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Measurement of surface roughness and flank wear on hard martensitic stainless steel by CBN and PCBN cutting tools

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Methodology of research

ABSTRACT

Purpose: The experiments with different operating parameters using CBN and PCBN tools on hard AISI 440 C material were investigated in this paper.

Design/methodology/approach: In this research AISI 440 C stainless was used under hard condition. The cutting tools are having three cutting edges and each edge repeated for 5 times. The test conducted by each cutting edge was termed as trail 1, 2, 3, 4 & 5. The length of cutting was 150 mm and each trail. The surface roughness and flank wear, crater wear and BUE were measured by SEM.

Findings: The surface roughness was low by CBN at high turning cutting speed and the flank wear was high. The surface roughness was high by PCBN tool than CBN tool and flank wear recorded was low for PCBN tool than CBN tool. The chips produced were saw tooth in all operating parameters. The CBN tool was unable to withstand heat at cutting zone and hence more flank wear occurred. The PCBN tool sustained the temperature and less tool wear occurred. More crater wear formed on PCBN tools where as CBN tool produced less crater wear. The formation of crater wear on the rake face was due to rough surface of the saw tooth chips.

Practical implications: The investigation results will provide useful information to applying CBN and PCBN cutting tools in hard turning stainless steels.

Originality/value: Hard turning is a latest technology and possible to turn all hard materials. The hard turning produce net shaped products and reduces machining time, low cost per products, etc. The difficult to cut materials like stainless steels was turned by super hard cutting tools like CBN and PCBN to achieve good surface roughness, dimensional control and reduced tool wear.

Keywords: Crater wear; Flank wear; Notch wear; Saw tooth chip; Surface roughness

1. Introduction

Hard turning has been applied in many areas like production of bearings, gears, shafts, axles, and other mechanical components since the early 1980s [1]. In particular, precision finishing of hardened steel components using super hard cutting tools offers manufacturers an attractive alternate to grinding. Hard turning by super hard tools like CBN and PCBN is an environmental friendly, help to reduce cost per product, good surface roughness, high productivity, and less tool wear. It is known that hard turning requires negative rake angle tools with reinforcement for cutting edge by way of chamfer. Tool wear is common in all the machining process and depend on the hardness of the work pieces, type of tool, rigidity of the machine tools, generation of heat, formation of chips and cutting parameters. Tool wear is a complex phenomenon. Typical wears that are likely to occur is shown in the Fig. 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 possess excellent mechanical properties such as high temperature strength, ability to maintain its shape at high temperature and hardness second to diamond [2]. In finish hard turning, high hardness of work piece, large cutting forces, and high temperatures at the tool tip –work piece interface impose extreme requirements for tool rigidity and tool wear resistance. CBN primarily is polycrystalline cubic boron nitride (PCBN) compact form and tipped (brazed) has proven to be technologically viable tool material for producing precise parts [3]. Very few literatures are available in hard turning of AISI 440 C martensitic stainless steels by CBN and PCBN cutting tools

2. Experimental procedures

2.1. Martensite stainless steel

AISI 410, 420 and 440 C are all considered as martensitic stainless steel and can be hardened like other alloy steels. In this research AISI 440 C stainless was used under hard condition. AISI 440 C is widely used in aero space industries for bearings, steam and water valves, pumps, turbines, compressor components, shafting, cutlery, surgical tools, plastic moulds, nuclear applications etc which demand high strength and high resistance to wear and corrosion [4]. It is having high viscosity, poor thermal conductivity, less corrosion, high work hardening rate and tendency to form built up edge (BUE) at tool edge. AISI 440 C steel is having high chromium and high carbon which possesses the highest mechanical strength in this group [5]. The materials were received as 50 mm diameter and 1000 mm long. Cut to 300 mm length and skin turned to remove oxide formation. The work pieces were centered on both sides to accommodate in the lathe centers. The heat treatment was carried at out side source by induction hardened process. The hardness was maintained between 45 to 55 HRC. The chemical and mechanical properties are shown in the Tables 1 and 2 respectively.

2.2. Equipments

The turning experiment was carried in a N.C. Harrison 440 Alpha lathe. The surface roughness was measured by 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 by MTJNR2020KL16N by Mitsubishi. The cutting tools are having three cutting edges and each edge repeated for 5 times. The test conducted by each cutting edge was termed as trail 1, 2, 3, 4 & 5. The length of cutting was 150 mm and each trail, the surface roughness and flank wear, crater wear and BUE were measured by SEM.

