Int J Adv Manuf Technol (2011) 57:541–553
DOI 10.1007/s00170-011-3320-8

ORIGINAL ARTICLE

Performance evaluation of CBN, coated carbide, cryogenically treated uncoated/coated carbide inserts in finish-turning of hardened steel

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Received: 28 June 2010 / Accepted: 4 April 2011 / Published online: 4 May 2011

Abstract In the present work, the performance of cubic boron nitride (CBN) inserts was compared with coated carbide and cryogenically treated coated/uncoated carbide inserts in terms of flank wear, surface roughness, white layer formation, and microhardness variation under dry cutting conditions for finish turning of hardened AISI H11 steel (48–49 HRC). The flank wear of CBN tools was observed to be lower than that of other inserts, but the accumulated machining time for all the four edges of carbide inserts were nearer to or better than the PCBN inserts. Results showed that tool life of carbide inserts decreased at higher cutting speeds. The surface roughness achieved under all cutting conditions for coated-carbide-treated/untreated inserts was comparable with that achieved with CBN inserts and was below 1.6 μm. The white layer formation and microhardness variation is less while turning with cryogenically treated carbide inserts than the CBN and untreated carbide. At low to medium cutting speed and feed, the performance of carbide inserts was comparable with CBN both in terms of tool life and surface integrity.

Keywords CBN · Coated carbide · Cryogenic treatment · Hard turning · MAZ

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1 Introduction

For finish machining of hardened steel, apart from grinding, hard turning has gained considerable attention. Hard turning is a fine finishing process in which rough machining and grinding can be eliminated [1, 2]. Polycrystalline cubic boron nitride (PCBN) tools are the preferred tool materials for machining of hardened steel [3]. However, the difficulty associated with compact CBN processing (high temperature and high pressure) and the high cost of CBN tools, have shifted the challenges for hard turning from technological feasibility to economical viability [4]. Apart from CBN tools, studies on use of ceramics and carbide tools for finish hard turning, under dry and wet conditions, have also been reported in the literature [5–8]. In recent years, tool manufacturers have provided wiper geometry on carbide cutting tools for turning applications with the purpose of increasing productivity and improving surface finish (www.coromant.sandvik.com). The use of wiper geometry tool resulted in fine surface finish as compared to grinding, in finish turning of hardened steel [9]. Advanced tool coatings with high temperature withstanding capacity on very fine, wear-resistant carbide substrate seem to be potential alternative to CBN tools within a particular range of workpiece hardness [4, 6, 9].

Cryogenic treatment is the process of cooling a material to −196°C, which helps in extending the tool life of tungsten carbide inserts and other tool steels [10, 11]. Deep cryogenic treatment of carbide inserts led to improvement in thermal conductivity and hot hardness value of the inserts. It resulted in lower tool wear, cutting forces, and surface roughness in comparison to untreated inserts [12]. Cryogenically treated tungsten carbide tools had much greater resistance to chipping compared to the untreated ones. Also these tools performed better than the untreated ones at higher cutting speeds. Finally, it was concluded that increase in wear resistance was due to an increase in the number of Z-phase particles after cryogenic treatment, and it was confirmed on the basis of photographs taken by a scanning electron microscope (SEM) [13]. Cryogenic treatment improves the chipping resistance and flank wear of carbide tools but this gain in terms of tool life from cryogenic treatment is more significant at medium cutting conditions as compared to higher cutting conditions [14]. During the turning of hardened W320 (AISIH10) hot working die steel with TiN-coated cemented carbide, mixed ceramic, and PCBN tools, results indicated that cemented carbide tools performed better at low cutting speed and feed rate conditions. However, with increasing cutting speed, its performance dropped dramatically. In all cutting conditions evaluated, mixed ceramic tools did not perform well, mainly due to its low toughness. PCBN tool, at low cutting speeds was susceptible to high wear caused by chipping, but with increasing cutting speed its performance improved [7]. A comparative study of low-cost TiN-coated tools and expensive CBN tools in hard turning by using an air–oil cooling system was conducted. The author concluded that it is possible to machine hard materials at a lower cost using TiN-coated tools instead of expensive CBN tools [15]. During the turning of hardened AISI 4340 steel using CBN–TiN-coated carbide and PCBN tools, result revealed that tool life of CBN–TiN-coated carbide inserts was approximately 18–20 min per cutting edge, whereas PCBN tools produced a tool life of 32 min. The cutting forces for the CBN–TiN-coated carbide inserts were slightly higher than those of the PCBN tools due to a slightly larger nose radius and a rough surface associated with the CBN–TiN-coated inserts. A cost analysis, based on a single cutting edge, shows that the CBN–TiN-coated carbide tools are capable of reducing machining costs, and, therefore, will be an important complement to PCBN compact tools for hard turning applications [4]. In hard turning, white layer is believed to be detrimental to the part performance and can affect its tribological performance, corrosion resistance, and fatigue life [16, 17]. Microhardness is very useful in identifying metallurgical changes such as white and dark layers at various depths below the machined surface [16, 18]. Thus a part from quantification of tool wear, it is important to address the surface characteristics issues.

Literature clearly indicates that the use cryogenic treatment and wear-resistant coatings with wiper geometry help in enhancing the tool life of carbide inserts [4, 7, 14, 15]. Further the use of wiper geometry in carbide inserts results in improved surface finish [www.coromant.sandvik.com, 19]. But in literature no study has been reported regarding the comparison of cryogenically treated, coated/uncoated carbide inserts and coated carbide inserts with CBN inserts under dry conditions in turning of hardened steel. It is convincible that the use of coated carbide and cryogenically treated uncoated/coated carbide tools under dry turning may present a solution with low tool cost for finish turning of hardened steel in comparison to expensive CBN tools. There is a demand for low-cost tool materials for hard turning. This study aims to evaluate the performance of coated carbide, cryogenically treated uncoated/coated carbide and CBN inserts under dry conditions for finish turning of hardened steel. An attempt has been made to critically examine tool life and the surface characteristics produced by these tools in hard turning over a range of cutting speeds and feeds with constant depth of cut.

2 Experimental procedures

Literature reveals that the cutting speed is the most dominant factor influencing tool life, followed by feed and depth of cut [4, 20, 21]. In finish hard turning, the

Table 1 Preliminary experiment

Speed (m/min)	Feed (mm/rev)	VBmax (μm)	Type of tool	Remarks
250	0.2	90	CBN	Surface was smooth
300	0.2	112	CBN	Surface was smooth
250	0.2	229	Coated carbide treated	Too much wear
300	0.2	390	Coated carbide treated	Too much wear
250	0.2	278	Coated carbide	Too much wear
300	0.2	472	Coated carbide	Severe chipping on cutting edge
250	0.2	412	Uncoated carbide treated	Severe chipping on cutting edge
300	0.2	590	Uncoated carbide treated	Cutting edge was broken

