

# Machinability of Hard Martensitic Stainless Steel and Hard Alloy Steel by CBN and PCBN tools by Turning Process

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**Abstract**—Hard turning of martensitic stainless steel is gaining importance in all manufacturing sectors like automobile and aerospace industries. Machinability of materials depends on surface roughness, tool wear, cutting forces, specific cutting pressure and work material hardness. In this paper, hard martensitic stainless steel AISI 440 C and SCM 440 alloy steel was used as work piece materials. CBN and PCBN cutting tools were used to turn these work materials. The operating parameters used were cutting velocity 100, 125, 150, 175 and 200 m/min with feed rate of 0.10, 0.20 and 0.30 mm/rev with constant depth of cut of 1.0 mm. The length of turning was 150 mm and 750 mm. Machinability of both materials and both tools were evaluated in terms of roughness, flank wear, cutting force and specific cutting pressure.

**Index terms**— Machining, Martensitic stainless steel, Surface roughness, Cutting force, Specific cutting pressure, Flank wear

## I. INTRODUCTION

Hard machining of materials is emerging as new process to reduce the cycle time, tool wear, obtain good surface roughness, cost reduction and dimensional accuracy. Machining of hard materials is difficult by high speed steel, ceramic tools, even more difficult on material like titanium alloy, Inconel 718 and martensitic stainless steel. These are all difficult to cut materials. Few attempts have been made on the machinability of hard martensitic AISI 440 C and SCM 440 alloy steel with respect to chip thickness ratio, shear angle, flank wear using CBN and PCBN tools. These tools are considered for cutting due to increased demand on surface quality and less tool wear. Machinability is poor in turning stainless steel owing to low thermal conductivity, high ductility, high strength, high fracture toughness and rate of work hardening.

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Work hardening of stainless steel is caused after a previous severe cutting operation by worn tool [1]. Sethilkumar et al. [2] turned hard martensitic stainless steel and found that it produced saw tooth chips in all operating parameters which increased the cutting forces. Turning of SCM 440 alloy steel is comparatively easier than stainless steel due to low carbon percentage and other alloying elements. Liew et al. [3] conducted study on cutting AISI 420 steel by using PCBN tool. The tool wear was due to abrasion and cutting temperature. The porosity, ductility, and the bonding strength of the grains in the tool, apart from its thermal conductivity have great influence on the fracture resistance of the tool. Fig.1. shows tool wear on single a point tool.

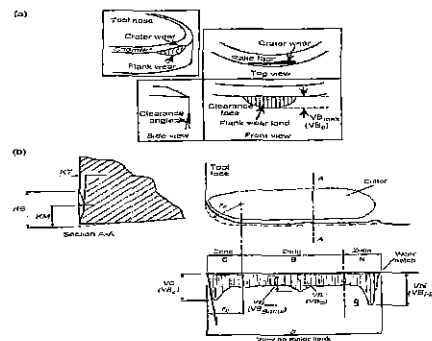


Fig 1. Diagram of worn cutting tool showing principal locations and types of wear [4, 5]

## II. PROCEDURE FOR EXPERIMENTAL WORK

### A. Work materials

In this research, there are two work materials considered and they are AISI 440 C martensitic stainless steel and SCM 440 alloy 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 steel 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 [7]. It has high viscosity, poor thermal conductivity, low 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 [8]. The materials were procured as 50 mm diameter and 1000 mm length. They were 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 out by induction hardening process. The hardness was maintained between 45 to 55 HRC. Experiments were conducted on the machinability of cutting tools CBN and PCBN tools. Tables 1 and 2 give chemical and mechanical properties of both materials. The rake angle is  $-6^\circ$ , side rake  $-6^\circ$  and end clearance angle of  $27^\circ$  with nose radius of 0.80 mm for both tools. The work materials were heat treated by induction hardening process and hardness between 45 to 55 HRC was maintained. The SCM 440 material is used in gears and shafts manufacturing. The SCM 440 material is best known as Cr-Mo. alloy steel. This grade steel is used in high tensile applications where wear resistance is of prime importance. This material is heat treated as other alloy steels.

