A review of turning of hard steels used in bearing and automotive applications

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Hard turning is a recent technology that involves machining of hard steels using modern machine tools. Hard machining presents challenges in terms of selection of tool insert with improved tool life and high-precision machining. Turning of hardened steels using single-point cutting tool has got considerable interest among manufacturers of ball bearings, automotive, gear, and die industry. Hard turning in the automotive industry and bearing applications typically has a number of potential benefits over traditional form grinding including lower equipment costs, shorter setup time, and fewer process steps which in turn provides high flexibility and ability to cut complex geometries. Moreover, the hard turning process is usually carried out without coolant/lubricant and thus, the problem of storage, handling, and disposal of cutting fluid is eliminated, and at the same time, it probably favors the health of operators. This paper presents an overview of the past research hard turning using hard turning tools such as PCBN, cubic boron nitride, Ceramics, Carbide, etc. Major hard turning cutting materials and effect of hard turning process parameters on cutting forces, heat generation during cutting, surface finish and surface integrity, and tool wear have been discussed in light of the findings of the past research.

Keywords: hard turning; hard tool materials; cutting parameters

1. Introduction

High-hardness materials include various hardened alloy steels, tool steels, case-hardened steels, super alloys, nitrided steels, hard-chrome coated steels, and heat-treated powder metallurgical parts. Finishing of hardened steel, (e.g. through hardened AISI 52100 steel for bearing applications, and case hardened steel 16MnCr5 for automotive gears and shafts) using hard turning using super hard cutting tools (PCBN, cubic boron nitride (CBN), Ceramics, and Carbide) was early recognized by the automotive industry as a means of manufacturing of precisely finished transmission components (Davim, 2011).

If hard turning is applied to the manufacture of complex parts, manufacturing costs can be reduced up to 30%, and US industries exploited the advantages of hard turning for an annual gain of up to $6 billion (Huang, Chou, & Liang, 2007). A qualitative comparison of the capabilities of hard turning and grinding processes in terms of work-piece quality, process flexibility, dimension and shape accuracy, etc. has been made by M’Saoubi, Outeiro, Chandrasekaran, Dillon, and Jawahir (2008).

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In the past, many studies have been carried out to explore different facets of the hard turning of alloy steel. Thiele and Melkote (1999) investigated the effects of tool edge geometry of CBN tools and workpiece hardness (45, 52, and 60 HRC) on the surface roughness and cutting forces in the finish hard turning of AISI 52100 steel. Their study showed that large edge hones result in higher forces in the axial, radial, and tangential directions as compared to those tools with small edge hone. Further, the effect of workpiece hardness on the axial and radial components of force was found to be significant, particularly for large edge hones. Ramesh, Melkote, Allard, Riester, and Watkins (2005) examined the differences in structure and properties of white layers formed during machining of hardened AISI 52100 steel (62 HRC) at different cutting speeds. Their results indicated that the grain sizes of white layers formed were considerably smaller than the grain sizes of the bulk. They also observed that white layers generated at higher machining speeds are coarser than those generated at lower speeds. Diniz, Gomes, and Braghini (2005) studied the hardened steel turning (SAE 01 steel with 58 ± 2 HRC hardness) with continuous, interrupted, and semi-interrupted cutting using two different kinds of CBN cutting tools (high CBN content material and CBN content material). Their main conclusion pointed out that the low CBN content tool is more suitable for continuous and semi-interrupted surfaces, whereas the high CBN content tool presents a slightly longer life during interrupted cutting. Umbrello, Rizzuti, Outeiro, Shivpuri, and M’Saoubi (2008) developed hardness-based flow stress and fracture models for machining AISI H13 (50-60 HRC) tool steel, which can be applied for a wide range of work material hardness using FEM. They implemented these models in a viscoplastic non-isothermal finite element model of the orthogonal cutting process and validated the results of these models using the data available in the literature. Umbrello, Ambrogio, Filice, and Shivpuri (2008) determined residual stresses distribution and optimal cutting conditions during hard turning of AISI 52100 bearing steel using the hybrid model based on the artificial neural networks (ANNs) and finite element method (FEM). Adesta, Riza, Hazza, Agusman, and Rosehan (2009) investigated tool wear of cermet tools and also surface roughness under different rake angles (0, −3, −6, −9, and −12) and different cutting speeds (1000 and 300 m/min). Their experimental results showed that increase in negative rake angles causes higher wear, shorter duration of tool life, and poor surface finish. Further, high cutting speed turning gave shorter tool life, high wear rate but finer surface finish than conventional one. Gaitonde, Karnik, Figueira, and Davim (2009a) analyzed the effects of depth of cut and machining time on surface roughness and tool wear during turning of high chromium AISI D2 cold work tool steel (59/61 HRC) using ceramic inserts with TiN coating (CC650, CC650WG, and GC6050WH). From their analysis, it was observed that the CC650WG wiper insert performs better with reference to surface roughness and tool wear. They also observed that the surface roughness is minimal at lower values of depth of cut and machining time in case of CC650 and CC650WG inserts machining, while the minimum surface roughness occurs at 0.4 mm depth of cut for hard turning with GC6050WH insert. Finally, they found that the CC650 conventional insert is useful in reducing the cutting force. Fnides, Yallese, Mabrouki, and Rigal (2009) investigated the effect of three cutting parameters on surface roughness in turning of X38CrMoV5-1 hardened steel treated at 50 HRC using mixed ceramic tool. Their results revealed that the effect of feed rate on surface roughness is more significant than cutting speed, whereas the depth of cut is not significant. Moreover, the highest level of cutting speed, 180 m/min, the lowest level of feed rate, 0.08 mm/rev, and the highest level of depth of cut, 0.45 mm, resulted in larger amount of material removal and also a good surface finish. Thamizhmanii and Hasan
(2010) evaluated the performance of CBN and PCBN tools based on flank wear and cutting forces during machining of AISI 440 C hard martensitic stainless steel. They observed high cutting forces during machining and they suggested that this may be due to heat and flank wear combinations. In addition, they also found that lower cutting forces lead to low flank wear and provide good dimensional accuracy of the work material including low surface roughness. Meyer, Köhler, and Denkena (2012) studied the effect of geometrical contact conditions between the tool (WBN560 with a CBN content of 56%) and the workpiece (AISI 5115 steel) on the cutting forces and tool wear during hard turning. Their results showed that the geometrical contact conditions have a significant influence on the forces, tool, and workpiece load as well as on the tool wear behavior. Moreover, they suggested that by applying a load-specific tool and process design, the tool operation behavior and the productivity of the process can be enhanced in a beneficial way.

