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Investigation of Surface Roughness and Flank Wear by CBN and PCBN Tools on Hard Cr-Mo Steel

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Abstract— **Hard turning is the latest technology and is used to turn hard materials by using cutting tools like CBN and PCBN. Certain hard materials like titanium, Inconel and stainless steel are pronounced as difficult to cut materials. The superior cutting tools effectively machine such hard materials and produces desirable surface roughness with less tool wear. The present research was carried on hard Cr -Mo alloy steel namely SCM 440 material by turning process. The hardness of the work materials were maintained between 45 to 55 HRC. The CBN produced low surface roughness and PCBN tool produced high surface roughness. The formation of crater wear was less in PCBN tool than CBN tool. Build up layer (BUL) was due to diffusion of work material on CBN and PCBN tools. PCBN tool withstand heat better than CBN. Formation of built up edge (BUE) is concern on PCBN tool and is less than CBN tool.**

Key words: Built up edge (BUE), Built up layer (BUL), Crater wear, Flank wear, Surface roughness,

I. INTRODUCTION

Hard turning has been applied in many areas like production of bearings, gears, shafts and other mechanical components since the early 1980s [1]. In particular, precision finishing of hard steel components using superior cutting tools offers manufacturers an attractive alternative to grinding. Hard turning by superior hard tools like CBN and PCBN help to reduce cost per product, produce good surface roughness, high productivity, and less tool wear. Environmental benefits, due to elimination of cutting fluids and a significant reduction in industrial waste, have been achieved using turning processes rather than grinding [2]. It is known that hard turning requires negative rake angle with reinforcement for cutting edge by way of chamfered edge. Tool wear is common in all the machining processes and depend on the work material hardness, type of cutting tool, rigidity of machine tools, generation of heat, formation of chips and cutting parameters. Tool wear is a complex phenomenon. A typical tool wear that are likely to form is shown in the figure 1. Tool wear, cutting forces, surface roughness and temperature induced by the cutting process by the cutting tool and work piece are the major error drive factors in hard turning. CBN and PCBN cutting tools possess excellent mechanical properties such as high temperature strength, ability to maintain its shape and strength at high temperature and hardness second to diamond [3]. In finish hard turning, high hardness of work material, large cutting forces, and high heat at tool tip - work material interface impose extreme requirements for tool rigidity and tool wear resistance.

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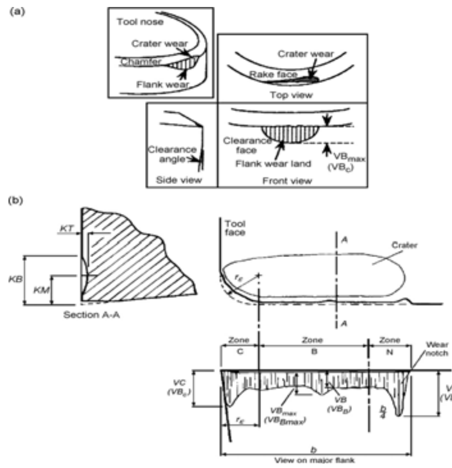


Figure1: Typical wear in a single point tool turning [3, 4]

II. EXPERIMENTAL PROCEDURES

The turning experiment was carried in a N.C. Harrison 440 Alpha lathe. The surface roughness was measured using Mitutoyo SJ 400 tester. The tool wears were measured using Scanning Electron Microscope (SEM)-Joel JSM 6380 LA equipment. The CBN cutting tool was manufactured by Mitsubishi and PCBN was by Kennametal. The tool holder was manufactured by MTJNR2020KL16N by Mitsubishi. The length of turning was 150 mm and the surface roughness, flank wear, crater wear and BUE were measured by SEM at the end of length of turning. The cutting tools have three cutting edges and each edge is repeated for 5 times. i.e. respective cutting edge turned for length of 750 mm. Tables 1 and 2 are shows chemical composition and mechanical properties of SCM 440 material respectively. The turning was carried at cutting velocity of 100, 125, 150, 175 and 200 m/min with feed rate of 0.10, 0.20 and 0.30 of mm/rev with constant depth of cut of 1.00 mm. The dry turning was done dry.