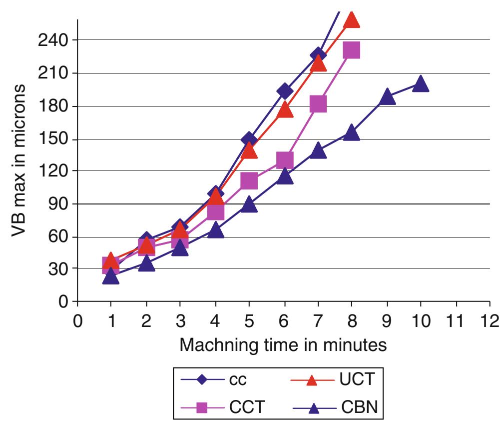


Fig. 1 Progression of maximum flank wear at *v*=95 m/min, *f*= 0.06 mm/rev

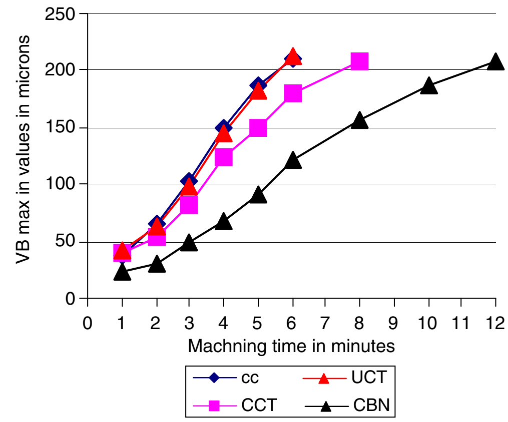


Fig. 3 Progression of maximum flank wear at *v*=137 m/min, *f*= 0.06 mm/rev

cutting speeds are between 80 and 200 m/min. The feeds and depth of cut are relatively small (<0.2 mm) [4, 21]. But in order to check the suitability of higher cutting conditions, in which CBN as well as carbide tools can be compared, the preliminary runs for 1 min machining time with fixed depth of cut of 0.15 mm were carried out as per Table 1.

After these preliminary investigations, the final conditions were selected. The cutting speed (*v*) was varied in three steps as 97, 137, and 180 m/min, with two values of feed (*f*) (0.6 and 0.11 mm/rev) and constant depth of cut (0.15 mm).

The work piece material used in this study was AISI-H11 hot tool die steel in the form of round bars of 32 mm diameter and 200 mm length, so that L/D ratio should not exceed 10 as per ISO 3685 standards [22]. The work piece was through hardened followed by tempering process to attain hardness of 48–49 HRC, which typically has a chemical composition of 0.33% carbon, 0.95% Si, 0.27% Mn, 5.32% Cr, 1.22% Cr, and 0.36% V. Longitudinal turning of the workpiece, under dry conditions, on a CNC lathe (Mori Seiki: MSC-ZL25MC-187, Japan) using a fresh cutting edge of different inserts in each combination of speed, feed, and depth of cut, was performed. A CVD-coated carbide grade with innermost coating layer of TiCN (titanium carbonitride), intermediate layer of Al_2O_3 (alumina oxide), and outermost layer of TiN (titanium nitride) having wiper geometry with designation CNMG120408-WF (GC4205) was used (www.coromant.sandvik.com). The CBN tools with designation CNGA120408 S01225 SE, having chamfered+honed (0.12 mm × 25°) cutting edge with low CBN content were selected as low CBN content tools are known to give better performance in finish hard turning [4]. Uncoated carbide grade with designation (CNMG 120408-23-H13A) recommended by manufacturer was selected (www.coromant.sandvik.com). All the inserts having 0.8-mm nose radius were selected, so that machining result could be compared under similar cutting conditions.

Both coated and uncoated tungsten carbide inserts were deep cryogenically treated under dry condition. The inserts were not exposed to the liquid nitrogen to eliminate the risk and damage of thermal shock. Inserts were placed in a container and the temperature was brought to −196°C in

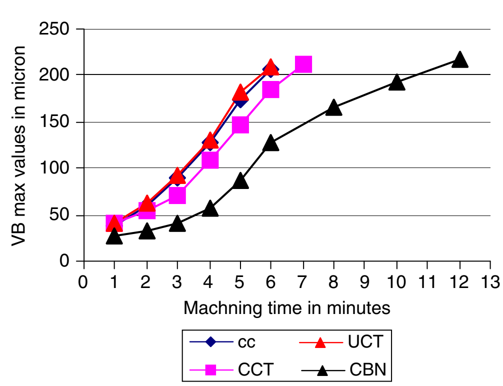


Fig. 2 Progression of maximum flank wear at *v*=95 m/min, *f*= 0.11 mm/rev

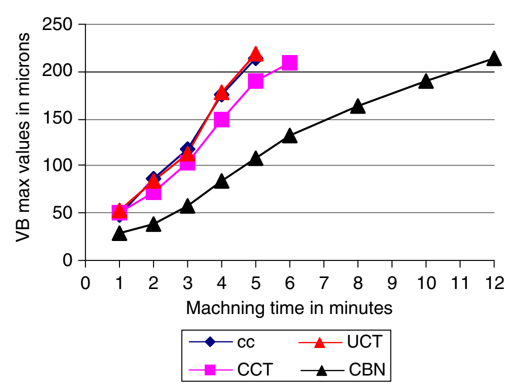


Fig. 4 Progression of maximum flank wear at *v*=137 m/min, *f*= 0.11 mm/rev

intervals by computerized control at the rate of 0.5°C/min. At each interval, the inserts were allowed to stabilize in 2-h increments. The temperature was held constant for 24 h before the process was reversed. The inserts were slowly brought to room temperature allowing the material to stabilize. Then the inserts were subjected to two tempering cycles to relieve the stresses induced by cryogenic treatment [10, 11]. The cutting inserts were clamped to a right-hand tool holder with ISO designation having −6° rake angle, −6° clearance angle, and 95°approach angle. Each single pass consisted of axial cutting length 175 mm and after every one, two, three, four, six, eight, 10, and 12 number of passes the amount of maximum flank wear (VBmax) and surface roughness (Ra) of the machined surface was recorded.

3 Results and discussions

3.1 Analysis of tool wear

According to standard ISO 3685, the time at which the tool ceases to produce a workpiece of desired size and surface quality usually determines the end of useful tool life [22]. The objective of finish hard turning is to produce machined components with surface roughness and dimensional accuracy equivalent to that of mechanical grinding processes [6]. Typically, a mechanical grinding process produces surfaces smoother than Ra=1.6 μm [4]. The same roughness, for the surface after the turning operation is the determining factor for selecting tool flank wear criterion. Based on this consideration, a flank wear criterion of VBmax=0.2 mm was chosen to evaluate the tool life. The selection of low VBmax, instead of VBmax=0.6 mm stipulated in ISO 3685 [4, 6, 22], is consistent with finish hard turning applications. The experiment was terminated when either of the following two conditions was arrived: VBmax≥200 μm, Ra≥1.6 μm. Maximum tool flank wear was measured using optical microscope having image analysis software. The worn tools were evaluated using scanning electron microscope at regular interval in order to understand the wear modes and mechanisms that affect the tool performance. Each set of experiments replicated twice and average value of VBmax was evaluated.

Progression of maximum flank wear (VBmax) with machining time in minutes at different cutting speeds and feed rates is presented in Figs. 1, 2, 3, 4, 5, and 6. From the graphs it is indicated that in all cases tool life is significantly affected by cutting speed followed by feed rate [4, 12, 21]. Tool life of all types of carbide inserts decreases as the cutting speed increases for both feed rates, because with increase in cutting speed for a given time the cutting temperature increases, which leads to rapid tool wear [4, 7, 12]. On the other hand for CBN tools, as the cutting speed increases the tool wear decreases for both feed rates up to v=137 m/min but again deteriorates at v=180 m/min. It is due to the thermal softening of the workpiece at higher cutting speeds. The performance of CBN tools is marginally better at 137 m/min speed than the 180 m/min speed, due to formation of protective layer at moderate speed [7, 21, 23]. Tool life marginally deteriorates when feed rate increased from 0.06 to 0.11 mm/rev at all cutting speeds [4]. In all the cases CBN tools showed superior performance followed by coated carbide cryogenically treated (cct), uncoated carbide cryogenically treated (uct), and then coated carbide untreated (cc).

