abrasive scratches of the ceramic tool (Fig. 12d). Therefore, this abrasion was caused by attrition (cyclical adhesion and removal of workpiece/chip material from the tool). The tool particles removed by attrition rubbed against the tool as they were dragged by the movement between workpiece and tool, unlike what occurred at higher cutting speeds. Trent and Wright (2000) state that attrition occurs more easily at

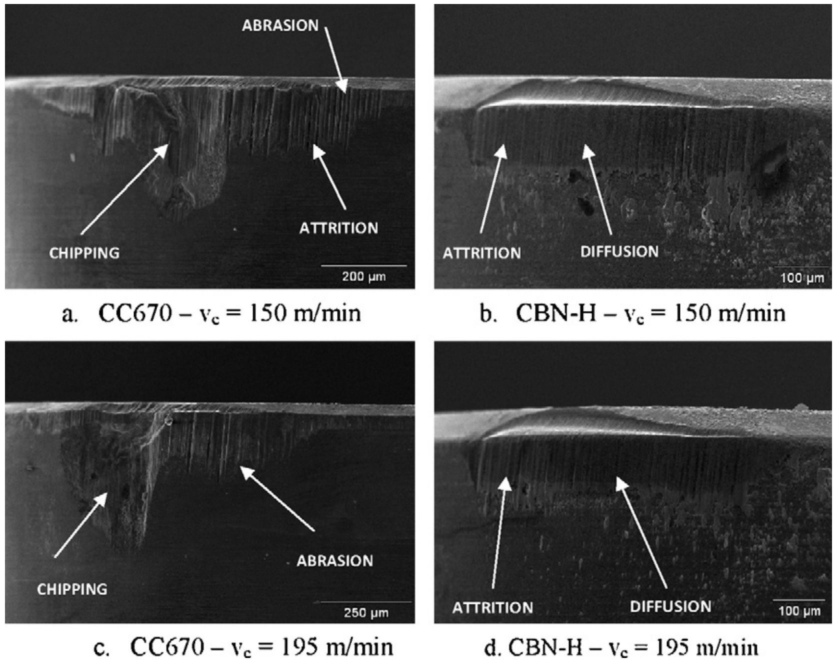


Fig. 11. SEM images of the cutting edges used in interrupted cutting.

moderate cutting speeds. The cause of chipping was the same as the previous one (mechanical), but was less intense due to lower impact energy (lower cutting speed).

For the CBN-H tools, the smooth aspect on the tool rake face suggests diffusive crater wear at both cutting speeds, since CBN does not have the same high chemical stability as that of the whisker-reinforced ceramic tool, as cited in Section 1. The ceramic tool presented shallower crater wear than the CBN tool (visual inspection). On the CBN-H flank face, iron was found in the lower periphery of the wear land at both cutting speeds (see Fig. 12f and h), suggesting that attrition with pulled out particles was the main wear mechanism. When removed from the tool, these particles probably caused abrasion (abrasive scratches shown in Fig. 12e and g) mainly in the region where chip thickness was small and the cutting pressure was higher. This attrition may have been favored by the presumably low cohesion between CBN and the binder material. The smooth aspect in the region where the chip thickness was larger (low cutting pressure) suggests that diffusion was the main wear mechanism in this region.

It is important to point out that no chipping occurred on the CBN-H cutting edge, even after 100 min of cutting (a lot of impacts against the surface interruptions), proving that its toughness is sufficient to a tool designed to be used in this kind of cut.

3.2.3. *Workpiece surface roughness*

Fig. 14 shows workpiece roughness in the interrupted cutting experiments. Again, as this figure indicates, workpiece roughness remained virtually constant during the life of the CBN tool, regardless of cutting speed, with values of 0.4 µm at the lowest speed and 0.6 µm at the highest speed, while the roughness obtained with the ceramic tool increased rapidly, exceeding 2.00 µm at 150 m/min. The same kind of roughness behavior was obtained by Diniz et al. (2009) in the interrupted hardened steel turning using whisker reinforced ceramic.

As mentioned earlier, these values can be related to the shape of the worn tool nose (Fig. 15). The increase in abrasive scratches caused a significant change in the ceramic tool nose shape (Fig. 15a), thus contributing to the increase in roughness values along the tool's life. However, the chipping that occurred at the ceramic tool's cutting edges did not contribute to the increase in roughness, as indicated by a comparison of Figs. 10a and 14. Chipping (which occurred when 70 cm^3 of chip material had been removed at v_c = 150 m/min) did not lead to a sudden increase in roughness values because it occurred on the main cutting edge, while it is the secondary cutting edge that is responsible for workpiece roughness. Similar to the results in continuous cutting, the CBN-H tool maintained a uniform nose shape (Fig. 15b). These results indicate that turning with the CBN-H tool can replace grinding operations on such surfaces because the Ra values obtained with this tool were always lower than 0.8 µm and mixed ceramic tools are not suitable to replace grinding in such operations.