Table1. Chemical composition of SCM 440 alloy steel

Material	C	Mn.	Cr	Mo
SCM 440	0.35-0.43	0.75-1.00	0.80-0.75	0.15-0.25

Table2. Mechanical properties of SCM 440 alloy steel

Material	Tensile strength (MPa)	Yield strength (MPa)	% of Elongation
SCM 440	664	556	--

III.RESULTS AND DISCUSSIONS

A. Surface Roughness

Surface roughness is an important quality for many machined work piece especially in cases where precision is important. Surface roughness in turning has been found to be influenced by a number of factors such as cutting speed, depth of cut, tool nose radius, work hardness, feed rate, and tool angles [5]. Figures 2 to 6 are graphical representation of surface roughness at cutting velocities of 100, 125, 150, 175 and 200 m/min. with feed rate of 0.10, 0.20 and 0.30 mm/rev. respectively The cutting edges of CBN and PCBN were new and turning was effective. The surface roughness produced at low cutting velocity of 100 m/min with feed rate of 0.10 mm/ rev was 0.38 μm and 0.42 μm by CBN and PCBN tool. As cutting velocity was increased to 125, 150, 175, 200 m/min with feed rate of 0.10 mm/ rev, the roughness obtained were 0.31, 0.32, 0.18 and 0.16 μm by CBN and 0.42, 0.40, 0.40, 0.45 and 0.37 μm by PCBN tool respectively. There were differences of 57 % of surface roughness within CBN itself where as PCBN tool the difference was only 7%. Even though percentage difference was low for PCBN, but CBN produced low value of 0.16 μm at cutting velocity of 200 m/min with 0.10 feed rate. Many researchers in machining reported that good surface finish can be achieved at high cutting velocities with low feed rates for a given depth of cut. As the feed rate was increased to 0.20 mm/rev, the values were 0.99 μm at cutting velocity of 100 m/min and 1.03 μm at 200 cutting velocity by CBN tool. The PCBN produced 1.62 μm at cutting velocity 100 m/min and 1.73 μm at cutting velocity of 200 m/min. When turning continued with feed rate of 0.30 mm/rev, CBN produced low value of 3.71 μm at low velocity of 100 m/min. and 3.74 μm high velocity of 200 m/min. This is shown in figure 2 for 150 mm length of turning by CBN and PCBN tools. When the length of turning continued for 300 mm with same operating parameter as that of 150 mm, here again, a low surface roughness of 0.22 μm was achieved at high cutting velocity 200 m/min and high surface roughness of 0.38 μm achieved at low cutting velocity.of 100 m/min. As the cutting velocity was increased form 100 to 200 m/min in multiples of 25 m/min, low roughness was achieved by CBN tool. PCBN tool produced a high roughness value of 0.48 μm at low cutting velocity and low value of 0.44 μm at high cutting velocity of 200 m/min. This is shown in the figure 3. Figure 4 is the graphical representation for 450 mm length of turning. The CBN tool at feed rate of 0.10 mm/rev achieved low surface roughness and as cutting velocity was increased, the surface roughness recorded low value than at low feed rates and they are 0.36, 0.36, 0.25, 0.19 and 0.28 μm. The PCBN tool corresponding parameters was 0.46 μm and end up with 0.28 μm at 200 m/min. The length of turning were completed for 600 mm and there was formation of flank wear at these operating parameters. At feed rate of 0.20 mm/rev, a low surface roughness of 0.99 μm was observed and decreased to 0.86 μm at 200 m/min cutting velocity. The PCBN tool on SCM 440 recorded value of 1.70 μm at cutting velocity of 100 m/min and 1.83 μm at 200 m/min cutting velocity. The differences between them were only 13 μm and are considered as low roughness. When the turning was continued up to length 750 mm, a low roughness of 2.09 μm and 2.14 μm between low and high cutting velocity respectively. The PCBN tool with feed rate of 0.30 mm/rev, surface roughness value 3.70 μm at low cutting velocity of 100 m/min and 3.59 μm at high velocity of 200 m/min. Low roughness value was achieved at low feed rate and low cutting velocity, whatever the length and flank wear formation. The CBN tool produced low surface roughness compared to PCBN tool.

