PERFORMANCE AND TOOL WEAR CHARACTERISTICS OF CUBIC BORON NITRIDE CUTTING TOOLS DURING HARD TURNING OF STEEL

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ABSTRACT
Hard turning has been receiving increased attention because it offers many potential benefits over grinding. One of the requirements for the better utilization of the hard turning process is to get a better understanding about the wear trend and the influence of cutting parameters on tool wear. In this work, cutting experiments were carried out to investigate the tool-wear behavior of CBN cutting tools in turning hardened steels. Experiments were conducted at three varying cutting speeds and the surface roughness of the work piece at various stages of tool wear was measured. The experiments confirm the predominant role of tool flank wear land in controlling the surface roughness in hard turning. As wear land increases the roughness also gradually increases and from the results shows that Ra is less than 1 µm at lower feed and depth of cut and all three cutting speed. The tool life index, for the specific tool material work piece combination, justifies high speed operation in hard turning.

Keywords: Hard turning, CBN cutting tool, Surface roughness, Flank wear land, Tool life

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>V_C</td>
<td>Cutting Speed (m/min)</td>
</tr>
<tr>
<td>f</td>
<td>Cutting feed (mm/rev)</td>
</tr>
<tr>
<td>b</td>
<td>Depth of cut (mm)</td>
</tr>
<tr>
<td>V_B</td>
<td>Tool Flank wear (mm)</td>
</tr>
<tr>
<td>Ra</td>
<td>Arithmetic mean deviation of the assessed profile (µm)</td>
</tr>
<tr>
<td>Rt</td>
<td>Total height of the profile on the evaluation length (µm)</td>
</tr>
<tr>
<td>Rz</td>
<td>Maximum height of the profile within a sampling length (µm)</td>
</tr>
<tr>
<td>T</td>
<td>Tool life (min)</td>
</tr>
<tr>
<td>n</td>
<td>Tool life index</td>
</tr>
<tr>
<td>C</td>
<td>Taylor’s tool life constant</td>
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<tr>
<td>HRC</td>
<td>Rockwell hardness ‘C’ scale</td>
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</table>

1. INTRODUCTION
The current need of manufacturing industries is to improve productivity and to ensure quality. These demands require stable processes with higher material removal rates and less processing time. In many systems, hardened parts are used to achieve certain design objectives, and these parts are to be machined and finished. The conventional methods of manufacturing such parts is through cutting of the desired part when the material is soft with suitable allowance for hardening and grinding, hardening and finish grinding. However, the total cycle time of manufacturing by this route is long.

Over the last few decades, machining, particularly turning of hardened components has become a reality. In hard turning, components having hardness in the range of 45 to 70 HRC are turned in a suitable machine tool. The advantage of hard turning over the conventional machining – hardening – grinding is many. Some of the significant advantages are: high flexibility and ability to manufacture complex profile in one setup, less cycle time, Lower cost of manufacturing and Environment friendliness (Tonshoff et al. 2000). Since hard turning involves turning materials with hardness in the range of 45 to 70 HRC, the machine tool used must of very high rigidity and capable of withstanding high dynamic cutting forces. Similarly the cutting tool material used for hard turning must have high hardness, high fracture toughness, high stability against abrasive particle, high resistance to mechanical stress and ability to maintain its shape at elevated cutting temperature (Tonshoff et al. 2000). The cutting conditions in hard turning process have to be optimally chosen considering various factors such as the quality of the surface produced in terms of surface roughness and surface integrity, the material removal rate and tool wear. Since hard turning is a finishing process, the surface finish of the components produced is an important parameter of the process output. The surface finish in hard turning is influenced by the cutting conditions, tool geometry, tool wear and the rigidity of the machine tool. However, among these parameter tool flank wear is a dynamic factor, which varies during the course of machining and adversely affecting the surface finish when it crosses certain limit. Therefore CBN tool wear is an important issue to be addressed for hard machining.

2. BACKGROUND
The technology of hard turning is being studied theoretically and experimentally for over 40 years (Tonshoff et al 2000).
Cutting tools used for hard turning require high hardness, high compressive strength, high resistance to abrasive wear, thermal resistance and chemical stability at elevated temperatures. Cubic Boron Nitride (CBN) is the preferred cutting tool material than poly crystalline diamond (PCD) for machining hardened steel since it has very high hardness and hot hardness and is chemically inert particularly in the presence of carbon absorbing materials. To understand the systematic development of cutting tool material in hard turning process the literature review can be presented, which includes studies on developing suitable tool materials, developing suitable tool geometry and tool edge geometry, developing coatings for enhanced tool life, identifying optimal cutting conditions, understanding the process of chip formation and identifying the various tool wear mechanisms.

