Int J Adv Manuf Technol (2016) 82:797–807
DOI 10.1007/s00170-015-7426-2

ORIGINAL ARTICLE

Effect of PCBN tool grade and cutting type on hard turning of high-chromium white cast iron

Adilson José de Oliveira[1] · **Denis Boing**[2,3] · **Rolf Bertrand Schroeter**[3]

Received: 20 February 2015 / Accepted: 11 June 2015 / Published online: 24 June 2015

Abstract The turning of mechanical construction and bearing steels is widely carried out using PCBN and oxide ceramic tools, even when materials have high hardness (40 to 60 HRC), reached after quenching and tempering heat treatment. However, mechanical components submitted to severe abrasive loads show, in addition to matrix hardness, the presence of a high-volume fraction of hard particles in the microstructure. Turning materials with a high content of hard particles in the microstructure will result in high rates of abrasive wear or damage to the cutting edges of the tool. Information regarding the turning of materials characterized by a high-volume fraction of carbides in the microstructure is limited in literature. The objective of this study was to determine the performance of two grades of PCBN tools (high CBN and low CBN content with an added ceramic phase) in the turning of high-chromium white cast iron applying continuous and interrupted cutting. Evaluations of tools' life, wear mechanisms at the tool cutting edges, roughness, and microstructure remaining on the turned surface were carried out. The results show that the grades with low CBN content and the addition of a ceramic phase, the tool life was three times longer than that of the grades with high CBN content. The most interesting result obtained concerns the microstructural modifications in a narrow subsurface layer of the turned material. Carbide fragmentation and alignment in the direction of the cutting shear plane were identified, which may potentiate the use of the material.

Keywords Turning · PCBN grades · White cast iron · Microstructural modifications

1 Introduction

Ferrous materials present a wide range of applications and attractive processing properties including high-strength, heat resistance, ductility at low temperatures, wear resistance, corrosion resistance, and fatigue resistance. The characteristics and potential applications of these materials are directly related to their microstructure. In steels for mechanical construction (shafts, bushings, brackets, holders, etc.) subjected to severe dynamic or cyclic loads, i.e., where high mechanical stresses are absorbed elastically by the component or an overload causes only permanent deformation without a fracture, the predominant microstructure is tempered martensite. In the cases where the application also involves repeated rolling and high compressive forces, such as steel for bearings, the microstructure also presents a small volume fraction of fine carbides. The spherical carbide particles of around 1 μm remaining in bearing steel are assumed to reduce metal contact between the rolling elements. In order to increase wear resistance, as in the case of cold work steels, the volume fraction and size of the carbide particles are increased. Primary and eutectic carbides from the melt are 1 to 100 μm, secondary carbides from the solid solution are 0.1 to 1 μm, while tempered carbides are 0.005 to 0.1 μm. Coarse hard carbides increase wear resistance, whereas very fine carbides increase precipitation hardening and creep resistance. In situations

---

✉ Adilson José de Oliveira
adilson@ct.ufrn.br

[1] Department of Mechanical Engineering, Technology Center, Federal University of Rio Grande do Norte, Natal, CP 1524, RN 59078-970, Brazil

[2] Department of Mechanical Engineering, Technology and Innovation Center, University Center of Brusque, Brusque, SC, Brazil

[3] Department of Mechanical Engineering, Laboratory of Precision Mechanics, Federal University of Santa Catarina, Florianópolis, SC, Brazil

where very high wear resistance is required, as in the case of mining equipment and rolling mills, a significant percentage of the microstructure is composed of a volume fraction of carbides in a scaffold form. In addition, the carbide size can be greater than 150 μm. Examples are high-chromium white cast iron and hard-facing layer deposited on steel or on a cast iron substrate used for blow bars of impact mills used to crush basalt [1].

From the perspective of machining, especially with single point tools, increasing the volume fraction and size of the carbides becomes a limiting factor in terms of the feasibility and process capability. In this regard, Boing [2] defined four classes of materials (A, B, C, and D) with a tempered martensitic microstructure associated with the volume fraction of carbides. Class "A" relates to materials with less than 1 wt% volume fraction of carbides, for instance, AISI 4140, 4340, and 8640 quenched and tempered steels. Class "B" encompasses materials with 1 to 5 wt% volume fraction of carbides, a typical example is AISI 52100 steel. Class "C" consists of materials with a 5 to 15 wt% volume fraction of carbides. This class includes the cold work tool steels (AISI D2 and D6) and high-speed steels (AISI M2). Finally, class "D" is composed of materials with volume fraction of carbides of over 15 wt%, such as high-chromium white cast iron and hard-facing layer deposited on steels or cast irons.

Classes "A" and "B" are extensively turned with hardness between 40 to 60 HRC, i.e., martensitic microstructure. Several researchers have expressed an interest in gaining better understanding of tool life, wear mechanisms, surface texture, and residual stresses. Tool grades of PCBN and oxide ceramic (pure, mixed, or reinforced with SiC whiskers) tools are used for continuous and interrupted cutting with effective cutting times of over 50 min, even at cutting speeds greater than 150 m/min. From the perspective of wear mechanisms, abrasion and diffusion are mainly identified on PCBN cutting edges and only abrasion on oxide ceramic cutting edges [3]. Mainly with the use of PCBN tools, it is possible to maintain roughness values below 0.8 μm Ra, which are compatible with ground surfaces [4]. Residual compressive stresses above 800 MPa are identified on the turned surface of bearing steels, which promote higher fatigue resistance when compared to ground surfaces. Tools with fresh cutting edges and larger contact area—like round inserts—induce more compressive residual stresses in a deeper region [5, 6].

There is a trend toward the use of PCBN tool grades for turning materials belonging to class "C." This is associated with the occurrence of high flank wear rates on the cutting edges and/or the reduced cutting time when using oxide ceramic grades. Yallese et al. [7] showed that the effective of cutting time for a tool of mixed oxide ceramic grade (Al_2O_3 + TiC) in the turning of AISI D3 steel (60 HRC) is lower than 7 min, using a cutting speed of 120 m/min. On the other hand, using a PCBN tool under the same conditions, the effective cutting time was over 30 min. Poulachon et al. [8] turned four quenched and tempered steels (AISI D2, AISI H11, AISI 52100, and 35NiCrMo16) with identical hardness (54 HRC). PCBN tools and a cutting speed of 180 and 230 m/min were used. The results showed that a higher rate of flank wear (VB_B) was observed for the AISI D2 steel and, according to the authors, the appearance of large carbides with a high hardness in the workpiece is more detrimental to the cutting tool than a homogeneous martensitic structure, even if the macrohardness is the same for all of the machined materials.