4. Discussion about tool wear results

4.1. *Tool wear and tool property comparisons*

Extracting the data shown in Figs. 4 and 10, Table 4 could be built. This table shows the wear rate of the tools (µm of flank wear divided per cm^3 of material removed). The curves shown in Figs. 4 and 10 presented a high slope at the beginning of tool life (the first measurement of flank wear already showed a large value) and some of them presented a higher slope at the end of tool life. However, all of them presented a certain steady growth of flank wear along a large portion of the experiment. To build Table 4, just this steady slope of the curves were taken into consideration.

It can be seen in Table 4 that, for cutting speed of 150 m/min in continuous cutting, the mixed ceramic wear rate was almost 3 times bigger than the CBN-L wear rate. As could be seen, abrasion was the main wear mechanism for both tool materials at this cutting speed. Therefore, hardness is the property to be considered to analyze this difference in the wear rate. Table 1 showed that, at room temperature, mixed ceramic hardness is 1900 HV and CBN-L hardness is 2850 HV. Therefore, CBN-L hardness is just 1.5 times higher than mixed ceramic hardness. The higher difference in flank wear rate must be caused by the tool thermal softening. Table 1 showed that the mixed ceramic hardness at 1100 °C is 800 HV. This table does not present CBN-L hardness at this temperature, but considering that the hardness drop was the same of the mixed

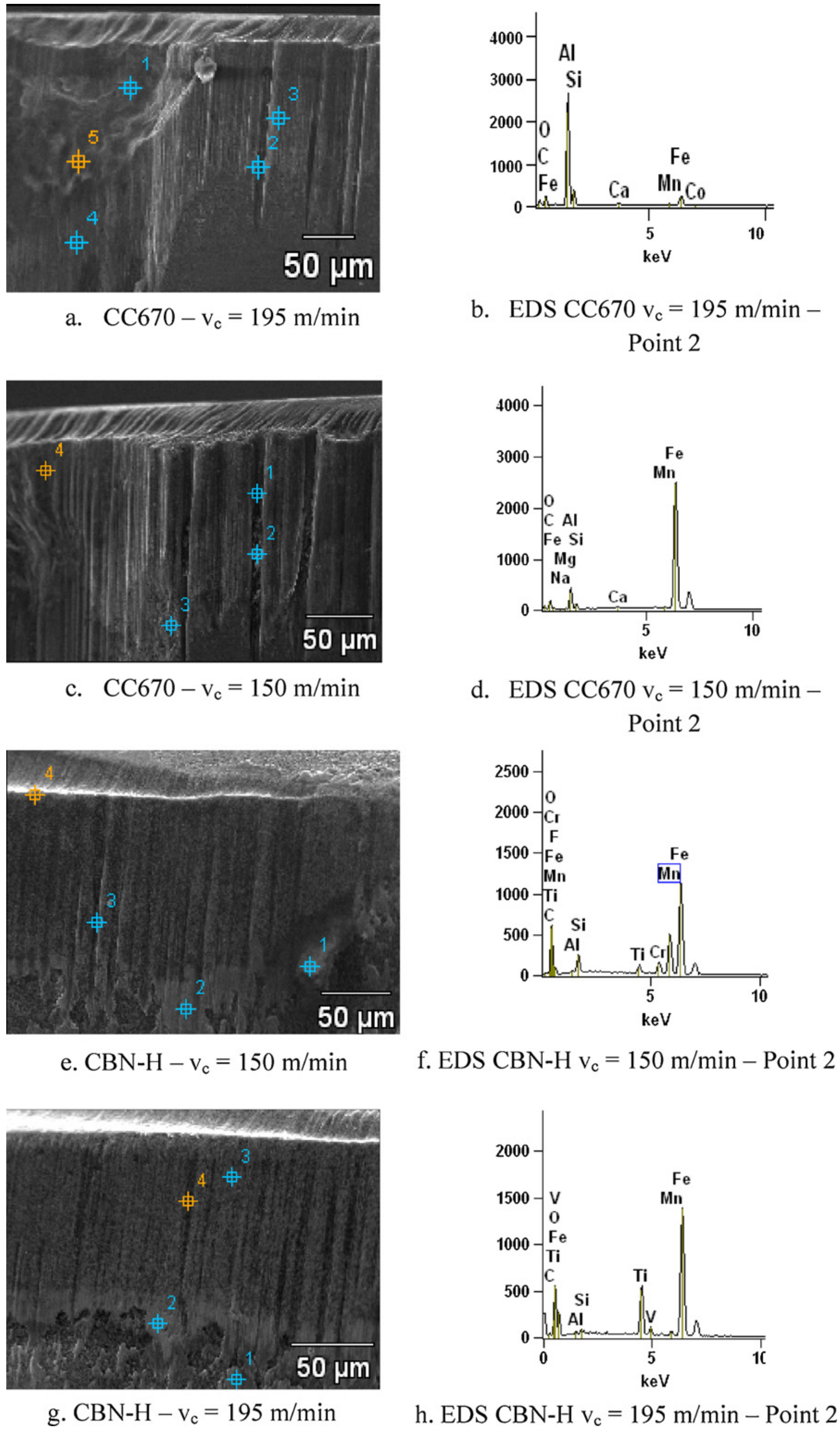
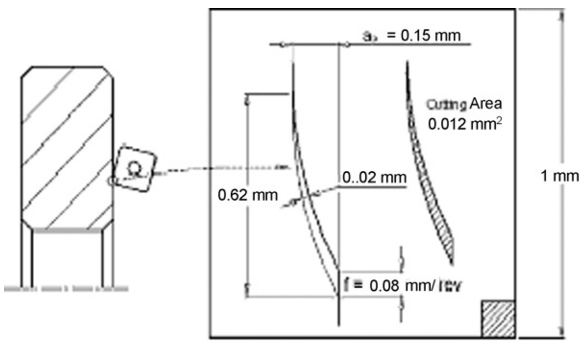


