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Performance evaluation of PCBN, coated carbide and mixed ceramic inserts in finish-turning of AISI D2 steel

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HIGHLIGHTS

- *Tool life of PCBN was longer than ceramic and carbide insert.*
- *Tool wear of PCBN was lower than ceramic and carbide inserts.*
- *Better surface roughness (Ra) was obtained with PCBN inserts.*
- *Ra for ceramic/carbide insert was below 1.6μm*
- *Ra was affected by the wear on the cutting tool.*

ABSTRACT

The present study compares the performance of three different cutting tools, viz., PCBN, mixed ceramic and coated carbide tool in finish turning of hardened D2 tool steel in terms of tool wear, surface roughness, and economic feasibility under dry cutting conditions. Results showed that tool life of PCBN inserts was better than mixed ceramic and coated carbide inserts. The flank wear of PCBN tools was observed to be lower than mixed ceramic and coated carbide inserts. The surface roughness achieved under all cutting conditions for mixed ceramic and coated-carbide inserts was comparable with that achieved with PCBN inserts and was below 1.6μm. Experimental results showed that the wear mechanism of ceramic tool is pre-dominantly abrasive wear at lower speeds and abrasive wear followed by adhesive wear at medium and higher speeds and for PCBN tools the dominant wear mechanism is abrasive wear and cratering at lower speeds followed by adhesive wear at higher speeds. For carbide tool the dominant wear mechanism was abrasive wear and cratering at lower speeds followed by adhesion and chipping at higher speeds. Obtained results revealed that PCBN tools can outperform both ceramic and carbide tools in terms of tool life under different machinability criteria used.

Keywords:
| Hard turning | PCBN | Coated carbide | Tool life | Surface roughness | Economic analysis |

1.0 INTRODUCTION

Hardened steel is often used in the automotive, tool and die industry to manufacture bearings, gears, shafts, cams, punches and dies, which require tight geometric tolerances, longer service life and good surface finish (König et al., 1993). The traditional approach for production of these parts involves a sequence of five steps viz., forming, annealing, rough machining, heat treatment followed by grinding operation to obtain the required surface finish. However, the grinding operation is time consuming, costly and limited to the range of geometries to be produced. With extensive research, advancement in material science and improved technologies, annealing and grinding procedures can be eliminated by applying hard turning process i.e., to perform finishing or semi-finishing operations directly on hardened steels. Hard turning is a process of single point cutting of a work-piece material that has hardness range of 40-62 HRC (Özel et al., 2007). High flexibility and ability to manufacture complex work-piece in a single step is the main advantage of hard turning compared to grinding. Moreover, hard turning can be performed without the use of coolants; therefore, hard turning provides an added advantage from the environment point of view (Kloke et al., 2005; Huang and Dawson, 2005).

According to ISO 3685 standard, the time at which the tool ceases to produce a work-piece of desired size and surface quality generally determines the end of useful tool life (International Organization for Standardization, 1993). Finish hard turning is to produce machined components with surface finish and dimensional accuracy equivalent to that of mechanical grinding processes (Jiang et al., 2006). Typically, a mechanical grinding process produces surfaces smoother than $Ra = 1.6$ μm (More et al., 2006; Jiang et al., 2006). The selection of low $VB_{max} = 0.2$ mm, instead of $VB_{max} = 0.6$ mm stipulated in ISO 3685 (Jiang et al., 2006; More et al., 2006; Dureja, et al., 2010) is consistent with finish hard turning applications. The experiments are terminated when either of the following two conditions arrive: $VB_{max} \geq 0.2$ mm (200 μm), $Ra \geq 1.6$ μm. PCBN, ceramic, cemented carbide and cermet tools are usually employed in hard turning process (Sales et al., 2009; König et al., 1993, Das et al., 2015; Bensouilah et al., 2016). The development of these cutting tool materials has led to the use of higher cutting speeds compared to that used in conventional machining processes, which in turn reduces machining cost and increases production rate. However, higher cutting speed leads to increase in cutting temperature at cutting zone, which leads to rapid wear of cutting tool which in turn affects dimensional accuracy, surface roughness and tool life. The ability of polycrystalline cubic boron nitride and ceramic tools to maintain a workable cutting edge at elevated temperature has made them the most preferable cutting tools materials in machining hardened materials such as cast iron, alloy steel and bearing steels (Sales et al., 2009; Chou and Evan, 1997; Luo et al.,1999; Dogra et al., 2011). Their high hot hardness, wear resistance and chemical stability enables them to withstand high mechanical and thermal loads during hard turning. Apart from CBN and ceramics tools, carbide tools for finish hard turning, under dry and wet conditions, have also been reported in the literature (Chinchanikar and Choudhury, 2013; Dogra et al., 2011; Lima et al., 2005). Moreover, the presence of multiple alloying elements like Cr, V, W, Ni, Mo in the chemical composition of steels leads to the formation of very hard carbide particles and increases its wear resistance in the structure when heat treated, resulting in excessive tool wear. The resultant cutting tool wear plays a main role during finish hard turning due to its effects on surface quality and dimensional accuracy.

Many studies have been carried out on hard turning using PCBN, ceramics and carbide tools. The mechanisms involved in the wear of these cutting tools, especially in hard machining, are rather complicated and may consist of different interacting effects related together in a complex manner. Primarily, depending on cutting conditions, tool compositions, tool geometry, cutting temperature, cutting forces, and frequency of interruption, the performance of the cutting tool is limited by nose wear, flank wear, crater wear, edge chippings, notch wear or combination of these (De Oliveria et al., 2009; De Godoy and Diniz, 2011; Ghani et al., 2015; Paulachon et al., 2004; Noordin et al., 2007; Kumar et al., 2006). The total wear generally observed in any cutting tool can either be a chemical wear (diffusion wear) or mechanical wear (adhesion, abrasion, and fracture wear), which are normally associated with the worn area on the cutting tool or by combination of these (Kumar et al., 2006; Sobiyi et al., 2015; Diniz et al., 2016). Those effects could be due to high mechanical, chemical and thermal loads generated during hard machining.

The capability to predict tool wear during hard turning is necessary to determine optimum cutting variables in order to avoid terrible tool failure, which leads to poor work-piece quality, damage of cutting tool edge and may affect machine tool performance. Moreover, it can be used to determine the optimum cutting speed for the minimum machining.

In the current context where tool steels for cold work operations are widely used, the need to provide useful information about the influence and the correlation between the machining parameters on tool wear, wear mechanism and surface roughness was the primary motivation for this study. This research will also provide valuable information to cutting tool manufacturers in the development of new products and machine tools in order to achieve cost effective machining under given parameters without compromising quality and manufacturing cost. Optical microscopy, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) have been used to study the wear performance and behavior of different tools.

2.0 MATERIALS AND METHODS

2.1 Materials

AISI D2 (High carbon and chromium tool steel) steel, used in this study, was obtained from Bhushan Alloys Pvt. Ltd., New Delhi, (India) in the form of a cylindrical rod of 55 mm diameter and 200 mm length. The work-piece was thorough hardened followed by tempering process to attain a hardness of 442 HV (45.1 HRC).

The compositions and properties of the as received material used in this study are listed in Table 1 and Table 2 respectively. Three different cutting tool materials were used in the present work and these are described in Table 1.