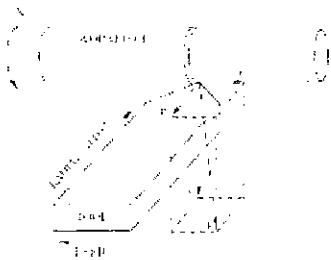


Fig. 2. Three forces acting on a single point tool [6]

TABLE 1  
CHEMICAL PROPERTIES

Grades	C %	Mn.	Cr.	Mo.
AISI 440 C	0.95/1.2 0	1.00	16/19	0.75
SCM 440	0.35/0.43	0.75/1.00	0.75/0.80	0.15/0.25

TABLE 2  
MECHANICAL PROPERTIES

Grades	Tensile strength (MPa)	Yield strength (MPa)	% elongation
AISI 440 C	1965	1900	2
SCM 440	664	556	--

TABLE 3  
OPERATING PARAMETERS

Parameters	Range
Cutting velocity – m/min	100, 125, 150, 175 & 200
Feed rate –mm/rev	0.10, 0.20 & 0.30
Depth of cut	1.00 mm constant

### B. Turning conditions

Turning tests were carried out on a high precision N.C. Harrison 450 lathe under dry turning conditions by varying cutting parameters such as cutting velocity, feed rate and constant depth of cut of 1.00 mm. The cutting conditions used are presented in the Table 3. Figure 3 shows the forces acting on a single point tool. 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 9265 B with data acquisition system. Each trial the flank wear, crater wear and BUE were measured by Scanning Electron Microscope (SEM). The surface roughness was measured by Mitutoyo surface SJ 400 tester. The length of turning was up to 150 mm and each time, surface roughness, tool wear and cutting forces were measured. It was decided that maximum flank wear of 0.30 mm as per ISO standard allowed and the experiments were stopped once it reached the said value.

## III. RESULTS AND DISCUSSION

### A. Surface roughness

Surface roughness of the turned part is dependent on mainly cutting conditions like cutting velocity, feed rate, and depth of cut. The fatigue life of the machined components is depends upon the surface roughness. This plays major role on the performance of the component and fatigue life. Even though, stainless steel is tough and difficult to cut material, it produced low surface roughness value at high cutting velocity and low feed rate by CBN tool than PCBN tool; correspondingly SCM 440 alloy steel produced marginally high value at the same operating parameters as that of stainless steel. It indicates that the plastic deformation by stainless steel is more than alloy steel. Figure 3 (a), (b), (c) and (d) is the graphical representation of roughness against cutting velocity for both CBN and PCBN tools for stainless steel and SCM 440 alloy steel. The results agreed with general trend of low value of roughness as the cutting velocity was increased for a given feed rate and depth of cut. The value obtained for 150 mm length was low than by 750 mm length by CBN tool in alloy steel turning than stainless steel. The PCBN tool produced high surface roughness than CBN tool. Once the turning completed for 750 mm, there were formation of flank wear and crater wear which determined the smooth surface. When turning stainless steel there were formations of erratic built up edges and this decreased the smoothness. At high cutting velocity the built up edge vanished. At the end of 750 mm length of turning, smooth surface deteriorated, but the values were lower at

edge formation. The built up edge, tool- chip contact length decreases and this in turn, reduces the cutting forces.

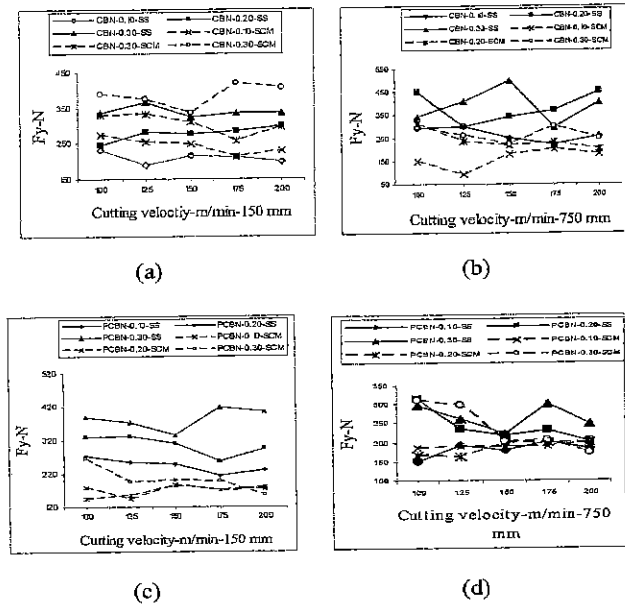


Fig.5. Graph for cutting force - (a). CBN-SS, (b) CBN- SCM, (c). PCBN-SS & (d). PCBN-SCM.

