Relationship between Flank wear and Cutting Force on the Machining of Hard Martensitic Stainless Steel by Super Hard Tools

S.Thamizhmanii* and S.Hasan

Abstract — **In this study, flank wear on CBN and PCBN tools due to cutting forces were studied. Turning tests were carried using cutting speeds of 100, 125, 150, 175 and 200 m/min with feed rates of 0.10, 0.20 and 0.30 mm /rev and constant depth of cut of 1.00 mm. The performances of cutting tools were evaluated based on the flank wear and cutting forces. The wears were measured by scanning electron microscope and the cutting forces measured by a dynamometer. There is clear relationship between flank wear and cutting forces while turning hard martensitic stainless steel by CBN and PCBN tools. Lower cutting forces leads to low flank wear and low cutting force provides good dimensional accuracy of the work material including low surface roughness. Flank wear formation was mostly caused by abrasion and less by adhesion. The built up edge formed reduced the cutting forces. High cutting forces are identified and this may be due to heat and flank wear combinations. Flank and crater wear on the rake face and hard metal deposition due to diffusion of metals on the cutting tool surface are the damages occurred during process.**

Key words: Cutting forces, Crater wear, Flank wear, Martensitic stainless steel,

I. INTRODUCTION

Hard turning has been applied in many areas like production of bearings, gears, shafts, axles, and other mechanical components [1-2]. AISI 440 C martensitic stainless steel is pronounced as difficult to cut materials and this can be hardened by regular process like other alloy steels. Turning of these types of materials require hard and tough cutting tools like CBN and PCBN tools. These types of cutting tools will reduce flank wear and withstand the heat generation. The generation of heat will produce low cutting forces due to thermal softening of the chips. It is known that 60 % of the heat generated by the turning is carried away by chips and the remaining is retained by work material and tool cutting edges. However, stainless steels are low thermal conductivity material and very small percentages of heat retained by the work material. Tool wears are complex phenomenon. Tool wear is common in all the machining processes and depend on the hardness of the work materials, type of tool, rigidity of the machine, heat, formation of chips and cutting parameters [2]. All these factors also contribute to the values of the cutting forces. Cutting forces, tool wear, surface roughness and temperature induced by the cutting process and work material are the major causes of error in hard turning. CBN and PCBN tools possess excellent mechanical properties such as high temperature strength, ability to maintain its shape at high temperature and hardness second to diamond [3]. Figures 1 and 2 shows the typical tool wear and forces on a cutting tool respectively.