3. Results and discussion

3.1. Surface Roughness

Surface finish in turning has been found to be influenced by a number of factors such as cutting speed, cutting depth, tool nose radius, work hardness, feed rate, and cutting edge angles [6]. The Figs. 2-6 show the graph for surface roughness for CBN and PCBN tool against cutting speeds for all trails. When turning AISI 440 C materials from 100 to 200 m/min cutting speeds having feed rate of 0.10 mm/ rev, the surface roughness values were 32, 27, 35 32 and 40 micron by CBN tool and 41, 42, 49 47 and 36 microns respectively by PCBN tools in the first trail. The values were almost equal by CBN and PCBN at low feed rate. The BUE formed on CBN and PCBN tool from the first trail. However, at high cutting speeds, the BUE unstable, weakened and disappeared. Breakage of BUE results low surface roughness values at high cutting speeds. The difficult to cut materials may be operated at low feed rate with high cutting speed in order to eliminate formation of BUE. If the BUE disappeared at high cutting speed, it was possible to obtain low surface roughness. The surface roughness produced was more at feed rate of 0.20 and 0.30 for all the operating parameters by CBN and PCBN tools. The work piece is low thermal conductivity material and the heat produced carried away by the chips. The heat produced at tool tip softens the cutting edge and more wear takes place on the flank side. Many researches have indicated that when there were increases in cutting speeds, the surface roughness value was low. In the case of turning AISI 440 C stainless steel, the surface roughness depends on the BUE, heat at tool tip and flank wear.

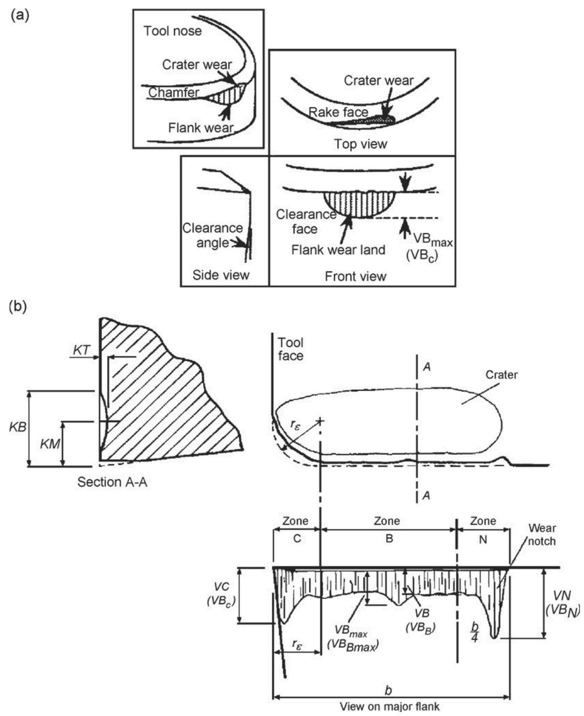

Fig. 1. Typical wear in a single point tool turning [2, 3]

The Figures 3, 4, 5 and 6 show graphical representation of cutting speed Vs surface roughness at cutting speeds of 125, 150, 175 and 200 m/min with feed rates of 0.10, 0.20 and 0.30 mm/rev for CBN and PCBN cutting tools respectively.

3.2. Tool flank wear

Generally speaking**,** flank wear was caused by friction between the flank face of the tool and the machined surfaces. Tool wear depends on the tool, work piece material (physical, mechanical and chemical properties), tool geometry, cutting parameters, cutting fluid, etc [2].