Fig. 12. EDS of whisker-reinforced ceramic tool (CC670) and CBN-H tool.

Table 4
Wear rate (mm of flank wear per cm^3 of material removed).

Continuous cutting			Interrupted cutting		
Tool material	v_c (m/min)	Wear rate (µm/cm^3)	Tool material	v_c (m/min)	Wear rate (µm/cm^3)
CC650	150	1.03	CC670	150	1.17
	270	1.26		195	2.22
CBN-L	150	0.35	CBN-H	150	0.40
	270	0.26		195	0.74



b. Cutting Geometry

Fig. 13. Flank tool wear V_B CC670 at 150 m/min and chip shape.

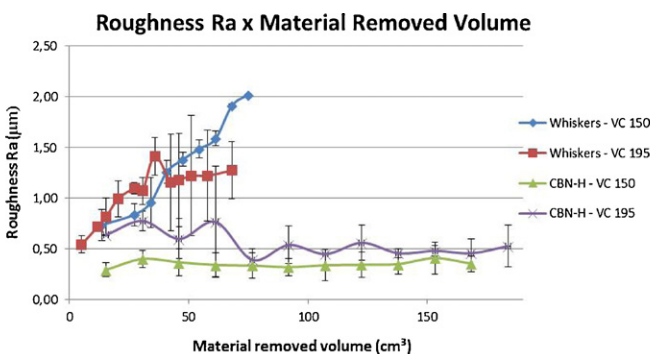


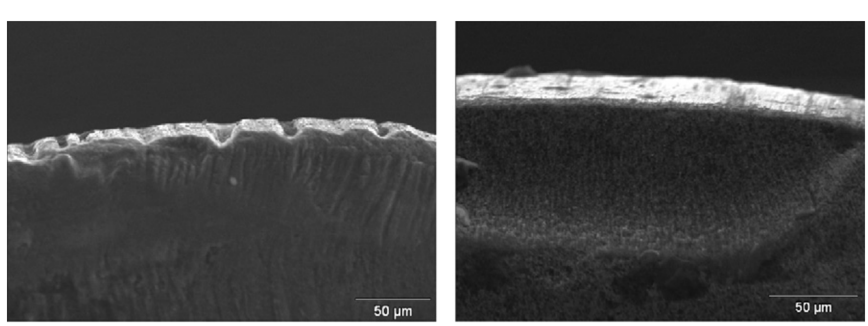
Fig. 14. Roughness Ra versus removed material volume in interrupted cutting.

ceramic tool (1100 HV), CBN-L hardness at 1100 °C is around 1750 HV. Therefore, the ratio between CBN-L and mixed ceramic hardness at this temperature is 2.2, what is closer to the ratio of CBN-L and mixed ceramic flank wear rates.