According to the limited publications available, the machining of components based on materials from class "D" is mainly carried out using hybrid or non-traditional processes. Masood et al. [9] used a hybrid process called laser-assisted machining, which combines laser technology with traditional machining methods, for the turning of high-chromium white cast iron. The concept involves focusing a laser beam (power of 1.38 kW and diameter of 1.4 mm) on the workpiece surface before the cutting edge of the turning tool. The results revealed that localized heating—with temperatures exceeding 1, 000 °C on the workpiece surface—promoted a reduction in the cutting and feed forces (24 and 22 %, respectively) when compared to turning without the use of a laser beam. On the other hand, difficulties with the application of laser-assisted machining in an industrial environment are related to the laser application distance and the positioning for the various cutting tools (drills, boring, and milling tools). Electro-discharge machining (EDM) is widely used with hard materials such as high-chromium white cast iron. However, a drawback is that only 15 % of the molten material is removed by flushing, while the remainder resolidifies on the workpiece surface to produce a re-cast layer. The extreme thermal and transformation stresses generated in the re-cast layer may also produce extensive surface cracks. The presence of these surface cracks and tensile residual stresses may negatively affect the material performance when submitted to mechanical loads [10].

An improved understanding of machined materials with a high volume fraction of carbides will allow the use of high-chromium white cast iron in a wide range of applications, which is limited due to manufacturing difficulties. Therefore, understanding tool life, superficial roughness and the final microstructure of the workpiece are essential for application in the large-scale machining of the material. The aim of this work was to evaluate the feasibility of turning high-chromium white cast iron (28 wt% of carbides in the microstructure) using two grades of PCBN cutting tools in continuous and interrupted cutting. Analysis of the effective cutting time, wear mechanisms, surface roughness, and microstructure of the chips and the machined surface was carried out to gain a better understanding of the process.

2 Material, equipment, and experimental procedures

The experiments were carried out in a horizontal turning center manufacturer by Romi, model GL 240, with 15 kW of power in the spindle motor and a speed rotation range of 4 to 4,500 rpm.

The workpiece material was high-chromium white cast iron, and it was characterized through determining the microstructure, hardness and chemical composition. The high-chromium white cast iron microstructure is composed of chromium carbides in a pearlitic matrix. Carbides are dispersed in the matrix, and their size is heterogeneous, with a length greater than 150 μm. The average hardness was 1,329 HV for the carbides and 492 HV for the matrix. The chemical composition indicated that the material is classified as grade II and type E, according to ASTM A532 [11].

The workpieces were designed to promote continuous and interrupted cutting, and the geometry adopted in this research was based on the work of Diniz and Oliveira [12]. Figure 1a, b shows the continuous and interrupted cutting workpieces, respectively.

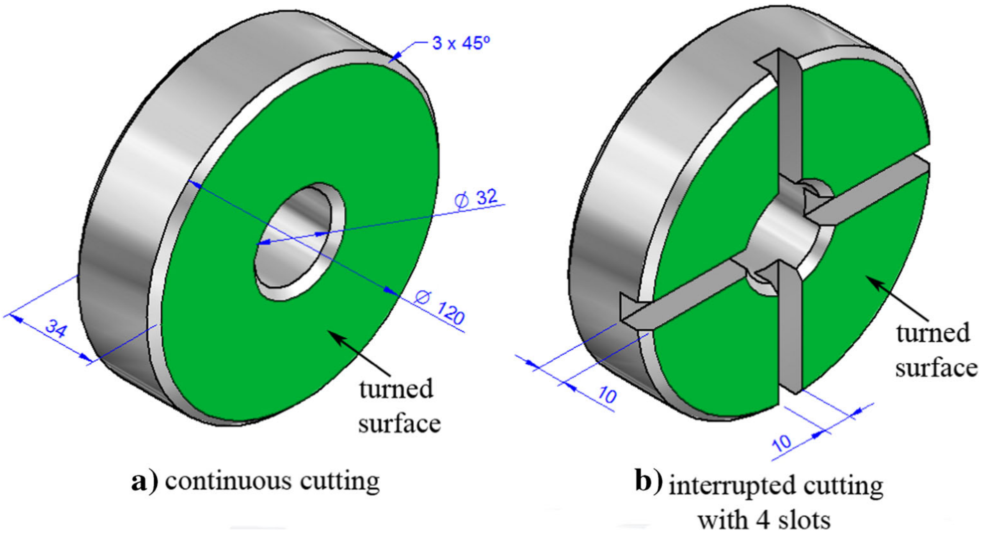
According to Fig. 1a, b, in order to minimize the shocks and avoid chipping on the cutting edge at the entrance and exit of the tool, chamfers were formed along the outer and inner workpiece edges (3 mm×45°). During the experiment, the chamfers were turned again when they were reduced to 0.5 mm×45°.

The experiments were based on a factorial design with two factors and two variables. The factors were PCBN grade and cutting type. The PCBN grade variables were: (a) high content of CBN (Sandvik grade 7050 or ISO H05, code SNGA 120412) and (b) low content of CBN with a ceramic phase added (Sandvik grade 7025 or ISO H20, code SNGA 120412). These tools were assembled on a tool holder (code PSKNL-2020K-12) and clamped with a top clamp and center pin combination aiming to promote high rigidity of the insert and, consequently, avoid chipping during the machining. Cutting type variables were: (a) continuous and (b) interrupted cutting, which occurs when the workpiece face is turned (see Fig. 1a, b).

The cutting conditions used were: cutting speed (v_c)= 200 m/min, feed (f)=0.08 mm/rev, and depth of cut (a_p)= 0.15 mm. There is restricted information available on the cutting parameters for high-chromium white cast iron in the manufacturer's tool catalog due to the limited industrial applications. Parameter specifications are based on the turning of materials belonging to class "C". Yallese et al. [13] turned AISI D3 quenched and tempered steel (60 HRC) with 7020 PCBN grade—a generation before the PCBN 7025 grade used in this work—with a cutting speed of 180 m/min and obtained an effective cutting time of close to 15 min. The aim of defining these cutting parameters, especially the cutting speed, is to promote the occurrence of different wear mechanisms on the cutting edges. Furthermore, the use of these parameters can demonstrate the technical and economic feasibility of turning high-chromium white cast iron.

