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Machinability of hard stainless steel and alloy steel using PCBN tools

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Materials

ABSTRACT

Purpose: of this paper was to find out the machinability of two hard materials - AISI 440 C martensitic stainless steel and SCM 400 alloy steel. It was analysed by measuring surface roughness, tool wear, cutting force and specific cutting pressure.
Design/methodology/approach: The approach was adopted using various operating parameters like cutting velocity, feed rate and a constant depth of cut. The results were obtained using various measuring instruments like surface roughness tester, dynamometer, scanning electron microscope.
Findings: Machinability of materials was easy in machining SCM 440 alloy steel than AISI 440 C stainless steel. Analysis was done by having low specific cutting pressure, low tool wear and low surface roughness.
Research limitations/implications: The research limitations on research was due to fast wear of tools while machining stainless steel than alloy steel even the same hardness was maintained.
Practical implications: More number of experiments could not conduct due to fast tool wear.
Originality/value: The materials used in this experiment were not used by most of the researcher. The results obtained can be used by the other researcher and may be references.
Keywords: Wear resistance; Heat treatment; Machining; Surface roughness

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1. 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. 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 presence of 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. Figures 1 and 2 show the tool wear on and cutting forces acting on a single point tool respectively.

2. Experimental procedures

2.1. 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 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 cantered on both sides to accommodate in the lathe centres. 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, side rake -6 and end clearance angle of 27 with nose radius of 0.80 mm for both tools. 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.

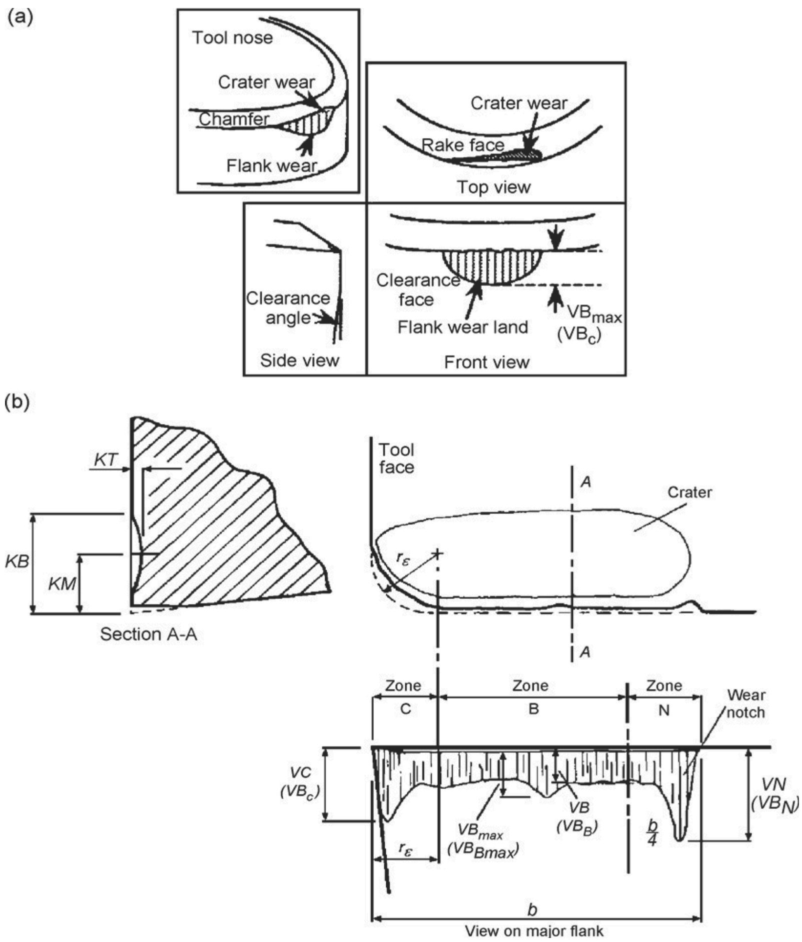


Fig. 1. Diagram of worn cutting tool showing principal locations and types of wear [4,5]

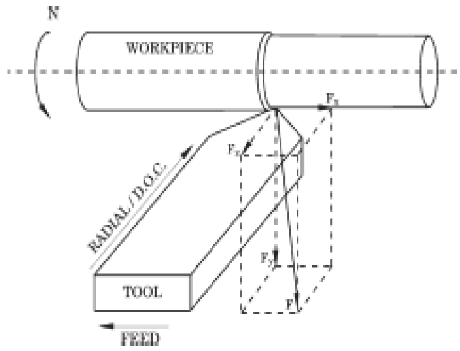


Fig. 2. Three forces acting on a single point tool [6]

2.2. 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.