2.1 Developing suitable material, Tool Geometry and Tool edge Geometry

Ceramic inserts are also being used for hard turning. Hodgson and Trendler (1981) carried out hard turning experiments to identify the suitable cutting tool material for machining hardened steel material. In their study authors performed the turning tests on three different varieties of hardened steels such as cold work steels (D2 and D6) and HSS steel (M2) using CBN and ceramic cutting tools. The Ceramic cutting tool did not perform satisfactorily while machining cold worked steel (D6) resulting to gross fracture and chipping of the cutting edge. On other hand CBN inserts performed better while machining hardened steel in terms of extended tool life even at higher cutting speeds. This study was also confirmed that tool life can be enhanced by providing a negative rake angle tool rather than a positive or zero rake. They also concluded that chamfered edges performed better than the conventional sharp edges. The influence of tool nose radius on surface roughness, cutting forces, tool wear and white layer formation had been systematically investigated by Kevin Chou and Husi song (2004). The authors were conducting finish hard turning experiments on hardened AISI 52100 steel using mixed ceramic tool inserts. Inserts with nose radius 0.8, 1.6 and 2.4 mm were used in the experiments. The experiments revealed the larger nose radius to contribute better surface finish but resulted in increased cutting forces and increased specific cutting energy.

Ozel et al (2005) performed the hard turning experiments on hardened AISI H13 steel using CBN inserts to study the effect of tool edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and cutting force. Their objective was to identify suitable edge geometry for better surface finish and improved wedge strength. In the study sharp, chamfered and honed edges were used. The honed edges were found to perform much better than sharp and chamfered edges in terms of surface finish, radial cutting force and tangential cutting force. Ozel et al (2008) introduced a ‘variable edge design’ on the cutting edge of CBN insert and experimentally studied its influence on cutting force, temperature distribution and tool wear. The results of experimentally obtained cutting forces were used to validate an FEA model. The investigation of the experiments concluded that variable edge tool inserts are better than the normally prepared edge in terms of reduced tool wear, less heat generation and less induced plastic strain on the work material during hard turning.

2.2 Tool Coating

Reginaldo et al (2007) undertook studies to report wear characteristics of a coated PCBN insert while machining hardened steel. Three different TiN and TiC-based coatings were used on PCBN to study wear behaviour and surface finish of the work piece. Finite element simulation model was used to estimate chip-tool interface temperature for studying thermal resistance of the coatings. The results show that the coatings acted as a thermal barrier between the work piece and PCBN tool, resulting in a small reduction at the substrate temperature.

2.3 Chip Formation

Serious efforts are being made to understand the basic mechanism of chip formation. Because of the high brittleness of the work material, it was not able to flow plastically under the high compressive stress but lead to the formation of a crack. The crack releases the stored energy and acts a sliding surface for the segmented material. Simultaneously the plastic deformation and the heating of work material occur at the vicinity of the cutting edge of the tool, facilitating the sliding of chip segment. This cycle repeats continuously leading to the severely segmented chip formation. (Konig et al 1990)

Through experimental investigations Shaw and vyas (1993, 1998) showed that saw toothed, wavy and segmented chips were formed in machining of hardened steel, due to catastrophic shear and plastic flow.

2.4 Tool Wear Mechanism

Since the rapid tool wear is the basic difficulty in hard turning, efforts are being made to understand the wear mechanism operating between the tool and work material in conditions prevailing during hard turning. One major difficulty in turning of hardened steels is the tool-wear caused by the hardness of the material. Wear behaviour CBN is influenced by many factors such as the composition of CBN material, work piece hardness, cutting condition and nature of cutting operation etc. The experimental investigation of Chou et al (1997) showed the wear rate of the CBN tool depends upon the carbide particle in the work material and size of the CBN grain in tool. The results of the experiments clearly indicated the wear rate to be directly proportional to the size of the carbide particle in.
Table 1 Chemical composition (% by weight) of the Workpiece material

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Al</th>
<th>Co</th>
<th>Cu</th>
<th>Ti</th>
<th>V</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.12</td>
<td>0.48</td>
<td>0.37</td>
<td>0.017</td>
<td>0.018</td>
<td>10.84</td>
<td>0.06</td>
<td>0.018</td>
<td>0.037</td>
<td>0.036</td>
<td>0.005</td>
<td>0.039</td>
<td>&lt;0.01</td>
<td></td>
</tr>
</tbody>
</table>

# - The remaining percentage is Fe

-the work material and inversely proportional to the size of the CBN grains.

