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ANALYSIS OF TOOL WEAR AND CUTTING FORCES DURING FINISH TURNING OF HARDENED STEEL WITH COATED CARBIDE AND CBN TOOLS

Engineering

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Manu Dogra

UIET, Panjab University SSG Regional Centre, Hoshiarpur, Punjab India

ABSTRACT

A study was undertaken to investigate the performance of coated carbide and CBN tools in finish turning of hardened steel. The effect of cutting conditions on tool wear and cutting forces of coated carbide and CBN inserts were analyzed. The tool life and cutting forces achieved with both the tools under similar cutting conditions were compared. The performance of coated carbide tools in terms of tool life was comparable with CBN tools at low and medium cutting speed tested. The performance of coated carbide tools were deteriorated at highest cutting speed tested. Results indicated that at low (80 m/min) to medium (130 m/min) cutting speed tested with selected flank wear criterion of VBmax=200 μm, coated carbide can become economical alternative to costly CBN tools for finish turning of hardened steel within the studied range of workpiece hardness (49-50 HRc).

INTRODUCTION

The hard turning process is to turn material whose hardness is higher than 45 HRc, which offers number of potential benefit over traditional grinding like high flexibility, increased material removal rates and possibility of dry machining (Huang et al., 2007; Dogra et al., 2010). PCBN tools are the preferred tool materials for machining of hardened steel (Huang et al., 2007). Despite the potential of hard machining to increase productivity and its competitiveness with grinding, this technology has not been adopted much in context of its industrial applications. There are two reasons to explain this, first the uncertainties related to integrity and accuracy of the machined surface and second, the difficulty associated with compact CBN processing (high temperature and high pressure) and the high cost of CBN tools. Particularly the second reason has shifted thechallenges for hard turning from technological feasibility to economical viability (More et al., 2006). Tool wear is the important parameter in hard turning, which controls the quality of machined surface. Tool wear not only reduces the part quality but also increases cutting forces drastically (EI-Wardany et al.,2000; Liew et al., 2004). Service life of hard turned components largely dependent upon their surface quality characteristics achieved after machining (Dogra et al., 2010). In the past, attempts were made to compare performance of coated carbide, ceramics and CBN tools in terms of tool life, cutting forces and surface integrity of the machined surface during the turning of hardened steel (Sales et al., 2009; Tae et al., 1999). In recent years,tool manufacturers have provided wiper geometry and wear resistant coatings, with high temperature withstanding capacity on carbide cutting tools for turning applications. The purpose has been to increase productivity and improve surface finish (Sandvik., 2014).
During the turning of hardened AISI 4340 steel using CBN–TiN coated carbide and PCBN Tools, the results revealed that tool life of CBN–TiN coated carbide inserts was approximately 18–20 minutes per cutting edge, whereas PCBN tools produced a tool life of 32 minutes. The cutting forces for the CBN–TiN coated carbide inserts were slightly higher than those of the PCBN tools due to a slightly larger nose radius and a rough surface associated with the CBN–TiN coated inserts. A cost analysis, based on a single cutting edge, shows that the CBN–TiN coated carbide tools are capable of reducing machining costs, and, therefore, will be an important complement to PCBN compact tools for hard turning applications (More et al., 2006).
The effects of cutting conditions and toolwear on chip morphology and surface integrity during high speed machining of D2 tool steel were investigated. Results indicated that microcracks and voids were formed on the machined surface due to low deformability of carbide grains (EI-Wardany et al., 2000).

During turning of hardened W320 (AISIH10) hot working die steel with TiN-coated cemented carbide, mixed ceramic and PCBN tools, the results indicated that cemented carbide tools performed better at low cutting speed and feed rate conditions. However, with increasing cutting speed, its performance dropped dramatically. In all cutting conditions evaluated, mixed ceramic tools did not perform well, mainly due to its low toughness. PCBN tool, at low cutting speeds was susceptible to high wear caused by chipping, but with increasing cutting performance improved (Sales et al., 2009). A comparative study of low-cost TiN coated tool and expensive CBN tool in hard turning, by using air-oil cooling systems, was conducted. The author concluded that it was possible to machine hard materials at a lower cost using TiN coated tools instead of expensive CBN tools (Tae et al., 1999). Apart from CBN tools, studies on use of ceramics and carbide tools for finish hard turning, under dry and wet conditions have also been reported in the literature (Lin et al ., 2008; Trent and Wright., 2000). The effect of tool wear is to increase cutting forces, cutting zone temperature, generate white layer, tensile residual stress on the surface and deteriorate the surface finish (Choi Youngsik., 2010; Guo et al ., 2009). For minimizing distortion of machine components, workpiece, fixture, and cutters the knowledge of forces generated during turning is important (Trent and Wright., 2000). But in finish hard turning the quantification of tool life in context of surface integrity of the machined surface is not clearly established. That means what amount of tool wear should be considered as tool life for achieving optimum surface integrity of the machined surface. This is required in order to establish hard turning in comparison to grinding for different industrial applications. Further the temperature distribution and the location of the maximum temperature at the chip-tool interface are important, as this has a dominant influence on tool-wear/tool-life, part quality, part accuracy and residual stresses that contribute to the useful fatigue life of the component.