Table 1: Work-piece and cutting tool description

Material	Name/Description	Composition
Work-piece	AISI D2	C (1.70),Si (0.30), Mn (0.30), Cr (12.00), W(0.50),V(0.10),Mo (0.60), Fe (balance)
Cutting tools	Mixed Alumina ceramic	70%Al_2O_3+30% TiC
	PCBN	CBN +TiN binder +TiN coating
	Coated Carbide	Multilayer TiC/TiCN/Al_2O_3 coated by TiN over a carbide tool

Table 2: Properties of work-piece (AISI D2) material

Properties	Density	Poisson's ratio	Elastic modulus	Thermal expansion	Melting point
	7.7 x 1000 kg/m^3	0.27-0.30	190-210 GPa	10.4 x $10^{-6}/^{o}$C	1421°C

2.2 Surface Roughness

Arithmetic roughness measurements Ra for each cutting condition was obtained with a contact stylus profilometer–Hommel Etamic, Jenoptik, Germany, (Model W5) with a stylus tip radius of 2 µm. The length examined was 3.2 mm with a cut-off length of 0.8 mm over three sampling lengths. The average of these three R*a* values was used to quantify the roughness achieved on the machined surfaces. Surface roughness in finish metal cutting is used as one of the indicators for evaluating the cutting tool life.

2.3 Cutting Tests

Dry finish testing was performed on AISI D2 steel using three different cutting tools. The cutting inserts were clamped to a right-hand tool holder with ISO designation PCLNR 2525 M12 having −6° rake angle, −6° clearance angle, and 95°approach angle as shown in Figure 1. Machining tests were carried out on a 5.2 kW general purpose centre lathe. The tool nose radius (rε) was kept constant at 0.8 mm for all the tool materials used. The diameter of the work-piece tested was 55 mm and the cutting length was 200 mm, so that L/D ratio does not exceed 10 as per ISO 3685 standards (Dogra et al., 2011).The tuning test consisted of axial cutting length 190 mm and after every one, two, three, four, five and eight number of passes, the amount of maximum flank wear (VB*max*) and surface roughness (R*a*) of the machined surface was recorded. Tool wear was monitored during tool life using an optical microscope and after the end of tool life, the cutting inserts were examined in a scanning electron microscope (SEM) equipped with an EDS system. Each test was carried out three times. Before carrying out each test, the work piece was pre-machined at a low cutting speed (30 m/min) using carbide tool to minimize the probable effect of tool wear on the machined surface during the previous pass. In the experimental work, three different cutting speeds of 110 m/min, 150 m/min and 190 m/min have been used. The feed (f) and the depth of cut (d) were kept constant at 0.05 mm/rev and 0.10 mm respectively. Maximum tool flank wear was measured using Leica DM 6000 advanced microscope and having image characterized using Leica image analysis software.

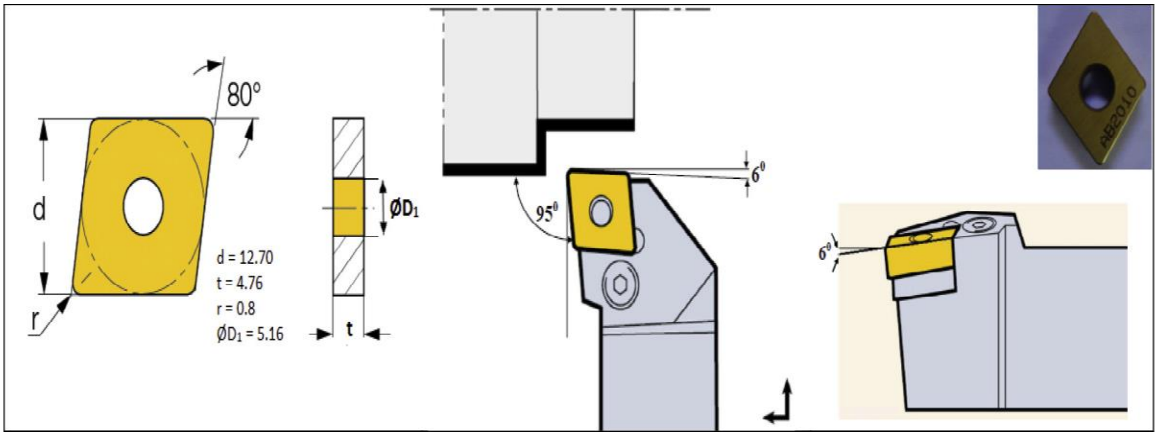


Figure 1: Insert with tool geometry

3.0 RESULTS AND DISCUSSION

3.1 Tool Wear and Tool Life

Progression of maximum flank wear (VB*max*) with machining time in minutes at different cutting speeds is presented in Figures 2 (a), (b) and (c). From the graphs, it is indicated that in all cases the flank wear increases with increase in cutting speed, which generally is the most significant factor affecting the tool life during machining of hardened steel (Reddy et al.,2009). No premature tool failure by chipping and fracturing was observed on any type of cutting inserts used, as can be seen in Figures 4 (a)-(i). The flank wear for PCBN and mixed ceramic inserts developed steadily which widened with progressing machining time i.e. the three zones of wear have been observed for PCBN and mixed ceramic cutting inserts at low cutting speeds (initial wear followed by steady wear and finally rapid stage wear). Whereas, the flank wear for coated carbide inserts seems to be linearly proportional to the cutting time at all the cutting speed used. The flank wear rate for all cutting inserts increased as the cutting speed increased because with increase in cutting speed for a given time, the cutting temperature increases which leads to rapid tool wear (Sales et al., 2009). However, the flank rate of PCBN inserts was less than that of mixed ceramic and coated carbide tools which is due to its ability to retain its hot hardness at elevated temperatures (De Godoy and Diniz, 2011). Moreover, for mixed ceramic and coated carbide tools, at the tool chip-interface, the high temperature generated resulting from high cutting speeds leads to accelerated tool wear due to decrease of their hot hardness and fracture toughness (Sobiyi et al., 2015; Sales et al., 2009). Furthermore, PCBN tools are high thermally conductive than the mixed ceramic tools, the higher thermal conductivity of PCBN tools allows the heat to flow out of the cutting region quickly and reduces the cutting temperature near the tool edge. This lower thermal conductivity in mixed ceramic tools, than in PCBN tools, contributed even further to tool thermal softening and increased the abrasive wear rate as can be seen in Figure 5 (c). PCBN cutting tool, however, showed better resistance to wear for all cutting speeds used because of its fracture toughness and ability to retain its hot hardness at elevated temperatures (Sobiyi et al., 2015; De Godoy and Diniz, 2011) and thus, can withstand the high temperature generated at the tool-chip interface.

For all the speeds used, PCBN cutting tools, due to their superior wear resistance and ability to retain their strength at higher cutting temperatures showed a better performance. Based on selected flank wear criterion, the tool life of different cutting tools at various cutting speeds is presented in Table 3. The corresponding tool life values for flank wear land width of 0.2 mm are given in Figure 3.