2. Major hard turning cutting tool materials

Material developments for the cutting tool, one of the most critical elements in metal cutting, have always been characterized by an increase in wear resistance to machine harder, tougher, or chemically reactive materials. For example, superhard materials such as ceramic and CBN were one of the main keys to enable the hard turning technology to be an alternative to grinding processes. Correlation between chemical, physical, and mechanical characteristics of cutting tool materials and their performances in cutting operations is therefore, a key issue for both tool manufacturers and users (Suresh, Basavarajappa, and Samuel, 2012).

Cutting tools must simultaneously withstand big mechanical loads and high temperatures. Temperature in the chip/tool interface reaches more than 700 °C in some cases such as turning of high hardness alloy steel (Davim, 2011). Additionally, the friction between tool and removed chip, on one hand, and tool against the new machined surface, on the other, is very severe (Davim, 2011). Bearing this in mind, the following main factors should be considered for a good tool design and post-manufacturing (Davim, 2011):

- Chemical and physical stability of cutting-tool substrate material must be maintained at high temperatures.
- Material hardness must be maintained to high temperatures suffered at the chip/tool interface.
- Tool material has to present high resistance for the abrasion and adhesion wear.
- Tool material must present enough toughness to avoid fracture, especially when operation to perform implies interrupted cutting.

The main tool materials that are used for hard turning include sintered carbides, ceramics (e.g. Al₂O₃ or Si₃N₄ etc.), and extra-hard materials (e.g. PCD, PCBN etc.). The selection of appropriate tool material is vital for process efficiency and depends on the accuracy and surface finish required. Within each type, hundreds of different grades are available from various tool material, cutting insert, and tool manufacturers. Therefore, the selection of appropriate tool-material grade is one of the most important tasks in hard turning in terms of obtaining efficient and stable machining process. The insert shape, tool holders, and optimal machining regime just add more complications to this multivariable optimization problem. Knowledge, as understanding the essence of hard
machining, and experience are prerequisites for success (Davim, 2011). The studies carried out by the researchers using cutting tool of the above-mentioned materials are describe in the following sections:

2.1. **Sintered carbide (hardmetal)**

Sintered carbide tools, also known as hardmetal tools or cemented carbide tools, are made by a mixture of tungsten carbide micrograins with cobalt at high temperature and pressure. Tantalum, titanium, or vanadium carbides can also be mixed in small proportions. This type of material in the straight grade or in the coated grades is mostly used today for hard machining and high-speed machining.

A sintered tungsten carbide also includes TiC (carbide with hardness 3200 HV) and in some cases TiCN, but they typically have a nickel–chrome binder. New grades with TaNbC and MoC increase the tool-edge strength against the cyclic impacts which finds typical application in milling. Tungsten carbide is very stable with respect to chemical and thermal aspects of machining, and is very hard as well. In most cases, cemented carbide degradation starts from the cobalt binder and the tungsten carbide–cobalt cohesion (Davim, 2011).