The tool life of cryogenically treated coated carbide inserts improved by 16–23% in different cases in comparison to untreated coated carbide inserts, which agrees well with previous findings [11, 12]. Cryogenically treated inserts performed well in comparison to untreated one, which is mainly due to improved thermal conductivity and hot hardness of the insert [12], more homogeneous carbide distribution, and relieving of stresses introduced during

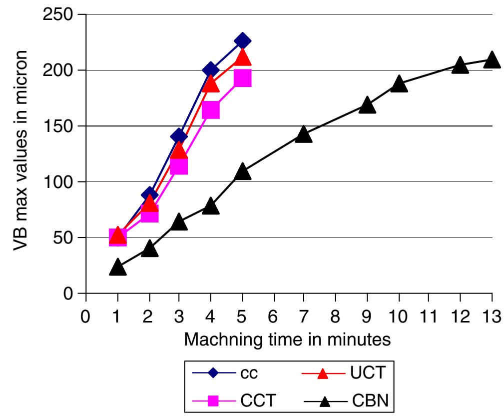


Fig. 5 Progression of maximum flank wear at v=180 min, f= 0.06 mm/rev

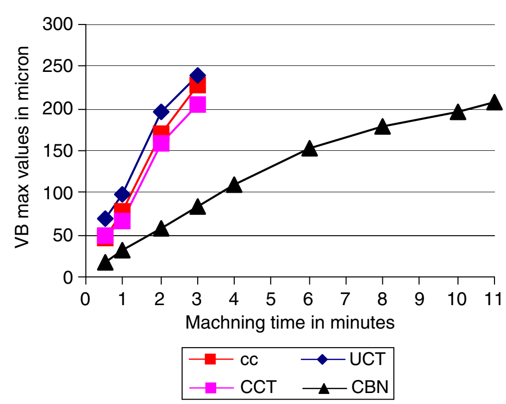


Fig. 6 Progression of maximum flank wear at v=180 m/min, f= 0.11 mm/rev

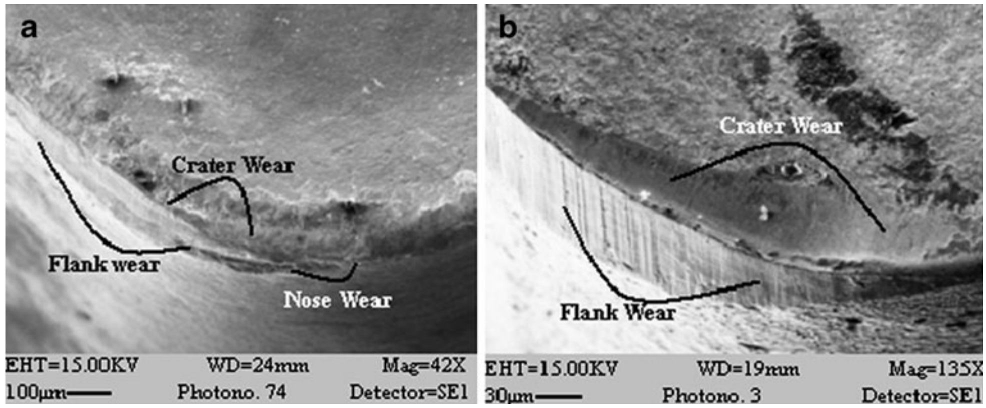


Fig. 7 **a** cct at v=95 m/min showing crater and showing flank wear after 3 min of machining, **b** uct insert at v=95 m/min, f=0.06 mm/rev crater and flank wear after 3 min of machining

synthesis of carbide tools [10]. The increase in thermal conductivity due to cryogenic treatment increases the heat dissipation capacity of the cutting tool and helps in decreasing the tool tip temperature, resulting in more hot hardness during machining [12]. Uncoated carbide inserts wear rapidly in first minute of machining in comparison to other inserts, which is due to the non-availability of wear-resistant coatings on uncoated inserts (www.coromant.sandvik.com). But as the machining progressed these inserts showed a compatible behavior with coated-carbide-untreated inserts. Based on selected flank wear criterion, at lowest speed (95 m/min) and feed (0.06 mm/rev) combination, the tool life was measured as 6 min for cc inserts, 7 min 30 s for cct inserts, 6 min 20 s for uct inserts, and 10 min 20 s for PCBN inserts. At highest speed (180 m/min) and feed (0.11 mm/rev) combination the tool life was measured as 2 min 30 s for cc inserts, 3 min for cct inserts, 2 min for uct, and 10 min 40 s for PCBN inserts. The machining time for each cutting edge of carbide inserts was not as long as that for the PCBN inserts. But the accumulated machining time for all the four edges of carbide inserts was better than or equal to the PCBN inserts. This observation indicates that cryogenically treated and coated carbide inserts can be a suitable alternative to PCBN inserts. The cost of per cutting edge with carbide tools is approximately 1/10th the cost of CBN tools. The low cost per cutting edge is achieved with coated carbide untreated followed by uncoated carbide treated, coated carbide treated, and then with CBN inserts.

3.2 Evaluation of worn tool inserts

Tool wear modes were analyzed on the basis of picture generated through SEM and optical microscope.

3.2.1 Carbide tools

As shown in Fig. 7a, b both flank wear and crater wear were observed for all the inserts tested under all cutting conditions. The tool wear zone occurs mostly near the tool nose radius on the flank side [4]. At all speed and feed combinations, crater wear was dominant in case of uncoated carbide inserts as shown in Fig. 7b, due to the non-availability of wear-resistant coatings [19]. For coated carbide inserts, both treated and untreated, the coating layer from the cutting edge (flank portion) was worn within the first minute of machining. Figure 8a shows that coating layer is removed in case of cc insert by severe plastic deformation, which mainly occurred due to high cutting temperature. Abrasion marks were also observed on the tool

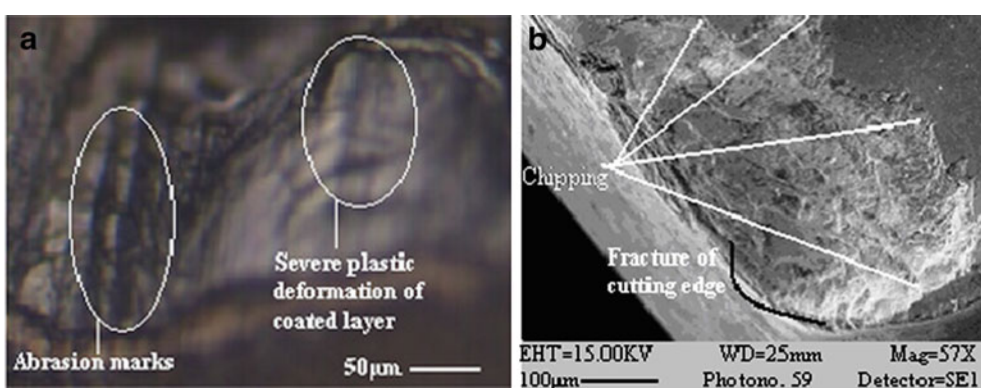


Fig. 8 **a** Coated-carbide-untreated insert at v=180 m/min, f=0.11 mm/rev showing plastic deformation of coating on flank surface, **b** coated-carbide-untreated insert at v=180 m/min, f=0.11 mm/rev showing crater wear due to chipping/fracture