An extensive literature review was presented by Cora Lahiff et al. (2007) to elaborate the wear modes and wear mechanism of various grades of CBN inserts. Tool wear mechanism is a complex phenomena and no single mechanism alone can provide a satisfactory tool wear explanation. The authors identified Two body abrasion caused by hard carbide particles and martensite in the workpiece, three body abrasion caused by the loosened CBN grains, diffusion wear and adhesion because of high temperature to be the predominant wear modes. They also observed the tool wear to depend on the composition CBN content and binder, tool edge geometry and machine tool stability.

2.5 Optimal Cutting Condition

The performance of CBN insert can be evaluated based on the surface roughness of workpiece and flank wear of the tool. Hard turning is usually carried out at low feeds and depth of cuts with normal cutting speeds without applying any coolant. Experimental work carried out by Neo et al. (2003) and Yallese et al. (2009) showed the surface roughness generated in finish hard turning to be mainly influenced by the cutting parameters such as cutting speed, cutting feed and depth of cut. Among these cutting parameters, cutting feed is the dominant factor contributing to the surface roughness. In their experimental study of hard turning, Yallese et al. (2009) showed the cutting forces to increase rapidly with increase in feed rate which in turn contributed to the stability of the machine tool. Experimental observations showed that cutting speed beyond 280 m/min to produce sparks which resulted in very poor surface finish and very rapid tool wear. The authors pointed out that the use of recommended range of cutting speed and cutting feed for better surface finish and for extended tool life.

The cost of manufacturing finished component is directly related to machining time and how long the tool can be used for continuous machining with the pre-requisite surface quality. Hence the deeper understanding of tool wear behaviour, tool life, and surface finish by selecting appropriate cutting condition is crucial criteria for the machining of hard material. Therefore the machinability characteristics of work-tool combination are required for all possible combinations and this is truer for the hard machining. Davim and Figueria (2007) used the orthogonal array experiments to determine the influence of cutting speed, feed and cutting time on the specific pressure and surface roughness and tool flank wear. The authors were carrying out experiments on cold work tool steel D2 (AISI) using ceramic cutting tool. The study showed the tool wear to be primarily influenced by cutting speed and the surface roughness to be influenced by feed and cutting time which is an indirect measure of tool wear.

3. EXPERIMENTAL WORK

The experiments were conducted on a Quest 8/15SP Hardinge CNC turning center (Figure 1) of 15kW capacity. CBN cutting tool insert with commercial grade DR 50 and ISO designation DNMA 150408 and tool holder DDJNL 2525 M15 were used in the experiments. While mounting the tool, care is taken to align the tool tip along the axis of rotation of the work piece. DR 50 has a low CBN content and particles are dispersed in ceramic matrix. This gives the material a lower thermal conductivity and greater wear resistance in finish hard turning operation. The work piece was a 55 mm diameter cylindrical rod of about 130 mm length made of high carbon, high chromium steel (AISI-D3, UNS No.T30403). The chemical composition of the work material in percentage by weight is given in table 1. The work piece was hardened by oil quenching from the temperature of 900 °C and then tempered at two stages at 350°C and 250°C.

Figure 1 Photographic Image showing the experiments in hard turning

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The final hardness obtained was 60 HRC and this was measured using Rockwell hardness tester. The micro hardness at the surface of the work piece material was observed to have a Vicker’s hardness number 694.2 HV.

The main objective of this experimental work is to study the influence of cutting speed on the wear behaviour of the CBN tool and the relation between the tool wear and the surface roughness at different cutting speeds. The turning experiments were carried out with a constant depth of cut of 0.1 mm and feed 0.05 mm/rev. Since hard turning operation is a finishing operation, the low value of feed and depth of cut employed is realistic. The cutting speed in the experiments was selected at three levels, which are 70, 100 and 130 m/min (Table 2).

<table>
<thead>
<tr>
<th>Cutting conditions</th>
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<tbody>
<tr>
<td>Cutting speed</td>
</tr>
<tr>
<td>70, 100 and 130 m/min</td>
</tr>
<tr>
<td>Cutting feed</td>
</tr>
<tr>
<td>0.05 mm/rev</td>
</tr>
<tr>
<td>Depth of cut</td>
</tr>
<tr>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

During each experiment the machining was interrupted approximately every five minutes or ten minutes of machining depending on the expected rate of wear. When the wear rate was expected to be steep the interruptions were frequent. At each periodical interruption the tool wear was measured using a tool maker’s microscope. The surface roughness of the work piece was also measured using a Taylor Hobson -Talysurf roughness tester during these interruptions. Experiments were continued till the tool flank wear land clearly crosses the limiting flank wear land value of 0.3 mm.