But in literature work pertaining to tool wear and cutting forces evaluation during finish turning of hardened steel by comparing the performance of carbide and CBN tool is scant. Thus this work aims to compare the performance of coated carbide and CBN tools in terms of tool wear and cutting forces for same cutting conditions.

EXPERIMENTAL PROCEDURE

Continuous turning of AISI 4340 steel was performed with both carbide and CBN. The work piece material used in the form of round bars of 55 mm diameter and 300 mm length, so that L/D ratio should not exceed 10 as per ISO 3685 standards (ISO-3685., 1993). The material was hardened followed by tempering process to attain hardness of 48-49HRc.

Two types of tools were used, CBN and coated carbide.A CVD coated carbide grade with innermost coating layer of TiCN (Titanium carbonitride), intermediate layer of Al2O3 (Alumina oxide) & outermost layer of TiN (Titanium Nitride) having wiper geometry with designation CNMG120408-WF was used (Sandvik ., 2014). The CBN tools with designation CNGA120408 S01225 SE, having chamfered and honed (25° & 0.12mm) cutting edge with low CBN content were selected, as low CBN content tools are known to give better performance in continous hard turning (More et al., 2006). Both the inserts having 0.8 mm nose radius were selected, so that machining result could be compared under similar cutting conditions. Longitudinal turning of the workpieces, under dry conditions, on a CNC lathe using a fresh cutting edge of different inserts in each combination of speed, feed and depth of cut, was performed.Each single pass consisted of axial cutting length 275 mm and after every 50 mm workpiece cutting length, the amount of maximum flank wear (VBmax) was measured using optical microscope.

The width of flank wear land was not uniform along the cutting edge. This kind of non-uniformity of flank land was observed under all the cutting conditions with both the tools. Thus it was decided to measure VBmax instead of VBavg as per ISO 3685 standard (ISO-3685., 1993) is consistent with finish hard turning applications. The worn tools were also evaluated using scanning electron microscope (SEM) at regular interval in order to understand the wear modes.

In finish hard turning, the cutting speeds are generally between 80 m/min and 200 m/min. The feeds and depth of cut are relatively small (<0.2mm) (Huang et al., 2007; More et al., 2006). On the basis of literature and recommendations of the tool manufacturers, the cutting speed (v) was varied in three steps as 80,130 &180 m/min, with feed f =.07 mm/rev and depth of cut ap=0.1 mm.

A turning dynamometer was used to measure cutting forces and the forces recorded with a PC-based data acquisition system. The combination of tool holder and insert geometry provided a 90°approach angle and -6° top rake angle. The two components of cutting force were recorded as VBmax reaches 200μm for each tool. These components are cutting force (Fc) and thrust force (Fp).

RESULTS AND DISCUSSIONS

Tool Wear

Progression of maximum flank wear (VBmax) of both the tools with machining time in minutes at different cutting speeds by keeping feed(f=.07 mm/rev) and depth of cut (ap=.1 mm) as constant is presented in Fig.1-3.Each insert was evaluated for flank wear measurement at regular interval of axial cutting length using optical microscope. From the figs it is indicated that with carbide tools, tool life was significantly affected by cutting speed (More et al., 2006; Sales et al., 2009).Tool life of carbide inserts decreased as the cutting speed increased, because with increase in cutting speed for a given time the cutting temperature increased, which lead to rapid tool wear (Sales et al., 2009; Trent and Wright., 2000).. But in particularly at low and medium speed the effect of cutting speed on tool life was less significant, that indirectly indicates the temperature generated during cutting was not too high which can lead to catastrophic failure of the coated carbide tools.