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The cutting forces are required to deform the material plastically and remove unwanted materials. Very few literatures are available in hard turning of AISI 440 C martensitic stainless steel. Chryssolouris [5] reported that wear pattern of CBN cutting tool is dependent on the percentage of martensite in the work material, the type, the size and composition of the hard phase after testing four different work materials with same hardness of 55 HRC. Plastic deformation and formation of over tempered martensitic were dominant subsurface defects when machining under both dry and wet conditions while machining martensitic stainless steel (JETHETE) [6]. Liew et al. [7] conducted study on cutting AISI 420 stainless steel by using PCBN tool. The tool wear was abrasion and was mainly due to cutting temperature. The porosity, ductility, and the bonding strength of the grains in the tool, apart from its thermal conductivity have great influences on the fracture resistance of the tool. Lin et al. [8] conducted study on austenitic stainless steel with depth of cut of 0.1 mm and feed rate between 0.04 to 0.06 mm per rev, the heat generated was low. As the cutting speed increased, cutting temperature increases. This softens the work material and surface roughness deteriorated. Barry and Byrne [9] found that the influence of saw tooth chips formation and rate of cutting tool wear appears to be related primarily to the resulting high frequency cutting force variation. The transition from continuous to saw tooth formation does not result in a change in the time averaged cutting or thrust force, it does result in a force variation such that the peak transient stresses are greater than the average contact stresses during continuous formation. Korkut and Donertas [10] studied the cutting forces relating to flank wear on AISI 1020 and AISI 1040 steel, increase in the cutting speed increases the cutting forces. The decrease in the cutting forces with decreasing cutting speeds when face milling AISI 1020 and 1040 steel materials at lower cutting speeds can be attributed to high built up edge formation. The built up edge, tool- chip contact length decreases and this in turn, reduces the cutting forces. The built up edge acts as another cutting edge with restricted contact length and therefore effectively reduce tool – chip contact length. Oraby and Hayburst [11] observed that the feed force F_X and the radial force F_Z were to be more strongly affected by tool wear than the cutting force F_Y. This was due to F_X and F_Z that are closely related to the sliding and friction which reflects the combined effects of F_X and F_Z and their respective friction conditions, in terms of the torque and power required to drive the lathe. They also found that radial force F_Z most affected by nose wear, while the feed force F_X was influenced by flank and notch wear. In general, if the wear in one area dominates, then the associated force component is most influenced. Agrawal et al. [12] turned cast austenitic stainless by titanium nitride coated and uncoated carbide tools. They found that coated cutting tool recorded more cutting force F_Y and feed force F_X than uncoated cutting tools. With the increase in tool wear, the contact area between the tool and the work piece increased and in consequence, high cutting forces arises. Pawade et al. [13] reported by turning Inconel 718 material by high speed machining by PCBN tool. The magnitude of cutting forces was two or three times higher than that of the other force components. The magnitude of cutting forces is lower at the high cutting speed of 475 m/min. than at the low cutting speed of 125 m/min. The volume and rate of the accumulation of the material ahead of the cutting edge due to various types of chamfer on it, influences the magnitude of the cutting forces to a great extent. Qian and Hossan [14] reported that the effect of cutting forces in turning hardened tool steels with CBN tool during machining of hard AISI 52100 steel that cutting forces increased with the increase of feed rate due to an increase in the chip load. The increasing trend of forces with increasing cutting speeds, feed rate, tool nose radius, negative rake angles and work piece hardness. Calamaz et al. [15] observed that the titanium alloy is difficult to cut materials that often generate segmental chips also known as saw tooth chips at relatively low cutting speeds. The chip segmentation affects the machining process – cutting forces, temperature, and work piece quality, thorough understanding is important.

II. EXPERIMENTAL PROCEDURES

A. Stainless steel

AISI 410, 420 and 440 A, B, 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 aerospace 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 [16]. It has high viscosity, poor thermal conductivity, little corrosion, high work hardening rate and tendency to form built up edge (BUE) at tool edge. AISI 440 C has high chromium and high carbon content and possesses high mechanical strength in this group [17]. The materials were received as 50 mm diameter and 1000 mm length. They are 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 by induction hardening process. The hardness was maintained between 45 to 55 HRC. The chemical and mechanical properties are shown in the tables 1 and 2 respectively.

B. Turning tests

The turning experiments were conducted using on NC Harrison 400 Alpha Lathe with 7.5 kw capacity. The cutting tools have three cutting edges and each edge was used 5 times. The test conducted by each cutting edge was termed as trial 1, 2, 3, 4 and 5. Five cutting velocities of 100, 125, 150, 175 and 200 m/min with feed rates of 0.10, 0.20 and 0.30 mm/ rev with a constant depth of cut 1.00 mm have been selected. The length of turning was 150 mm. All the tests were performed under continuous turning conditions with dry turning. The cutting forces component F_Y, feed force component F_X and radial or thrust force component F_Z were measured on line by Kistler dynamometer type 9265 B with data acquisition system. Each and every trial the flank wear, crater wear and BUE were measured by SEM and diffusion by EDS analyses. The cutting processes were continued until the tool flank wear of 0.30 mm reached. The CBN cutting tool is manufactured by Mitsubishi and PCBN tool is by Kennametal. The tool holder used was by MTJNR 2020 KL16N by Mitsubishi.

Table1. Chemical composition of AISI 440 C stainless steel

Materia l	C%	Cr. %	Mn %	Mo %	Si %	P %	S %
AISI 440 C	0.95-1.20 .	1.00	1.00	16-18	0.75 max.	0.04	0.03

Table2. Mechanical properties of AISI 440 C stainless steel

Material	Tensile strength (MPa)	Yield strength (MPa)	% of elongation
AISI 440 C	1965	1900	2

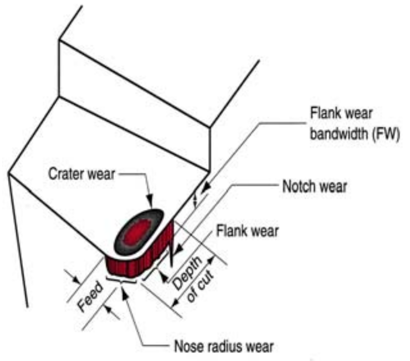

Figure1: Typical tool wear on a single point tool [3]