4. RESULTS AND DISCUSSION

The results obtained in the experiments described above are analysed to understand the wear behaviour of the cutting tool at various cutting speeds and the relation between the surface roughness and flank wear land.

4.1 Wear Behaviour of the Cutting tool at various cutting speeds

The value of the tool flank wear land measured at various time instants of machining for all the three cutting speeds is given in Figure 2. The overall trend of tool wear curves for hard turning, confirm to the general tool wear pattern. Moreover as expected in any metal cutting operation the wear becomes steeper and more rapid for higher cutting speeds. Though the different wear regions were not very clearly distinguishable, one can easily see the rate of wear becoming very high as the flank wear land value crosses the 0.3 mm mark, for all the three cutting speeds. The tool life of CBN at the cutting speed 70 m/min was 70 min and for 100 m/min, 130 min were 38 min, 20 min respectively.
All the three graphs indicate a gradual deterioration of surface roughness as the flank wear land of the tool increases. It can also be observed that, when the flank wear land is below 0.3 mm, the Ra value of the surface roughness remains well within 1 µm, for all the cutting speeds. Even at the point when the flank wear land was about 0.3 mm the Ra value of surface roughness for various cutting speeds was found to be about 0.7 µm. This shows that as a manufacturing process, hard turning can be employed for finish machining as an alternative to grinding. The deterioration in the surface roughness becomes very steep as the wear land crosses the critical value of 0.3 mm.

4.3 Effect of wear on tool life and productivity

The effective life of the cutting tool that is the machining time corresponding to 0.3 mm of flank wear land was computed for all the cutting speeds. Figure 6, shows the plot between the tool life and the cutting speed in a log-log plot. The straight line obtained shows that the tool wear behavior follows the classical Taylor’s equation of $V_c T^n = C$. The slope of the straight line in figure 6 indicates the $1/n$, where $n$ is the tool life index in the Taylor’s tool life equation. The parameter ‘$n$’ is a very rough indicator of the level of influence of the cutting speed on the tool life. Higher the value of ‘$n$’ signifies relatively lower influence of cutting speed on tool life and ‘$n$’ is influenced by the tool material – work material combination.

The material removal volume for machining at cutting speed 70 m/min corresponding to the allowable wear criteria from the graph is 25.65 cm³ and when it is referred to cutting speed 100 m/min and 130 m/min is 21.5 cm³ and 15 cm³ respectively (Table 3)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Cutting speed (m/min)</th>
<th>Chip Volume (cm³)</th>
<th>% of fall in Stock removal as compared to $V_c=70$ m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>25.65</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>21.5</td>
<td>15.5</td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>15</td>
<td>42</td>
</tr>
</tbody>
</table>

From this graph (figure 6), the value of $n = 0.5102$. The ‘$n$’ values for conventional machining of steel using carbides or High Speed Steel will be in the range of 0.1 to 0.2. This signifies a relatively low influence of cutting speed on tool life in hard turning. On the basis of the allowable flank wear criteria $V_B = 0.3$ mm the statistics of the chip removal volume was represented in Figure 7. This investigation allows to observe the total volume of material that can be machined within the useful tool life of CBN tool inserts for the various levels of cutting speeds. It is significant in allowing the user to choose a suitable cutting speed from the productivity point of view. It can be clearly seen from the figure 7 that for the cutting speed of 70 m/min have better performance in terms of more volume of material removal for flank wear criterion $V_B = 0.3$ mm as compared to other two.
ratio 1.3, the material removal is falls by 15.5%. This allows the user to make a suitable compromise between the speed of operation and the useful life of the cutting tool.

5. CONCLUSION
Tool wear studies were conducted using CBN inserts at three different cutting speeds. The results of the experimental work are summarised as follows.

1. The conventional three phases of tool wear namely the initial run-in wear; steady state wear and rapid tool wear are not clearly distinguishable.
2. Flank wear land, the parameter governing the tool life increases rapidly as the cutting speed was increased. Tool life at the cutting speed 70 m/min was approximately 4 times that of tool life at 130 m/min for a feed of 0.05 mm/rev and depth of cut of 0.1 mm. This makes the suitable trade off between higher productivity and higher tool life necessary.
3. The flank wear of the cutting tool also significantly affects surface roughness of the workpiece. There is a marked degradation of the surface roughness as the flank wear land of the tool crossed the critical value of 0.3 mm.
4. When the flank wear land remains with in 0.3 mm, the surface roughness (Ra) value remains well with in 0.7 µm making the process comparable to grinding operation.
5. While studying the level influence of cutting speed on tool life of CBN tools, it was observed that cutting speed has a relatively low influence on tool life when compared to high speed steel and carbide cutting tools.

REFERENCES