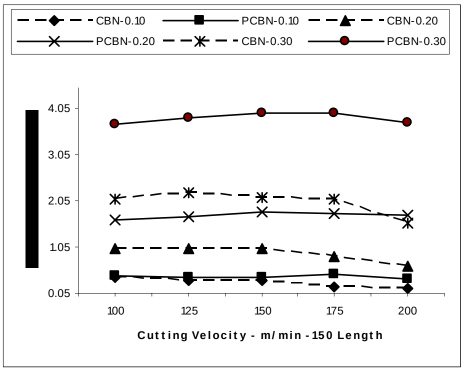


Figure2. Cutting velocity- Roughness- 150 mm length

B. Tool Wear

Mechanical wear is resulted by abrasion and adhesion. The flank wear formation is a serious problem in machining of materials irrespective of their condition. The flank wear formation is not a gradual wear. It can happen rapidly at the start or delayed. The wear condition depends upon the work material properties and qualities, their alloying elements, condition at which it is being machined (soft or hard condition), operating parameters, types of tool and machine stabilities. The formation of flank wear and crater wear mostly due to rubbing of the tool on the flank side with work material and movement of the chips on the rake face of the tool. The flank wear and crater wear will affect the surface quality which is primary concern for any machined components. Wear by moving components is inevitable but it can be minimized. The machining of hard materials is greatly influencing the wear. The machining by superior tools like CBN and PCBN tools was undertaken to minimize tool wears and maximize the output. Tool wear results in undesirable effects: less in dimensional accuracy of the finished product, possible damage to the work piece, decreased surface integrity, residual stress, surface roughness, and amplification of chatter during the cutting process. For these reasons, it is important to evaluate tool wear and to predict tool life [6]. Mechanisms responsible for tool failures are abrasive, adhesive and diffusion wear [6-7]. Abrasive and diffusion wear involves the development of a crater behind the cutting edge of the tool. Generally speaking, flank wear was caused by friction between the flank side of the tool and fresh or machined surface. Tool wear mainly depends on the tool, work material (physical and chemical properties), tool geometry, cutting parameters and cutting fluid [3]. Flank wear generally attributed to rubbing of the tool with work material at the interface, causing abrasive or adhesive wear and at high temperatures. Abrasion is the main wear mechanism in flank wear, built up edge (BUE) and irregular wear are often faces in machining some hard materials especially stainless steel. The area of contact was more at low cutting velocity and low feed rate and in turn increases wear rate and heat. There was formation BUE during turning at low cutting velocity with low feed rate due to constant contact and increase in temperature. This helps to form BUE and as the cutting zone temperature increased, softens and decreased the strength of BUE [8]. Figures 7 to 11 are the graphical representation of flank wear against cutting velocities for length of turning from 150 to 750 mm in multiples of 150 mm. Wear also includes the application or transfer of material and changes in its properties due to friction. The tool wear is a result of mechanical and chemical interactions of the tool with the work piece and can be written as [9].

$$Wear_{total} = W\ mech + W\ chem \qquad (1)$$

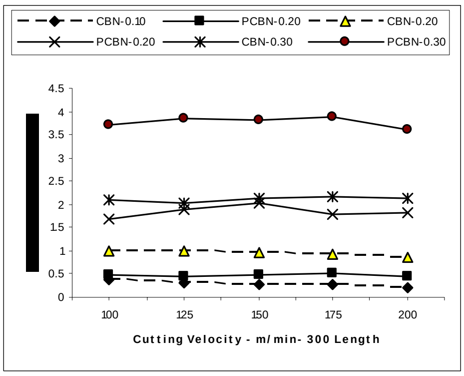


Figure3. Cutting Velocity –Roughness- 300 mm length

The wear mechanisms of a cutting tool edge are closely related to cutting temperature. Low cutting temperatures produce pressure welding which results in a BUE, while high cutting temperatures which are the results of oxidation and enhanced diffusion. In high speed turning with increase in cutting speed, the contact temperature will rise sufficiently to come up to or even exceed the heat resistivity of the cutting tool. With the increase in feed rates, contact temperature on the rake face increased. As a consequence, this causes displacement from flank wear to crater wear with subsequent chipping [11].