Table 4 also shows that, for cutting speed of 270 m/min in continuous cutting, the mixed ceramic wear rate was 4.8 times bigger than the CBN-L wear rate. This ratio is bigger than that obtained at 150 m/min. To build the same considerations for cutting speed of 270 m/min is more difficult, since abrasion was the main wear mechanism for the mixed ceramic tool, but for CBN-L tool, diffusion was also significant. Therefore, since the difference between the wear rates cannot be attributed just to the difference in hardness, because diffusion was the main wear mechanism of CBN-L wear, it can be said that CBN-L tool hardness decreased less with the increase in temperature caused by the increase of cutting speed. Based on this result, it can be said that CBN-L hardness at room and high temperatures is very suitable to turn continuous surfaces of hardened steel and further improvements in the development of this material must be concentrated in the increase of its chemical stability with steel.

For interrupted cutting, for both cutting speeds used in the experiments (150 and 195 m/min), the whisker-reinforced ceramic wear rate was almost 3 times bigger than the CBN-H wear rate. As already seen, whisker reinforced tool reached the end of tool life mainly due to the chipping caused by the frequent impacts against the workpiece interruptions and, CBN-H tool edge did not chip. Therefore, their difference in toughness is the first property to be addressed in an attempt to correlate tool wear with tool properties. However, as can be seen in Table 1, the difference of fracture toughness of these 2 tool materials is not so high to explain such a difference in the tool wear rate. The fracture toughness of CBN-H and whisker reinforced ceramic are, respectively, 10 and 8 MPa m$^{1/2}$. Therefore, some other fact supposedly stimulated the edge chipping during the cutting with whisker reinforced ceramic. Very likely, tool wear weakened the cutting edge and facilitated the occurrence of chipping. It was already seen that abrasion also occurred on the wear land of whisker reinforced ceramic. This phenomenon is much likely to occur in ceramic than in CBN-H due to the large difference of hardness. The CBN-H room temperature hardness is 4000 HV, while the whisker reinforced hardness is 2000 HV (see Table 1). Therefore, the ceramic low hardness made possible the abrasive wear process, what, together with the chipping caused by the tool impacts, led the ceramic tools to the end of their lives. For the CBN-H tool, because abrasion was not important due to the high hardness, the low wear rate caused by diffusion and attrition did not weaken the cutting edge and so, even with toughness not much higher than the whisker reinforced tools, the cutting edge was able to withstand all the impacts against workpiece interruptions for 100 min of cutting time.

Another interesting point to be addressed based on the results shown in Table 4 is that three of the four ceramic wear rates were similar (ranging from 1.03 to 1.26). Just when the highest cutting speed (195 m/min) was used in interrupted cutting, the wear rate was much higher than these values (2.22), due to the chipping of the cutting edge caused by the more frequent and intense impacts against the workpiece interruptions in this cutting speed. This result is another point to confirm that abrasion was the main wear mechanism when ceramic tools were used. As already cited before, abrasive generally depends on the distance cut (Childs et al., 2000), which is proportional to the volume of material removed, since feed and depth of cut were the same in all experiments. It is also important to remember that, as already cited, when cutting speed increased in the continuous cutting with mixed ceramic, thermal softening occurred not just in the tool, but also in the workpiece material in the cutting region, what helped the wear rate to remain constant. Another point to be remembered is that, in interrupted cutting, besides abrasion, chipping of the edge also occurred when cutting speed was 150 m/min. However, it occurred close to



Tool nose shape CC670 – Vc = 150 m/min   Tool nose shape CBN-H – Vc = 150 m/min

Fig. 15. CBN-H and CC670 tool nose shape in interrupted cutting.

the end of tool life and, therefore, was not able to change wear rate significantly.

The same did not occur for the CBN tools: the CBN-H values of 0.40 and 0.74 are higher than the CBN-L values of 0.35 and 0.26. The wear rates of CBN tools were higher in interrupted cutting because the interruptions of the machined surfaces, even not causing edge chipping as already seen, stimulated attrition, which, for CBN tools, only occurred in interrupted cutting. Trent and Wright (2000) affirm that attrition wear usually occurs when material flow is irregular, and contact with the tool is less continuous. The irregular material flow necessary for attrition wear to occur can be caused, among other reasons, by interrupted cutting.