One experiment consisted of successive radial turning passes on one of the surfaces (from larger to smaller diameter, i.e., using a variation in the rotation to maintain the cutting speed at 200 m/min), as shown in Fig. 1 using the same cutting edge, up to the moment, the tool reached the end of its life. Each experiment was carried out three times. Dry cutting was used for all experiments.

Flank wear was inspected several times during the tool life, using an optical microscope. Tool life was considered to have ended when the flank wear reached VB_B=0.20 mm. At the end of the tool life, the worn inserts were examined under a scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDS) system in an attempt to understand the wear mechanisms. The surface roughness was monitored



a) continuous cutting

b) interrupted cutting with 4 slots

Fig. 1 Workpiece geometry used for turning experiments to promote: **a** continuous cutting and **b** interrupted cutting (×4) during the tool life. For this analysis, the experiments were interrupted every 2.5 min (effective cutting time), and a portable roughness meter was used, which was adjusted to measure 5 sampling lengths (λc) of 0.8 mm.

Chip samples were collected during the first pass of each cutting edge in order to characterize differences in the morphology as a function of the turning. Also, specimens were removed from the workpiece in order to verify changes in the subsurface layers promoted by heat and mechanical loads from the cutting. The removal of samples was carried out with abrasive jet machining in order to avoid thermal damage to the material. After metallographic preparation, chips and the turned surface samples were examined under an optical microscope equipped with a digital camera.

3 Results and discussions

3.1 Tool life

Figure 2 shows the results for the tool life in all experiments based on both the cutting time and turned area. Although it is true that the tool–workpiece contact time is shorter when interrupted cut is tested, the time for turning a workpiece face is the same. For this reason, a separate assessment of the tool life was performed.

Despite the severe cutting conditions applied in these experiments, considering the interrupted cutting and the high fraction of carbides in the workpiece bulk microstructure, catastrophic failures were not observed on the PCBN cutting edges. This is the first indicator of the feasibility of implementing these machining conditions in industrial environments. All experiments were finished at the limit of the tool life (VB_B=0.2 mm).

According to the analysis of variance results, considering a 90 % confidence interval, the workpiece geometry and tool grade significantly influenced the tool life. The low CBN content grade (CBN 7025) showed better performance in the continuous cutting compared to interrupted cutting. The addition of a ceramic phase in low-content CBN grades promotes a reduction in the thermal conductivity from 100 (high-content CBN) to 44 W m^{-1} K^{-1} (low-content CBN). Thus, it is assumed that a larger portion of the heat load is conducted to the chip and workpiece, contributing to the fact that the low-content CBN grade (CBN 7025) supports, more efficiently, the high temperature and tribological conditions imposed during the continuous cutting of high-chromium white cast iron. However, the presence of the ceramic phase reduces the hardness and toughness of PCBN grades, which are fundamental properties in turning under interrupted conditions. These factors suggest a considerable reduction in the tool life for interrupted cutting with CBN 7025. This point will be demonstrated in greater detail in relation to the tool wear mechanism [14, 15].

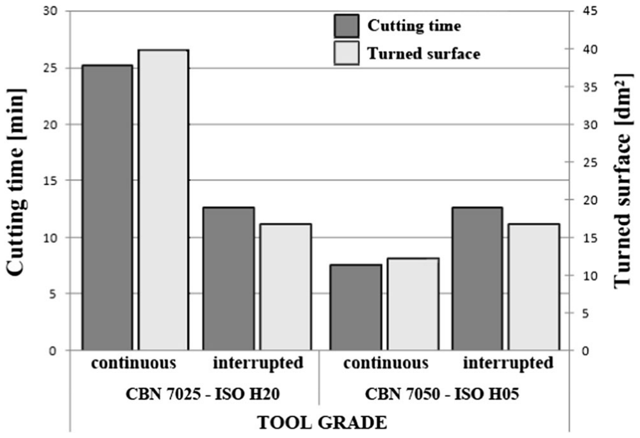


Fig. 2 Tool life for all experiments

Figure 2 also shows a different behavior, in terms of tool life, when high CBN content grade (CBN 7050) was used. In this case, interrupted cutting promoted a slight increase in tool life, which was 1.38 times longer than in the case of continuous cutting (the hypothesis for this phenomenon will be discussed below). The results obtained in this study for high-content CBN grades (CBN 7050) in continuous and interrupted cutting are similar to those reported by Diniz and Oliveira [12] and Oliveira et al. [3]. For an industrial application, there is strong evidence that the application of PCBN tools in interrupted cutting promotes better performance for materials classified as class “A”.

An interesting result in this study is that using a newer PCBN grade for the turning of high-chromium white cast iron, the tool life was inverted. In other words, for materials classified as class “D”, using low-content CBN grades, a better performance was obtained for continuous cutting. Under this condition, the results were in contrast to those obtained by Diniz and Oliveira [12] and Oliveira et al. [3]. However, it is noteworthy that in these previous studies AISI 4340 steel with 56 HRC (material classified as class “A”) were turned.

Smith [16] reported that high-content CBN grades (i.e., CBN 7050) have approximately 90 % of CBN particles and the binder phase is generally cobalt. Thus, these tools have high values for the thermal conductivity and strong chemical affinity for high-chromium white cast iron when compared to low-content CBN grades. The high temperature and chemical affinity of the high-content CBN grade for the material being machined promotes binder phase dissociation in the tool substrate, facilitating wear mechanisms such as abrasion, caused by the hard particles present in the turned material microstructure. A further source of abrasive wear of the flank face is the CBN particles dissociated from the substrate, which can cause three-body abrasion [17].

Besides the inherent properties of low-content CBN grades, an additional hypothesis to explain the longer cutting time for CBN 7025 in continuous cutting is related to the inhibition of borides during the PCBN sintering process, especially TiB_2 and similar compounds. Materials of this generation of PCBN grades are almost free of TiB_2, which promotes better cutting edge resistance to fracture and microchipping as well as a slight increase in the tool life. Improved cutting edge resistance suggests that the tool wear mechanism was predominantly abrasive, inhibiting microchipping. In the turning of high-chromium white cast iron, for some PCBN grades in continuous cutting, shocks between the hard carbides—present in the workpiece—and the cutting edge in the presence of high temperatures have a worse effect on the tool life than the shocks promoted by interrupted cutting [18].