Table 1.
Chemical composition of AISI 440 C

Material	C	Mn	Si	Cr	Mo	P	S
AISI 440C	0.95 -.20	1.0 0	1.00	16 - 18	0.75 max.	0.04	0.03

Table 2.
Mechanical Properties of AISI 440 C

Material	Tensile Strength (MPa)	Yield Strength (MPa)	% of Elongation
AISI 440C	1965	1900	2

Flank wear generally attributed to rubbing of the tool with work piece at the interface, causing abrasive and/or adhesive wear and at high temperatures. Abrasion is the main wear mechanism in flank wear. BUE and irregular wear are often faced in machining stainless steels. At low cutting speed, the contact between work piece and flank of the tool was more and rubbing action continued for more time. The cutting zone temperature increases, this softens and decreases the strength of the BUE [7]. Tool flank wear was strongly influenced by the interactions between cutting tool and work piece in the form of contact stress and cutting temperature [8]. As the cutting speeds and feed rates are increased, the rubbing action also faster and more heat produced even though less contact time exist.. The generation of heat at flank side softens the edge and more wear occurred. The increase in cutting speeds wears the tool faster and reduces the life of the tool [8]. When the contact time was more at low speeds, the BUE formed which in turn act as another cutting edge. The BUE formed more in CBN tool thank in PCBN tool. The Figure 7 show the cutting speed Vs flank wear for both CBN and PCBN tool at cutting speed of 100 with feed rates of 0.10, 0.20 and 0.30 mm/rev respectively . The Figures 8, 9, 10, and 11 shows the graphical representation for Cutting speed Vs flank wear for 125,150, 175 and 200 cutting speeds with feed rates of 01.0, 0.20 and 0.30 respectively. It was clear indication that the flank wear low at low cutting speed and feed rate. As the cutting speed with feed rate was increased low flank wear was observed for both the tools. The Figure 12 a, b, c, d, and e shows flank wear at cutting speed of 200 with feed rate of 0.30 mm/rev for CBN cutting tool. The Figure 13 a, b, c, d, and e shows flank wear for PCBN cutting tool at cutting speed of 200. The ridges and grooves formed on the flank side due to martensite particles present in the work piece materials. In all the tests, the tool temperature increased with the cutting length and it was seen as red hot at tool tip and work piece contact point. When the tools were used for subsequent trails, the temperature increased due to increased tool flank wear. The ridges and grooves were formed on the flank side due to mechanical plowing occurred and material adhered on the flank side.

3.3. Crater wear

Crater wear occurs on the rake face of the tool. The crater wear affects the tool geometry. The most important factors influencing crater wear was temperature at the tool tip interface and the chemical affinity between tool and work piece materials [9].