Aslan (2005) investigated the wear behavior of different cutting tools such as TiCN coated tungsten carbide, TiCN + TiAlN coated tungsten carbide, TiAlN coated cermet, mixed ceramic with Al₂O₃ + TiCN, and CBN, in end milling of X210 Cr12 cold-work tool steel hardened to 62 HRC. The results of his investigations indicated that the TiAlN coated carbide and cermet tools perform slightly better than TiCN coated carbide tool which can be attributed to better high-temperature properties of TiAlN compared to TiCN. Further, he also found that CBN tool exhibits the best cutting performance in terms of both flank wear and surface finish and the highest volume of metal removal is obtained with CBN tool. Arsecularatne, Zhang, and Montross (2006) studied wear and tool life for tungsten carbide WC cutting tool during machining of AISI 4142 steel and AISI 1045 steel, and also for PCBN cutting tool during machining of AISI 52100 with two different hardness values of 60HRC and 62HRC. It was concluded from their study that the most dominant tool wear mechanism for WC is diffusion and for PCBN is chemical wear. Lima, Avila, and Abrao (2007) performed a study which is concerned with continuous turning of AISI 4340 steel hardened from 250 up to 525 HV using coated carbide tools. They assessed machining forces, tool life, and wear mechanisms. The results of their study indicated that the machining force components increase with the work material hardness, however, the cutting force components decrease slightly as the work hardness increase from 250 up to 345 HV. Further, tool wear was lower when machining the workpiece with a hardness value of 345 HV as compared to machining of the workpiece possessing hardness of 250 HV steel. Finally, it was observed that the abrasion is the principal wear mechanism and catastrophic failure takes place when attempting to machine the 525 HV steel. Chowdhury and Dhar (2011) investigated the tool wear and surface roughness for varying cutting parameters under dry and Minimum Quantity Lubrication (MQL) environment while turning hardened medium carbon steel using coated carbide insert. The results of their study indicated that the application of MQL technique significantly helps to obtain better performance of coated carbide insert in comparison to dry condition. Hwang and Lee (2010) studied the effect of cutting parameters (nozzle diameter, cutting speed, feed rate, and depth of cut) on cutting forces and surface roughness of carbon steel AISI 1045 using coated carbide inserts under MQL and wet turning conditions. They found that cutting speed and depth of cut show
opposite effects on the cutting force and therefore, they suggested that cutting conditions
should be set under a clear standard because the optimal combination of cutting param-
eters could be different depending on machinability. Moreover, cutting speed and depth
of cut showed opposite effects on surface roughness in MQL turning and it produced
better surface roughness compared to wet turning. They also observed that the MQL
turning provides more advantages than wet turning.

2.2. Ceramics
Ceramics are very hard and refractory materials, withstanding more than 1500 °C with-
out chemical decomposition. These features recommend them to be used for the machin-
ing of metals at high cutting speeds and in dry machining conditions. Ceramic tools are
based primarily on alumina (Al₂O₃), silicon nitride (Si₃N₄), and sialon (a combination
of Si, Al, O, and N). Alumina tools can contain titanium, magnesium, chromium, or
zirconium oxides distributed homogeneously into the alumina matrix to improve
toughness (Davim, 2011)

Several researches have been done to study the effect of hard turning on different
types of ceramics tools. Luo, Liao, and Tsai (1999) in their research revealed the wear
behavior of ceramic and CBN tools in the turning of AISI 4340 hardened alloy steels. It
was found from their study that the main wear mechanism for the CBN tools is the
abrasion of the binder material by the hard carbide particles of the workpiece and for
the ceramic tools it is adhesive wear and abrasive wear. They also found that there is a
protective layer formed on the chip–tool interface which plays an important role in wear
behavior of CBN and ceramics tools. Kumar, Durai, and Somakumar (2003) studied the
machinability of EN 24 steel (HRC 40 and HRC 45) using two types of ceramic cutting
tool materials namely, Ti[C, N] mixed alumina ceramic cutting tool and zirconia tough-
ened alumina ceramic cutting tool. It was found from their study that the performance
of ceramic cutting tools is good in the machining of hardened steel and Ti[C, N] mixed
alumina ceramic cutting tool produces the best surface finish. Gaitonde, Karnik,
Figueira, and Davim (2009b) analyzed the effects of depth of cut and machining time
on machinability aspects such as machining force, power, specific cutting force, surface
roughness, and tool wear, with the use of second-order mathematical models during
turning of high chromium AISI D2 cold work tool steel with CC650, CC650WG, and
GC6050WH ceramic inserts. From their analysis, it was revealed that the CC650WG
wiper insert performs better with reference to surface roughness and tool wear, while
the CC650 conventional insert is useful in reducing the machining force, power, and
specific cutting force. Elmunafi (2012) evaluated the performance of wiper coated cer-
amic tool when turning ASSAB DF-3 grade hardened steel with hardness 55 HRC. Their
study showed that the effects of cutting speed and feed rate on the tool life are statisti-
cally significant. They also found that the effects of cutting speed and feed rate on the
surface roughness are statistically significant, specifically, at high cutting speed and low
feed rate. Accordingly, wiper inserts were able to produce better surface finish.
Maňková, Kovac, Kundrak, and Beňo (2011) studied the influence of cutting parameters
on accompanying phenomena during hard turning of hardened steel with hardness of
HRC 55 using mixed oxide ceramic inserts (70% Al₂O₃ + 30% TiC). They concluded
that hard turning has many advantages in comparison to other processes in machining
of hardened steels. Fnides, Yallese, Mabrouki, and Rigal (2011) stated the effect of cut-
ting parameters on cutting force components in hard turning of AISI H11 hot work tool
steel (50 HRC) using a mixed ceramic tool. They found that the depth of cut is the
dominant factor affecting cutting force components. Additionally, the feed rate influences tangential cutting force more than radial and axial forces. Finally, the cutting speed affects radial force more than tangential and axial forces. Zhao, Yuan, and Zhou (2010) investigated the cutting performance, failure mode, and mechanism of the Al₂O₃-based composite ceramic tool material reinforced with WC microparticles and TiC nanoparticles in both continuous and intermittent turning of hardened AISI1045 steel. Their study revealed that the tool life of the Al₂O₃/WC/TiC ceramic tool increases when the cutting speed increases to 170 m/min. They also observed that the longer tool life of the Al₂O₃/WC/TiC composite ceramic tool is attributed to its synergistic strengthening/toughening mechanisms induced by the WC microparticles and TiC nanoparticles.