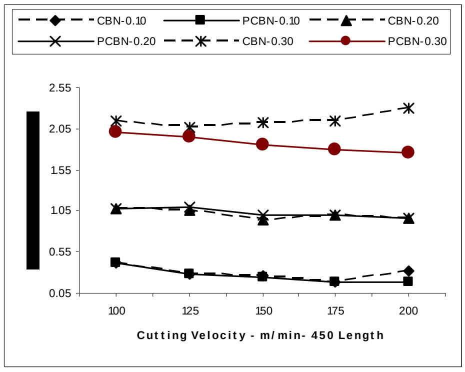


Figure4. Cutting velocity – roughness for 450 mm length

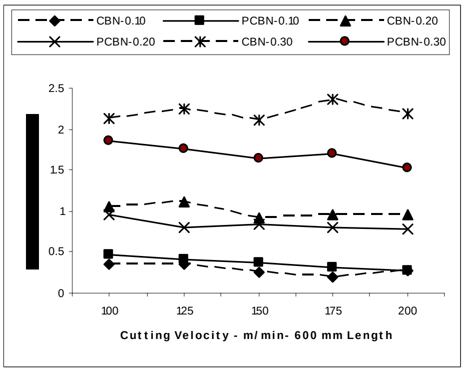


Figure 5. Cutting velocity – Roughness -600 mm length

While turning by CBN tool at low cutting velocity of 100 m/min with feed rate of 0.10 mm/rev takes longer time to accomplish turning for a given size. This causes rubbing of between flank side and work surface. At low operating parameters, longer time is required to machine, more rubbing and form wear on the flank side of the tool. When machining at low operating parameters, rubbing action is more and heat generated at tool chip interface also increases.

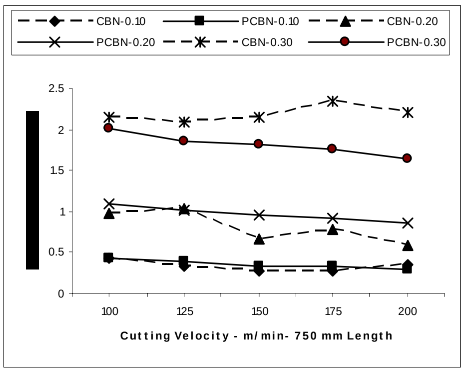


Figure 6. Cutting velocity – Roughness-750 mm length

At start of the experiments, cutting edges were fresh and turning was effective. When operating at low cutting velocity of 100 m/min. with feed rate of 0.10 mm/rev. formation of flank wear was started and it was 0.029 μm. As the cutting velocities were increased to 125, 150, 175 and 200 m/min. flank wear increased and found to have values of 0.058, 0.028, 0.047, 0.049 μm. by CBN tool. The PCBN tool produced flank wear of 0.023, 0.017, 0.017, 0.018 and 0.028 μm at cutting velocity of 100, 125, 150, 175 and 200 m/min with feed rate of 0.10 mm /rev respectively. The flank wear on PCBN tool was less by 50% than CBN tool. At feed rate of 0.20 mm/rev. flank wear more than 0.10 feed rate and flank wear at feed rate of 0.30, more at feed rate of 0.10 and 0.20 mm/rev. The tool has to remove more materials with less time for a given length of machining and this subjected to severe stress on the tool tip. This is shown in figure 7. As the length of turning is more, the tool wears are increased due to increase in the contact area and made it possible to deteriorate. The formation of flank wear at every stage of machining is increased. Flank wear formed were deteriorated faster than previous tests. Flank wear at every stage of machining increased due to abrasive action of already formed wear. More flank wear was noticed at high cutting velocity with high feed rates. Figures 7 to 11 show graphical representation of flank wear at every 150 mm length of turning. Even though more contact was maintained at low cutting velocity with low feed rate, the formation of flank wear was low compared to high feed rate and low feed rate. As the feed rate was increased, more plough force required to deform material in short time and formed more flank wear. The CBN tool produced high flank wear at high cutting velocity with high feed rate. The flank wear formed by PCBN tool is less than CBN tool at low and high cutting velocity. The flank wear occurred was mainly due to abrasion. The adhesion of material was also found on the rake surface of the tool. The wear resistance was less by PCBN tool, the adhesion of material on the rake face of the tool was less due to less heat at cutting zone. Figure 12, a, b, c and d shows the flank wear formed at different cutting velocities and feed rates. Figure 12 b shows the material diffused on the flank side. Figures 14 and 15 are view by SEM on PCBN tool at different cutting parameters.