Table1.
Chemical properties

Grades	C %	Mn	Cr	Mo
AISI 440 C	0.95/1.20	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

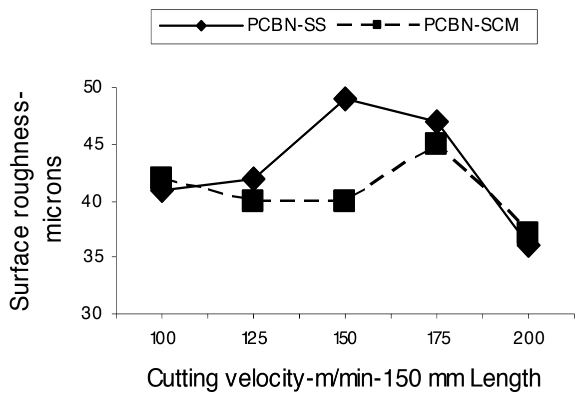
Parameters	Range
Cutting velocity - m/min	100, 125, 150, 175 & 200
Feed rate -mm/rev	0.10, 0.20 & 0.30
Depth of cut	1.00 mm constant

3. Results and discussion

3.1. 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 depended 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 on SCM 440 alloy steel than AISI 440 C stainless steel. It indicates that the plastic deformation by SCM 40 steel is more than alloy stainless steel. Figure 3 (a, b) show the graphical representation of surface roughness against the various cutting velocity. As the cutting velocity increased, the surface roughness has less or equal to same value up to cutting velocity of 200 m/min, but they are variation in all the cutting velocity. The built up edge formed also by stainless steel at cutting tool contributed towards roughness in stainless steel and this was due to quality characteristics of stainless steel.

a)



b)

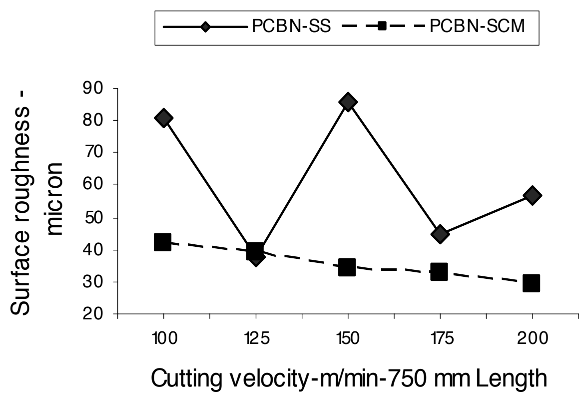
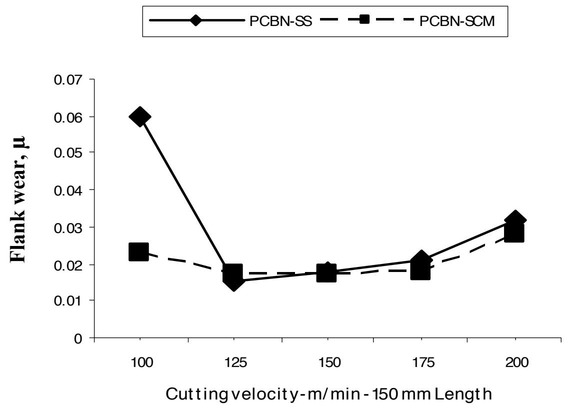


Fig. 3. Cutting velocity Vs surface roughness at feed rate of 0.10 mm/rev

3.2. Flank 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.

a)



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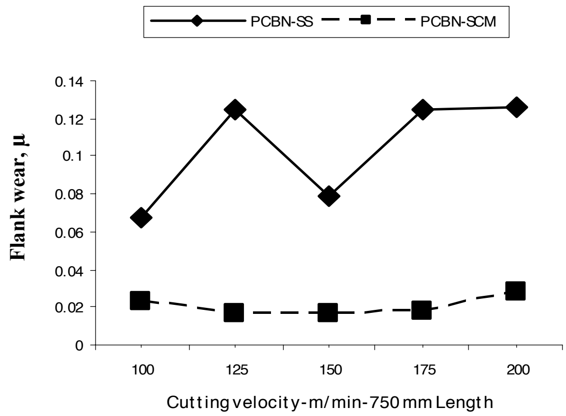