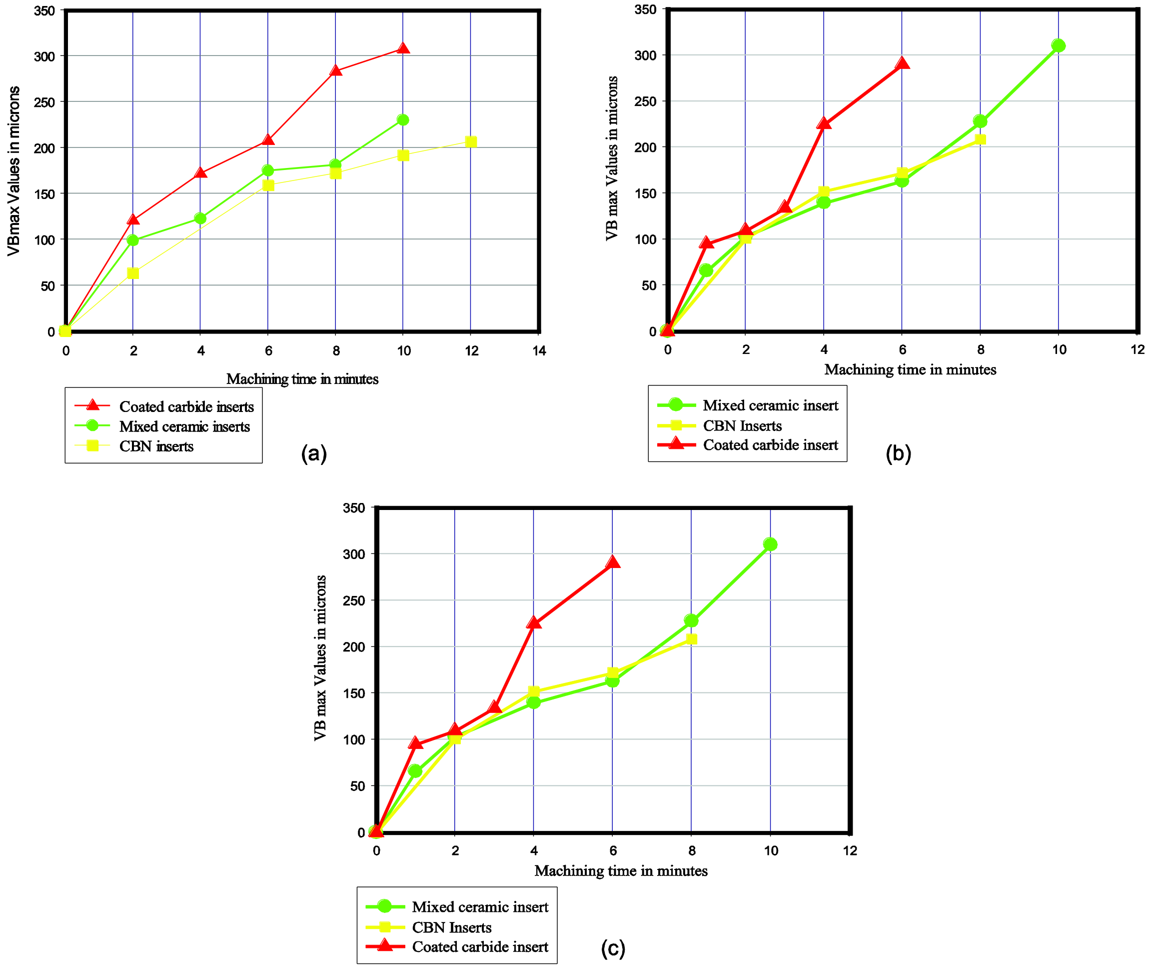


Figure 2: Progression of maximum flank wear at (a) v=110 m/min, (b) v=150 m/min and (c) v=190 m/min, f=0.05 mm/rev, DOC =0.10 mm

Table 3: Tool life values (mins.) for the used tool materials at flank wear land width of 0.2 mm

Tool material	**Coated carbide**	**Mixed alumina**	**PCBN**
V =110	5.5 mins	8.8 mins	11.3 mins
V=150	3.6 mins	7.1 mins	7.5 mins
V=190	3 mins	5 mins	5.7 mins

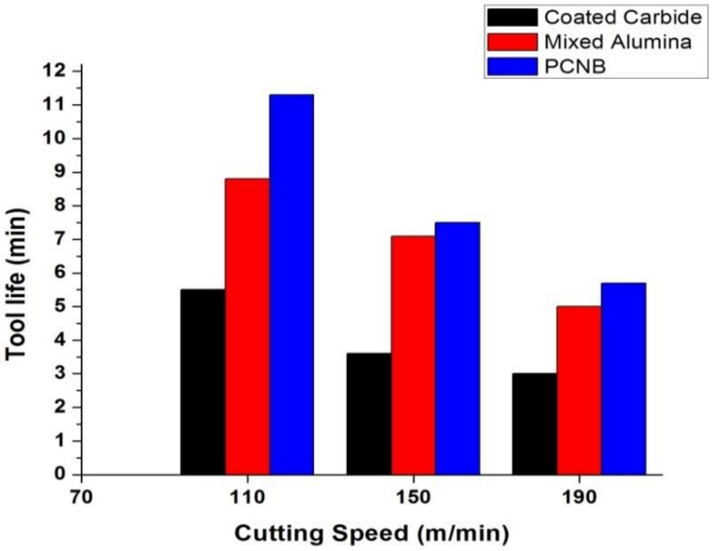


Figure 3: Tool life values (minutes) for the use tool materials at flank wear land width of 0.2 mm

3.2 Wear Mechanisms

3.2.1 Wear Mechanisms of Ceramic Cutting Tools

The optical images of ceramic cutting inserts are shown in Figure 4 (a)-(c) and SEM micrographs are shown in Figure 5 (a)-(c). The figures show that no chipping, breakage or catastrophic failure was observed on the cutting edge of the insert, indicating that the cutting parameters were adequate and the stiffness of the tool fixture assembly and work-piece was suitable for turning operation. Figures 4(a) and 5(a) indicate that the wear band of mixed ceramic tool at a speed of 110 m/min is mainly abrasive tracks and partly due to adhesion of the work-piece material on worn surface. This indicates that the dominant wear mechanism is mainly abrasive wear, which may be caused directly by contact of hard work-piece particles with the tool (Diniz et al., 2016; Sales et al., 2009). In addition, the EDS analysis of point 2 on the worn surface, as can be seen Figure 6(a), reveals that a small amount of adhered-particles like iron, Cr, V,W are found on the worn surface, which are transferred from the work-piece during the turning test. When the speed was increased to 150 m/min, no chipping or breakage of cutting edge was found on the tool, as can be seen Figures 4(b) and 5(b). However, at this cutting speed mixed ceramic tool has comparatively more rough worn surface after the cutting process. Analysis of the SEM micrographs in Figure 5(b) shows the presence of parallel grooves on tool flank surfaces for tested ceramic tool. These grooves are oriented along the cutting speed direction. This phenomenon is the result of intense abrasive wear (Paulachon et al., 2004; Luo et al., 1999). There are also large amounts of adhered materials like Fe and Cr from work-piece on the worn surface as confirmed by EDS analysis, as shown in Figure 6(b). When the cutting speed was further increased (v=190 m/min), the dominant wear mechanism observed is abrasive wear with deeper and wide grooves, as can be seen Figures 4(c) and 5(c), when compared with the parallel marks at two other speeds. The formation of deeper grooves could be because of pulling of the fragments of the carbide grains out of the tool surface and dragging it across the flank face, thus removing the tool material (De Godoy and Diniz, 2011; Sobiyi et al., 2015). Moreover, the EDS analysis (Figure 6(c)) of many points has shown the significant presence of adhered Fe and Cr from the work-piece material covering the grooves and the ridges on the flank area of the tool.

3.2.2 Wear Mechanism of PCBN Cutting Tools

Figure 4(d)-(f) shows the optical micrograph and Figure 5(d)-(f), the SEM micrograph of the worn PCBN cutting tool surfaces. The figures show the cutting tools flank face and rake face. The most dominant wear mode in PCBN cutting tools is flank and crater wear, which can be seen easily in the SEM micrographs.