The built up edge acts as another cutting edge with restricted contact length and therefore effectively reduce tool – chip contact length. The stainless steels are low thermal conductivity materials and retention of heat was low by the work materials. At low cutting velocity, the area of contact by tool tip with work materials surface is more and this caused more friction. The friction increased the rubbing of the tool tip and work which generated heat at cutting zone. The heat generated was not shared by work material, tool tip and chips which normally take place in turning. The heat generated was observed by stainless steel and shared by tool tip and chips. If there was retention of heat by work material and this help the materials to be softer. In the absence of the above, more cutting force recorded while turning stainless steel than by alloy steel. In actual situation, the heat was shared by work material, tool tip and chips by alloy steel. The retention of heat on work materials help to soften the chips and less cutting force is required to remove the material. The force by CBN tool was more on stainless steel than alloy steel. PCBN tool required less cutting force due to less wear. Figure 5 (a), (b), (c) and (d) show the graphical representation of cutting forces. Cutting force by PCBN tool on SCM 440 was low than stainless steel.

### C. Specific cutting pressure ( $\beta$ )

In general, specific cutting pressure varies depending on the cutting velocity, feed rate and depth of cut [9]. Machining performance of a cutting tool is largely dependent on the

cutting pressure, force and temperature. It depends largely on the stability of the tool wedge geometry. The wedge geometry can be affected by deformation of the tool material, chipping of the material over the cutting edges and reactions between tool – materials. The deformation is largely thermal dependent. When machining heat insulating material, temperature of machining can be a dominant parameter affecting the tool performance. Sreejith et al. [15] found that increase in the cutting temperature possibly thermal softening of the work material can result in a steady cutting pressure. The generation of cutting temperature is largely affecting the cutting edge, geometry of the tool by way of tool wear. It is possible that the tool may get displaced in radial or axial direction affecting the dimensional accuracy of the work material. The specific cutting pressure can be calculated by equation 1 [9].

$$\beta = \text{cutting force / area} \quad (\text{N sq.mm}^{-1}) \quad (1)$$

$$= F_Y / f \times \text{depth of cut}$$

where  $F_Y$  is the cutting force,  $f$  is the feed rate and  $d$  is the depth of cut. The specific cutting pressure is largely dependent on area of the chip section ( $f \times d$ ).

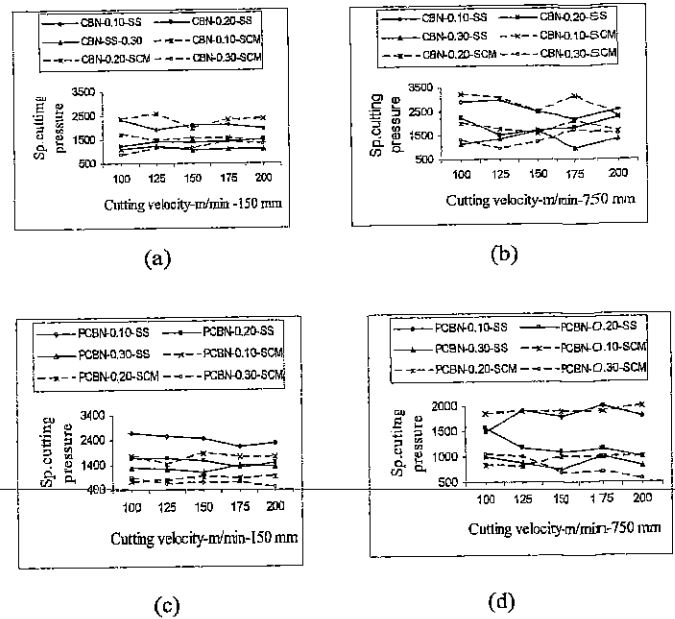


Fig.6. Graph for specific cutting pressure - (a). CBN-SS, (b) CBN- SCM, (c). PCBN-SS & (d). PCBN-SCM.