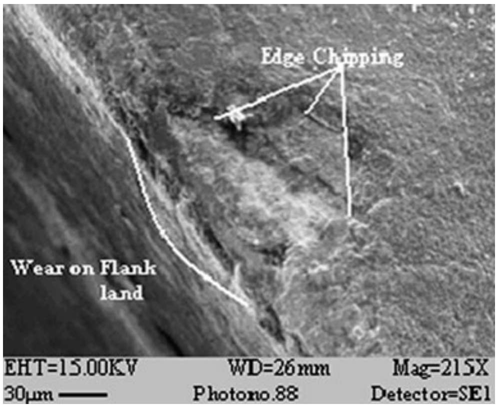


Fig. 9 SEM view of cct insert at v=180 m/min, f=0.11 mm/rev showing both flank and crater wear

flank surface [7]. In Fig. 8b, at high speed and feed combination severe chipping took place, due to which coated-carbide-untreated (cc) inserts underwent rapid wear. Similar kind of rapid tool wear with chipping/fracture was observed with all carbide inserts at high speed and feed combination, due to high temperature generated during cutting [7, 19]. As shown in Fig. 9, performance of cct inserts was better than that in case of cc inserts. It was due to improved thermal conductivity and hot hardness of the treated insert [12]. Thus it is not favorable to use carbide tools at high cutting speed and feed combination for hard turning.

In Fig. 10a–c at low cutting speed, abrasion and adhesion followed by plastic deformation were dominant wear mechanisms. Abrasion wear occurred due to hard carbides present in the workpiece [7]. In all the cases, with carbide inserts two-body abrasion was dominant, while signs of three-body abrasion as indicated with circle in Fig. 10a were also observed. Three-body abrasion was due to removal of hard particle from the surface, which acted as a medium of three-body abrasion between workpiece and tool flank face [3, 7]. As indicated in Fig. 10c built-up edge appears in low cutting speed and feed rate in which the interface temperature is not high enough to overcome the hammer-hardened effect and hardening of phases present in the workpiece material [3].

Results show that abrasion, adhesion followed by plastic deformation at low speed, and chipping and fractures at high speed were the dominant wear mechanisms in the carbide inserts. Whereas for cryogenically treated inserts at high cutting speed the impact of chipping/fracture wear was low in comparison to untreated inserts.

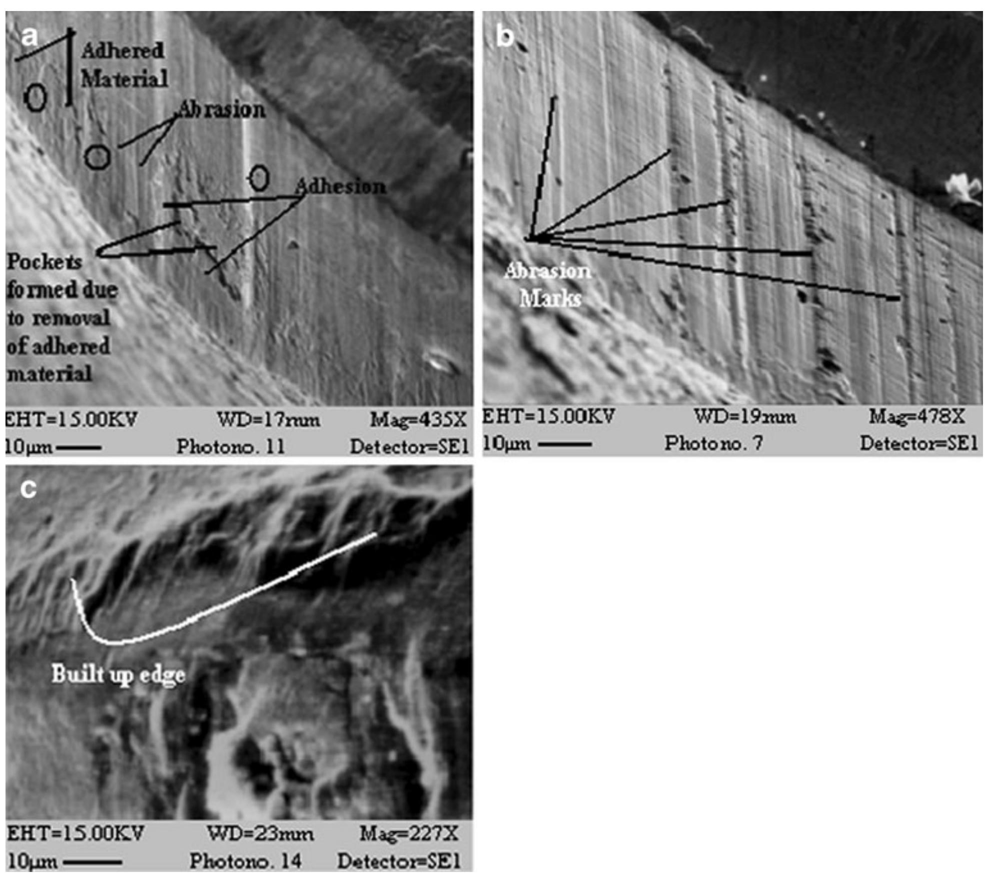


Fig. 10 **a** cc insert at v=95 m/min, f=0.06 mm/rev showing flank wear with three-body abrasion marks indicated with circle, **b** uct insert at v=95 m/min, f=0.06 mm/rev showing flank and crater wear, **c** coated-carbide-treated (cct) insert at v=95 m/min, f=0.06 mm/rev showing built-up edge on flank face

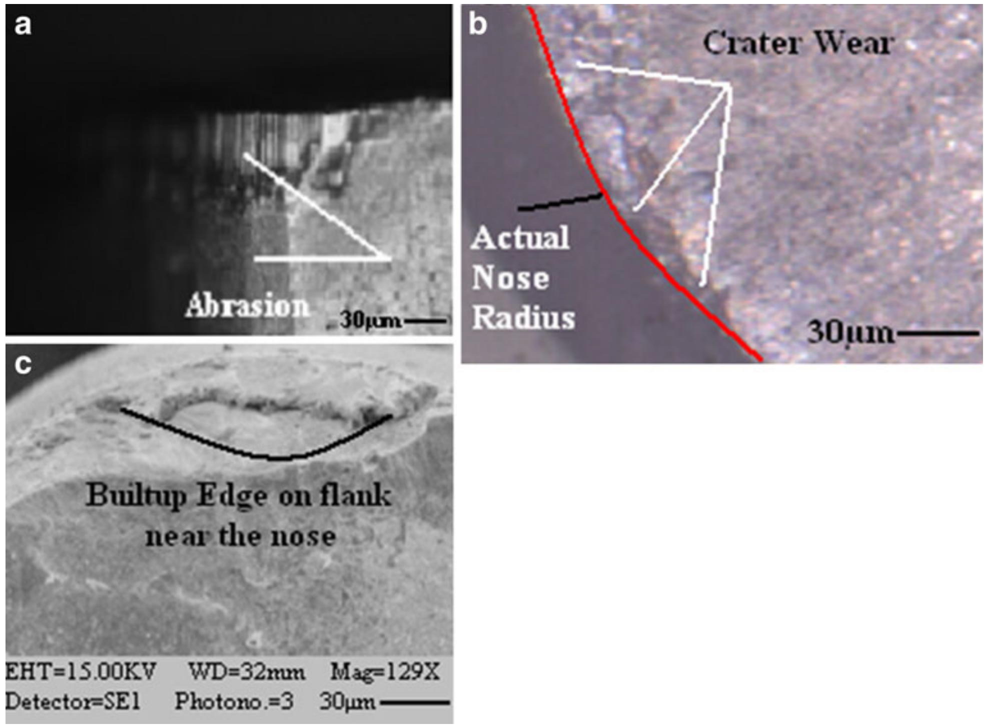


Fig. 11 **a** CBN insert at v=95 m/min, f=0.06 mm/rev showing flank wear after 8 min of machining, **b** CBN insert at v=95 m/min, f=0.06 mm/rev showing crater wear after 8 min of machining, **c** CBN insert at v=95 m/min, f=0.06 mm/rev showing built-up edge after 3 min of machining