Abrasive wear mechanism is more predominantly observed for PCBN tools on the flank face while it is moderate at the chip-tool interface on the rake face. Other wear mechanisms such as BUE, adhesion, and plastic deformation were also observed on the cutting tool surfaces.

Figures 4(d) and 5(d) clearly show smooth abrasive wear (marks parallel to the cutting direction) on the flank face and evidence of built up layer on the rake face of the PCBN inserts. The grooves or scratch marks formed on the flank face of the PCBN tool resulted from the rubbing of hard carbide particles of the work-piece on the flank face of insert (Luo et al., 1999). The smooth abrasive wear is mainly observed with PCBN cutting tool when cutting hardened steel, as a result of the small feeds and strength of the cutting tool (Sobiyi et al., 2015; Motorcu, 2011). More analysis of Figure 4(d) shows a significant built-up edge formed at low cutting speed and feed combination because of moderate interface temperature rise and diffusion/affinity of work-material for tool under these cutting conditions (Dogra et al., 2011). When the speed was increased from 110 m/min to 150 m/min, the cutting temperature also increased, which created a possibility of chemical wear between the cutting tool and the work-piece material. This wear phenomenon is generally reported when machining hardened steels using PCBN (Chou and Evans, 1997; Lahiff et al., 2007). Clear evidence of built up edge, abrasion, adhesion and diffusion is shown in Figure 5(e). Furthermore, with this increase in cutting speed, there is increase in temperature, which leads to diffusion and oxidation of the tool surface (Dogra et al., 2011). The composition of the adhered metal on the cutting insert consists of the constituents of the work-piece material with elements such as, Fe, Si, Cr, and O formed during oxidation, was confirmed by EDS analysis, as can be seen in Figure 6(e). When the cutting speed was further increased to v=190 m/min, adhesion along with abrasion become the dominant wear mechanism, as can be seen in Figure 5(f). Because at higher cutting speed, cutting temperature increase, the higher cutting temperature has great influence on the formation of larger amounts of adhesion and the adhered layer thus formed was worn away due to high frictional force, which led to plucking of material from tool face. Moreover, the high temperature probably causes the binder resistance to drop, resulting in loss of cohesion with PCBN, thus facilitating the removal of a large volume of tool material (Sales et al., 2009). Figure 5(f) shows the shallow pocket formed as the adhered material was removed. The EDS analysis of many points have shown the significant presence of adhered Fe, V, Si, W, and Cr from the work-piece material on the flank area of the tool, as can be seen in Figure 6(f).

3.3.3 Wear Mechanisms of Carbide Cutting Tools

Figure 4(g)-(i) shows the optical micrographs and Figure 5(g)-(i), the SEM micrographs of the worn carbide cutting tool surfaces. As shown in Figure 5(g)-(i), both flank wear and crater wear were observed for all the inserts tested under all cutting conditions. The tool wear zone occurred mostly near the tool nose radius on the flank side. For coated carbide inserts, the coating layer from the cutting edge (flank portion) was worn within the first minute of machining. In Figure 5(g), at low cutting speed, abrasion and adhesion, formation of BUE followed by plastic deformation were dominant wear mechanisms. Abrasion wear occurred due to hard carbides and impurities present within work-piece (Sales et al., 2009). Figure 6(g) shows the EDS analysis of the cutting inserts in terms of relative intensity of the counts and the energy. The figure demonstrates the transfer of material like Fe, Cr, Si and Mg from the work piece on the tool surface. As indicated in Figure 5(g), built-up edge also appeared at low cutting speed (Dogra et al., 2011). When the speeds were increased from 110 m/min to 150 m/min, the wear mechanism observed for the cutting insert was similar to those observed at v =110 m/min. However, chipping of the cutting edge was also observed which may be possibly due to tangling of the chips. In Figure 6(h), spectrum 1 and 4 clearly identifies titanium, aluminum and oxygen from the multilayer coating and a small peak of tungsten from the base tool material. The spectrums also identify the significant presence of adhered iron and chromium from the work-piece over the carbide tool. As shown in Figure 5(i), as the cutting speed was further increased to v=190 m/min, severe chipping took place, due to which coated-carbide inserts underwent rapid wear. On the other hand, abrasive marks along with adhered material were also observed on the tool worn surfaces. Abrasion wear, which can be seen mainly in Figure 5(i), on the flank face, occurred due to high contents of hard carbides in the work-piece material (Arsecularatne et al., 2006; Sales et al., 2009). In this case, two body abrasion could be the most important, but three-body abrasion could also have occurred due to hard particles removed from surface by chipping, which could have acted as a medium of three-body abrasion between work-piece and tool flank face (Sales et al., 2009; Dogra et al., 2011). The composition of the adhered metal on the cutting insert was confirmed by EDS analysis and is shown Figure 6(i). The adhered material consists of the constituents of the work-piece material with elements such as, Fe, Cr, and V.