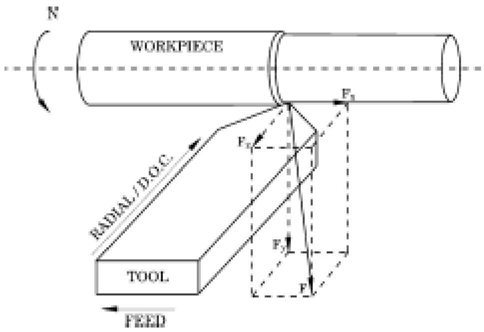

Figure 2: Forces action on a tool [4]

III.RESULTS AND DISCUSSION

A. Flank wear

While turning for 150 mm length of turning at cutting velocities of 100, 125, 150, 175 and 200 m/min with feed rates of 0.10, 0.2 and 0.30 mm/rev, there were initial flank wear due to sharp cutting edges on both CBN and PCBN tools. However, the flank wear by CBN tool was more at feed rate of 0.10 mm /rev than feed rate of 0.20 and 0.30 mm / rev. There were differences between CBN and PCBN tools on flank wear. Flank wear by PCBN tool was less than CBN tool. At feed rate of 0.20 mm/ rev, flank wear was less than 0.10 feed rate and far less by feed rate of 0.30 mm/rev. As the cutting velocities were increased, the rate of flank wear also increased in all feed rates both by CBN and PCBN tools. At high feed rate, the flank wear was less. This is shown in the figure 3 a. As the length of turning continued for 300 mm, formation of flank wear by CBN tool continued to increase. The flank wear was low at feed rate of 0.10 mm/rev but increases as the velocities were increased. The flank wear formation rate of CBN tool is always higher than PCBN tool. The maximum flank wear 0.30 mm was exceeded at cutting velocity of 200 m/min with feed rate of 0.10 mm/ rev for the

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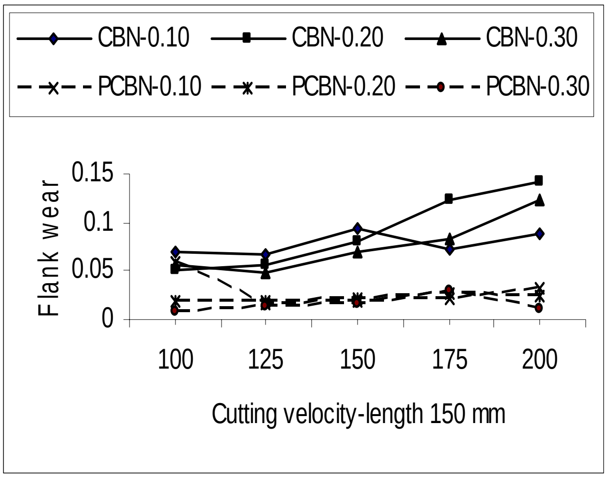
length of 750 mm and it was 0.342 mm. On the other hand, at feed rate of 0.20 and 0.30 mm / rev, flank wear rates were 0.311 and 0.231 mm by CBN tool respectively. On contrary, PCBN tool recorded flank wear of 0.126 mm at cutting velocity of 200 m/min with feed rate of 0.10 mm/rev. Flank wear at feed rate of 0.20 and 0.30 mm /rev were 0.122 and 0.106 mm respectively at the end of 750 mm length turning. Figure 3 a to e show flank wear formed at various length of turning. The study showed that flank wear occurs much earlier on CBN tools than PCBN tools. In CBN tool, flank wear chipping and built up edges occurred. Korkut et al. [17] studied the tool wear formation by AISI 304 stainless steel. The generation of heat by turning is not dissipated rapidly due to the low thermal conductivity. The flank wear formation was much affected by heat when the area of flank side increased. Flank area was increased, rubbing action was more. The increased flank area increase the heat generation at low cutting velocity. The generated heat was shared by chips and tool tip. The retention of heat softens the tool tip and increased the wear. Many researches studied the effect of chip affecting the wear of the tool. It was known that with the increase of cutting velocities the flank wear increased clearly and the flank wear is caused by abrasion. The chipping occurred due to high cutting temperature and the pressure on the tool tip is the main cause of the chipping. Built up edges were observed both on CBN and PCBN tools. The formation of built up edges on PCBN tool was low in size than CBN tool. This was due the characteristics of the stainless steel material. At high cutting velocities, the built up edges break and disappeared. From the SEM examination, wear were due to abrasion process on both cutting tools. However, the intensity of formation was low in PCBN tool than CBN tool. The element of Fe was observed on CBN and PCBN tools from the work material as well by diffusion. Many researchers have observed that saw tooth chips were formed while machining difficult to cut materials like stainless steel and in these test there was also the formation of saw tooth chip noticed in all turning parameters by both cutting tools. The saw tooth chips had rough surface and it abraded the flank wear the rake face of the tool causing crater wear. The diffusion of work material was found on the crater and diffusion is a chemically activated process due to tribo-chemical reactions occurring at high temperature. The EDS analyses, confirms that material transfer take places as a result of chemical affinity between the work material and tools, which accelerate the rise in temperature at tool – chip interface and therefore responsible for layer formation. Flank wear was more due to abrasion and less due adhesion. The chipping of cutting edge was due to heat at tool tip which softens the edges and pressure at cutting zone. The PCBN tools were able to withstand more generated heat than CBN tools. The flank wear and crater wear were the dominant tool wear types. Abrasion and diffusion were the dominant wear mechanisms on both CBN and PCBN tools. Figure 5 (a) to (c) are the SEM images on flank wear and 5 (d) to (e) are for the crater wear by CBN tool. Diffusion of work material was seen on the crater on the rake face as shown in the Figure 5 (d) to (e). Built up edges were noted both by CBN and PCBN tools, however, the sizes were different. The chipping by CBN tool is shown in the Figure 5 (h) and this was due to high temperature and load at cutting edge. Figure 6 (a) to (h) are the SEM images on PCBN tool. There was a thick layer of work material on the rake face of tool which prevents crater to form. The notch wear formed at the end of the tests. The flank wear by PCBN tools showed better performance at feed rate of 0.20 and 0.30 mm/rev than low feed rate of 0.10 mm/ rev. than CBN tools. Diffusion of diffusion of work materials was noticed on the rake face of the tool by EDX analysis and shown in the figures 5 (d & e) and 6 (d & f).