2.3. Extra-hard materials

PCD and PCBN are extra-hard materials. There are several grades in the PCD and PCBN groups. PCD is suitable for tools focused on machining abrasive non-ferrous metals, plastics, and composites. PCBN finds applications in the machining of hardened tool steels and hard cast irons. PCD plates are obtained by a high temperature and pressure process where synthetic diamond grains are sintered with cobalt. CBN is a polymorph boron-nitride-based material. It possesses high mechanical properties due to its crystalline structure and its covalent link. It has been industrially produced since 1957, starting from hexagonal boron nitride put under high pressures (8 GPa) and temperatures (1500 °C). With a lower hardness (<4500 HV) than diamond (>9000 HV), CBN is the second-hardest synthetic material. The CBN grains are sintered together with a binder to form a composite, PCBN. The size, shape, and ratio of CBN/binder define the different PCBN grade (Davim, 2011).

The literature reveals that many researchers have suggested effect of hard turning on CBN and PCBN cutting tools (Chowdhury and Dhar 2011; Diniz et al., 2005; Elmunafi 2012; Lima et al., 2007). In addition, many studies have been conducted to investigate the performance of CBN and PCBN tool in machining of various hard materials. Oliveira, Diniz, and Ursolino (2009) investigated the performance of PCBN and alumina-based ceramic reinforced with silicon carbide tools during turning of AISI 4340 steel with 56 HRC under continuous and interrupted cutting. The results of their study indicated that the longest tool life is achieved using PCBN in continuous turning, but similar tool longevity is attained in interrupted turning using both PCBN and ceramic. Also, the roughness values were lower for both continuous and interrupted surfaces when PCBN tools were used. Sahin (2009) compared the tool life of mixed alumina ceramic with that of Al₂O₃ (70%):TiC (30%) matrix and CBN cutting tools during machining of AISI 52100 steel. They showed that the CBN cutting tool has the best performance than that of ceramic-based cutting tool. Poulachon, Moisan, and Jawahir (2001) studied various modes of wear and damage of PCBN cutting tool under different loading conditions during turning of AISI 52100 steel in order to establish a reliable wear model. Their results led to the conclusion that the main wear mechanism of the PCBN tools is abrasion and it depends not only on the chemical composition of the PCBN, and the nature of the binder phase, but also on the hardness value and above all on the microstructure of the machining work material. They also found that use of TiN coated PCBN improves the tool-wear and hence the tool-life by reducing the diffusion wear between workpiece and tool rake face. Diniz, Ferreira, and Filho (2003) investigated the influence of cutting speed under three cutting conditions: dry cutting, wet cutting, and minimum volume of oil i.e. MVO (oil flow of 10 ml/h) on CBN tool wear.
in turning of AISI 52100 hardened steel. Their results revealed that dry and MVO cuttings produce most of the time, similar values of flank wear which is always smaller than the values obtained during wet cutting. They also observed that highest cutting speed for three cutting conditions gives the smallest value of surface roughness. Poulachon, Bandyopadhyay, Jawahir, Pheulpin, and Seguin (2003) examined the influence of the microstructure of different hardened tool steels (AISI D2 cold work steel, AISI H11 hot work steel, 35NiCrMo16 hot work steel, and AISI 52100 bearing steel) on the wear of PCBN cutting tools under dry turning. They observed a large variation in tool wear in the machining of these steels. Further, they found that the flank grooves are correlated to the microstructure of these steels, namely the presence of various carbides. Benga and Abrao (2003) studied the machinability of hardened 100Cr6 bearing steel (62-64 HRC) under dry turning using mixed alumina, whisker reinforced alumina, and PCBN inserts. As far as tool life is concerned, they obtained best results with the PCBN compact, followed by the mixed alumina tool at low feed rates and by the whisker reinforced alumina when feed rate was increased. Poulachon, Bandyopadhyay, Jawahir, Pheulpin, and Seguin (2004) investigated the tool wear mechanisms of CBN cutting tools in finish turning of the hardened steels (AISI D2 cold work steel, AISI H11 hot work steel, 35NiCrMo16 hot work steel, and AISI 52100 bearing steel), treated at 54 HRC. They observed a large variation in tool-wear rate in machining of these steels. They also found that the generated tool flank grooves are correlated with the hard carbide content of the workpieces. In addition, they also performed a crater wear study in which they found the appearance of an adhesive third body which could induce a chemical wear in the tool. Kurt and Seker (2005) investigated the effects of chamfer angle of PCBN cutting tools on the cutting forces and the cutting tool stresses, principal, and Von Mises stress, in finishing hard turning of AISI 52100 bearing steel. Their results revealed a great influence of the chamfer angle on the cutting forces and tool stress. Based on their work, they concluded that critical chamfer angle is 20° in finishing hard turning of AISI 52100 bearing steel. Galoppi, Filho, and Batalha (2006) tested different types of CBN inserts with wiper geometry, coated with TiAlN and TiN as well as with no coated ones, during hard turning of tempered DIN 100Cr6 steel. Their results revealed significant cracking on the coating surface layer of both TiAlN and TiN coated tools which resulted in the removal of the surface hard coating by cracking. Further, they also found that the cratering that arises on insert surfaces is similar to that found on the no coated inserts. Finally, they observed that the inserts with a wiper geometry presents longer tool