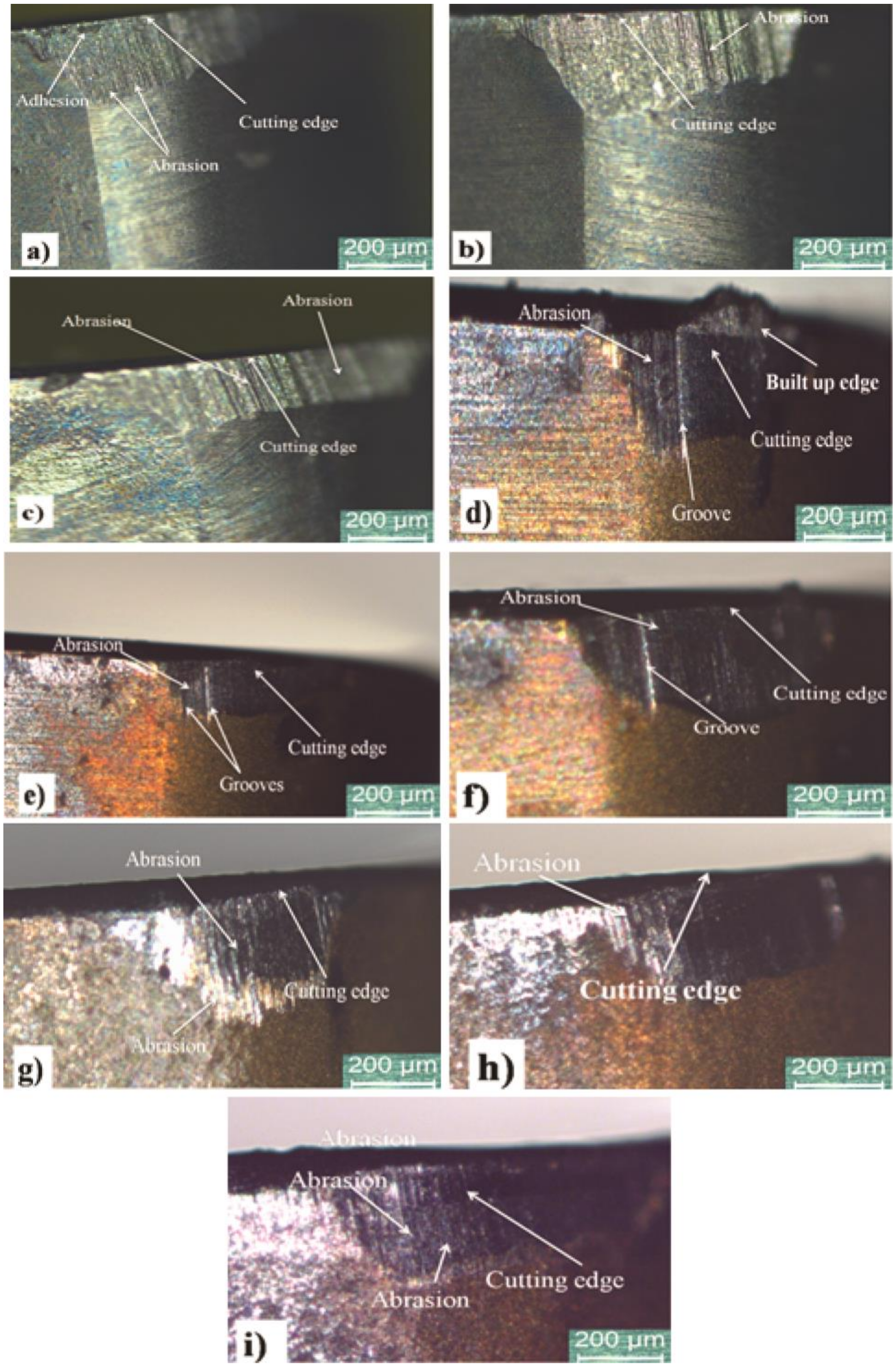


Figure 4: Optical micrographs of the worn cutting inserts (a) Mixed ceramic (110 m/min) (b) Mixed ceramic (150 m/min) (c) Mixed ceramic (190 m/min) (d) PCBN (110 m/min) (e) PCBN (150 m/min) (f) PCBN (190 m/min) (g) Carbide (110 m/min) (h) Carbide (150 m/min) (i) Carbide (190 m/min)

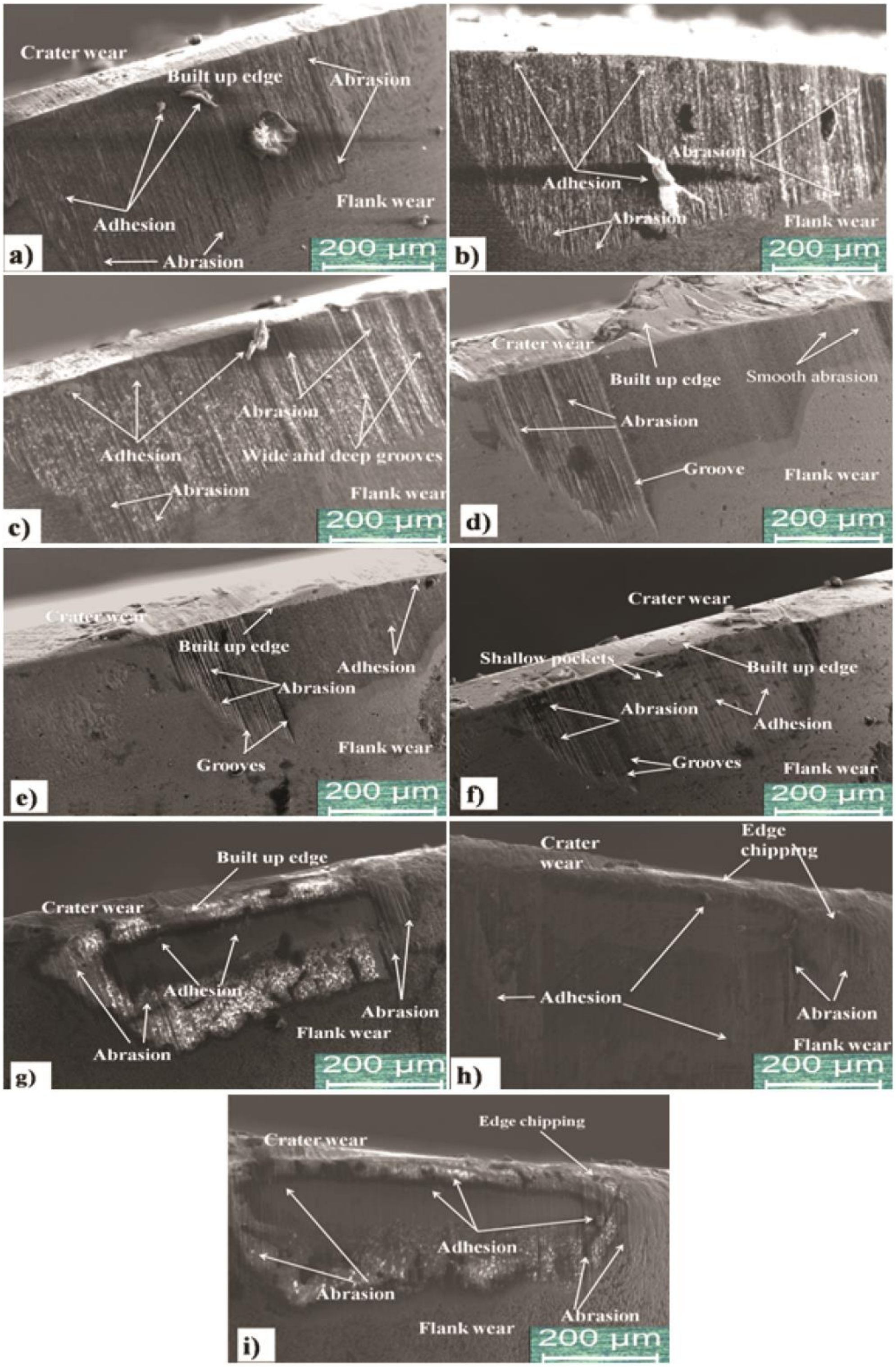
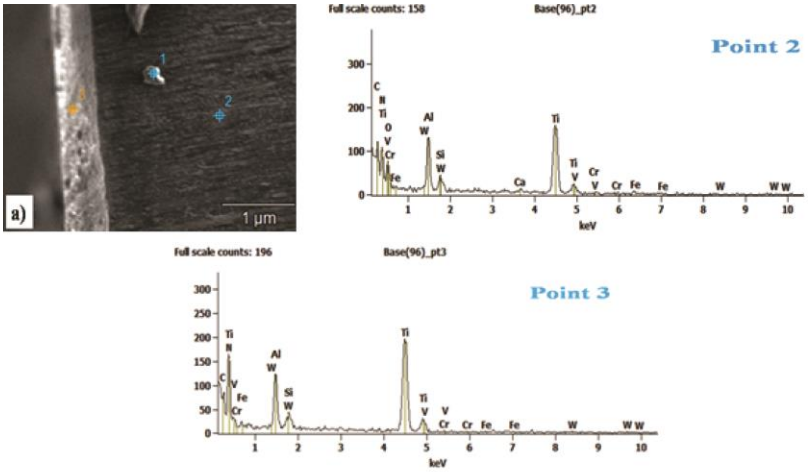
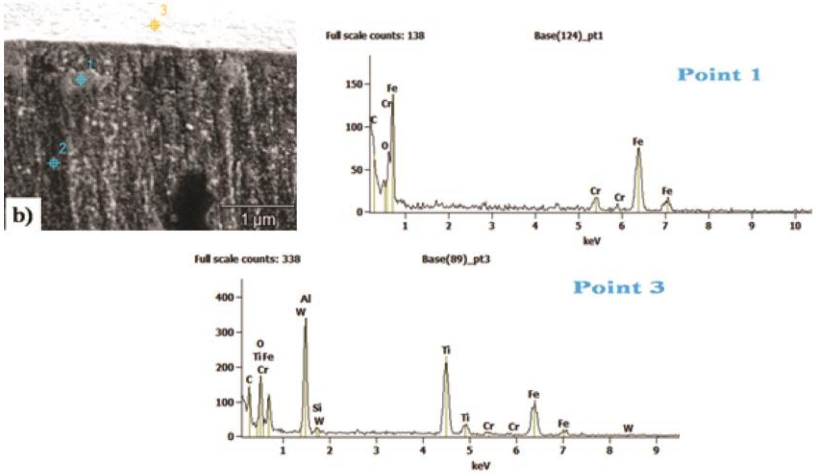