3.2.2 CBN tool

Figure 11a, c shows flank face of CBN insert after machining at low cutting speed. In Fig. 11a, abrasion marks are dominant on the flank face, due to scratching of the tool face by hard carbide particles of the workpiece. Because at low cutting speed, the cutting temperature is comparatively low and the degree of the softening of work material is not significant. The binder of the tool is abraded by hard particles of the workpiece material. Figure 11c shows a significant built-up edge after 3 min of machining at low cutting speed and feed, because of moderate interface temperature rise and diffusion/affinity of work material for tool under these cutting conditions [4, 7, 21, 23]. Figure 11b shows a crater wear after 8 min of machining, with progression of crater wear the tool nose shape varies. A significant crater wear was observed in all the cases for CBN tool. Figure 12 shows a sticking layer called diffusion and thermal barriers, which remained on the surface and protected the tool surface from wear. As the cutting speed increased from 95 m/min to 137 m/min, the cutting temperature increased, which led to diffusion and oxidation on the tool surface [21, 23] As shown in Fig. 13a, b as the cutting speed was further increased to v=180 m/min, adhesion become the dominant wear mechanism. Because at higher cutting speed, cutting temperature increased and the adhered layer was worn away due to high friction force, which led to plucked material from tool face [7, 23]. Figure 13c shows the shallow pocket formed as the adhered material was removed. The cutting edge became weak and tool wore rapidly [21]. At low cutting speed, abrasion was the main form of wear. Diffusion and adhesion followed by plastic deformation were the main wear mechanisms at higher cutting speed.

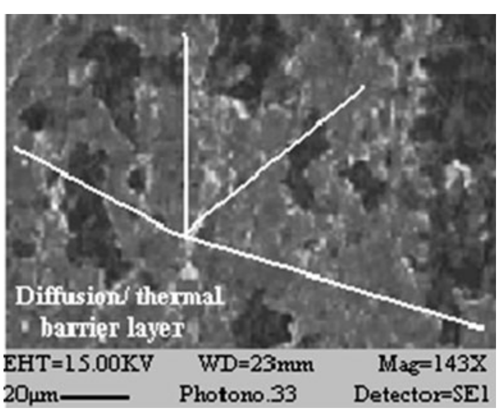


Fig. 12 CBN insert at v=137 m/min, f=0.06 mm/rev showing diffusion layer after 2 min of machining

4 Surface roughness

The surface roughness, Ra (µm), of the machined samples was measured at the same intervals as for tool wear with a surface analyzer (SJ-401; Mitutoyo) with a cut-off length of 0.8 mm over three sampling lengths, which were distributed circumferentially at an angle of 120°. The average of these three values of surface roughness Ra was used to quantify

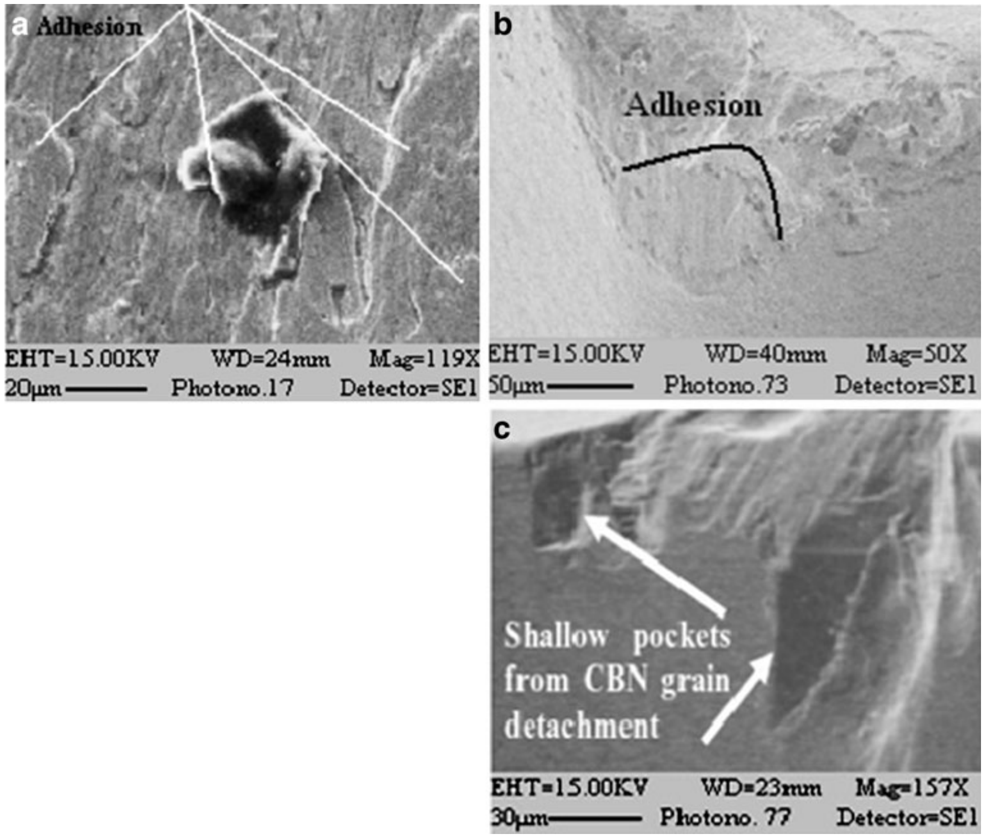


Fig. 13 **a** CBN insert at v=180 m/min, f=0.06 mm/rev showing adhesion on the tool face, **b** CBN insert at v=180 m/min, f=0.11 mm/rev showing adhered material near the nose of insert, **c** CBN insert at v=180 m/min, f=0.06 mm/rev showing shallow pockets formed after detachment of material

the roughness achieved on the machined surfaces. Surface roughness is important indicator of the surface integrity of machined parts and correlated to the tool wear [4, 6]. Theoretical surface roughness can by estimated by Eq. 1, where f is feed rate, r_e nose radius of tool [4, 19]. The theoretical surface roughness is well below the control criterion of 1.6 µm for both the feed rates selected in this study.

$$\mathrm{Ra} = \frac{f^2}{18\sqrt{3}r_e} \tag{1}$$

For turning tests, the Ra values were in the range of 0.3–1.58 µm except for uncoated inserts, which showed the suitability of cc, cct, and CBN inserts tested under all the cutting conditions for hard turning. The surface roughness values observed for samples turned with different inserts at 95 m/min speed and 0.06 and 0.11 mm/rev feed rates, respectively, are plotted in Fig. 14a, b.