The specific cutting pressure also determines the machined surface and influenced by the status of the cutting wedge, specific cutting pressure / cutting force which are indirect indicators of the status of the cutting edge. The pressure is a function of cutting force and also specific cutting pressure decrease with increasing speed for given feed rate and depth of cut. At low values of the feed rate, the material is subjected to low strain rate [9]. The effect of cutting velocity on the specific cutting pressure  $\beta$  is shown in the figure 6.

high velocity. The smooth surface was obtained by CBN on SCM 440 alloy steel than stainless steel. When machining by PCBN tool, smoother surface was obtained in alloy steel machining than stainless steel.

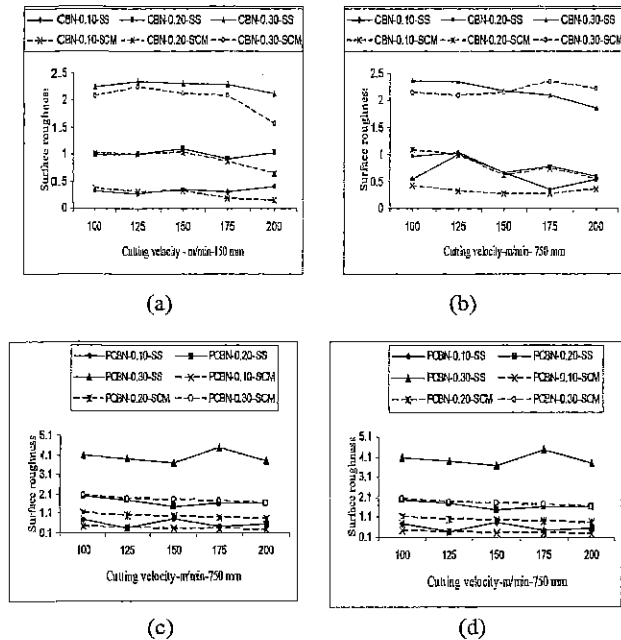


Fig. 3. Graph for surface roughness - (a). CBN-SS, (b) CBN-SCM, (c). PCBN-SS & (d). PCBN-SCM.

### B. Tool wear

The wear of the tool is influenced by phenomenon namely, flank wear, crater wear, diffusion, thermal softening, and notching at depth of cut and trailing edge [9]. The flank wear is primarily attributed to rubbing action of the tool along mechanical surfaces, causing abrasive, diffusive and adhesive wear mechanisms and also high temperatures, which affect the tool material properties as well as the work materials [10]. S.K.Sikadar and M.Chen [11] concluded that increase in flank wear area results in an increasing area of contact between the tool tip and the work material. The greater the value of the flank wear area, the higher the friction off the tool on the work material and high heat generation will occur, this ultimately causes the high value of cutting force. Figure 4 (a), (b), (c) and (d) is the graphical representation of flank wear against cutting velocity. Figure 7 (a), (b), (c) & (d) show the view by scanning electron microscope for flank wear and crater wear formed while turning stainless steel. Figure 7 (e) shows the formation of flank wear with built up edge Procedure for Paper Sub which is common in turning stainless steel. Formation of built up edge were erratic and can be eliminated by increasing the cutting velocity and supply of lubrication. As the turning was initiated for 150 mm length, the cutting edges were fresh and much easy penetration was possible by both CBN and PCBN tools. The penetration on alloy steel was much easier than by stainless steel which was an indication that flank wear were caused less by alloy steel than stainless steel. The flank wear

were formed very much due to the abrasive action between tool and hard carbide present in the work material. More hard carbide was present on the stainless steel than alloy steel even though same hardness was maintained. This is reflected on the formation of flank wear and crater wear. While turning stainless steel, saw tooth chips were produced and this abraded the rake face of the tool. Flank wear formation was more erratic and no uniform wear occurred by stainless steel. It is quite natural that more flank wear and crater wear formation due to the reason mentioned above at the end of 750 mm length. PCBN tool was not much affected by both materials and it more abrasive resistant. Flank wear by CBN tool was more than PCBN tool.