Figure 5: SEM micrographs of the worn cutting inserts (a) Mixed ceramic (110 m/min) (b) Mixed ceramic (150 m/min) (c) Mixed ceramic (190 m/min) (d) PCBN (110 m/min) (e) PCBN (150 m/min) (f) PCBN (190 m/min) (g) Carbide (110 m/min) (h) Carbide (150 m/min) (i) Carbide (190 m/min)


a)
1 µm
1
2
3
Full scale counts: 158
Base(96)_pt2
Point 2
keV
Full scale counts: 196
Base(96)_pt3
Point 3
keV

(a)


b)
1 µm
1
2
3
Full scale counts: 138
Base(124)_pt1
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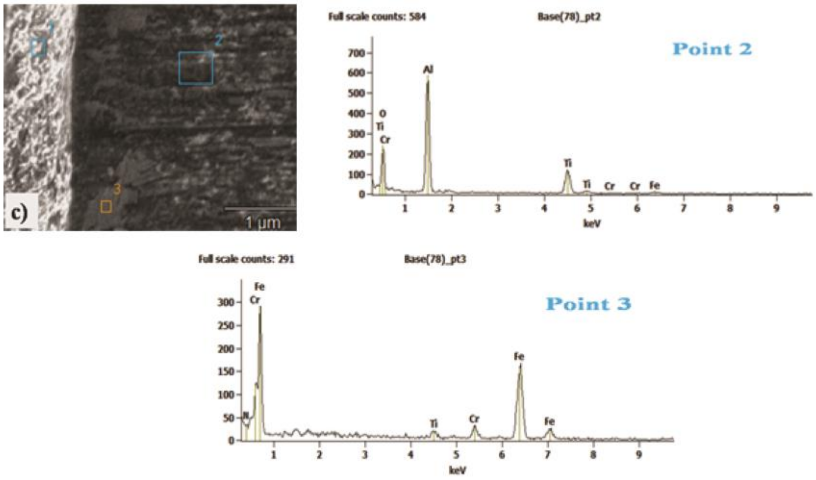
keV
Full scale counts: 338
Base(89)_pt3
Point 3
keV

(b)


c)
1 µm
1
2
3
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Base(78)_pt2
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keV
Full scale counts: 291
Base(78)_pt3
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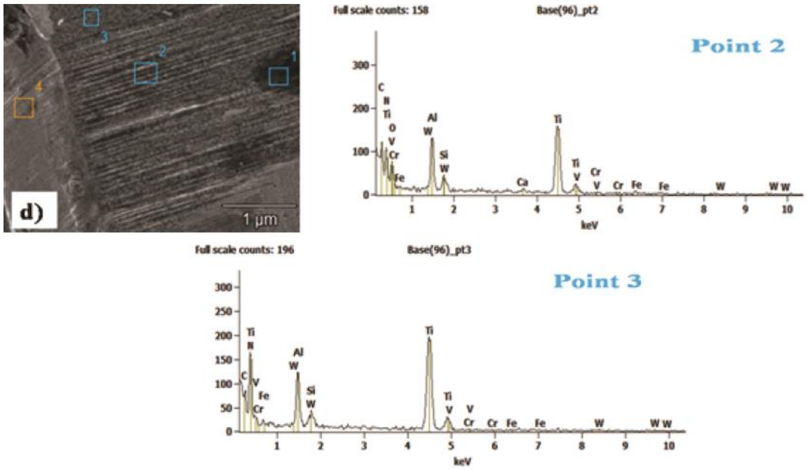
keV

(c)


d)
1 µm
1
2
3
4
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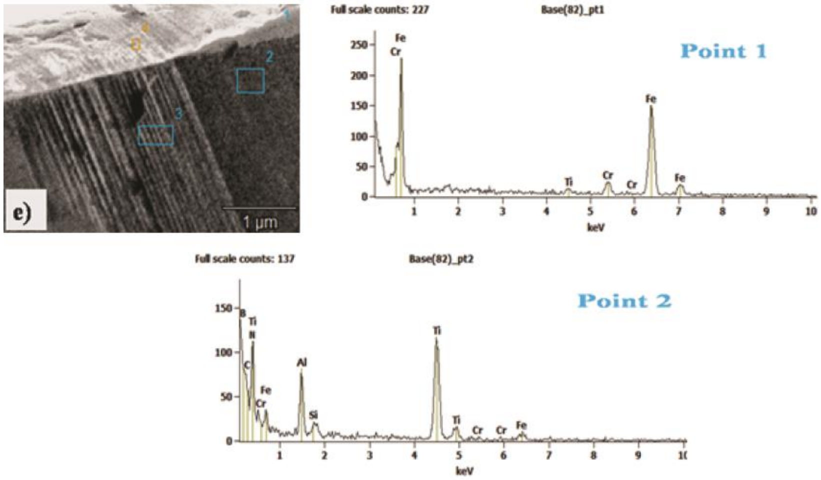
Base(96)_pt2
Point 2
keV
Full scale counts: 196
Base(96)_pt3
Point 3
keV

(d)


e)
1 µm
1
2
3
4
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keV
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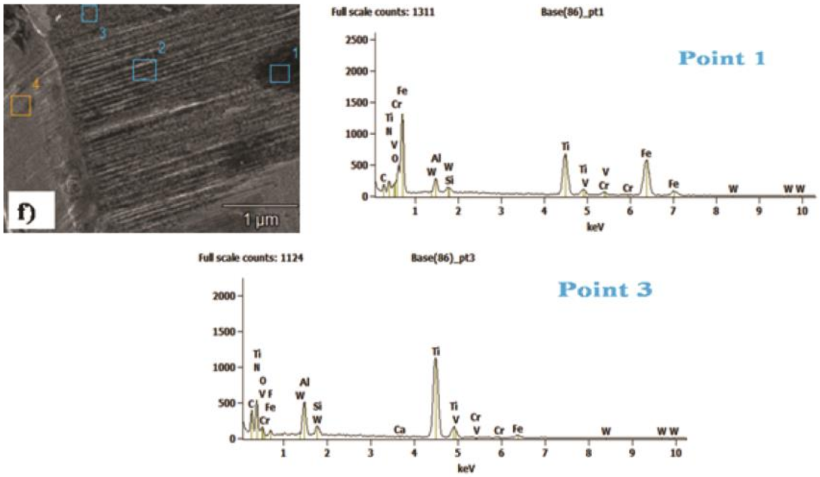
Base(82)_pt2
Point 2
keV