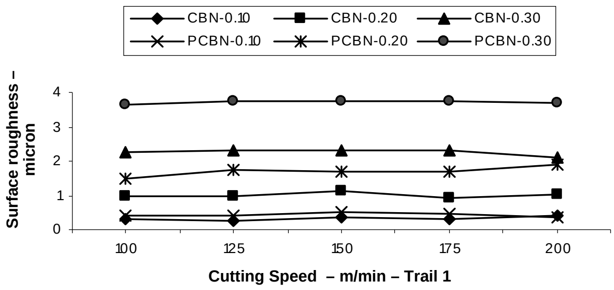

Fig. 2. Cutting speed vs surface roughness - Trail 1

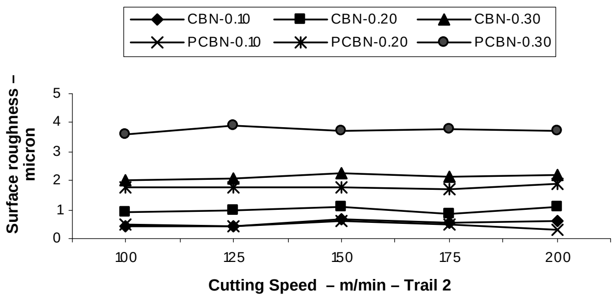

Fig. 3. Cutting speed vs surface roughness-Trail 2

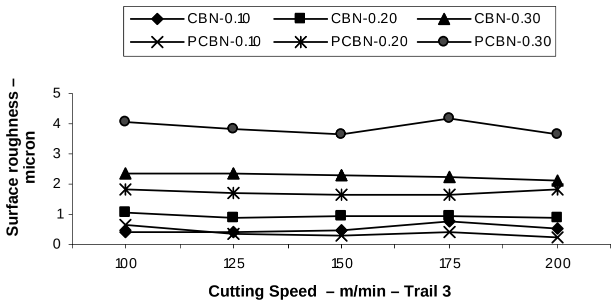

Fig. 4. Cutting speed vs surface roughness - Trail 3

During machining, flow of chips on the rake face result in severe friction and thus lead to material removal, referred as crater wear [10]. The abrasion was a mechanically activated form of wear, which depend upon on the material properties like hardness, carbides, martensite structure, etc. The Figure 12 f, g, h, i, and j show formation of crater wear for CBN tool at cutting speed of 200 m/min. The Figure 13 f, g, h, I j, and k shows the crater wear formed at cutting speed of 200 having feed rate of 0.30 for PCBN cutting tools. The formation of crater wear while turning AISI 440 C was more due to flow of saw tooth chips on the rake face. The saw tooth chips has rough surface which abrades the rake face more. At high cutting speeds with low feed rate, the flow of chips was slow and abrades the rake face slowly. The temperature prevails at rake face at low feed rate was also responsible for formation of crater. Due to the heat at rake face diffusion of work materials also take place and seen on the rake face CBN and PCBN. The diffused material formed as solid layer on the crater and acted like a coating which prevents further deepening of crater.