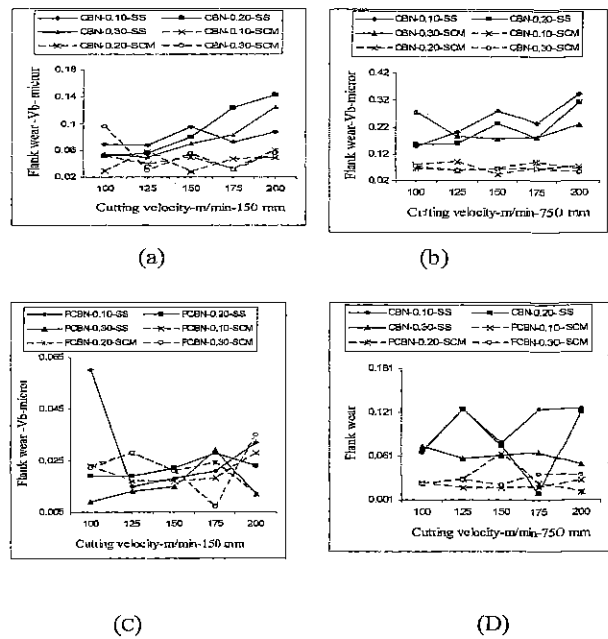


Figure 5: Graph for flank wear-(a) CBN-150, (b). CBN-750, (c). PCBN-150 & (d). PCBN-750.

### C. Cutting force

In turning operation three force components are acting on the tool. The cutting force  $F_y$  is acting normal to the cutting edge, a force action on the feed direction known as feed force  $F_x$  and thrust force  $F_z$  is acting on the Z direction. Feed force  $F_x$  is acting parallel to work material and thrust force  $F_z$  are acting perpendicular to material axis. Cutting force and thrust force plays major role in the machinability of any material. Therefore, cutting force is primarily considered here. Cutting velocity increased, cutting and feed forces decreased [12]. Lima et al. [13] concluded that when turning AISI 4340 steel with low feed rates and constant depth of cut, the forces were higher with softer steel. Korkut and Donertas [14] 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 the formation of high built up

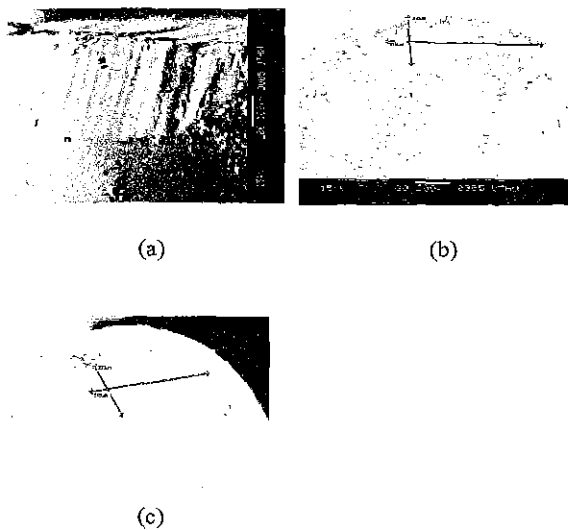


Fig.7. SEM view on flank wear, crater wear and built up edge by CBN tool on stainless steel.

Figure 6 shows the specific cutting pressure for 150 and 750 mm length of turning for CBN and PCBN tools at various feed rates. The ideal condition is between 175 to 200 m/min cutting velocity with high feed rates to obtain low specific cutting pressure which will dimensional stability. In this research, a reduction of specific cutting pressure  $\beta$  as cutting velocity was increased at given feed rate and depth of cut possibly due to reduction in the shear strength of material caused by the high temperature.

#### IV CONCLUSION

The conclusions were drawn from the experiments by CBN and PCBN tools.

1) Surface roughness of the stainless steel in terms of value was low at high cutting velocity with low feed rate. Turning stainless steel by CBN tool produced low value than alloy steel. The roughness by PCBN tool was more than CBN tool.

2) Flank Wear formation was low by PCBN tool than CBN tool. The PCBN tool is tough enough to resist wear and low flank wear formed at high cutting velocity with high feed rate. PCBN tool experienced low value in SCM 440 steel and more by stainless steel. This was due presence of high carbon and chromium elements. They produced hard carbides and more abrasive in nature. The presence of flank and crater wear also affected the cutting force  $F_y$ .

3) Stainless steel is a low thermal conductor of heat. It reflected in the cutting force on both tools. High cutting velocity and feed rate produced high heat due to less time taken to deform material and increased the heat generation. Generation of heat by alloy steel was shared by the chip, tool and work material which softens the chips and lower cutting force recorded than stainless steel.

4) Specific cutting pressure is low or nearly at high velocity with high in all cutting parameters for both materials which is an indication that the force are low due to reduction in the shear strength of material caused by the high temperature.

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