(e)


f)
1 µm
1
2
3
4
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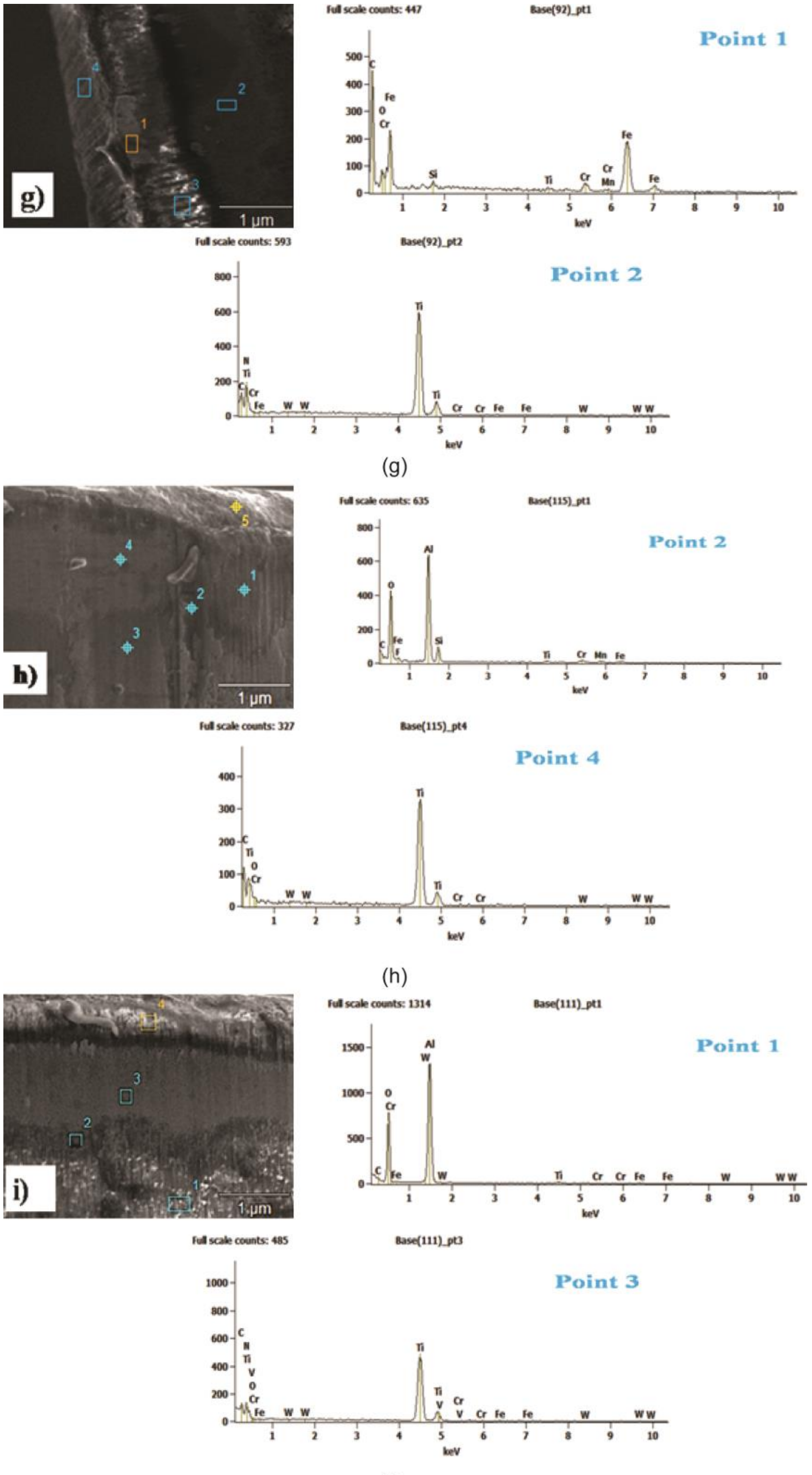
Base(86)_pt1
Point 1
keV
Full scale counts: 1124
Base(86)_pt3
Point 3
keV

(f)



(g)

(h)

(i)

Figure 6: EDS pattern of the worn cutting inserts (a) Mixed ceramic (110 m/min) (b) Mixed ceramic (150 m/min) (c) Mixed ceramic (190 m/min) (d) PCBN (110 m/min) (e) PCBN (150 m/min) (f) PCBN (190 m/min) (g) Carbide (110 m/min) (h) Carbide (150 m/min) (i) Carbide (190 m/min)

3.3 Surface Roughness

Surface roughness in finish metal cutting is used as one of the indicators for evaluating the cutting tool life. The surface finish produced during hard turning of AISI D2 Steel while using the PCBN, mixed ceramic and coated carbide tool was found to be satisfactory.

Figure 7 shows the variation of surface roughness with cutting time at different cutting speeds for different types of cutting inserts used. For coated carbide insert, the Ra value for first few minutes of machining increases (running in period) and after that there is only a marginal increase in the Ra value followed by a continuous increase in the surface roughness values. The reason for the marginal increase in the Ra value is due to effective flattening of corner radius for some time and smooth progression of tool wear (Dogra et al., 2011). After that tool wear increase rapidly, due to which surface roughness value increases continuously for the rest of machining time. The surface roughness is significantly affected by tool wear (Ghani et al., 2015; De Godoy and Diniz, 2011; Noordin et al., 2007). Same pattern was followed by the coated carbide tools at higher speeds. The surface roughness values observed for samples turned with different inserts at 110 m/min speed and 0.05 mm/rev feed rates, respectively, are plotted in Figure 7. For PCBN inserts and mixed ceramic inserts, as the machining progresses, the R*a* value almost remained constant for first few minutes and only increased at the end of tool life. This behavior is due to effective flattening of the corner radius and smooth progression of tool wear (Huang and Dawson, 2005; Dogra et al., 2011). The surface roughness increases with increasing cutting time because the blunt/worn-out tool results in chatter marks on the machined surface and decreases the surface finish (Dureja et al., 2010).

For coated carbide inserts at higher speeds (150 m/min and 190 m/min), the R*a* value continuously increases with increase in machining time due to non-uniform wear of the flank face. But for these inserts at the end of tool life (VB_{max} = 200 µm), the R*a* value remains below 1.6 µm under present cutting condition. The surface roughness values achieved with the PCBN tools first remains stable and then increases marginally at the end of tool life. This is because of thermal softening of the work-piece at higher speed and the smooth progression of flank wear does not change the tool nose radius much, once it is flattened (Sales et al., 2009; Dogra et al., 2011).

The effect of increase in cutting speed resulted in increase in surface roughness produced by mixed ceramic cutting inserts. For mixed ceramic insert, the increase in surface roughness values is moderate at initial cuts for both speeds used but starts increasing with progressing time, as the tool is worn out resulting in chatter marks and debris on the machined surface. These findings can be explained by the shape of tool nose at the end of tool life. Figure 5(a)-(i) shows the presence of deep abrasion marks or scratches on the tool noose of the ceramic insert. These deep scratches or abrasion marks greatly alter the tool nose, causing the surface roughness to increase. The effect of tool vibration and tool wear has a significant effect on the surface finish of the machined component (Sobiyi, 2015). The surface roughness observed with PCBN cutting inserts was lower than the coated carbide insert and mixed ceramic insert due to lower tool wear, less distortion of cutting edge and tool nose at highest speed used.