The surface roughness is significantly affected by tool wear [12, 19]. For carbide inserts, as the machining time increases, the Ra value for first few minutes marginally decreases or remains constant, but after that it increases continuously. For CBN inserts, as the machining progresses, the Ra value decreases and only increases at the end of tool life. This behavior is due to effective flattening of the corner radius and smooth progression of tool wear [4]. But for cct as well as cc inserts uniform Ra values were observed for first few minutes of machining. These values were comparable with Ra values of CBN inserts. It was due to availability of wiper geometry on the cc and cct inserts. After that tool wear

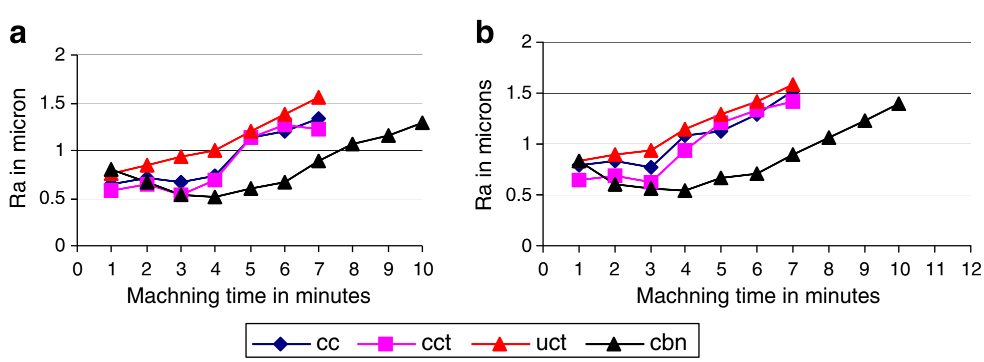
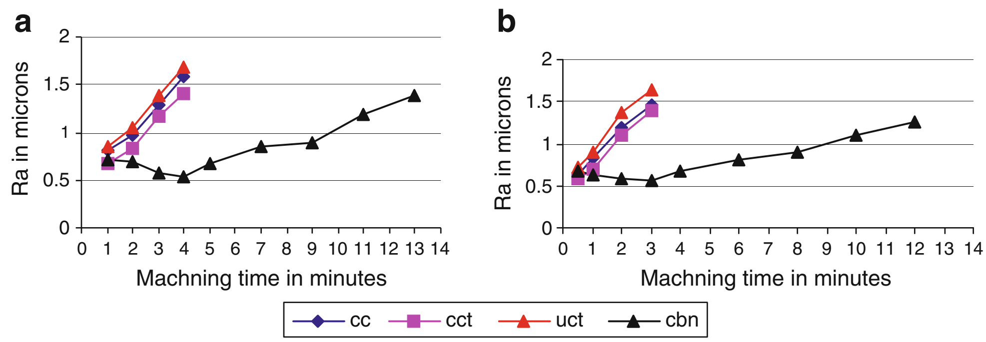


Fig. 14 **a** Variation of Ra at v=95 m/min and f=0.06 mm/rev, **b** variation of Ra at v=95 m/min and f=0.11 mm/rev

Fig. 15 **a** Variation of Ra at v=180 m/min, f=0.06 mm/rev, **b** variation of Ra at v=180 m/min, f=0.11 mm/rev



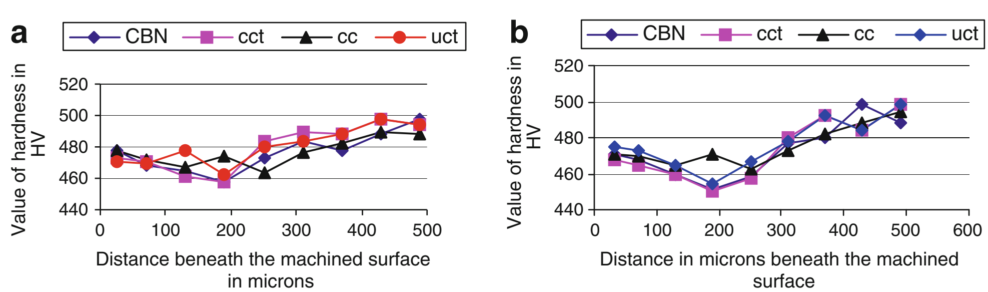
increases rapidly, due to which Ra value continuously increases for rest of the machining time [19]. For uct inserts, Ra value continuously increases with increase in machining time due to non-availability of wiper geometry as well as coating. Ra values observed for uct inserts were higher than the Ra values for the other inserts under all cutting conditions. The surface roughness observed with cct inserts was lower than that with the untreated inserts, which was due to lower tool wear, lower tool tip temperature, and less distortion of the cutting edge [12]

The surface roughness values observed for samples turned with different inserts at 180 m/min speed and 0.06 and 0.11 mm/rev feed rates, respectively, are plotted in Fig. 15a, b. For carbide inserts at higher speed (180 m/min) the Ra value significantly increases with increase in machining time due to non-uniform wear of the flank surface. But for these inserts at the end of tool life (VBmax=200 µm) the Ra value remains below 1.6 µm under all cutting conditions. For uct inserts at the end of tool life the Ra value marginally exceeds the rejection criterion of 1.6 µm. The surface roughness values achieved with the CBN tools are close to the theoretical values. The Ra value of samples machined with CBN inserts first reduces/remains stable and then marginally increases at the end of tool life. It is because of thermal softening of the workpiece at higher speed, which reduces the tool wear [7, 21]. For CBN tools the smooth progression of flank wear does not change the tool nose radius much once it is flattened [4]. The lower feed rate produces a poorer surface finish, which is due to increase in ploughing action at low feed rates [4].

5 Analysis of microhardness

Hard machining causes changes in the microstructure of machined surface and, consequently, to the mechanical properties and quality of the surface produced. Thus it must be taken into account for improving product performance [16, 17]. Microhardness measurement is very useful in identifying metallurgical changes at various depths below the machined surface [17]. For microhardness measurement, samples were sectioned from the workpiece as VBmax reaches 200 µm for each insert with an abrasive cutter, polished with successively fine grit mesh of 180, 240, 400, and 600 followed by polishing Al_2O_3 paste on 0.03 µm polishing paper until a mirror-like surface was obtained [17]. The subsurface microhardness was measured with an automated microhardness tester equipped with a Vickers indenter in accordance with ISO 14577 [24]. The tool flank wear and cutting speed are dominant process parameters to produce variation in microhardness beneath the machined surface [16, 25–27], so microhardness measurements were taken when tool reached a VBmax of 200 µm or Ra reached 1.6 µm and both at the highest and the lowest speeds. Five hardness measurements were taken at the same depth below the surface but well spaced to avoid interference between each indent. An average of these five readings was taken to plot the results given in this study [16, 17]. The applied load varied from 0.05 to 0.5 kg and the indentation time was 10–15 s in accordance with the depth from the machined surface. The first indentation was started at 20–25 µm and last indentation was

Fig. 16 **a** Microhardness variation beneath the machined surface at v=95 m/min, f=0.06 mm/rev, **b** Microhardness variation beneath the machined surface at v=95 m/min, f=0.11 mm/rev



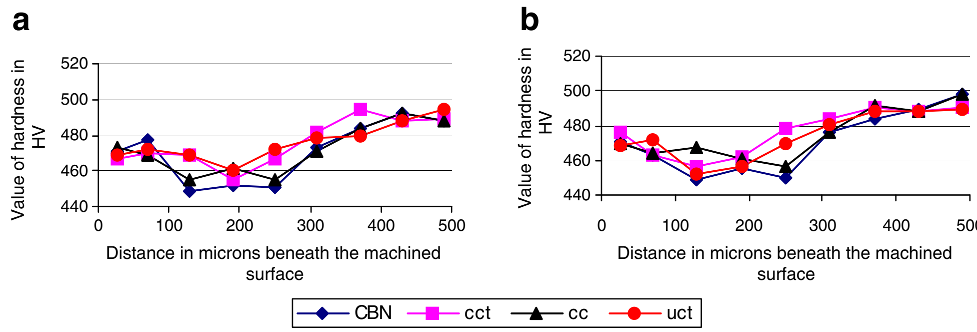


Fig. 17 **a** Microhardness variation beneath the machined surface at v=180 m/min, f= 0.06 mm/rev, **b** microhardness variation beneath the machined surface at v=180 m/min, f= 0.06 mm/rev machined surface at v=180 m/min, f=0.11 mm/rev

performed at 490 µm from the machined surface. This measurement helped to arrive at the demarcation between the machine-affected zone (MAZ) and the bulk material.