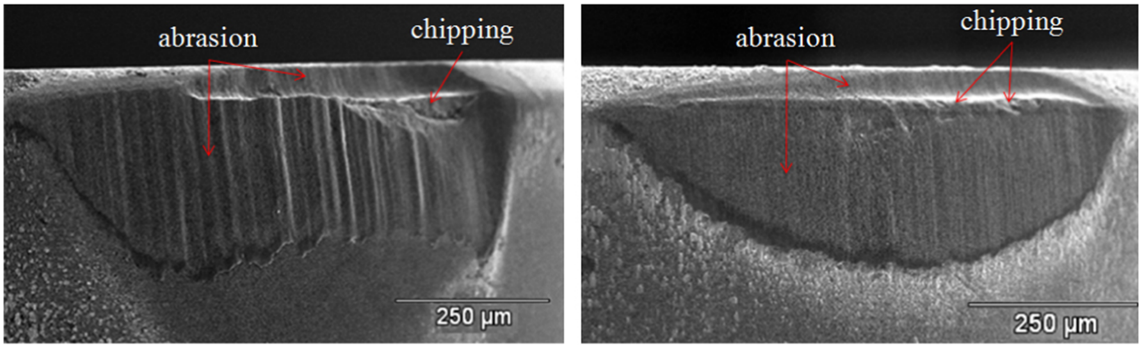
The cutting edge resistance and crack inhibition of CBN 7025 grade suggested that the sintering process has been strongly improved for this tool generation. A patent describes improvements in low-content CBN grade, adding ZrN at levels of 2 to 10 % to the binder phase and controlling the amount of Al. ZrN addition improves the cutting tool performance in continuous cutting without reducing the tool life in interrupted cutting, considering the hypotheses that ZrN addition acts as a lubricant, reducing the heat generated by friction, besides acting as an inhibitor of crack propagation. This patent may point the way toward future improvements in tool life for continuous and interrupted cutting when using PCBN tools for turning high-chromium white cast iron and similar materials which are difficult to machine [19].

The results reported herein infer that CBN 7025 grade (low-content CBN) promotes better performance in the turning of high-chromium white cast iron in continuous cutting. On the other hand, in interrupted cutting, the two CBN grades promoted similar performance. Furthermore, CBN 7050 grade (high CBN content) is not recommended for cases which require both continuous and interrupted cutting for materials composed of a volume fraction of carbides above 15 wt. %. Details regarding the wear mechanisms which led to this conclusion will be detailed in the next section.

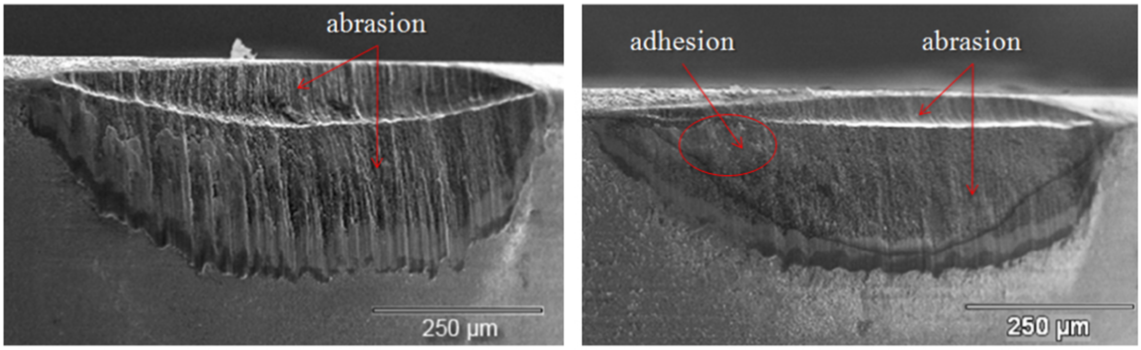
3.2 Tool wear mechanisms

Figure 3 shows images of the worn flank face (taken by in a SEM) for all cutting conditions at the end of the tool life.

On analyzing the CBN 7025 cutting edge for continuous cutting, a condition which promoted longer tool life, abrasive marks can be observed in the cutting direction on the flank and rake faces (Fig. 3a). This wear topography corresponds to an abrasion mechanism [20, 21]. Compared to the other images in Fig. 3, these abrasive marks are more pronounced (the topography differs from that of other worn cutting edges, as discussed below). As seen in Fig. 3, for all conditions, the edge microgeometry was consumed by wear. Furthermore, on using CBN 7025 grade in continuous cutting (Fig. 3a), the cutting edge was extremely weakened, such that the rake angle changed from negative to positive (considering the



A) CBN 7025 – Continuous Cutting **B)** CBN 7025 – Interrupted Cutting



C) CBN 7050 – Continuous Cutting **D)** CBN 7050 – Interrupted Cutting

Fig. 3 View of the worn flank face

crater formed). Microchipping shown in Fig. 3a was observed only at the end of the tool life is important to highlight; however, even with the notable change in geometry, the cutting edge endured the severe machining conditions, notably resisting the cyclic mechanical shocks promoted by the carbides from the machined material on the cutting edge. One hypothesis to explain the cutting edge strength is directly related to the patent published by Dahl [18]. As previously mentioned, Dahl suggested that the inhibition of borides during the PCBN sintering process, particularly TiB_2 and similar compounds, promotes better cutting edge resistance to fracture and microchipping. Moreover, the addition of a ceramic phase as a binder in low-content CBN grade reduces the thermal conductivity, thus inhibiting the diffusion mechanism [15].

Also, regarding the cutting edge strength in the case of low-content CBN grade, Fig. 3b shows an edge used in interrupted cutting. Along this cutting edge, there is mainly evidence of the abrasion mechanism on the rake and flank face. However, the abrasive marks are shallower when compared to the previous condition described. In addition to the abrasive wear (Fig. 3b), the presence of several microchips can be observed. Although microchipping did not hinder the cutting edge action, it accelerated tool wear through peeling in the wear region and the displacement of these small fragments caused strong abrasion on the cutting edge surfaces.

The wear topographies shown in Fig. 3a, b (same CBN grade) differ in relation to the depth of the abrasive scratches and also the distribution of the wear marks along the flank face. In the case of continuous cutting, the flank wear is regularly distributed along the contact flank face land. For interrupted cutting, it can be noted that the flank wear is less severe at the ends, near the secondary cutting edge, and this is termed VB_C wear according to ISO 3685 [22]. Homogeneous flank wear along the entire edge was identified by Diniz and Oliveira [12] in the continuous and interrupted turning of AISI 4340 steel (class A) and Grzesik [15] in the continuous turning of AISI 5140 (class A). Both authors attributed VB_C wear to the reduced chip thickness in the secondary cutting edge region, causing a material side flow and increased specific cutting pressure.