C. Diffusion wear

The flank wear in tools, initially occurs due to abrasion and as the wear progresses, the temperature increased causing diffusion. Diffusion processes between the chip and the top rake face of the cutting edge result in crater wear, and oxidation reactions with the environment induce scaling of the cutting edge. It is a transfer of chemical elements between the tool and chip. For example, it is possible to observe the diffusion of material from tool to machined work piece and simultaneously observe diffusion of iron from work piece to tool. This phenomenon causes a crater on the surface of the tool which decreases the mechanical properties of the tool. The diffusion is active when contact temperature is high. At high cutting speeds, this diffusion becomes the main wear mechanisms [7]. The diffusion wear was observed by the increased of the tool and chip temperatures. Mechanical wear is caused by abrasion and adhesion, when chemical wear is caused by carbon transformation and diffusion. The temperature in the cutting zone was not measured, but the high temperature developed in this zone promotes different wear mechanisms. The temperature rised to such an extent to diffuse the work material. As the cutting was increased, there is a transition in wear mechanisms from abrasion and adhesion to diffusion. Almost 98% of the mechanical energy consumed in machining operation is converted into heat energy [10]. The yield strength of the tool material at the cutting edge could have decreased sharply. The increase of the tool edge interface caused tool failure at cutting edge Figure 13, a, b, c and d shows the diffusion of material on the rake face. Figures 16 work material deposited on the rake face of the tool by EDS process.

D. Crater wear

When the chips moving on the rake face with heat moves slowly and forms crater. The heat at tool tip interface is enough to soften the tool edge and loose its cutting strength. As the process is continuously performed, more crater wear occurred. This wear occurs on the rake face of the tool. The crater wear affects the tool geometry. The most important factors which influence crater wear are temperature at the tool tip interface and the chemical affinity between tool and work material [7]. The high contact temperature and stresses at the interface caused significant crater wear in the form highly localized shear deformation. The temperature at tool chip interface generates heat and the chips are moving on the rake face with enough heat which causes to form crater. The formation of crater wear was due to temperature of the chips and rubbing of the surface. The hard carbides or hard martensite structure of the work material abrades the rake face in combination of the heat formed crater wear. The heat at tool tip interface is enough to soften the tool edge and loose its strength. The tools which undergone more number of passes experienced extensive chipping of the tool material by the irregular flow of chip over the tool rake face. A.Deville et al [6] noted that the depth of crater increased as the cutting speed increased.

E. Notch wear

Notch wear occurs by the rubbing of the machined surface with the cutting tool at the boundary where the chip is no longer in contact with the tool. The machine surface may develop a thin work hardened layer; this contact could contribute to notch wear [11]. The work hardening of the work material is common and one of the reasons for the formation of notch wear. The optimum feed rates depend on the cutting velocity. The optimum is required to reduce the cutting forces, surface quality and better dimensional control with low tool wear.

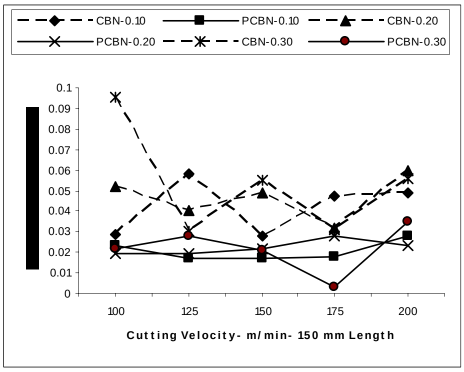


Figure7.Cutting velocity Vs flank wear -150 mm length of turning.