Cutting Force

Force is required to deform the material plastically though there is a dependency on certain factors. The cutting forces are very sensitive to chemical composition, hardness, micro-structure, type of cutting tools used, machine stability, heat generation and operating parameters. There are three forces acting on a single point tool which is shown in the Figure 2. One of the most promising techniques for indirect detection of tool wear appears to be the measurement of cutting forces. Force signals are highly sensitive carriers of information about the status of machining process and hence, they are the best alternatives to tool wear monitoring [18]. During machining any ductile materials, heat is generated at the (a) primary deformation zone due to shear and plastic deformation, (b) chip-tool interface due to secondary deformation and sliding and (c) work – tool interfaces due to rubbing. All the heat sources produce maximum temperature at the chip-tool interface which substantially influences the chip formation mode, cutting forces and tool life. Out of the three forces acting, cutting force was more than other two forces. However, depending upon the wear of the tool, forces may vary. The cutting force F_Y was affected by flank wear and crater wear and this may affect the feed force F_X and radial forces F_Z. The measured cutting forces for both CBN and PCBN tool inserts are given in Figure 4 (a) to (e). When the feed rate increased with the increase of cutting velocities, high forces were required to deform the material within short period of time. This raises the high temperature at tool tip – work material interface. The heat generated was carried away by the chips rather than retention by work material. Some amount of heat was retained by the tool tip. Increase in the feed rate increases the cutting force. The removal of material take place in a short time for a given length required high cutting forces. The removal of material increased the plastic deformation and also generated more heat.