One explanation for the curved distribution of the flank wear shown in Fig. 3b is related to the material microstructure and process temperature. The high-chromium white cast iron microstructure is heterogeneous and consists primarily of a pearlite matrix with large chromium carbides (greater than 150 μm) in scaffold form, which promotes a very rigid structure. In the case of steels machined by Diniz and Oliveira [12] and Grzesik [23], the microstructures are homogeneous (tempered martensite) and susceptible to deformation at elevated temperatures promoted by shear. The rigid structure of white cast iron inhibits chip side flow in the secondary cutting edge region, along with the large carbides anchored in the matrix and the lower temperatures associated with interrupted cutting. The reason for the lower temperature in interrupted cutting is that for each quarter turn the cutting edge touches a region of the workpiece without close contact with the shearing region due to the presence of channels. This phenomenon promotes the curved abrasive land wear along the flank face.

Similar wear land characteristics were observed by Arsecularatne et al. [17] in the turning of material classified as class C. Furthermore, a topographical comparison suggests that the heat generated during continuous cutting promotes a reduction in the tool substrate hardness, thus allowing the rigid structure of carbides in the machined material to form deeper marks in the worn topography.

High-content CBN grades typically have a metallic material as the binder and thus they have similar hardness and higher toughness compared to low-content CBN grades [15]. Despite the difference in the properties, the same tool life was observed in interrupted cutting for the two grades (CBN 7025 and CBN 7050) and the wear land topographies were very similar. However, some differences can be highlighted in relation to the wear mechanism. The wear topography on the CBN 7050 cutting edge, shown in Fig. 3d, suggests that the main wear mechanism was also abrasion on the rake and flank faces. The absence of microchips is directly related to the increase in toughness as a function of the substrate composition for high-content CBN. In relation to the cutting edge, the presence of an adhesion mechanism was also observed for the secondary cutting edge. Figure 4 shows details of the adhesion on the CBN 7050 cutting edge applied in interrupted cutting.

This wear mechanism is mainly observed in machining at low temperature (as suggested in this application) and is dependent on the chemical interaction between the tool substrate and the workpiece [24]. EDS analysis (detail "A" of Fig. 4) identified high levels of Fe and Cr, chemical elements present in the workpiece composition, providing evidences adhesion. Adhesion of the workpiece material on PCBN cutting edges in interrupted cutting was also observed by Ko and Kim [25], in the turning of material classified as class B.

Figure 3c shows the CBN 7050 cutting edge wear topography after continuous cutting. Intense abrasive marks can be seen on the rake and flank faces. Although the cutting edge topography only shows evidence of the abrasion mechanism, diffusion cannot be discarded. The binder material in high-content CBN grades (usually metallic) has a strong chemical affinity with the workpiece material and continuous cutting (high temperature) promotes conditions suitable for the diffusion mechanism. Moreover, the high temperature reached in continuous cutting promotes a significant reduction in the binder material strength, facilitating the dissociation of the CBN particles from the substrate, which could contribute to the abrasive wear (three-body abrasion). In addition to the complex tribological system, due to the cutting edge strength reduction, carbides in the workpiece material microstructure

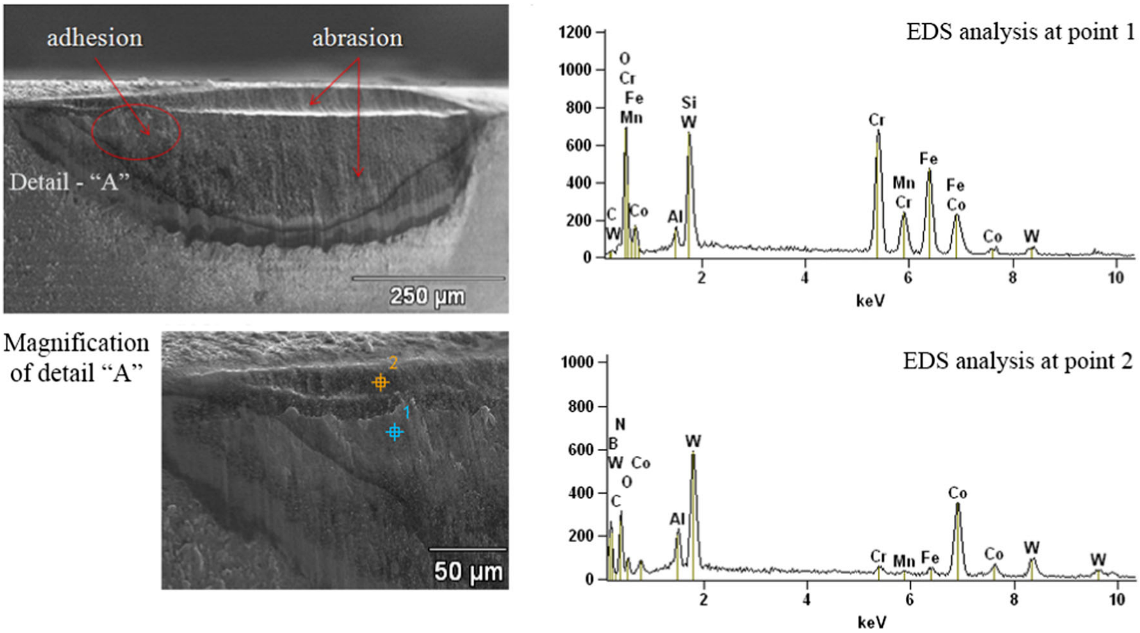


Fig. 4 Evidence of adhesion on CBN 7050 cutting edge in interrupted cutting

act more severely as abrasive agents, resulting in higher wear rates. However, the wear topography of the CBN 7050 cutting edge land (high-content CBN) differs significantly from that of the other grades. Considering that the cutting edge was relatively low compared to the initial baseline, it seems that this phenomenon is directly related to the grade properties being inappropriate for continuous cutting applications (see cutting time in Fig. 2). However, no chipping or catastrophic failure was observed for this condition, highlighting the appropriate relationship between the hardness and toughness properties in the grades with a high-content of CBN.

Although the workpiece material with a high volume fraction of carbides in the microstructure was turned under severe conditions (interrupted cutting and cutting speed of 200 m/min), there were no catastrophic failures on the cutting edges. Abrasion was the main wear mechanism observed with the exception of the CBN 7050 grade in interrupted cutting. In this case, there was evidence of adhesion of the workpiece material mainly on the secondary cutting edge. Microchipping was only observed for the CBN 7025 grade (low-content CBN), in continuous and interrupted cutting. Under all conditions analyzed there was no clear evidence of a diffusion wear mechanism.