As already cited, Diniz et al. (2009) turned the same kind of surfaces (continuous and interrupted) of the same material, but for both surfaces they used whisker reinforced ceramic tool (recommended for interrupted cutting) and CBN-L tool (recommended for continuous cutting). For continuous cutting, the wear rate of the ceramic reinforced tool was 6.5 times bigger than the wear rate of CBN-L tool. The reason for a higher value than that obtained in this work (here mixed ceramic and not whisker reinforced ceramic was used in continuous cutting) is that, in Diniz et al. (2009) work, besides abrasion, diffusion also occurred in the ceramic reinforced tool, because its chemical interaction with steel is higher than the CBN-L chemical interaction. Therefore, whisker reinforced ceramic tool is not suitable to be used in continuous cutting.

For interrupted cutting, in Diniz et al. (2009) work, the wear rate of the ceramic reinforced tool was almost the same of the CBN-L tool. Again this result is different from the result obtained in this work. Here, the whisker-reinforced ceramic wear rate was almost 3 times bigger than the CBN-H wear rate (CBN-L was not used in interrupted cutting in this work). Therefore, CBN-L wear rate in interrupted cutting is also around three times higher than the CBN-H rate, proving that really CBN-L cannot be used in interrupted cutting.

4.2. Which tool material is the most suitable for turning hardened steel

It could be seen in the results of this work that CBN tools presented longer tool lives (or slower tool wear) than ceramic tools for both, continuous and interrupted machined surfaces. Based just in these results, it is impossible to decide which tool is suitable to be used in turning of hardened steel, since ceramic (which present shorter lives than CBN) is much cheaper than CBN (6.5 times when comparing CBN with mixed ceramic and 15 times when comparing CBN with whisker reinforced ceramic) and, consequently, the price of the tool per machined part, is lower using ceramic. However, the objective of this work is not to compare the cost of machined parts with both tool, but, as it was written in the introduction, “to determine the best tool for continuous and interrupted turning of hardened steel from the standpoint of tool wear, tool life and workpiece surface roughness.” Therefore, from this standpoint, the best tool is CBN for both kinds of surfaces, not just because tool lives were longer (or tool wear rates were lower), but also because it was the only tool material able to keep surface roughness in levels similar to those demanded of grinding operations. It is not also the objective of this work to indicate which process is better, grinding or turning, because to answer this question it would be necessary to discuss subjects like material removal rate, operation time and costs, flexibility and environmental suitability, which will not be done here. But one thing has to be stated: if a company decides that to use turning instead of grinding in the finishing operation of hardened steel parts, CBN is the tool material to be used, mainly if the demanded workpiece surface roughness is low. This is true for both, continuous and interrupted surfaces.

5. Conclusions

Based on the results of this work in the radial turning of AISI 4340 steel with 56 HRC with CBN tools (high and low content with an added ceramic phase) and with ceramic tools (mixed and SiC whisker-reinforced), and in conditions similar to those used in this work, it can be concluded that:

- In both, continuous and interrupted cutting, the CBN tool flank wear rate was much lower than the ceramic wear rate at all cutting speeds used.
- In continuous cutting, the main wear mechanism of the ceramic tool was abrasion, while that of the CBN tool was abrasion for the lowest cutting speed and diffusion for the highest cutting speed.
- In interrupted cutting, the main wear mechanism of the ceramic tool was abrasion at high cutting speeds. At low cutting speeds, abrasion was stimulated by attrition. In both cases, sudden chipping of the cutting edge occurred in response to mechanical shocks. The wear mechanisms of the CBN tool were diffusion and attrition. Chipping of the edge did not occur on the CBN tool, proving that it is a suitable tool to be used in interrupted cutting.
- The workpiece roughness values obtained with the ceramic tools during their lives were considered high for an operation intended to replace grinding, because the type of wear these tools underwent caused considerable variations in the tool nose shape. In contrast, the wear of the CBN tool did not cause major variations in the shape of the nose, mainly in its secondary cutting edge, enabling the roughness values to remain consistently low throughout the tool’s life.
- Based on the results of this work and on the results of the past two others carried out by the same research group (Diniz et al., 2009; Diniz and Oliveira, 2008) it can be concluded, in terms of tool life and surface roughness, that CBN performs better than ceramic in both, interrupted and continuous surface. It was also concluded in these works that, in spite of the higher price of the CBN tool compared with ceramic, it is the only tool material that is able to turn hardened steels, achieving very long tool lives and obtaining levels of surface roughness suitable for an operation aiming to replace grinding.

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