life compared with no coated tools. Remadna and Rigal (2006) explored the parameters of hard steel turning (alloyed steel 52HRC) with a CBN tool. They analyzed the correlation between tool wear and the direction of cutting force. Their results showed that the cutting forces increase gradually with increasing of cutting distance and tool flank wear. They also revealed that the wear of CBN does not directly or appreciably affect the manufactured surface. More, Jiang, Brown, and Malshe (2006) measured tool wear and evaluated machining performance of CBN–TiN coated carbide inserts and PCBN compact inserts in turning of AISI 4340 hardened steel. They observed that the flank wear is mainly due to abrasive actions of the martensite which is present in the hardened AISI 4340 alloy. Further, they found that the crater wear of the CBN–TiN coated inserts is less than that of the PCBN inserts because of the lubricity of TiN capping layer on the CBN–TiN coating. Arsecularatne, Zhang, Montros, and Mathew (2006) investigated the machinability of AISI D2 steel of hardness 62 HRC using PCBN tools. They found that the most feasible feeds and speeds fall in the ranges 0.08–0.20 mm/rev and 70–120 m/min, respectively, and that most of the tested PCBN
tools reach the end of life mainly due to flank wear. Moreover, the highest acceptable values of tool life and volume of material removal were obtained at the lowest speed (70 m/min), indicating that this speed is more suitable for machining the selected tool/work material combination. They also found that the highest feed results in the highest volume of material removal and lower feeds result in higher tool life values. They suggested that the most appropriate feeds for AISI D2 steel are 0.14 mm/rev for finishing operations and 0.20 mm/rev for roughing operations. Lin, Liao, and Wei (2008) studied tool wear mechanisms in turning of AISI 4340 alloy steels by CBN tools which contained 50% and 45% of CBN, respectively, and also TiC based-binder, under varying cutting speeds. It was observed from their results that at low cutting speed, the binder of the hard particles of the cutting tool is removed from the substrate due to high cutting force and the tool wear is mainly due to abrasion. Their study revealed formation of a protective layer, resulting from the diffusion of the bond material of the cutting tool, on the chip–tool interface when the cutting speed was increased. The layer so formed works as a diffusion barrier and reduces tool wear rate which results in the prolonged life of the CBN tool. They also found that at further higher cutting speed, (i) cutting temperature becomes the dominant factor instead of the cutting force which causes inhomogeneous shear strain, and a transition from continuous chip to saw-tooth chip, (ii) the friction force increases because of the very irregular chip–tool contact and it results in the removal of the protective layer, and (iii) the bond between tool particles gets weakened due to serious diffusion between the work material and the cutting tool. Subsequently, hard particles of the tool get detached from it and the tool life is reduced. Özel (2009) investigated the influence of different edge micro-geometry of PCBN tools on forces, stresses, friction, and tool wear during turning of alloy steel AISI 4340. On the basis of the results of their study, they made the following conclusions: (i) variable micro-geometry insert edge design reduces the heat generation and stress concentration along the tool cutting edge significantly which improves the tool life, (ii) variable micro-geometry insert cutting edge induces less plastic strain on the machined workpiece which improves surface integrity, and (iii) variable micro-geometry insert edge design reduces tool wear depth and wear rate. Yallese, Chaoui, Zeghib, Boulanouar, and Rigal (2009) investigated the behavior of a CBN tool during hard turning of 100Cr6-tempered steel. They observed that the cutting speeds ranging from 90 to 220 m/min is the most interesting cutting conditions for the system CBN7020-100Cr6. However, they found that beyond 280 m/min the machining system becomes unstable and produces significant sparks and vibrations after only a few minutes of work. Further, they found optimal productivity at the speed of 120 m/min with an acceptable tool flank wear below 0.4 mm. Godoy and Diniz (2011) made a comparison between the performance of CBN and ceramic tools in continuous and interrupted cutting of AISI 4340 steel. They concluded that in both continuous and interrupted cutting, the CBN tools exhibit a much better performance with respect to both tool life and workpiece surface roughness than the ceramic tools. Zawada-Tomkiewicz (2011) evaluated the surface finish in a continuous dry turning of EN 41Cr4 low chromium alloy steel with 58 HRC using PCBN coated and uncoated tools. He observed that the hard turning with PCBN tools can produce a very smooth and uniform surface. Also, in the case of the PCBN coated tool material, the wedge’s wear was almost unnoticeable. Further, the random part of the generated surface was significantly greater for the PCBN coated cutting tool material. Deepakkumar and Sadaiah (2011) investigated the effects of cutting speed, feed rate, and different cutting environments (dry, wet, and MQL) on the surface roughness and tool wear during turning of AISI 4340 steel using CBN
insert. They analyzed the effect of cutting parameters and determined its optimum condition by using ANOVA technique. They found that increase in the cutting speed and feed rate results in decrease in $R_a$ value. In addition, he observed the $R_a$ value for dry and wet turning as 1.2 and 1.1 $\mu$m, respectively, while in the case of turning in MQL condition, the $R_a$ value was 0.9 $\mu$m. Finally, the results of their study indicated that as cutting speed and feed rate increase, the tool wear value increases.