3.3 Surface integrity

The surface integrity was analyzed considering two variables: surface roughness and microstructural modification of the turned subsurface. The surface roughness is directly related to the turning operation kinematics, insert radius, feed rate, and progression of the worn topographies, among other random phenomena inherent to the process. For all cutting conditions investigated, the turned surface roughness values increased along the tool life. Figure 5 shows the evolution and the change in the grade (according ISO 1302 [26]) of the surface roughness during the tool life.

As shown in Fig. 5, interrupted cutting promoted lower surface roughness values when compared to continuous cutting, considering the parameter Ra. One hypothesis for this behavior is connected to the flank wear topography of the cutting edges, since the other parameters that influence the surface roughness were held constant. Based on Fig. 3, it is suggested that the continuous cutting conditions caused greater modification of the cutting edge geometry (mainly on the secondary cutting edge—Fig. 3a). The higher roughness values for the continuous cutting could be due to the fact that, mainly at the end of the tool life, the presence of relatively deep scratches in the cutting direction on tool flank surface are

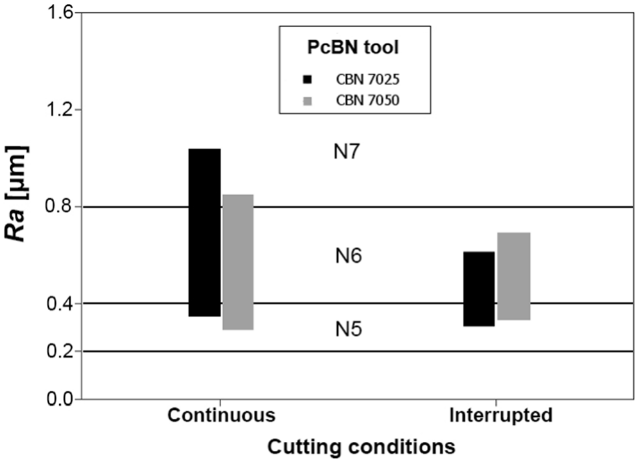


Fig. 5 Roughness values (Ra) for continuous and interrupted turning of high-chromium white cast iron

reproduced on the turned surface. Regarding the flank surfaces used in interrupted cutting, see Fig. 3b, d, a smoother appearance can be noted when compared to those used in continuous cutting. A similar influence of the tool wear topography on the roughness values has been previously reported by Penalva et al. [27] and Yallese et al. [13].

The surface roughness values, at the end of the tool life, remained within the N6 grade (up to 0.8 μm on the Ra scale) for interrupted cutting. However, in continuous cutting, the 7050 grade reached surface roughness values corresponding to the transition region between N6 and N7 grades. Therefore, in continuous cutting, surface roughness values using 7025 grade (low CBN) promote a change during the tool life from N5 grade at the beginning to N7 grade at the end. The N6 grade corresponds to typical roughness (Ra) values reported in the literature by various authors for the end of tool life, including: Bouacha et al. [28], in the turning of AISI 52100 with 64 HRC using low-content CBN grades; Ko and Kim [25] in the interrupted turning of AISI E52100 with 62 HRC using high and low CBN grades; and Yallese et al. [7], in the turning of AISI D3 tool steel with low CBN grades.

The surface roughness results showed lower values for the turning of high-chromium white cast iron, but for good reliability and application in an industrial environment it is necessary to understand the microstructure of the layers below the turned surface. In this regard, chip analysis provides an initial indication. Figure 6 shows the initial high-chromium white cast iron microstructure and also the morphology of the chips.

All chips analyzed were morphologically classified as segmented, characterized by a distinct lamellar formation and a format similar to saw teeth. According to Fig. 6b, irregular frequency of the lamellar formation occurred due to the microstructural heterogeneity of the workpiece material, which promoted the nucleation and propagation of cracks on the shear plane at different positions (different frequency) for the segmented chip formation. Another hypothesis to explain this phenomenon is the presence of thermoplastic catastrophic shear, also known as adiabatic shear [21, 29].