Figures 16a, b and 17a, b show the microhardness distribution beneath the machined surface of samples turned at low and high cutting speed, when the VBmax reaches 200 µm. The microhardness distributions of all the samples showed a softened layer beneath the machined surface due to the formation of dark zone by heat produced during machining, which is not an over-tempered zone [25, 26]. The thickness of white layer formed in all the cases in this study was from 1.8–4.2 µm and first indentation started at a distance of 20–25 µm from machined surface. Thus, it was not possible to measure the hardness of white layer and only microhardness result of dark layer (which is softer than bulk material) [27], and bulk material was observed. In all the cases, the MAZ value is less for the sample turned with cryogenically treated coated and uncoated carbide inserts in comparison to CBN and coated carbide inserts, which is due to improved thermal conductivity of cryogenically treated inserts [12].

The bulk hardness of all the samples is between 484 and 498 HV. Figure 16a shows that the values of microhardness approaches to bulk hardness after 250 and 260 µm, respectively, beneath the machined surface for sample turned with coated carbide cryogenically treated insert and with uncoated cryogenically treated carbide inserts, while with CBN and cc it reaches after 280 and 330 µm, respectively. Almost similar trend was found in other samples also. In all the conditions tested the thickness of MAZ varies from 250 to 340 µm. The machine-affected zone is less with cryogenically treated inserts in comparison to samples turned with CBN and coated carbide inserts under all cutting conditions. These results are also supported by optical micrograph of subsurface structure from Fig. 21a–d under white layer section.

The feed rate did not affect the surface microhardness beneath the machined surface much significantly for the all the samples tested [18].

Microhardness measurements of white layer sample shown in Fig. 22 plotted in Fig. 18 indicate that hardness value near to the surface is higher than the bulk hardness due to presence of thick white layer. After that, the hardness value decreases due to the presence of dark layer [16, 17, 27].

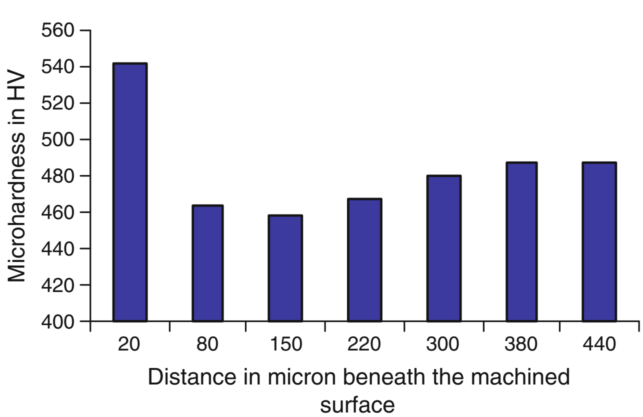


Fig. 18 v=180 m/min, f=0.11 mm/rev with cc insert

6 White layer

White layer is thermally induced, phase transformed layer [28]. Tool flank wear and cutting speed introduce higher cutting temperatures on the machined surface, and are therefore dominant factors for white layer formation in hard turning [27, 28]. Samples were prepared in similar way as were prepared for microhardness measurement [17] and then etched for about 10 s using 2% Nital solution, washed with flowing water and dried with hot air in order to analyze white and dark layers formation by an optical microscope [16]. All the samples were tested under microscope for white layer formation after 5–7 min of machining and also at the end of tool life of each insert. Figure 19a, b shows the variation of white layer thickness with cutting speed for cc, cct, uct, and CBN insert at feed= 0.06 and feed=0.11 mm/rev, respectively. Results show that thickness of white layer increases with increase in cutting speed, which is mainly due to the rise in temperature during cutting [16]. In all cases, the magnitude of white layer

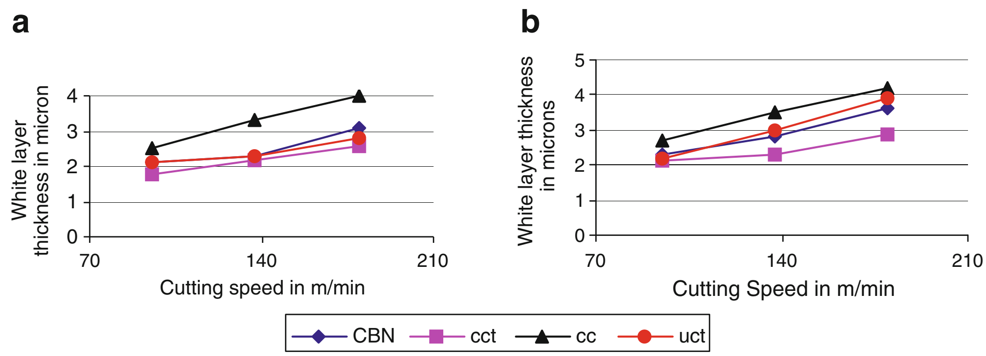


Fig. 19 **a** Variation of white layer formation with cutting speed at feed=0.06 mm/rev after 7 min of machining, **b** variation of white layer formation with cutting speed at feed=0.11 mm/rev after 5 min of machining

formed while turning with cryogenically treated inserts, is less in comparison to that with other inserts. This is mainly due to improved thermal conductivity of the cryogenically treated inserts [12]. Increase in feed from 0.06 to 0.11 mm/rev at fixed cutting speed marginally increases the thickness of white layer. Results show that white layer thickness increases with increasing cutting speed followed by increase in feed rate [16].

The tool wear is a significant factor to produce the white layer in hard turning [16, 17, 28]. Figure 20a–h shows the subsurface structure of different samples analyzed under optical microscope. As indicated in Fig. 20a after 3 min of machining time with cc insert at 95 m/min speed and 0.06 mm/rev feed, there is a very thin or almost negligible white layer on the machined surface. On the other hand significant white layer with dark layer/transition zone is seen and under same cutting conditions when VBmax value reaches 200 μm as shown in Fig. 20b. Same behavior was observed with all other inserts [17, 27]. The result clearly indicates that tool wear is a dominant factor for white layer formation.

As shown in Fig. 21a–c, the samples turned with cryogenically treated insert show less white layer thickness and low depth of dark layer/transition zone in comparison to untreated coated carbide and CBN insert at same cutting conditions (speed=180 m/min, feed=0.06 mm/rev, VBmax=140 μm), which is mainly due to improved thermal conductivity of cryogenically treated insert [12]. For all the cutting conditions tested, the thickness of white layer varies from 1.8–4.2 μm.

In order to see the effect of tool wear on white layer formation one set of experimentation at speed=180 m/min and feed=0.11 mm/rev was performed, in which maximum flank wear exceeds 600 μm. As shown in Fig. 22, white layer of 23 μm was observed with distinct dark zone [16, 17, 28].