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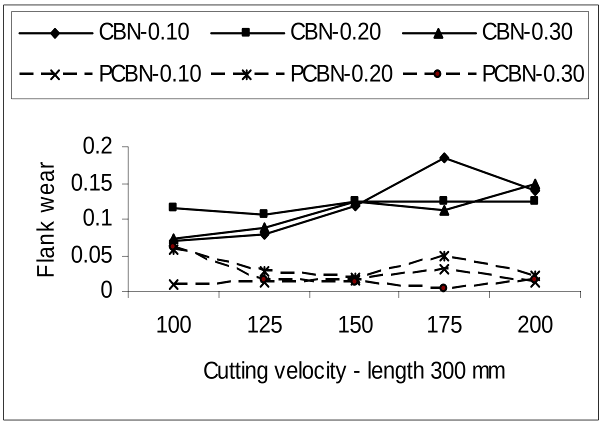

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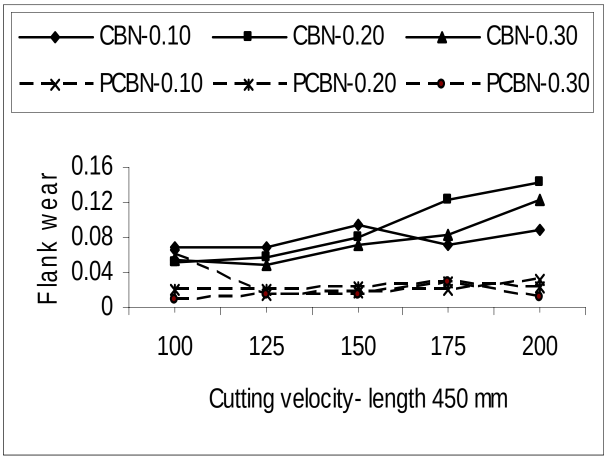

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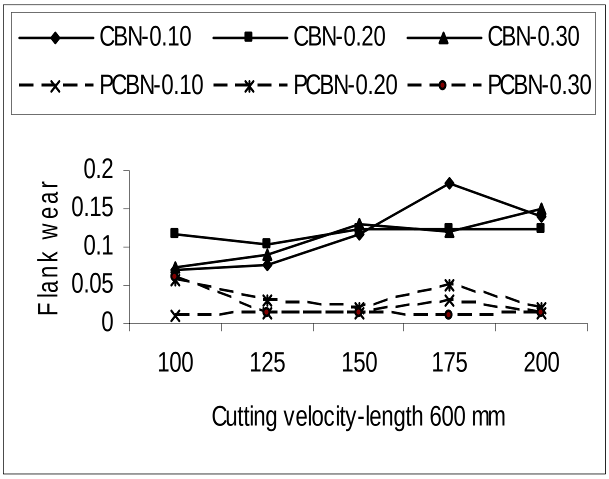

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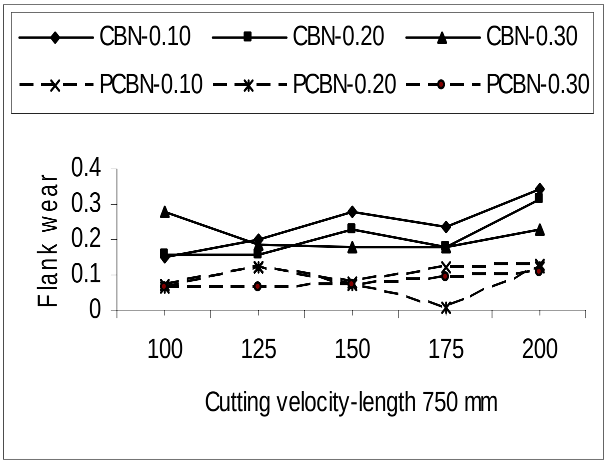
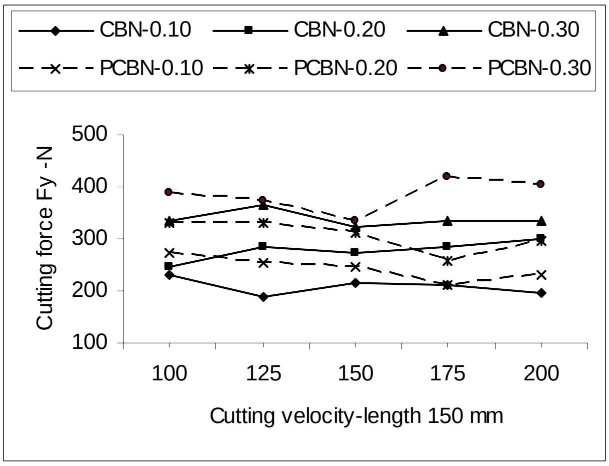


(e)

Figure 3: Cutting velocity Vs flank wear for – a. 150, b. 300, c. 450, d. 600 and e. 750 mm length of turning.