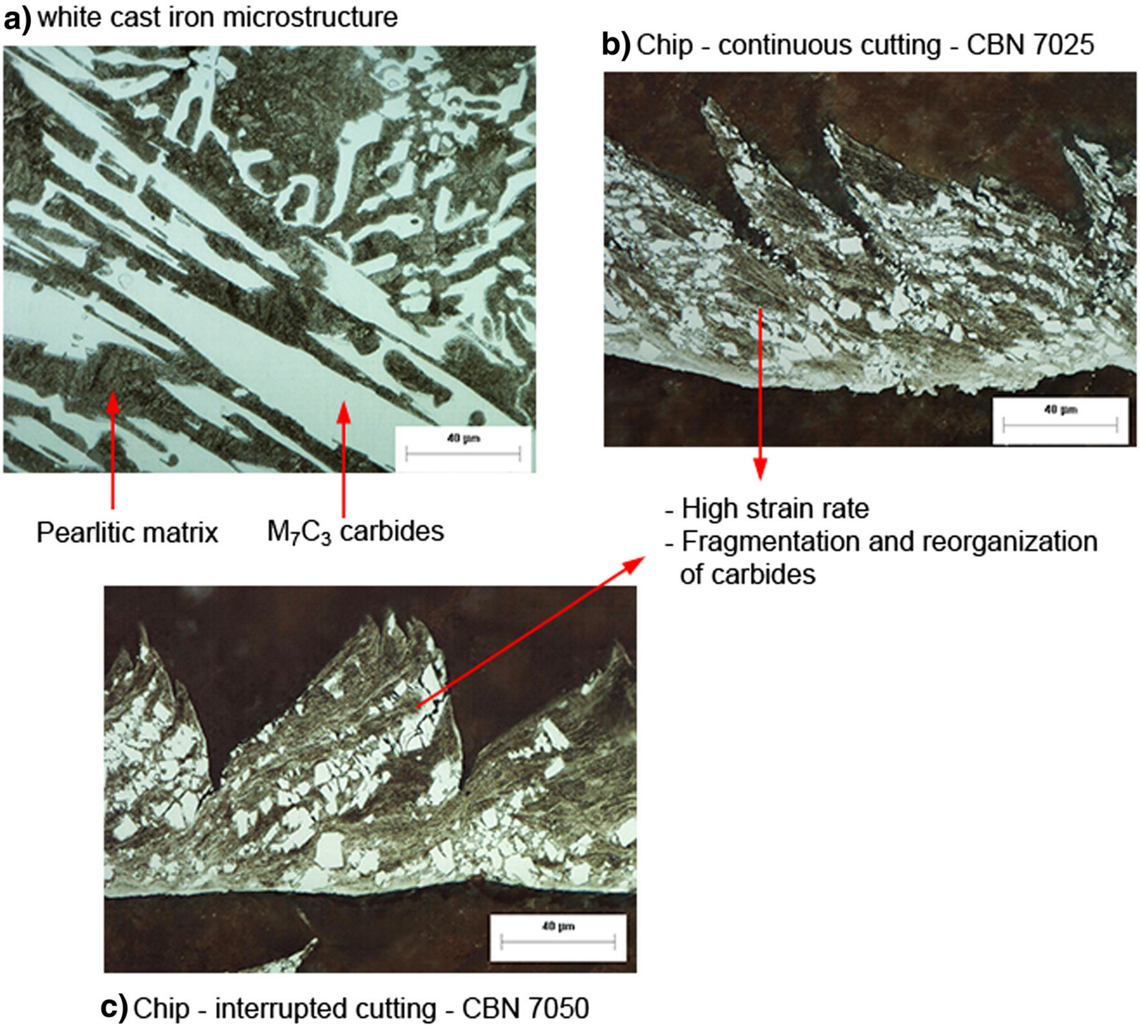


Fig. 6 High-chromium white cast iron microstructure. **a** initial microstructure, **b** chip morphology turned with CBN 7025 grade in continuous cutting, and **c** chip morphology turned with CBN 7050 grade in interrupted cutting

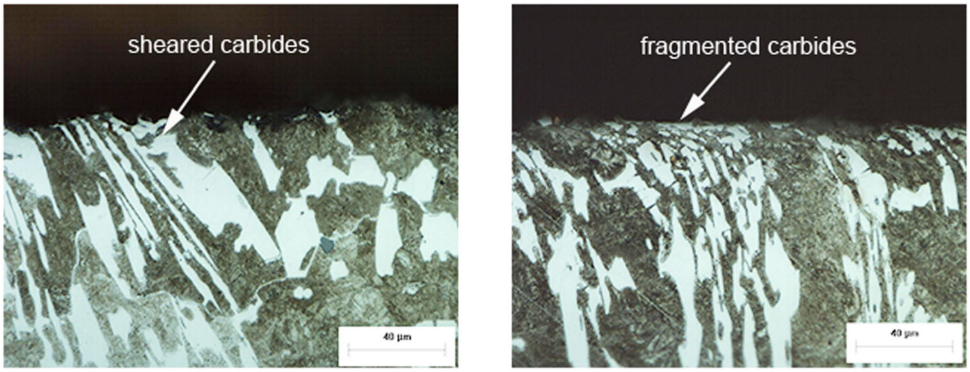
The most interesting and unexpected phenomenon is the fragmentation of M_7C_3 chromium carbides in the chips. On analyzing Fig. 6b, c, a clear difference between the sizes of the carbides in the material before (larger than 100 μm) and after (not exceeding 10 μm) turning is apparent. Another interesting aspect of the chip microstructure is that the carbides were repositioned in the matrix with a preferred alignment direction, apparently following the direction of the shear plane. This phenomenon was also observed by Ren et al. [30] in the machining of high chromium hardfacing materials. According to these authors, this is related to the high rates of elastic and plastic deformations of the material during the chip formation. The low fracture resistance of the carbides and the cutting temperature at the chip-tool interface also are related to this phenomenon.

The fragmentation of the carbides in the chips suggests that the same phenomenon may occur on the machined surface, altering the surface properties, such as ductility, fracture toughness, and wear resistance. This can represent a significant advantage in the application of high-chromium white cast iron in new segments, since the turning operation can be applied as a step in the surface preparation and modification. Figure 7 shows the integrity of the layer below the turned surface at the beginning and end of the tool life.

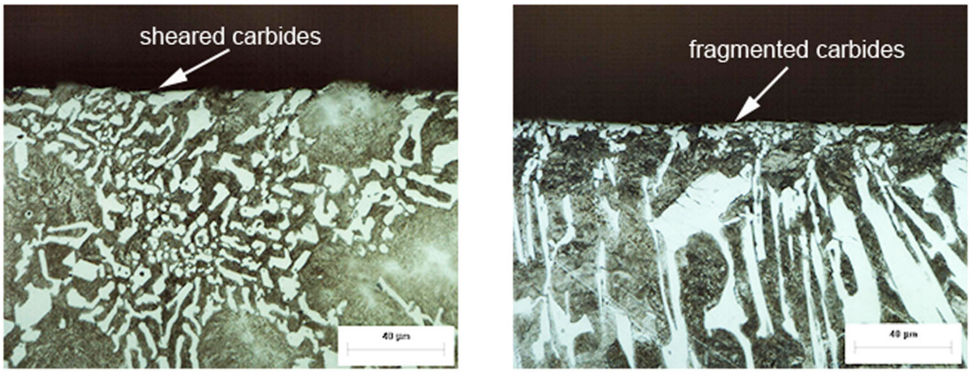
Figure 7 shows the changes promoted by the cutting edge action at the beginning and end of the tool life. Figure 7a, c shows the changes promoted by the CBN 7025 tool in the first pass of continuous and interrupted cutting. Under these conditions, the edges show no significant geometric changes suggesting that during cutting the carbides were sheared efficiently or were pulled from the matrix material. On the other hand, Fig. 7b, d shows that, at the end of the tool life, carbides were fragmented in a layer approximately 10 μm below the turned surface. An explanation for this is that, at the end of the tool life, cutting edge undergoes a gradual loss of material (see Fig. 3) leading to a larger area of contact between the tool flank surface and the workpiece material. This could inhibit the shear of the carbides, which are fragmented and rearranged in the matrix material.

Considering the carbide fragmentation in the layers below the turned surface, shown in Fig. 7b, d, with regard to promote subsurface modifications, the use of a round or wiper tool geometry is recommended. Such geometries would promote a larger area of contact in the secondary cutting region (promoting high specific cutting pressure) with the turned material and also carbide fragmentation through plastic and elastic deformations during chip formation. This condition could also improve the surface roughness because the secondary cutting edge is mainly responsible for the formation of a smooth surface. Conversely, a larger area of tool-workpiece contact can reduce the tool lifetime.

