Hard Turning Cutting Tool Materials used in Automotive and Bearing Manufacturing Applications – A review

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Abstract. Hard turning for the machining of hardened steels by using super abrasive cutting tool materials is a comparatively newer manufacturing technology. Due to phenomenal advancements in super abrasive tool materials and machine tool technologies, hard turning becoming a potential alternate machining process to the traditional grinding. Hard turning offers many distinguished benefits over grinding process including fewer machining setups, shorter manufacturing time, lower manufacturing cost, achieving grinding comparable product quality. Fewer machining setups bring higher manufacturing flexibility, and lower the investment cost in machine tools in comparison to grinding. It is possible to carryout hard turning without coolant that eliminates the detrimental effect of coolants on the human health and environment. These benefits made hard turning a popular alternative for the automotive and bearing manufacturing industries for machining of cam shafts, gears, crank shafts, bearings, dies and mould. This paper reviews the researches that were performed on hard turning using cutting tool materials; cemented tungsten carbide (WC), poly-crystalline cubic-boron-nitride (PCBN) and ceramics. The research findings related to the effect of cutting parameters, tool geometry and surface coating on the tool life and tool wear phenomena of these hard turning tool materials in the hard turning of major steels used in automotive and bearing manufacturing industries have been discussed.

1. Introduction

Hard turning refers to the metal machining process for the various hardened steels with the help of single point super abrasive tool on modern CNC turning machine. The hardness of steels is usually ranges from 48 to 68 HRC [1-4]. Hard turning is applicable for the machining of various steel materials such as case-hardened steels, alloy steels, full hardened tool steels, super alloys, steels coated with hard chrome surface coatings, nitride steels, and heat-treatable sintered powder metal parts [5]. Finish machining of hardened steels, (e.g. through or full hardened steel AISI-52100, SAE-01 for bearing parts and case-hardened steel 20Mn5Cr5 or 16MnCr5 for automotive transmission parts) by hard turning process using super abrasive cutting tools (poly-crystalline cubic-boron-nitride - PCBN), ceramics, and cemented tungsten carbide were very well recognized in past by the automotive and bearing industries for the manufacturing of precision transmission parts [6]. Grinding was the only choice as a conventional or traditional machining process for the manufacturing of precession parts. Now-a-days, hard turning is establishing itself as a better alternate manufacturing methodology to grinding for the manufacturing of various dies, moulds and transmission parts (e.g. gears, crank shafts, bearings and cam shafts) due to some of its distinct features over traditional grinding such as; better flexibility as
manufacturing of intricate shapes can possible on a single setup resulting into lower machining time. The machining feasibility in dry environment is one of the top most advantages of hard turning; it is possible to carryout machining without the environmentally harmful lubricants, coolants. All such benefits of hard turning resulted in substantial reduction in manufacturing time and cost [7-12]. There can be a reduction of 30% in overall machining costs with the application of hard turning process for the manufacture of the parts cited above. The resultant benefits of annual saving up to $6 billion has been realized by the United States industries by applying hard turning against grinding [13].