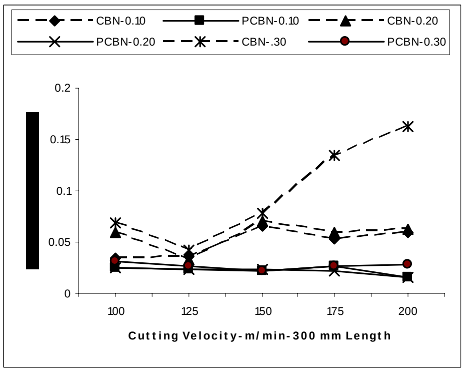


Figure8. Cutting velocity Vs flank wear -300 mm length of turning

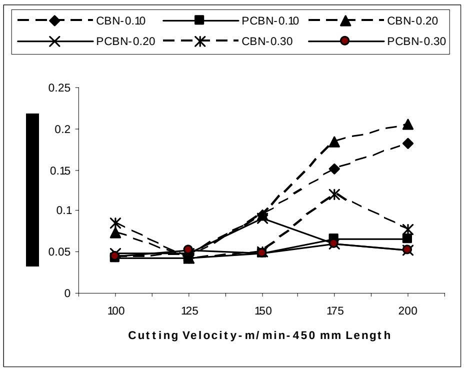


Figure9. Cutting velocity Vs flank wear -450 mm length of turning

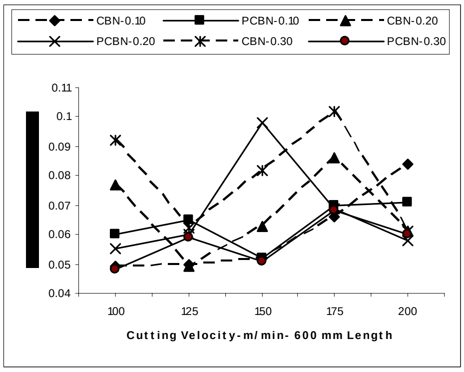


Figure10. Cutting velocity Vs flank wear -600 mm length of turning

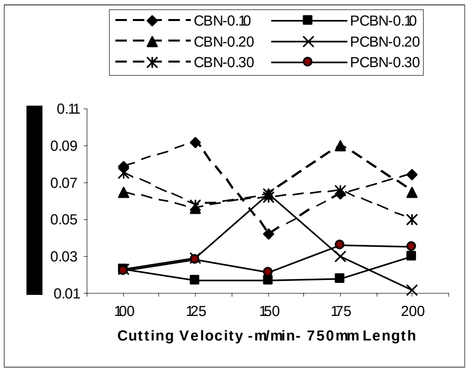
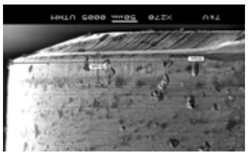


Figure11. Cutting velocity Vs flank wear -750 mm length of turning



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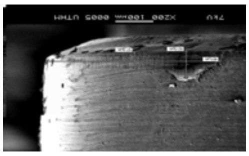

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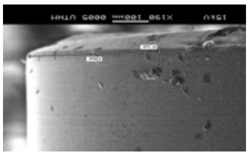

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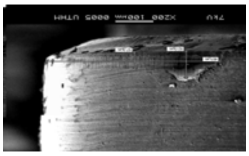

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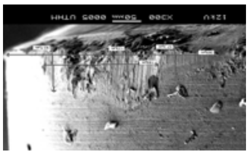
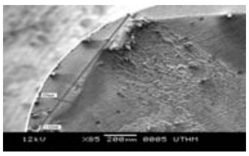


(g)

Figure12. SEM view on flank wear by CBN tool –
(a). 100-0.10-750, (b). 100-0.20-750, (c). 125-0.10- 750,
(d). 125-0.20-750, (e). 175-0.30-SCM- 600,
(f). 175-0.30-SCM-600, (g). 175-0.30-SCM- 600.