7 Conclusions

Hard turning experiments with various cutting speeds and feed rates at constant depth of cut were carried out on AISI H10 steel. The effect of cutting speed, feed rate, and cryogenic treatment on tool life, surface roughness, microhardness variation, and white layer formation was analyzed. At v=95 m/min with both feed rates, carbide inserts demonstrated a tool life of 5–7 min per cutting edge approximately, whereas CBN inserts produced a tool life of 9–10 min. At v=180 m/min with both feed rates, carbide inserts demonstrated a tool life of 3–4 min per cutting edge approximately, whereas CBN inserts produced a tool life of 11–12 min. Further the tool life of treated carbide inserts is approximately 16–23% better than that of the untreated inserts.

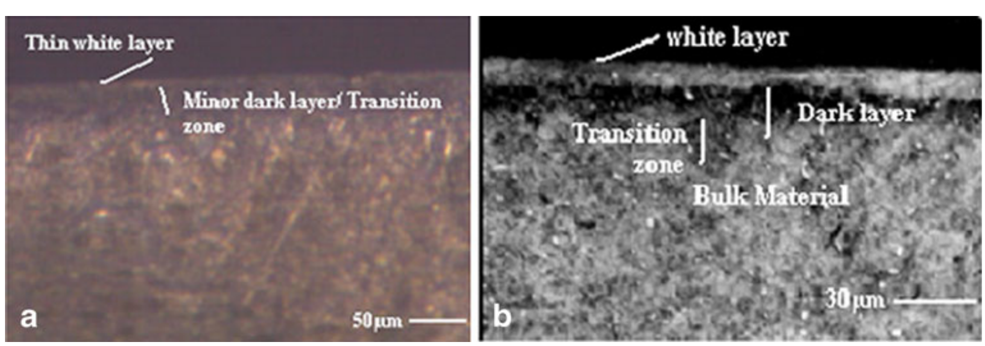


Fig. 20 **a** White layer thickness with cc insert after 3 min of machining, **b** white layer thickness with cc insert as VBmax reaches 200 μm

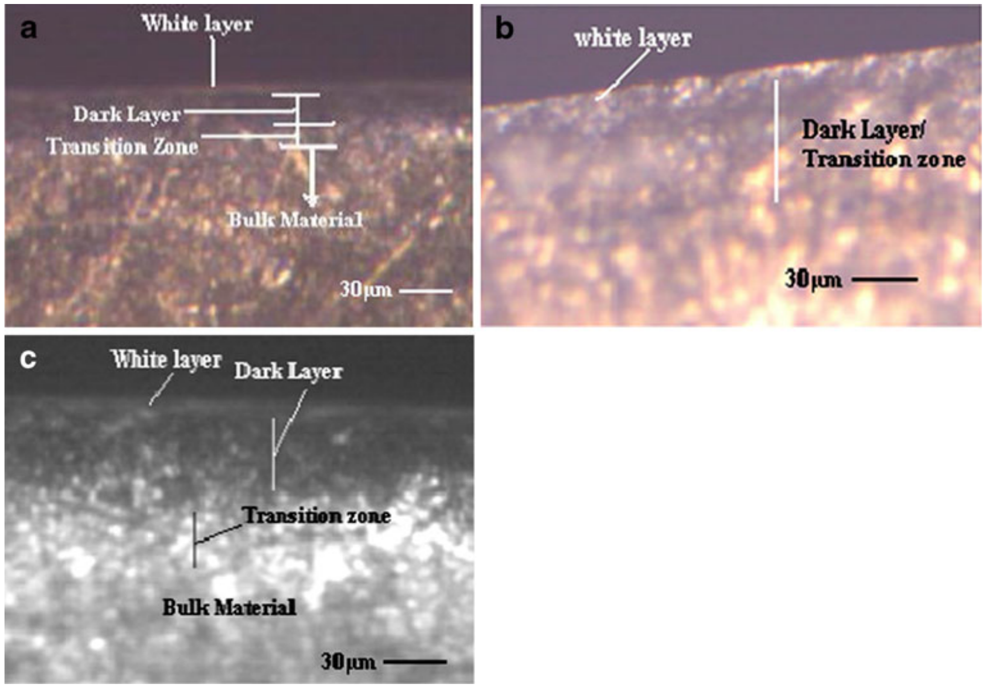


Fig. 21 **a** White layer thickness with uct insert, **b** white layer thickness with CBN insert, **c** white layer thickness with cc insert

Carbide tools performed better at low and medium cutting speed; however, with increasing speed, the tool wore rapidly due to high cutting temperature. The suitable machining conditions for carbide inserts both treated and untreated were identified as cutting speed 97 and 137 m/min and feed rate as 0.06 and 0.11 mm/rev, corresponding to fixed depth of cut of 0.15 mm. Under these conditions the surface integrity and tool wear achieved with carbide tools was comparable with CBN tools, so these can act as economical alternative to costly CBN tools in hard turning within studied range of workpiece hardness. At high cutting speed, carbide tools underwent chipping/fracture failure. CBN tools at low cutting speed were susceptible to high abrasive wear, but tool life improved with increasing cutting speed.

The surface roughness achieved under all cutting conditions for coated-carbide-treated/untreated inserts was comparable with that achieved with CBN inserts and was below 1.6 μm. Whereas uncoated-carbide-treated inserts gave poorer surface finish in comparison to other inserts, which was mainly due to non-availability of wiper geometry and absence of wear-resistant coatings. Very thin white layer is observed under all conditions with both CBN and carbide inserts. The white layer thickness was marginally less with cryogenically treated inserts. The microhardness values observed with carbide inserts were comparable with those of CBN. Low machine-affected zone was observed while turning with cryogenically treated inserts in comparison to MAZ observed with the other inserts. By selecting a tool life criterion of VBmax=200 μm in this study, optimum surface integrity, i.e., smoother surface having Ra<1.6 μm was achieved which is comparable with grinding. Further a very thin white layer was produced in all the cases with VBmax=200 μm. Thus, it is clear that in hard turning by keeping a flank wear criterion as VBmax=200 μm, optimum surface integrity comparable with grinding can be achieved.

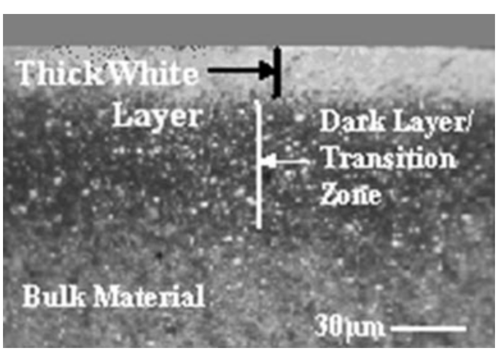


Fig. 22 Sample turned at v=180 m/min, f=0.11 mm/rev with CBN inserts, VBmax=610 μm

The results show that while turning with carbide inserts surface integrity achieved was comparable to that achieved with CBN inserts. The machining time for each cutting edge of carbide inserts was not as long as that for the PCBN inserts. But the accumulated machining time for all the four edges of carbide inserts was nearer to or better than the PCBN inserts. As the cost of per cutting edge of carbide inserts is quite less than the CBN inserts, so carbide inserts both treated and untreated are capable of reducing the machining cost without compromising on the surface integrity and therefore will be important alternative to CBN inserts for hard turning applications. The deep cryogenic treatment of carbide inserts may be used in hard turning for better machining performance.

Acknowledgments The authors wish to thank the Institute of Auto Parts and Hand Tools, Ludhiana, for their support in cryogenic treatment of the inserts and Indian Institute of Technology, Roorkee for providing characterization facilities.

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