In the past, much experimentation was conducted on the hard turning of various alloy steels. Varaprasad et al [14] investigated the effects of cutting parameters on tool wear pattern in hard turning of AISI-D3 cold work tool steel with the help of ceramic inserts CC6050 by using RSM based DOE. Their study showed that the depth of cut has highest significance on tool flank wear. The feed rate and cutting speed have little influence. Diniz et al [15] experimented on the machining of SAE-01 steel (hardened to 58 ± 2 HRC). Their experiments were on the machining of continuous and interrupted features using two varieties of CBN inserts (high and low CBN content). They found that for the continuous and semi-interrupted feature machining, the low CBN content insert proved to be more suitable and high CBN content insert produced longer tool life in interrupted features machining. Khamel et al. [16] investigated the effects of machining parameters on cutting force, tool life and surface finish in hard turning of bearing steel AISI-52100 with CBN tool. They had used ANOVA and the composite desirability optimization technique based on RSM. The results state that both speed and feed are strong influential parameters that affect surface roughness and tool life and the cutting force is mostly affected by the depth of cut. Bartarya and Choudhury [17] have developed a force prediction model for hard turning of EN31 steel (hardened to 60±2 HRC) using CBN insert with edge honning and without coating. They have used DOE (full factorial) to develop the regression models for surface roughness and cutting force. Their study showed that the three cutting forces are highly affected by the depth of cut followed by the feed rate and speed has little significance. Ozel et al [18] did the investigation to understand how the cutting forces and surface finish is affected by tool geometry, cutting conditions and workpiece hardness in hard turning of AISI-H13 steel. The results revealed that the cutting forces are affected by tool geometry, cutting conditions and workpiece surface hardness. However the surface finish is greatly affected by tool geometry. Liu et al [19] presented an experimental study on the distribution of residual stress and how it is affected by insert nose radius and tool wear. They have experimented on bearing steel JIS-SUJ2. PCBN tools with three types of nose radius (1.2mm, 0.8mm and 0.4mm) were used. The results from the study showed that at the initial stage of machining, the distribution of residual stress on the machined workpiece surface is highly affected by insert nose radius. As the nose radius increases, the residual stress is converted to tensile stress alongwith the significant increase in residual compressive stress. Ren et al [20] studied on the hard turning of materials with high chromium hardfacing. They have found that the temperatures during machining is increased with the increase in speed and feed. However, the average temperatures were found in the range of 600 to 700 °C.

2. Superhard tool materials used in hard turnings
There is continuous evolution of various cutting tool materials with significant wear resistance properties for the machining of materials with higher hardness, toughness and chemically reactivity. In view of this, the super abrasive tool materials such as CBN or PCBN, ceramics and tungsten carbides are the key enablers for hard turning. Therefore, the study on the mechanical, physical, and chemical properties of tool materials and their performances characteristics in machining are the subject of interest for both the cutting tool manufacturers and user industries [21].

Extreme pressure and temperature are exerted on the cutting tools during machining. Therefore, it is very important that the tools must have requisite properties to counter different wear phenomenon such as plastic deformation, fracture, chemical wear and should retain sharp cutting edge for a longer cutting time. The important criteria’s that need to be considered while selecting or designing a tool are listed below.
- High hot hardness so that the tool hardness should not drop at elevated temperatures.
- High strength, resilience and stiffness so that they do not break and able to machine with positive geometries without breakage and edge chippings.
- High wear resistance to machine hard and abrasive job materials.
- Low frictional coefficient to counter built up edge.
- Better specific heat and thermal conductivity to carry heat away from the cutting interface.

The major superhard tool materials for hard turning are sintered or cemented tungsten carbides (WC), ceramics (e.g. SiC, Si3N4 or Al2O3 etc.), CBN or PCBN. The requirement of finished part quality parameters such as geometrical accuracy and surface roughness along with the machining process efficiency are the governing criteria for the selection of appropriate cutting tool material. There are different grades of tool materials with different cutting edge geometries available from various tool suppliers. Hence, the selection of most suitable grade of tool material and cutting edge geometry are two key factors in establishing a stable and efficient hard turning process. The different experiments conducted by the researchers using the above tool materials have been presented below:

2.1. Cemented tungsten carbide

Cemented carbide belongs to a class of hard and wear-resistant refractory materials. The hard tungsten carbide (WC) particles are cemented (bound) together with the help of a metal binder called as cobalt, at high temperature (1400-1500°C). Other alloying elements such as titanium, tantalum are also mixed in small proportion for different application [22].