Superficial integrity modifications observed in Fig. 7, especially at the end of tool life, can alter the surface properties



a) CBN 7025 - first pass - continuous cutting **b)** CBN 7025 - worn tool - continuous cutting



c) CBN 7025 - first pass - interrupted cutting **d)** CBN 7025 - worn tool - interrupted cutting

Fig. 7 Integrity of the layer below the turned surface at the beginning and end of the tool life of the component, resulting in greater wear resistance, ductility and fracture resistance by inhibiting the spread of cracks. These modifications may expand the scope for the industrial application of high-chromium white cast iron, or even enhance the performance of existing applications. In this regard, further research needs to be carried out to determine the conditions under which the microstructural modifications can be beneficial.

4 Conclusions

Based on the results obtained in these experiments it can be concluded that in the turning of high-chromium white cast iron with a PCBN tool:

- The low-content CBN grade (7025) showed better performance in the turning of high-chromium white cast iron in continuous cutting. For interrupted cutting, the two PCBN grades (7025 and 7050) showed similar results.
- Catastrophic failure or chipping on the PCBN cutting edges was not identified, verifying that the grades and set up used in the experiments provided appropriate stiffness to perform hard turning operations promoted by high-chromium white cast iron.
- The main wear mechanism observed was abrasion, however, adhesion was also observed for high-content CBN grade (7050) in interrupted cutting. Microchipping was only identified for low-content CBN grade (7025) in continuous and interrupted cutting.
- Segmented chips were observed for all machining conditions. The M_7C_3 primary chromium carbides present in the microstructure of the workpiece material were fragmented and rearranged in the chip.
- The surface roughness, at the end of tool life, remained within the standard N6 (up to 0.8 μm on the Ra scale), except for the low-content CBN grade (7025) in continuous cutting, for which N7 class was achieved.
- Important microstructural modifications in the layer below the turned surface were observed, especially at the end of tool life, where the carbides in the workpiece microstructure were fragmented and rearranged in the matrix material.

Acknowledgments The authors wish to thank Sandvik Coromant for the tools supplied for the experiments and also for support during the experiments and analysis of the results.

References

1. Berns H, Theisen W (2008) Ferrous materials: steels and cast iron. Springer, Leipzig
2. Boing D (2010) Analysis of PCBN tool life in turning of high chromium white cast iron. Dissertation, Educational Society of Santa Catarina, http://www.sociesc.org.br/pt/pesquisa/conteudo.php?&lng=2&id=810&mnu=1323&top=0&crs=140. Accessed 20 Jan 2014
3. Oliveira AJ, Diniz AE, Ursolino DJ (2009) Hard turning in continuous and interrupted cut with PCBN and whisker-reinforced cutting tools. J Mater Process Technol 12–13:5262–5270
4. Hashimoto F, Guo YB, Warren AW (2006) Surface integrity difference between hard turned and ground surfaces and its impact on fatigue life. CIRP Ann 55:81–84
5. Choi Y, Liu R (2006) Rolling contact fatigue life of finish hard machined surfaces. Part 2. Experimental verification. Wear 261: 492–499
6. Matsumoto Y, Hashimoto F, Lahoti G (1999) Surface integrity generated by precision hard turning. CIRP Ann 48:59–62
7. Yallese MA, Rigal J-F, Chaoui K, Boulanouar L (2005) The effects of cutting conditions on mixed ceramicand cubic boron nitride tool wear and on surface roughness during machining of X200Cr12 steel (60 HRC). Proc Inst Mech Eng B J Eng 219:35–55
8. Poulachon G, Bandyopadhyay BP, Jawahir IS, Pheulpin S, Seguin E (2004) Wear behavior of CBN tools while turning various hardened steels. Wear 256:302–310
9. Masood SH, Armitage K, Brandt M (2011) An experimental study of laser-assisted machining of hard-to-wear white cast iron. Int J Mach Tools Manuf 51:450–456
10. Tabrett CP (1996) The electro-discharge machining surfaces of high-chromium white irons. J Mater Sci Lett 15:1792–1794
11. ASTM Standard A532 (1993) Specification for steel castings, ferritic and martensitic, for pressure containing parts, suitable for low temperature service. ASTM International, West Conshohocken
12. Diniz AE, Oliveira AJ (2008) Hard turning of interrupted surfaces using CBN tools. J Mater Process Technol 1–3:275–281
13. Yallese MA, Chaoui K, Zeghib N, Lakhdar B, Rigal JF (2009) Hard machining of hardened bearing steel using cubic boron nitride tool. J Mater Process Technol 209:1092–1104
14. Koch KF (1996) Technologie des Hochpräzisions-Hartdrehens. Dissertation. RWTH Aachen
15. Grzesik W (2008) Advanced machining processes of metallic materials—theory, modelling and applications. Elsevier, Amsterdam
16. Smith GT (2008) Cutting tool technology. Springer, London
17. Arsecularatne JA, Zhang LC, Montross C, Mathew P (2006) On machining of hardened AISI D2 steel with PCBN tools. J Mater Process Technol 171:244–252
18. Dahl L (2010) Cubic boron nitride cutting tool insert with excellent resistance to chipping and edge fracture. United States patent US 7, 670,980 B2
19. Malik AS (2012) Sintered cubic boron nitride cutting tool. United States patent US 2012/0000138 A1
20. Astakhov VP (2006) Tribology of metal cutting. Elsevier, Amsterdam
21. Trent EM, Wright PK (2000) Metal cutting. Butterworth-Heinemann, Woburn
22. Int. Org. for Standardization. ISO 3685 (1993) Tool-life testing with single-point turning tools
23. Grzesik W (2008) Influence of tool wear on surface roughness in hard turning using differently shaped ceramic tools. Wear 265:327–335
24. Klocke F, König W (2008) Fertigungsverfahren 1 - Drehen, Fräsen, Bohren, Springer
25. Ko TJ, Kim HS (2001) Surface integrity and machinability in intermittent hard turning. Int J Adv Manuf Technol 18:168–175
26. Int. Org. for Standardization. ISO 1302 (2002) Geometrical product specification (GPS)—indication of surface texture in technical product documentation.

27. Penalva ML, Arizmendi M, Diaz F, Fernández J, Katz Z (2002) Effect of tool wear on roughness in hard turning. CIRP Ann 51: 57–60
28. Bouacha K, Yallese MA, Mabrouki T, Rigal JF (2010) Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool. Int J Refract Met Hard Mater 28:349–361
29. Shaw MC (2004) Metal cutting principles. Oxford University Press, New York
30. Ren XJ, James RD, Brookes EJ, Wang L (2001) Machining of high chromium hardfacing materials. J Mater Process Technol 115:423–429