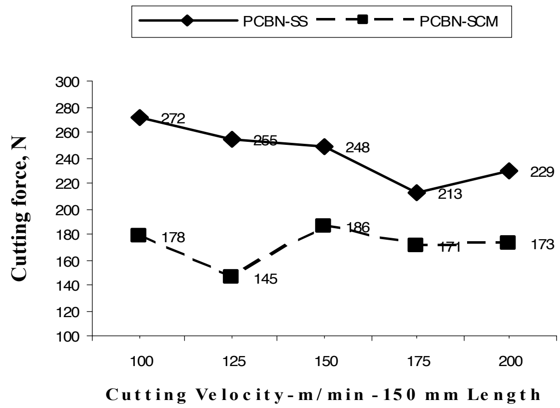
Fig. 4. Cutting velocity Vs flank wear at feed rate of 0.10 mm/rev

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. The flank wear is contributing dimensions of the component whatever the machining process. During starting of the machining, the cutting edges are fresh and effecting cutting is possible for all the materials. They are exceptions in removing stock of material by tool. Figure 4 (a, b) is the graphical representation of flank wear formed by PCBN tool for two materials. The flank wear formed at low cutting velocity by stainless steel was high due to contact between the tool and work materials. Flank wear at various velocities during 150 mm length was lower than 750 mm length of machining. Formation of built up edge acting as coating to prevent the formation of flank wear whenever it exists. Figures 6 and 7 show the flank wear by PCBN on tool for both stainless steel and SCM 440 alloy steel respectively. Figure 6 (b) shows the flank wear with built up edge formed.

3.3. Cutting force F_Y

Figure 5 (a, b) shows the graphical representation of cutting force with feed rate of 0.10 mm for 150 and 750 mm length of turning. Cutting force is caused by plastic deformation of materials. Forces varied based on the hardness of work materials, operating parameters, formation of chips, temperature developed, tool wear etc.

a)



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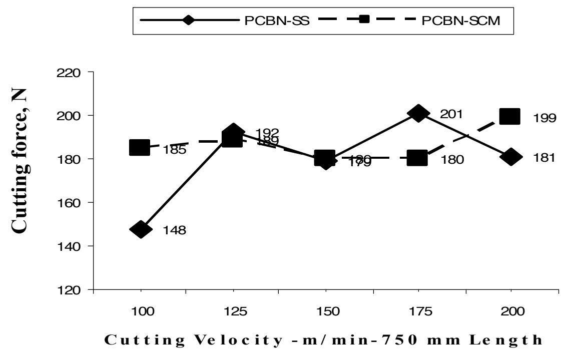

Fig. 5. Cutting velocity Vs cutting force at feed rate of 0.10 mm/rev

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 edge formation. The built up edge, tool- chip contact length decreases and this in turn, reduces the cutting forces. The formation of built up edge also contributed towards the forces acting. It act as another cutting edge and made the cutting more effective. From the graphical representation, it was clear that machining stainless steel produced low cutting forces due to heat at tool tip and work surface zone. This was due to heat at cutting zone is shared by the chips which softens the chip and made machining more effective. Figure 8 shows the saw tooth chip formed while machining stainless steel which also reduce the cutting force.

3.4. Specific cutting pressure - (β)

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. The cutting wedge 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].

$$\beta = \text{cutting force} / \text{area} \quad (N/mm^2) \qquad (1)$$

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

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 × d). The specific cutting pressure also determines the machined surface and influenced by the status of the cutting edge, 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]. As the cutting force was low in the specific cutting pressure would be low in machining.