Yigit et al [23] studied that carbide tools coated with CVD multi-layer coating enhances tool life and reduces the cutting force in comparison with uncoated tools. Ciftci [24] reported that the carbide tools coated with TiN multi-layer CVD coating exhibits lower coefficient of friction than Al2O3 multi-layer CVD coated tools in hard turning of austenitic stainless steels. Shihab et al [25] conducted their experiments using TiN/ TiCN/ Al2O3/ TiN multi-layer coated carbide tools for establishing the relation between cutting parameters and the cutting temperature in the machining of AISI-52100 steel. They have found that speed and feed rate affects cutting temperature significantly. It is reported that the optimal temperature (566.593 °C and 592.028 °C) is attained at the speed of 100.12 m/min-250 m/min, feed rate of 0.13 mm/rev-0.22 mm/rev and depth of cut of 0.20 mm-0.85 mm. Dogra et al [26] reported the wear phenomenon of both carbide and CBN tools in hard turning of AISI-8620 steel (49–50 HRC). They have established that CBN tool produces the longest tool life. It was observed that the tool life of carbide tools is significantly affected by interrupted surfaces, while the tool life of CBN tool was not affected much by interruptions. However, the surface integrity achieved with both the tools were comparable with each other. There was no white layer created in interrupted and fully interrupted surfaces turning with both tools and the surface roughness observed below 1.6 μm with both tools.

Selvam and Senthil [27] experimented on hardened medium carbon C45 steel with TiN coated carbide insert. The C45 steel is used as a raw material for transmission components (crankshafts, connecting rods, axle beams, push rods), shafts and machine spindles. They have concluded in their report that surface finish is significantly affected by tool nose radius followed by the feed rate, depth of cut and spindle speed. Mondal et al. [28] conducted the experiments on 16MnCrS5 steel (43 HRC) under wet and dry condition to judge the machining performance of TiC coated carbide inserts with wide groove and plain chip breaking geometry. They have found that the turning can be possible even at speed of 268 m/min with coolant. But the insert failed miserably when tried under dry condition. Cutting velocity was observed as an influential parameter on cutting forces in comparison to the dry or wet machining environment. They have concluded that the rate of tool wear is less in wet condition than dry condition for the both geometry inserts. The lesser wear rate in wet condition was due to reduction in friction and temperature at tool-part interface. Chinchanikar and Choudhury [29] studied the wear phenomenon of cemented tungsten carbide inserts in different conditions; uncoated, coated with PVD single-layer
TiAlN coating, and CVD multi-layer MT-TiCN/Al2O3/TiN coating in dry hard turning of 35 HRC AISI-4340 steel. Investigation results indicated that the cutting speed can be increased from 62 m/min to 200 m/min with a single layer coating on an uncoated insert. The cutting speed can be further increased to 300–350 m/min with the multi-layer coated inserts. The wear rate was lower while machining using inserts with single-layer TiAlN coating. The wear rate increases rapidly after removal of coating thin layer. Subsequently the wear rate of multi-layer coated inserts is dominated after the removal of upper thin layer. Similar trend was also seen for the cutting force components which increases rapidly with the occurrence of the tool failure. The prominent forms of tool wears were observed as the crater wear, flank wear and catastrophic failure.

2.2. Ceramics

Ceramics are non-metallic inorganic materials. The use of ceramic cutting tools are increasing due to the advent of ceramic-matrix composites and ceramic alloys. The metal cutting ceramic tools are based on either alumina (Al₂O₃) or silicon nitride (Si₃N₄). The three main Al₂O₃-base tool materials are Al₂O₃-TiC, Al₂O₃-ZrO₂ and silicon carbide (SiC) whiskers reinforced Al₂O₃. Other Al₂O₃ base ceramics have additives of TiN, TiB, Ti(C,N) and Zr(C,N). Due to brittleness of ceramic tools, special edge preparation or treatment (edge honing) is done to prevent cutting edge chipping off [30].