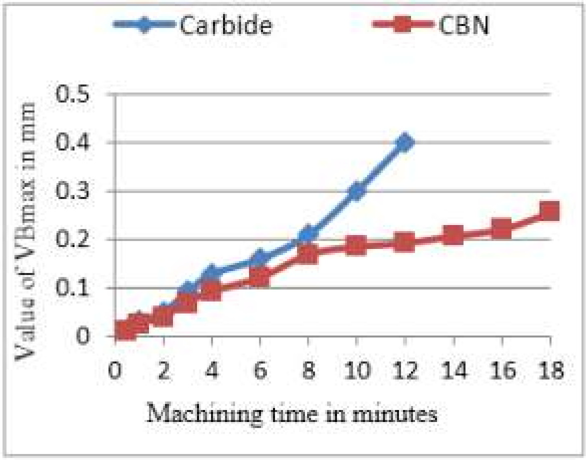

Figure.1Progression of maximum flank wear at v=80m/min, f=.07mm/rev

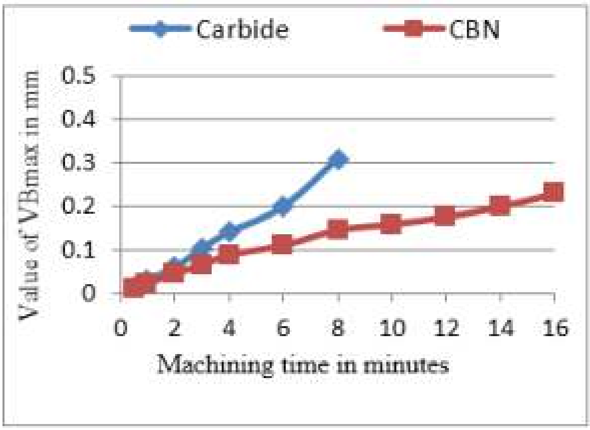

Figure.2Progression of maximum flank wear at v=130m/min, f=. 07mm/rev.

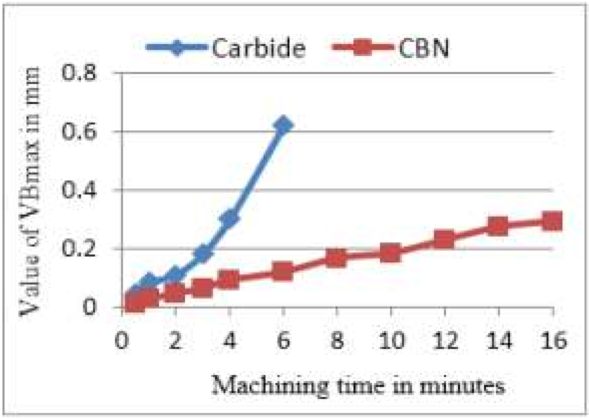

Figure.3 Progression of maximum flank wear at v=180m/min, f=. 07mm/rev.

Sudden increase in the flank wear of carbide tools was observed at the highest cutting speed (V=180 m/min), the cause was chipping and breakage of the cutting edge, making it to reach the end of tool life as shown in Fig.4. This shows that the tool underwent catastrophic failure (More et al., 2006). On the other hand for CBN tools, as the cutting speed increased the tool wear decreased up to V=130 m/min but again deteriorates at V=180 m/min. It was due to the thermal softening of the workpiece with rise in cutting speed cutting speeds. But at speed of 180m/min the crater wear plays a significant role in the reduction of tool life as the chips travel speed on the crater face enhances, which resulted in larger crater wear and thus reduced tool life in comparison to speed of 130m/min (Hua et al.,2006).