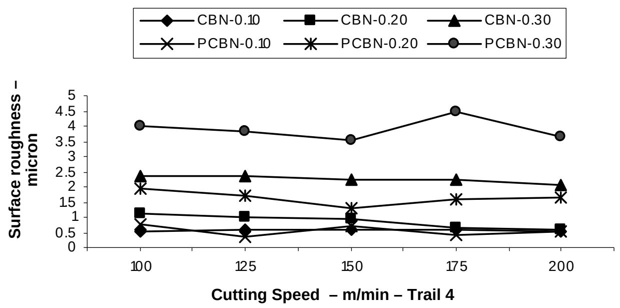

Fig. 5. Cutting speed vs surface roughness-Trail 4

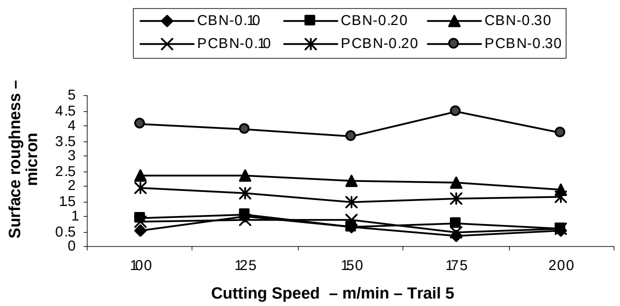

Fig. 6. Cutting speed vs surface roughness-Trail 5

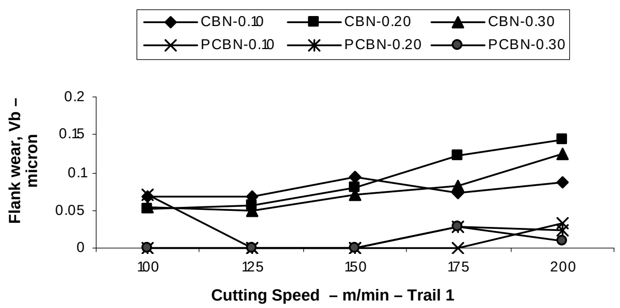

Fig. 7. Cutting speed vs flank wear –Trail 1

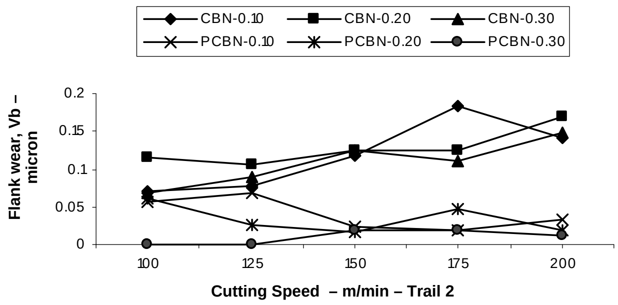

Fig. 8. Cutting speed vs flank wear –Trail 2

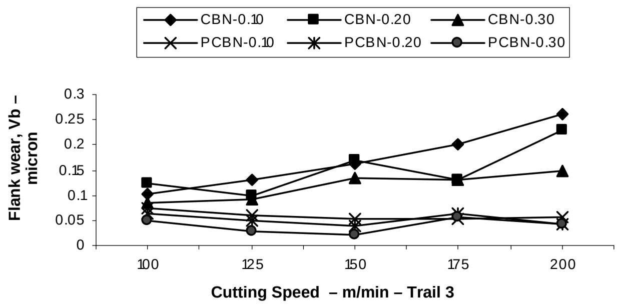

Fig. 9. Cutting speed vs flank wear –Trail 3

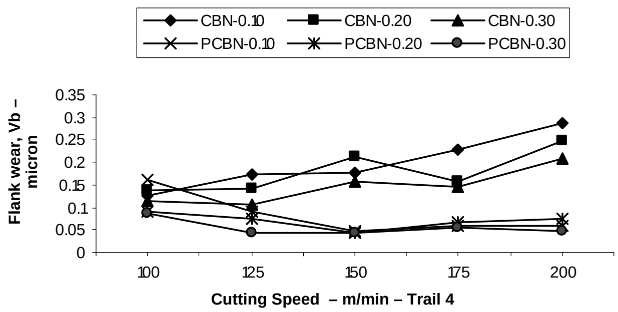

Fig. 10. Cutting speed vs flank wear –Trail 4

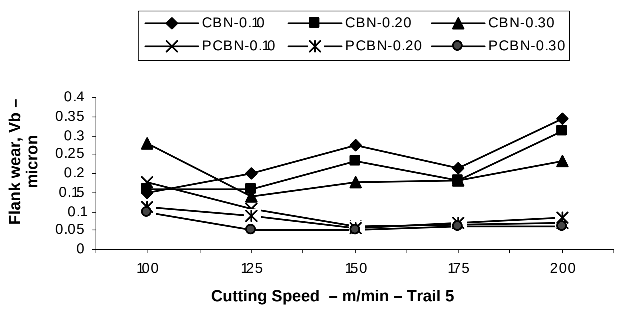

Fig. 11. Cutting speed vs flank wear –Trail 5

3.4. 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 machined surface may develop a thin work hardened layer; this contact could contribute to notch wear [9]. The work hardening rate by stainless is common and one of the reason for notch wear to form.

3.5. Chips formation

The saw tooth chips were formed while turning CBN and PCBN cutting tool. The mechanism involved in the formation of saw tooth chip is very complex. It was attributed to the adiabatic shear on the shear plane or cyclic cracks at the free surface of the chip. There is no standard criterion to predict the onset of saw tooth chip formation [11, 12].The saw tooth chip formations were demonstrated by G.Poulachon and A.L. Moisan [13]. The cutting mechanisms of hard materials lead to the formation saw tooth chips, which can be classified as way chip, segmental chips, shear localized chip, and discontinuous chips. Saw tooth chips cover localized shear, adiabatic shear, as well as catastrophic shear. Such chips are periodic and formed of identical segments, their morphology being the result of instability condition depending on:

- the mechanical, thermal, thermo-mechanical properties of the material,
- cutting conditions
- the divergence of shearing in the shear zone,
- the possible interaction between primary and secondary shearing zones,
- dynamic response of the machine- tool structure and its interaction with the cutting process.

The machinability of high strength steels include the conditions under which the formation of adiabatic shear band can occur, adiabatic shear covers both the coupled mechanical and thermal phenomenon, the result being a thermal softening of the steel, such self –catalytic and cyclic plastic deformation will occur particularly if the conductivity poor. The reduction of chip thickness with the increase of work hardness results from the increase of shear angle. The chips are subjected to severe deformation, and the heat generated during cutting flow mostly into the chip. The high temperature would concentrate on the local shear band of the chip. Hence, saw tooth chip is formed. The high hardness of the work material was more; the material is more brittle, which in turn causes the fracture energy required during cutting to be smaller. This leads to the chip more readily developing a saw tooth appearance [14]. Due to smaller deformation and larger chip thickness [15]. The formation of chips involve shearing of the work material in the region of a plane extending from the tool edge to the position where upper surface of the chip leaves the work piece. A very small amount of strain takes place in a short time period. The material was fragmented in the primary zone and chips come out as fine chips. The sizes of the chips are very small. These chips were different from continuous and discontinuous obtained during the most turning operations. The chips produced by turning may have straight, helix, spiral, and tangled and have considerable strength which cause crater wear. All the above reasons attributed to saw tooth formation. The Figure 14, a, b, and c show saw tooth chips and c shows the area affected by heat. These types of saw tooth chip abrade the tool rake face and create scar on the rake. High stresses generated at the tool –chip interface during machining may also cause plastically deformed grooves and ridges on the flank face. A.Senthilkumar et al [16] observed that saw tooth chips were formed while machining martensitic stainless steel and produced notch wear.