Gaitonde et al [31] studied on AISI-D2 steel using ceramic insert CC650WG with wiper geometry. They have found that the increase in feed rate resulted in increase in power and decrease in specific cutting force, but the cutting force requirement was low at lower cutting time and feed rate values. The RSA also corroborates that the minimal surface roughness is attained with lower cutting time and feed rate and higher spindle speed values. The maximum wear of tool is observed at 150 m/min spindle speed with all feed rate values. Davim [32] studied on tool wear phenomena of ceramic tool in turning of 60 HRC AISI-D2 tool steel. The effect of speed was high than cutting time on the wear propagation. The resulted high flank wear on tool cutting edge deteriorated the surface roughness. The feed rate influences the specific cutting pressure, whereas surface finish is influenced by both cutting time and feed rate. It was possible to achieve surface finish below 0.8 μm and dimensional accuracy below IT7 with suitable adjustment in cutting parameters which can be comparable with grinding outcomes. Ferreira et al [33] in their research on hard turning of AISI-H13 steel with conventional and multi-radii ceramic tools. The surface finish is affected by tool edge geometry and feed rate significantly, whereas cutting speed has insignificant effect. Better surface roughness is attained with multi-radii geometry tool in comparison with conventional geometry tool. Drupal et al [34] carried out experimental investigation on AISI-4140 steel hard turning in dry condition using mixed ceramic insert Al2O3+TiCN with PVD-TiN coating. The results reveal that the surface roughness is affected by the feed rate, followed by cutting speed. However, cutting velocity in association with feed-depth of cut interaction affects the tool flank wear. Davoudinejad and Noordin [35] studied on 58 HRC DF-3 tool steel using mixed ceramic PVD-TiN coated inserts with chamfer and honed edge geometry with the help of ANOVA. The chamfered edge geometry produced longer tool life. The ceramic tool exhibited flank, crater and abrasive wear phenomena. The optimum values of tool life and material removal rate is attained at spindle speed of 155 m/min for both insert geometries. The combination of machining parameters (155–210 m/min cutting speed and 0.125–0.05 mm/rev feed rate) and with chamfer edge geometry, better surface finish is resulted. The cutting force had a decreasing relationship with cutting speed increase and affected considerably by tool wear. The higher values of cutting forces were observed with honed edge geometry.

2.3. Poly crystalline cubic boron nitride (PCBN)/CBN

PCBN/BN is the second hardest material (hardness 4500 HV) after PCD (hardness 9000 HV). It is synthesized by combining boron and nitrogen atoms to form a compound of hexagon structure called boron nitride (BN), which further converted into cubic boron nitride (CBN) at high temperature and pressure [36-37]. Individual CBN crystals are binded together (sintered) with the help of ceramic binders resulting into poly-crystalline cubic-boron-nitride (PCBN) [38].
Shalaby et al. [39] conducted experiments on 52 HRC D2 steel using Al2O3+TiC mixed ceramic, PCBN and PCBN with TiN coating inserts. They have reported that the prolonged tool life and lower cutting force is observed with mixed ceramic insert than PCBN insert. This is because of better thermal and chemical stability and formation of Cr-Ox lubricating films at high temperature during machining. However such characteristics was not exhibited by PCBN tools. The wear mechanism of PCBN tool was observed as combination of abrasion, adhesion, and diffusion, which is not improved even with TiN coating. They have concluded that Ceramic tools are the most suitable choice over PCBN for D2 steel cutting. Yallese et al. [40] experimented on 60HRC 100Cr6 steel hard turning using CBN tool to study the tool wear, temperature changes, cutting force and surface roughness. CBN tool exhibits better wear resistance characteristics. The maximum amount of generated heat was carried away with chips. At cutting speed of 280 m/min, heavy vibration and sparking were observed only after few minutes of cutting. Beyond this speed, stabilization of surface roughness is observed because of reduction in cutting forces at high speed, resulted in a stable machining condition. Optimal value of flank wear (below 0.4 mm) was observed at 120 m/min speed. Guddat et al. [41] conducted their experiments on 58-62 HRC AISI-52100 through hardened steel using PCBN inserts with wiper land. They studied the behavior of wiper geometry on cutting forces and surface integrity with the help of statistical DOE model. Their analysis reported that significant improvement in surface roughness and higher residual compressive stress were observed with the wiper geometry inserts in comparison with the conventional geometry inserts. Bushlya et al. [42] studied on continuous cut high speed machining (120 m/min – 180 m/min) of cold work tool steel to present a performance comparison of various superhard tools comprising of cBN-binderless, ceramic-bound and cBN-wBN materials. The experiments were conducted both in dry and wet condion. The performance of various tool material combination was studied in relation to surface roughness, cutting force and surface integrity at sub-surface. For the above stated combined criteria, it was observed that low-cBN content tools with ceramic binder exhibits excellent tool performance.