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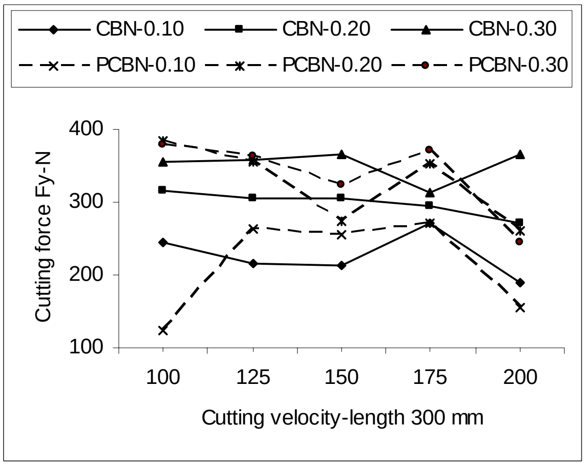

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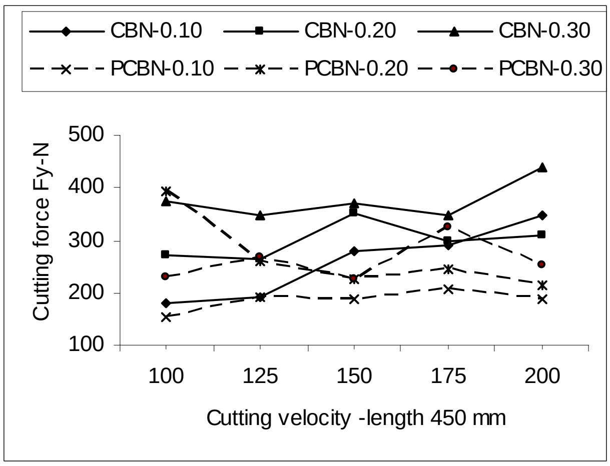

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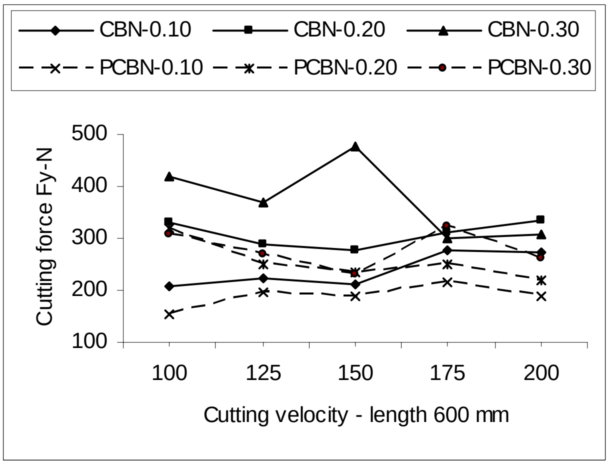

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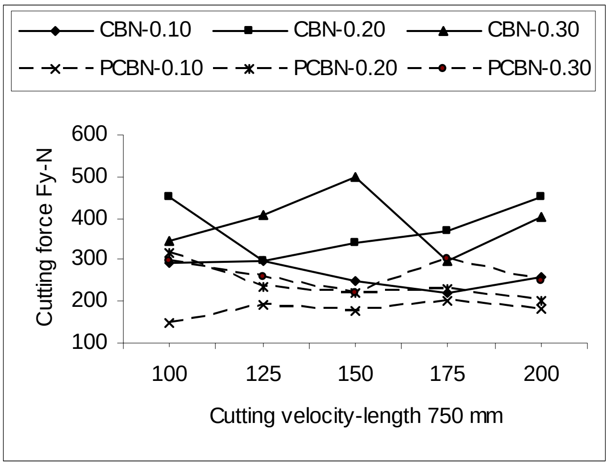

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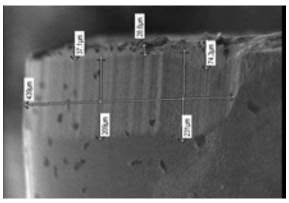
Figure 4: Cutting velocity Vs cutting force Fy- a. 150, b. 300, c. 450, d. 600 and e. 750 mm length of turning