3. Effect of process parameters in hard turning:

Machining parameters such as cutting speed, feed rate, and depth of cut do affect the production costs and product quality. Thus, it is important to use optimization technique to determine optimal levels of these parameters so as to reduce the production costs and to achieve the desired product quality simultaneously. One of the main objectives in the optimization of a turning process is minimization of the cost of production and maximization of the production rate while keeping the quality of machined parts as per design specifications. The cost of machining is strongly related to the material removal rate. The material removal rate for a turning operation is given by the product of cutting parameters (cutting speed ($V_c$), feed rate ($f$), and depth of cut ($d$)). Therefore, if an increase in productivity is desired then an increase in these three cutting parameters is required. But, there are limits to these cutting parameters since they also have an effect on the tool life, tool wear, surface quality, cutting forces, cutting temperature, etc. Keeping this in view, many researchers have investigated effect of these parameters pertaining to hard turning. The following sections present the findings of some of the research studies involving these parameters with reference to hard turning.

3.1. Studies on cutting forces

The forces acting on the tool are important aspect of machining. Knowledge of the cutting forces is needed for the estimation of power requirements, the adequately rigid design of machine tool elements, tool-holders, and fixtures, for vibration free operations.

Many force measurement devices like dynamometers have been developed which are capable of measuring tool forces with increasing accuracy. Power consumed in metal cutting is largely converted into heat near the cutting edge of tool, and many of the economic and technical problems of machining are caused directly or indirectly by this heating action (Sharma, Dhiman, Sehgal, & Sharma, 2008).

By measuring the cutting forces, one is able to understand the cutting mechanism such as the effects of cutting variables on the cutting force, the machinability of the workpiece, the process of chip formation, chatter, and tool wear. It has been observed that engineering calculations used for obtaining the force values give some errors when compared to experimental measurements of the forces. The cutting force in even unsteady state conditions is affected by many parameters and the variation of cutting force with time has a typical characteristic. Cutting forces can be resolved into three components i.e. the radial thrust force ($F_x$), feed force ($F_y$), and tangential cutting force ($F_z$). Usually, the tangential cutting force is the largest of the three components, though in finish turning the radial thrust force is often larger, while the feed force is minimal. The findings of some of the research studies pertaining to the effect of cutting parameters on cutting forces are presented below.

The cutting forces increase drastically when machining materials with hardness higher than about 45 HRC (Davim, 2011). Kurt and Seker (2005) investigated the
effects of chamfer angle on the cutting forces and the stresses on the PCBN cutting tools in finishing hard turning of AISI 52100 bearing steel. They found that the chamfer angles (20° and 30°) have a great influence on the passive cutting forces and Von Mises tool stresses distribution. Lee (2011) developed a theoretical model to predict cutting forces for machining AISI 4140-hardened materials (45 HRC) that contain more than 0.58% carbon. His predicted values of cutting forces from the model were found to be in good agreement with those measured from an experiment of hard machining of AISI 4140 steel heat-treated. Panzera, Souza, Rubio, Abrao, and Mansur (2012) investigated the effect of the cutting parameters (cutting speed, feed rate, and depth of cut) on the cutting force components during dry turning AISI 4340 steel using coated carbide inserts. The results of their study indicated that the three components of the turning force decrease slightly as cutting speed increases and also they increase linearly with feed rate and depth of cut. Further, the results of analysis of variance (ANOVA) revealed that the three components of the force are not significantly affected by cutting speed but they are significantly affected by feed rate and depth of cut. Aouici, Yallese, Fnides, and Mabrouki (2010) studied the influence of the cutting parameters (cutting speed, feed rate, and depth of cut) on cutting force components, surface roughness, temperature in the cutting zone, and tool life during turning of AISI H11 steel treated at 50 HRC using CBN tool (57% CBN and 35% Ti(C, N)). Their results indicated that (i) tangential cutting force is very sensitive to the variation in cutting depth, (ii) thrust force is dominating compared to both others cutting forces, (iii) surface roughness is very sensitive to the variation of the feed rate, and (iv) the temperature is greatly influenced by the cutting speed.

3.2. Studies on heat generation and cutting temperature

Most of the energy in the cutting process is converted into heat. This heat is generated by plastic deformation and friction at the tool–chip and the tool–workpiece interfaces. The generation of the heat during machining increases the temperature in the cutting zone which affects the strength, hardness, wear resistance, and life of the cutting tool and causes difficulty in controlling the dimensional accuracy and surface integrity. The temperature also causes thermal damage to the workpiece and affects its properties and service life.