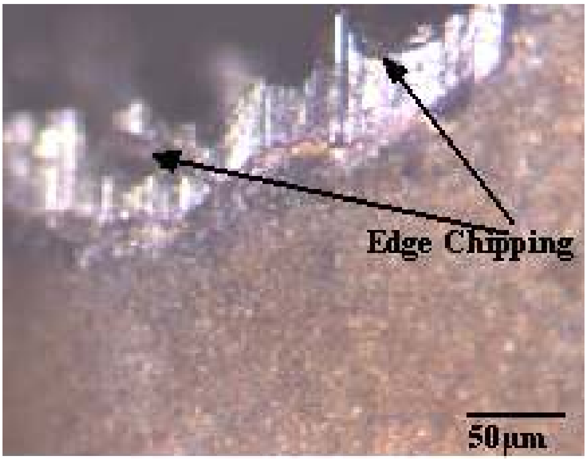

Figure.4 Carbide insert after 2 min of machining at V=180m/min, f=.07mm/rev

At low cutting speed of 80 m/min, with CBN tool, the binder present in cutting tool got easily abraded from the substrate by the hard particles of the work piece. As the effect of thermal softening was not significant at lower cutting speed, thus the tool life was comparatively low at the cutting speed of 80 m/min than that at the medium speed (130 m/min) tested (Huang et al., 2007; Lahiff et al., 2007). At the highest cutting speed (180 m/min) tool life of CBN tool decreased, as the effect of thermal softening of the workpiece in studied range of workpiece hardness was overpowered by the adhesion kind of wear. It is interesting to note here that tool life of carbide tool was comparable with that of the CBN tool in the first few minutes of machining in particular at low (80 m/min) and medium (130 m/min) cutting speed tested. This was due to availability of wear-resistant multilayer coating on the carbide tool. At low and medium cutting speeds with carbide tool, apart from minor chipping on the cutting edge, progression of flank wear (VBmax) was gradual.

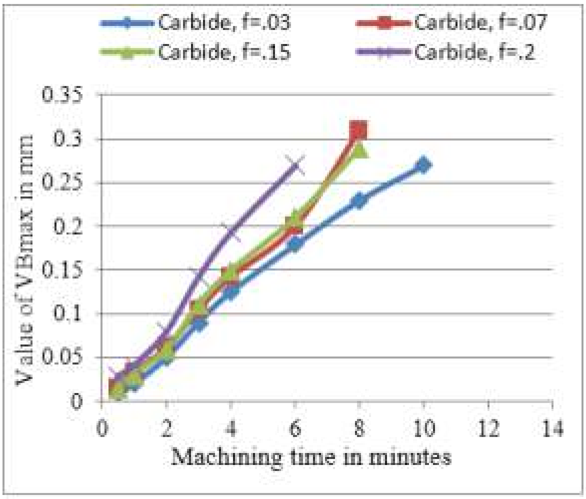

Figure. 5 Tool wear with different feed rates at V=130m/min with carbide tool

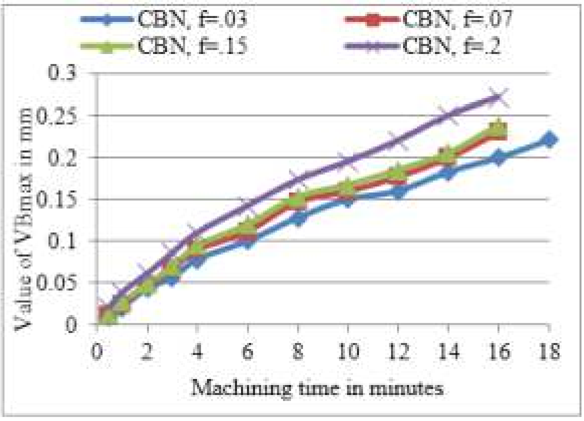

Figure. 6 Tool wear with different feed rates at V=130m/min with CBN tool

Figure 5and 6 respectively show the progression of tool wear with carbide and CBN tool with machining time at V=130 m/min and different feed rates. When the feed rate increased from .07mm/rev to .15 mm/rev no significant decrease in tool life was observed with both the inserts (EI-Wardany et al., 2000). While at highest feed rate (f =0.2 mm/rev) tested, significant increase in tool wear of both the tool was observed. At highest feed rate used with carbide tool after first minute of machining, the noise produced during cutting was changed and lot of chatter/ waviness was obtained on the machined surface. Also at lowest feed tested, minor drop in the tool wear was observed. The result indicated that varying the feed between .07 mm/rev to .15 mm/rev did not affect the tool wear, while taking feed less than .07 mm/rev or more than .15 mm/ rev can affect the tool wear significantly for both the tool used. So in order to optimize the material removal rate and tool wear any value between .07 mm/rev to .15 mm/ rev of feed may be selected in hard turning applications under the studied range of cutting speed and depth if cut.

CUTTING FORCES

Analysis of cutting forces was carried out and Fig. 7 & Fig.8 show the values of force components with machining time of both the tools at V=80m/min and V=180m/min cutting speeds respectively as VBmax approaches 200 μm.