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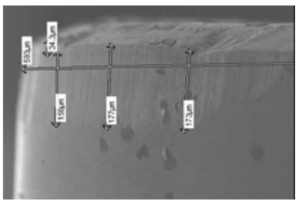

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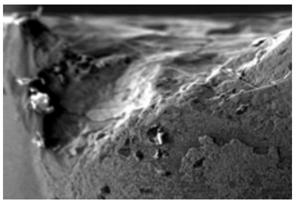

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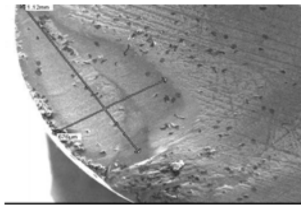

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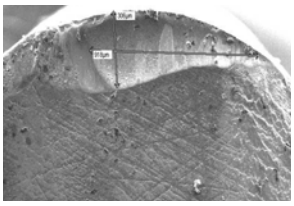

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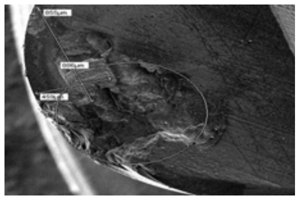

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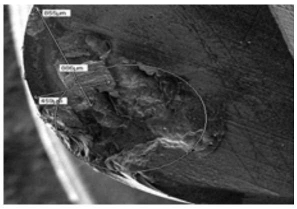
Figure 5: SEM images on CBN tool.



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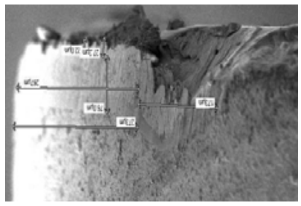

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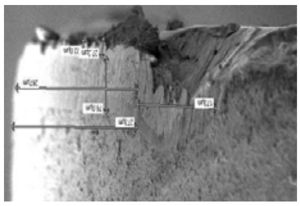

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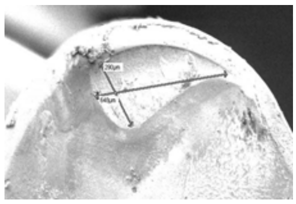

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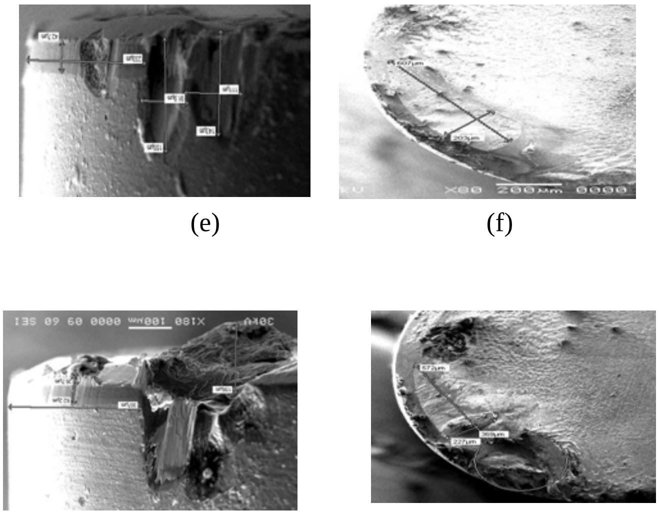

(e) (f)

(g) (h)

Figure 6: Flank and crater wear by SEM on PCBN tool.

SEM images show built up edges were formed in all the cutting parameters at low cutting velocities, which decrease the cutting forces. The built up edge acts like another cutting edge even though the built up edge is small in sizes and reduces the cutting force. The best way to reduce the built up edge is to increase the cutting velocity and make it as unstable. This breaks the built up edges and carried along with the chips. The built up edge decreased the tool – chip contact length and in turn reduces the cutting force. Cutting force increased with the increase in feed rate due to an increase in chip load.

IV. Conclusion

There is clear relationship between flank wear and cutting forces while turning hard martensitic stainless steel by CBN and PCBN tools. The lower the cutting force leads to low flank wear and low cutting force provides good dimensional accuracy of the work material including the surface roughness. Flank wear formation was more by abrasion rather than by adhesion. The built up edge formed reduced the cutting force and also the heat at cutting zone. Flank wear and crater on the rake face and hard metal depositions on the cutting tool surface are the damage that takes place during turning process. The greater the values of flank wear area, the higher the friction of the tool on the work material and high heat generation occurred.

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