The temperature in the cutting zone is affected by the cutting parameters. In addition, it also depends on the properties of the workpiece material, as well as on the physical properties of the tool. Therefore, considerable attention has been paid to the measurement and prediction of the temperatures at the tool, chip, and workpiece in the metal cutting (Aouici et al., 2010; Özel, 2009). The cutting tools that are used for machining should possess adequate hot hardness to withstand elevated temperatures generated at high-speed condition. Under these conditions, most tool materials generally lose their hardness resulting in the weakening of the interparticle bond strength and consequently, tool wear gets accelerated as reported by Ezugwu, Bonney, and Yamane (2003). Amritkar, Prakash, and Kulkarni (2012) performed machining of SAE 8620 material at various cutting speed and feed rate using uncoated tungsten carbide tool. They designed and developed a simple and economical technique of temperature measurement i.e. tool-work thermocouple setup for the measurement of the cutting temperature for which they calibrated the setup in order to establish a relationship between obtained e.m.f. during machining and the cutting temperature. They used regression analysis for establishing the relationship between temperature and the generated voltage.
They evaluated the performance of the setup for the different material like EN19, EN31, mild steel, SS 304, and SAE 8620 using uncoated tungsten carbide tool. Their obtained results confirmed that the setup is having better accuracy and good repeatability. Further, they observed that the tool-work thermocouple technique is the best method for measuring the average chip–tool interface temperature during metal cutting. Sutter, Faure, Molinari, Ranc, and Pina (2003) studied the effects of the cutting speed and depth of cut on the temperature profile at the chip during an orthogonal machining of 42 CrMo 4 steel using standard carbide tools TiCN coated. They performed the machining with a gas gun. It was found from their results that the temperature at the chip increases with the increase in both cutting speed as well as the depth of cut. Ren, Yang, James, and Wang (2004) determined the cutting temperatures during hard turning of high chromium hardfacing materials using PCBN tools. They found that the average cutting temperatures ranged from 600 to 700 °C which increased with higher cutting speed and feed rate. Abukhshim, Mativenga, and Sheikh (2005) used FEA to estimate the amount of heat flowing into the cutting tool in high-speed turning of AISI 4140 high strength alloy steel using uncoated cemented carbide. Their results showed that the maximum temperature at the tool–chip contact increases with cutting speed but not linearly and this could be attributed to the trend of the heat fraction flowing into the tool. Sutter and Ranc (2007) measured the temperature during machining of two steels i.e. C15 and 42CrMo4 for a range of cutting speed around 15–65 m/s. Their results showed that the increase in cutting speed from 10 to 65 m/s maximizes temperature at the chip continuously. List, Sutter, and Bouthiche (2012) predicted the interface cutting temperature and its relation with the crater wear mechanism. Their work was focused on the domain of the high-speed machining above 20 m/s. They analyzed the mechanical and thermal parameters that influenced the temperature distribution at the tool rake face.

3.3. Studies on surface finish and surface integrity

The surface integrity of a machined surface is defined in terms of residual stresses, surface roughness, microhardness, etc. Surface roughness and dimensional accuracy play an important role in the performance of a machined component. High cutting forces and high localized temperatures may dramatically affect the surface integrity, often resulting in the development of high tensile residual stresses in the machined surfaces. Residual stress on the machined surface and the subsurface is known to influence the service quality of a component, such as fatigue life, tribological properties, and distortion. Therefore, it is essential to predict and control it for enhanced performance as suggested by several researchers (Adesta et al., 2009; Aouici et al., 2010; Benga & Abrao, 2003; Chowdhury & Dhar, 2011; Diniz et al., 2003; Elmunafi, 2012; Fnides et al., 2009; Gaitonde et al., 2009; Godoy & Diniz, 2011; Kumar et al., 2003; More et al., 2006; Poulachon et al., 2001; Ramesh et al., 2005; Sharma et al., 2008; Thamizhmanii & Hasan, 2010; Thiele & Melkote, 1999; Yallese et al., 2009; Zawada-Tomkiewicz, 2011). In addition to the research studies cited above, Hua et al. (2005) analyzed the effects of cutting edge geometry, workpiece hardness, and cutting parameters, such as cutting speed and feed rate on subsurface residual stress in hard turning of AISI 52100 bearing steel. It was revealed from their analysis that hone edge plus chamfer cutting edge and aggressive feed rate help to increase both compressive residual stress and penetration depth. Moreover, using medium hone radius (0.02–0.05 mm) plus chamfer was good for keeping tool temperature and cutting force low, while obtaining desired residual stress.
profile. Rech et al. (2008) provided a comprehensive characterization of residual stresses that were developed in dry turning of a hardened AISI 52100 bearing steel using PCBN tools. For better understanding of the experimental results, they investigated the generated residual stresses in hard turning or in ‘hard turning + belt finishing’ by two complementary ways: an experimental X-ray diffraction characterization after each step of the process, and a finite element model of the belt finishing operation. Additionally, they explored the sensitivity of some parameters such as the lubrication and the indentation force during belt finishing. They observed that the belt finishing process improves the surface integrity by the induction of strong compressive residual stresses in the external layer and by a great improvement of the surface roughness. In addition, they also found that among the process parameters of the belt finishing technique, the lubrication is a key parameter to get compressive stresses. Caruso, Umbrello, Outeiro, Filice, and Micari (2011) examined the effects of the tool cutting-edge geometry, workpiece hardness, cutting speed, and microstructural changes (white and dark layers) on the residual stresses in dry orthogonal hard machining of AISI 52100 steel using PCBN tool inserts. Their results showed that tool geometry, workpiece hardness, and cutting parameters significantly affect the surface residual stress, maximum compressive residual stress below the machined surface, and its location. Moreover, microstructural analysis showed that thermally-induced phase transformations have a significant impact on the magnitude and location of this maximum compressive residual stress peak.