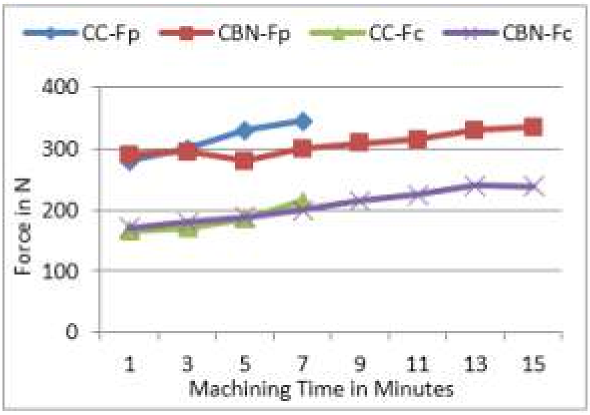

Figure.7 Progression of forces with machining time of both the tools at V=80m/min, f=.07mm/rev

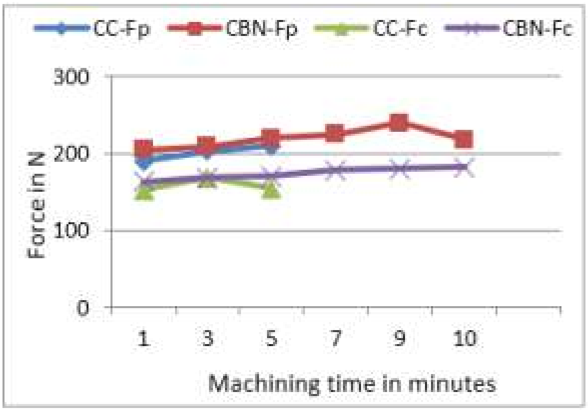

Figure.8 Progression of forces with machining time of both the tools at V=180m/min, f=.07mm/rev

Force data obtained from the dynamometer has been averaged and presented in relation to the machining time. The thrust force (Fp) was the largest force component followed by cutting force regardless the cutting conditions and the type of tool used. This is due to the relatively small feed and depth of cut compared to the nose radius of tools and a negative rake angle (Zhou et al.,2003). The results indicated that with the progression of machining time (i.e. increase in flank wear) both the force components increased, but a significant rise in the radial force (Fp) was observed, as compared to cutting force component, with both the tools. Thrust force was approximately1.5 to 2.5 times higher than the cutting force (More et al., 2006). As shown in figures with CBN tool, in the first few minutes of machining, the values of forces obtained under all cutting conditions were marginally higher than those obtained with coated carbide tool. This was due to the availability of chamfer and honed geometry on CBN tools (Abdullah and Ulvi., 2005). But as the machining progressed the effect of flank wear dominated the edge geometry effect, i.e. force components increased with carbide tool as carbide tool had got more flank wear in comparison to CBN at same machining time.

Both the force components (Fp,Fc) were higher at the lower cutting speed. Because at lower cutting speed, less heat was generated and thermal softening was less, which gave rise to higher cutting forces. At the highest cutting speed for both the tools, both Fp and Fc decreased in comparison to lowest speed tested. This was due to thermal softening of the workpiece at the highest speed (Li and Mohammad., 2007). As shown in Fig.7with the progression of machining time for both the tools, where flank wear was more dominant than the crater wear, the cutting force component increased significantly, due to increase in sliding friction between tool and workpiece. As indicated in Fig.8, for CBN tool,with the progression of machining time at the highest cutting speed due to dominant temperature and crater wear, the thrust force component decreased with machining time, because carter wear shifts the rake angle towards positive. Also a drop in the cutting force with carbide tool was observed, because at the highest cutting speed, tool had undergone severe chipping and was no longer in complete contact with the workpiece.The reduction in cutting forces mainly due to change in cutting edge geometry (Trent and Wright., 2000).

CONCLUSIONS

The CBN tool presented a longer tool life than the carbide tool per cutting edge under all the cutting conditions tested. But the accumulated machining time for all the four edges of carbide tool was better than or equal to that for the CBN tool. In particular at low (80 m/min) and medium cutting speed (130 m/min), the tool life of carbide tool was comparable with that of CBN tool. Chipping and breakage of cutting edge, which led to sudden increase in flank wear was observed with carbide tools in particular at highest cutting speed (180 m/min) tested. At low (80m/min) and medium (130m/min) cutting speed with selected tool life criterion, feed and depth of cut, coated carbide tool can become an economical alternative to costly CBN tool in terms of tool life achieved in finish turning of hardened steel. In order to optimize the material removal rate and tool wear any value between .07 mm/rev to .15 mm/ rev of feed may be selected in hard turning applications under the studied range of cutting speed and depth of cut. The thrust force (Fp) is the largest force component followed by cutting force regardless the cutting conditions and type of tool used. This is due to the relatively small feed and depth of cut compared to the nose radius of tools and a negative rake angle. At highest cutting speed for both the tools, both Fp and Fc reduces in comparison to other two speeds. This was due to thermal softening of the workpiece at highest speed.

Future work will be dedicated on analysis of surface quality and what values of tool wear will be taken as tool life criterion for achieving an optimum surface integrity in hard turning will also be analyzed.

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