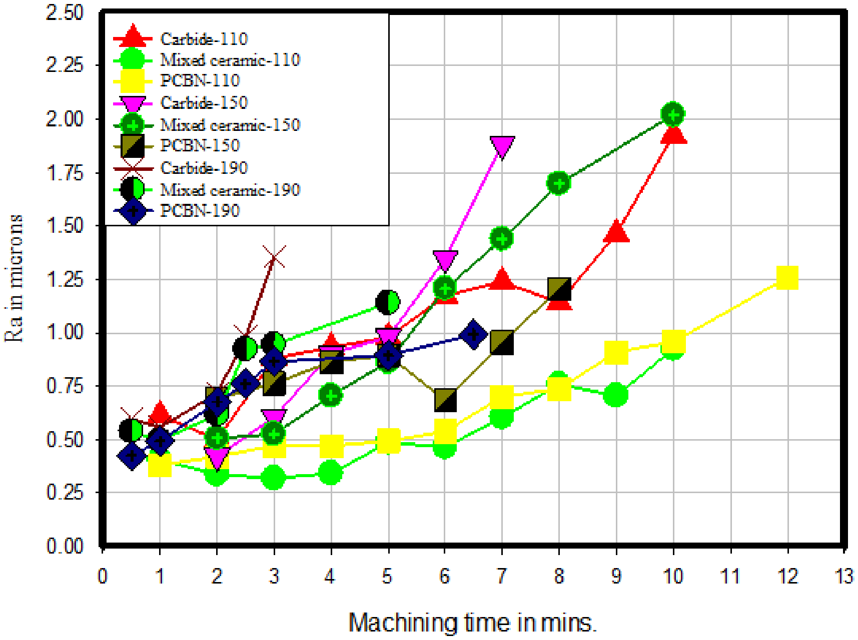


Figure 7: Variation of R*a* at different cutting speeds, f=0.05 mm/rev, DOC=0.10 mm

3.4 Economic Analysis

Economic analysis with respect to the metal cutting process is an essential element in efficient manufacturing system because of large expenses involved. The basic attempt of any manufacturing process is to produce components of acceptable quality at the minimum possible cost. Therefore, cost analysis based on total machining cost per part according to Gilbert's approach (Sahoo and Sahoo, 2013) was performed for the comparison of economic feasibility between: PCBN, mixed alumina ceramic and coated carbide inserts in turning. The cost analysis was done for turning a cylindrical work-piece with a finished diameter (D) of 55 mm, length of cut (L) 200 mm , varying cutting speed parameters (V = 110, 150 and 190 m/min), feed(f) = 0.05 mm/rev, and DOC(d) = 0.1 mm. Considering flank wear criteria VB = 0.2 mm. The study is based on measured tool life of various cutting inserts used (see Table 3). As per current machining practice, the labour charge, the machine charge and the overhead, the total cost of the machine time and labour (x) is estimated to be ₹250 per hour (4.16 /min). With these parameters, the machining time per part (Tc) can be calculated using the following formula (Sahoo and Sahoo, 2013; More et al., 2006).

$$Tc = \frac{\pi DL}{1000V.f} \tag{1}$$

Where D is the finished diameter of work-piece (mm), L the axial length of the work to be cut (mm), f the feed (mm/rev), and V is the cutting speed (m/min). Therefore; the machining cost per part = x.Tc

If Td is the downtime in minutes to change the tool and the work-piece and T is tool life for one cutting edge, then the tool changing cost per part is given by:

$$\text{Tool changing cost per part} = xT_d(T_C/T) \tag{2}$$

The cost of commercially available, TiN coated tool inserts is approximately ₹800 per piece. The cost of mixed ceramic insert is approximately ₹1200 per piece. The cost of PCBN insert is approximately ₹3200 per piece. Therefore, the mean value of a TiN coated carbide inserts is ₹200, mixed ceramic tool is ₹300 and PCBN inset is ₹800 respectively. The tool cost per part is estimated by:

$$\text{Tool cost per part} = y\ (Tc/T) \tag{3}$$

The total machining cost per part (C) is the sum of machining cost per part, the tool changing cost per part and the tool cost per part:

$$C = x.Tc + xT_d(T_C/T + y\ (T_C/T) \tag{4}$$

Results of the cost analysis based on the above data are given in Table 4. This table describes the cost of machining per part at various cutting speeds using different types of cutting tools. It can be seen that the total machining cost savings in machining using mixed ceramic inserts is approx. 52% compared to PCBN and 10% compared to coated carbide inserts at cutting speed of 110 m/min. Similarly, at 150 m/min, the percentage saving using mixed ceramic inserts is 49% with respect to PCBN inserts and 25% with respect to coated carbide inserts. The total machining cost saving at 190 m/min using mixed ceramic tools is 55% as compared to PCBN inserts and 12% with respect to coated carbide inserts. The machining time for each cutting edge of mixed ceramic and carbide inserts was not as long as that for the PCBN inserts, but the accumulated machining time for all the four edges of mixed ceramic and coated carbide inserts was nearer to or better than the PCBN inserts. As the cost of per cutting edge of mixed ceramic and coated carbide inserts is quite less than the PCBN inserts, as such, mixed ceramic and coated carbide inserts are capable of reducing the machining cost without compromising on the surface finish and therefore will be important alternative to PCBN inserts for finish hard turning applications.

Table 4: Comparison of machining costs for inserts in finish hard machining

SI. No.	Description	Multilayer TiN coated carbide tool			Mixed ceramic tool			PCBN		
1.	Speed	110 m/min	150 m/min	190 m/min	110 m/min	150 m/min	190 m/min	110 m/min	150 m/min	190 m/min
2.	Costs									
i	Operations cost, x, @ ₹250	4.16	4.16	4.16	4.16	4.16	4.16	4.16	4.16	4.16
ii	Machining cost per part (xTc)	26.12	19.15	15.12	26.12	19.15	15.10	26.12	19.15	15.10
iii	Tool life for single edge (T)	5.5	3.66	3	8.9	7.16	5	11.3	7.66	5.66
iv	Tool changing cost per part [xTd(Tc/T)]	23.74	26.14	25.16	14.67	13.36	15.10	11.55	12.49	13.39
v	Mean value of single cutting edge (y)	200	200	200	300	300	300	800	800	800
vi	Tool cost per part [y(Tc/T)	228.3	251.6	242	211.68	192.73	217.8	444.6	480.41	513.07
vii	Total machining cost per per part (C), (ii+iv + vi)	₹278	₹297	₹282	₹252	₹225	₹248	₹482	₹512	₹542

CONCLUSION

The wear mechanism of mixed ceramic, coated carbide tools and PCBN cutting tools during hard turning of AISI D2 steel was studied. Based on the results and analysis of the machinability study of finish hard turning, the conclusions including aspects related to tool wear, surface roughness, and economical feasibility are presented:

1. During machinability study in hard turning, it is observed that the tool life for PCBN cutting tools is higher than coated carbide and mixed ceramic tools at all the cutting speeds used.

2. In continuous cutting, the main wear mechanism of the mixed ceramic tool was abrasion while that of the PCBN tool was abrasive wear and cratering and for coated carbide tools were abrasive wear, adhesive wear and cratering at lowest cutting speed. At moderate and highest cutting speed, the failure of mixed ceramic tools is predominantly by abrasive wear and adhesive wear, while PCBN fails by abrasive wear, adhesive wear and cratering at moderate speeds and abrasive wear along with severe adhesive wear at highest speed. For carbide tools, abrasion, adhesion along with chipping was the cause of failure at moderate and highest cutting speeds.
3. The surface roughness produced was within the recommended range of finish hard turning i.e. within 1.6 µm for all cutting tools used. Better surface roughness R*a* was produced by PCBN inserts for all the speeds used when compared to the surface produced by the mixed ceramic and carbide cutting tool.
4. A cost analysis based on a single cutting edge shows that the mixed ceramic tools are capable of reducing total machining cost per part and therefore will be an important complement to coated carbide and PCBN tools for finish hard turning applications.
5. PCBN tools performed better than mixed ceramic and coated carbide tools in terms of tool life under different machinability criteria used.

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