Figure 5 (a, b) show the specific cutting pressure for both the materials by PCBN tool. When the specific cutting pressure (β) is low due to cutting forces because the feed rate and depth of cut remain the same.

a)

b)

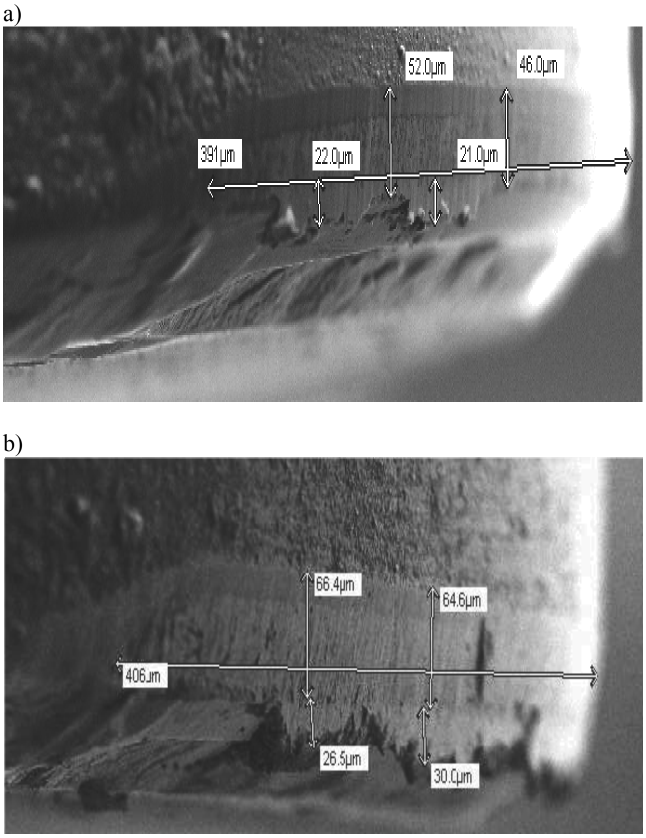

Fig. 6. Flank wear and built up edge formed - (a) after 150 mm length of turning (b) 750 mm length of turning by PCBN tool on stainless steel.

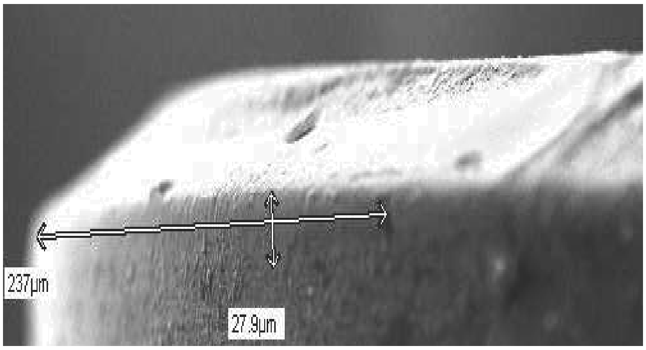

Fig. 7. Flank wear by PCBN at the end of 750 mm length of turning

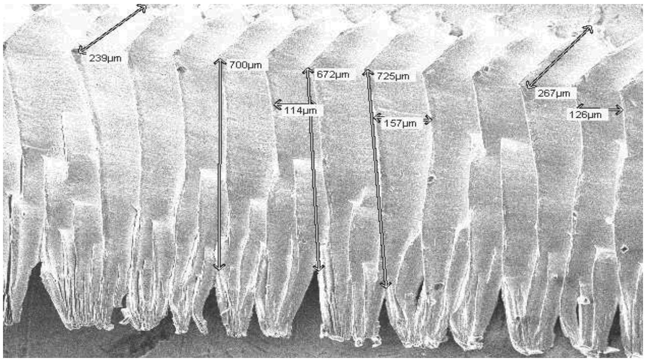

Fig. 8. Saw tooth formed by stainless steel

4. Conclusions

The experimental investigations have shown the machinability of PCBN tools while machining AISI 440 C stainless steel and SCM 440 C alloy steel.

The surface roughness produced in machining stainless steel was erratic or following any trend. It varied in all cutting parameters. However, it was low at high velocity with low feed rate whereas SCM 440 alloy steel produced low roughness at high velocity.

Flank wear by AISI 440 C stainless steel was high and also produced built up edge at the 750 mm length of turning. In case of SCM 440 alloy steel, flank wear was low even at high velocity. Cutting force by AISI 440 C stainless steel was low and SCM 440 alloy steel was high. The variations were due to heat at tool tip and work material zone.

The specific cutting pressure is also form cutting force but varied based on area of the chip (feed rate and depth of cut) which is constant for the given parameters. At low value of specific cutting pressure, machinability was good. Machinability by stainless steel is good than alloy steel due to cutting force.

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