3. Experiments on the tool life and tool wear phenomena

Extreme temperature and pressure are exerted on cutting tools during machining due to the severe friction that occurs between chips and workpiece interface (metal-to-metal contact) resulting into tool wear. The tool wear predominantly affects the machined part dimensional accuracy and surface integrity [43]. Therefore, it is very much essential to study the tool wear phenomena in hard turning to address issues such as catastrophic tool failure, cutting edge breakage or chipping off, deterioration of workpiece surface integrity to establish a stable and economical machining condition [44-45].

In the past century, extensive research works were carried out by the researchers [46-50] to understand and predict the effect of various factors on tool wear behavior and mechanism. Diniz and Oliveira [51] investigated on 56 HRC AISI-4340 steel with continuous, semi interrupted and interrupted features using two grade of tools; high CBN content and low CBN content. The 7020 grade produced longer tool life irrespective of types of surface features. Based on the tool geometry it is observed that the tools with chamfered edge produced longer tool life in continuous cutting, whereas the tools with rounded edge exhibits better results in interrupted cutting. Oliveira et al. [52] studied the behavior of whisker-reinforced ceramic and PCBN tool in the machining of hardened steels with interrupted and continuous cutting features. In continuous cutting, the longest tool life was obtained with PCBN tool. For the interrupted cutting, similar longer tool life was found with both ceramic and PCBN tool. However, in view of surface roughness, PCBN tools exhibited better results for both continuous and interrupted cutting. Elmunafi et al. [53] studied on tool life of coated carbide tool in hard turning of AISI-420 steel hardened to 47-48 HRC using MQL system and castor oil as cooling media. The experiments were conducted under cutting velocity of 100, 135, 170 m/min. and feed rate of 0.16, 0.2, 0.24 mm/rev. It was reported that the tool life had an inversely proportional relationship with cutting velocity and feed rate. Chinchanikar and Choudhury [54] studied on the flank wear mechanism of coated tungsten carbide tools in relation with machining parameters, workpiece hardness and type of coating in hard turning of AISI-4340 steels of different hardness values. They have found that PVD
coated tools shows crater wear as dominant wear phenomena and CVD coated tools shows flank wear as dominant wear phenomena. Also, they have reported that the foremost causes of tool wear are adhesion and abrasion in case of CVD coated tool, whereas abrasion, adhesion and diffusion are the main reason of wear for PVD tools. Dogra et al. [55] presented a comparative study on the tool flank wear of CBN inserts with respect to coated carbide inserts and cryogenically treated uncoated and coated carbide inserts in hard turning of 48-49 HRC AISI-H11 steel. They have reported that CBN insert shows lower flank wear values in comparison with other inserts.

4. Summary
Hard turning is becoming a popular machining process for hardened steels in bearing, automotive and other manufacturing industries. Grinding was used traditionally for machining of such materials till recent past. However, the technological evolution in cutting tool materials and machine tool technology made hard turning an alternate machining method to grinding. Hard turning offers distinct benefits over grinding, due to which it has created great interest among the research community. This paper has presented literature reviews on few of the past researches and focuses on hard turning of major steels and cutting tools materials used in bearings and automotive industries. Following are the conclusions drawn from the findings of the past researches which are reviewed and presented in this paper:

- The benefits of hard turning over traditional grinding includes substantial amount of reduction in manufacturing time and costs, achievement of grinding comparable surface quality.
- Hard turning is possible in dry condition, eliminating or reducing the use of hazardous coolant. This characteristic makes hard turning as an environment friendly green machining process.
- Hard turning encounters tremendous mechanical loads and high temperature. To sustain such high heat and load, the super hard cutting tool materials such as cemented tungsten carbide with surface coating, ceramic and PCBN are the suitable tool materials for hard turning.
- The component hardness and its features, machining parameters, tool material and geometry significantly affect the tool wear and tool life.
- The crucial information gained from the study of the tool wear phenomena in hard turning can be used as a basis for the cutting tools design, cutting parameters and tool wear optimization that in turn will help in establishing economical manufacturing strategies.

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