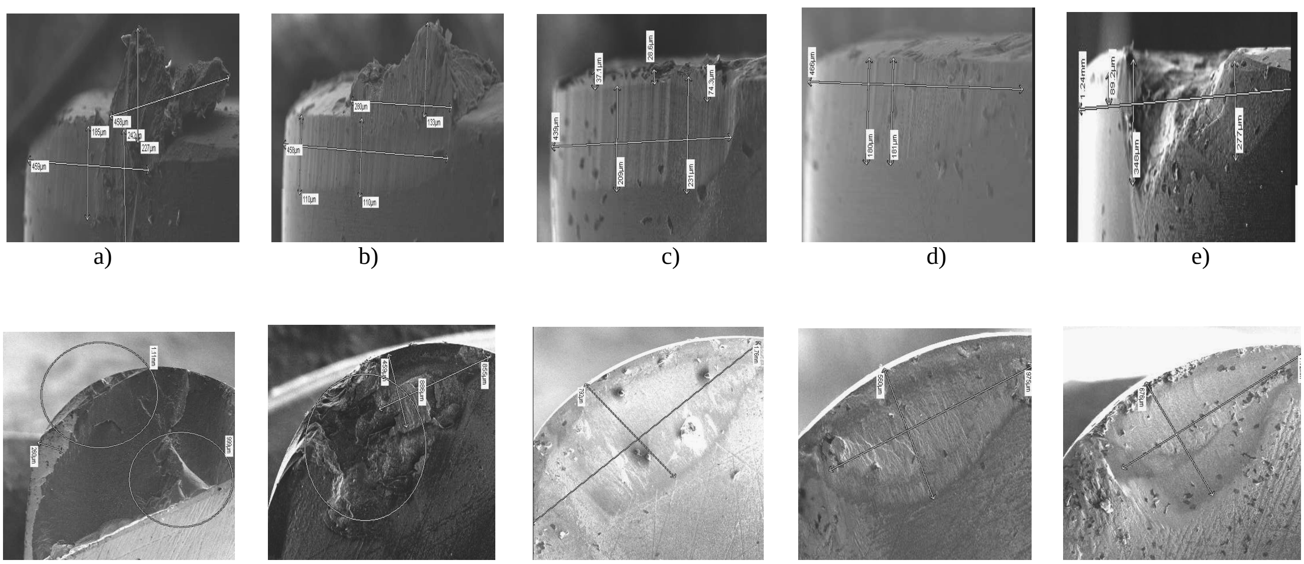

Fig. 12. SEM views on CBN tool for wear and crater wear at cutting speed of 200 m/min