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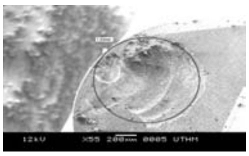

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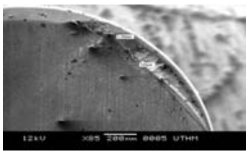

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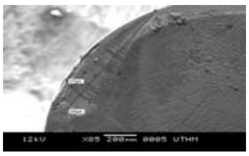
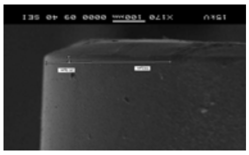


(d)

Figure13. SEM view on crater wear by CBN –
(a).100-0.30-750. (b). 150-0.30-750, (c). 175-0.10-750,
(d). 200- 0.30-750.



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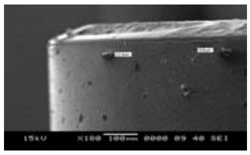

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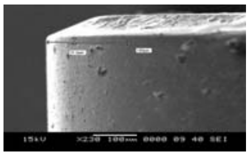

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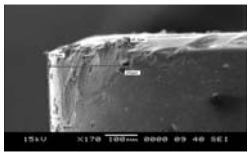
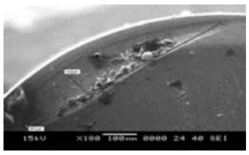


(d)

Figure14. SEM view on flank wear by PCBN tool –
(a). 100-0.20- 450, (b).100-0.30-450, (c). 175-0.10-450,
(d). 175-0.30-PCBN.



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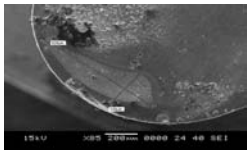

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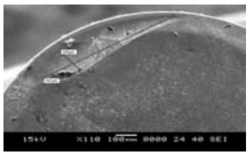

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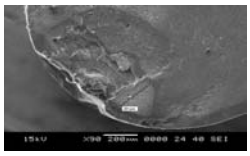
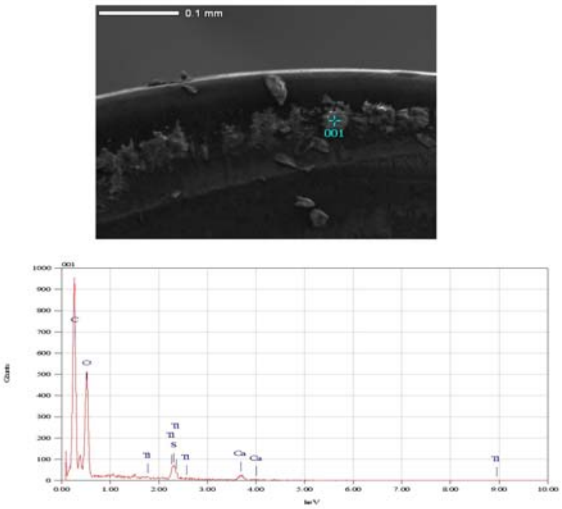


(d)

Figure15. SEM view on crater wear by PCBN tool –
(a) 175-0.10-450, (b) 175-0.30-450, (c).200-0.10-450,
(d). 200-0.30-450.



Element	(keV)	mass%	Error%	At%	Compound	mass%	Cation	K
C K	0.277	49.79	0.08	62.26			106.1442	
O K	0.525	34.76	0.30	32.63			82.1475	
S K	2.307	5.40	0.64	2.53			16.2073	
Ca K	3.690	6.13	2.09	2.30			19.8300	
Ti M	2.267	3.91	2.72	0.29			10.2952	
Total		100.00		100.00				

Figure 16.EDS on SCM by CBN tool at cutting velocity of 200 with feed rate of 0.10.

IV CONCLUSION

The work has provided a number of findings which are very useful in the process of turning SCM 440 alloy steel using CBN and PCBN cutting tools.

Flank wear affects surface roughness. Abrasion, adhesion and diffusion are the main wear mechanisms in flank wear formation. Crater wear normally formed on the chamfered edge of the tool but it did not affect the tool wear very much. However, chipping of the cutting edge do happen. There was also some diffusion of material on crater wear of CBN and PCBN tool. This diffusion happened due to high temperature during the turning process. The diffused material caused built up layer over a wider area. Diffusion between chip and rake surface cutting edge caused crater wear and oxidation reaction induced scaling of the cutting edge [12].

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