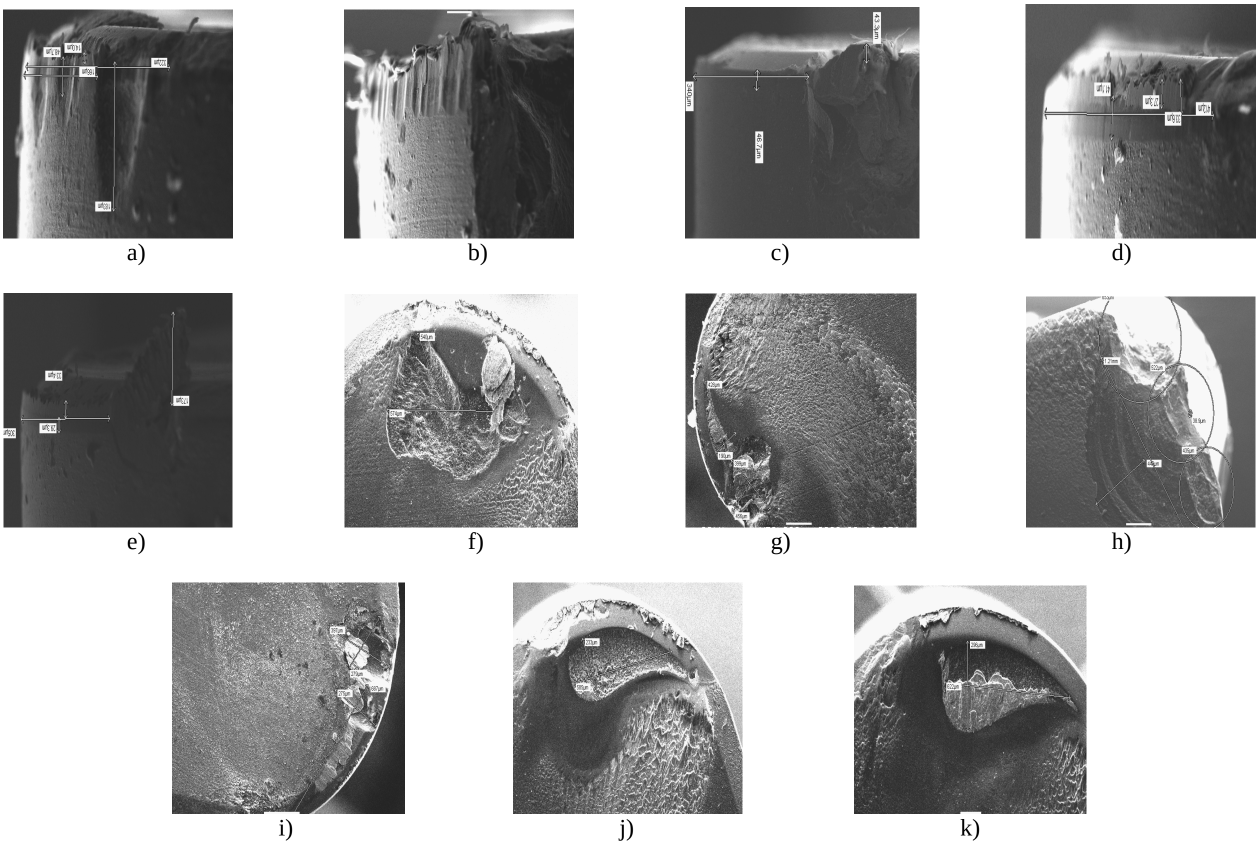

Fig. 13. SEM views on PCBN tool for flank wear and crater wear

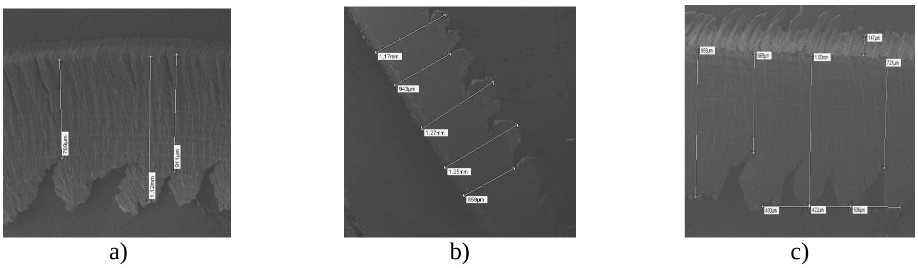

Fig. 14. SEM view on saw tooth chips

4. Conclusions

The experiments with different operating parameters using CBN and PCBN tools on hard AISI 440 C material were investigated and the findings are given below.

1. The difficult to cut materials is preferred to operate at high cutting speed and low feed rate for a given depth of cut. The CBN tool produced low surface roughness at high cutting speed with low feed rate where as the PCBN tools produced high surface roughness in value for the same operating parameters as that of CBN tools. The BUE were formed at low cutting speed and at also high cutting speeds. The surface roughness depends on the built up edge, tool tip temperature and flank wear both by CBN and PCBN cutting tools. The BUE disappeared at high cutting speeds.
2. The formation of flank wear on CBN tool was more and was due to more of abrasion and diffusion. The flank wear was less in PCBN tool at high speeds. The wear was mainly due to abrasion by hard martensite particles. The materials deposited on the flank side by diffusion act as shield and prevent flank wear formation. The tests show that temperature has significant influence on the tool wear.
3. Diffusion of material has occurred and deposited over the flank and crater on both CBN and PCBN cutting tools. The diffused

material deposited more on the rake face especially on the crater. This was due to high heat concentration by chips. These acted like shield and reduce further crater formation.

4. The formation of saw tooth also affects the crater wear due to more rubbing action. The surface of saw tooth chips was rough which increase the crater. The black shade at the back of saw tooth chip shows area affected by heat. Refer Figure 14 c.
5. The saw tooth also affects surface roughness which needs to be studied separately.

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