On the other hand, a number of investigations have been carried out in the past to assess the surface roughness that could be achieved with hard turning in comparison to grinding. Asilturk and Akkus (2011) investigated the effects of cutting speed, feed rate, and depth of cut on surface roughness during dry turning of AISI 4140 (51 HRC) with coated carbide cutting tools. Their results indicated that the feed rate has the most significant effect on the surface roughness. In addition, the effects of two factor interactions of the feed rate-cutting speed and depth of cut-cutting speed appear to be important. Aouici, Yallese, Chaoui, and Mabrouki (2012) investigated the effects of cutting speed, feed rate, workpiece hardness, and depth of cut on surface roughness in the hard turning of AISI H11 steel (hardened to (40; 45; and 50) HRC) using CBN which is essentially made of 57% CBN and 35% TiCN. Their results showed that both the feed rate and workpiece hardness have statistically significant effect on the surface roughness. Further, the best surface roughness was achieved at the lower feed rate and the highest cutting speed. Umbrello et al. (2011) investigated the effects of cryogenic coolant on surface integrity in orthogonal machining of hardened AISI 52100 bearing steel using chamfered CBN tool inserts. The results of their study showed that the use of cryogenic coolant significantly affects the surface integrity and improves product’s functional performance. Grzesik, Żak, Prażmowski, Storch, and Palka (2012) explored the effect of cryogenic cooling on the surface integrity produced in hard turning of low alloy 41Cr4 steel with hardness of 57 ± 2 HRC using low content CBN tools containing about 60% CBN. They confirmed that hard machining produces surfaces with acceptable surface roughness and, in some cases, with attractive service properties. They also observed that cryogenic hard cutting operations can partly eliminate grinding operations in cases when white layer is not produced. Abhang and Hameedullah (2012) determined the optimum cutting parameters (cutting speed, feed rate, tool nose radius, and concentration of solid–liquid lubricants (MQL)) for the multiperformance characteristics (surface roughness and chip thickness) in the turning of EN-31 steel by using the grey relational analysis coupled with factorial design. They concluded that gray relational analysis coupled with factorial design can effectively be used to obtain the optimal
combination of cutting parameters. Additionally, they observed that the surface roughness and the chip thickness in the turning process can be improved effectively through this approach. Finally, they found that the minimum surface roughness and smallest chip thickness are 9.83 μm and 0.32 mm, respectively, which are obtained at optimal conditions at: 1200 rpm cutting speed; 0.06 mm/rev feed rate; 0.8 mm nose radius; and concentration of solid–liquid lubricant (10% boric acid + SAE-40 base oil. Islam (2013) investigated the effect of cooling method, blank size, and work material on the dimensional accuracy characteristics (diameter error and circularity) and surface roughness of turned parts under three turning conditions (dry, flood, and MQL) for different materials (aluminum (AISI 6061), mild steel (AISI 1030), and alloy steel (AISI 4340)). He analyzed the results by applying three methods: traditional analysis, Pareto ANOVA, and Taguchi method. He noticed that cooling method, blank size, and work material have demonstrated considerable effects on the dimensional accuracy characteristics, whereas the effect of these parameters on surface roughness is relatively low. He also revealed that while work material has the greatest effect on diameter error and surface roughness, the major contributor to circularity is blank size. Finally, dimensional accuracy and surface roughness of different work materials were influenced differently by the cooling methods, and in most cases the best result was achieved by MQL.

3.4. Studies on the tool wear

During machining, the cutting tools are subjected to severe forces and temperature which may cause tool wear and therefore, it is necessary to study and predict the tool wear during machining for the effective design of cutting tools and determination of cutting conditions that will lead to the formulation of the tool change strategies. Intensive research studies pertaining to the tool wear have been carried out in the past century which has contributed greatly to the understanding of the factors responsible for the tool wear and also the tool wear mechanisms. Many researchers focused their studies on the prediction of the tool wear during hard turning (Adesta et al., 2009; Arsecularatne et al., 2006, Arsecularatne et al., 2006; Aslan, 2005; Chowdhury & Dhar, 2011; Diniz et al., 2003; Elmunaifi, 2012; Fnides et al., 2009; Gaitonde et al., 2009; Galoppo et al., 2006; Godoy and Diniz, 2011; Huang et al., 2007; Kumar et al., 2003; Lima et al., 2007; Lin et al., 2008; Luo et al., 1999; Meyer et al., 2012; More et al., 2006; Oliveira et al., 2009; Özel, 2009; Poulachon et al., 2001, 2003, 2004; Remadna & Rigal, 2006; Sahin, 2009; Suresh et al., 2012; Thamizhmanii & Hasan, 2010; Yallese et al., 2009; Zawada-Tomkiewicz, 2011; Zhao et al., 2010). In addition to the references cited before for the tool wear study, Grzesik and Zalisz (2008) investigated the wear phenomenon of the mixed ceramic tips during dry hard turning of AISI 5140 steel (60 HRC). They performed finishing cuts under varying feed rate, constant cutting speed of 100 m/min and small depth of cut of 0.2 mm. It was observed from their results that depending on the mechanical and thermal conditions generated on the wear zones, the wear mechanisms involve abrasion, fracture, plastic flow, material transfer, and tribochemical. El Hakim, Abad, Abdelhameed, Shalaby, and Veldhuis (2011) studied the performance of different tool materials, PCBN (CBN+TiN), TiN coated PCBN (CBN+TiN), mixed alumina ceramic (Al2O3+TiC), coated tungsten carbide (TiN coated over a multilayer coating (TiC/TiCN/Al2O3)) in the machining of medium hardened steel AISI T15 HSS. Their results indicated that the mixed alumina ceramic and coated carbide tool materials have longer tool life than PCBN tools when they machined the selected workpiece material.
Chinchanikar and Choudhury (2013) investigated the effect of workpiece hardness, cutting parameters, and type of coating for coated cemented carbide inserts on flank wear during turning of hardened AISI 4340 steel at different levels of hardness. The results of their study revealed that flank wear is dominant wear form for CVD coated tool and crater wear is dominant wear form for PVD coated tool. Further, they found that abrasion and adhesion are the main causes for wear of CVD coated tool and abrasion, adhesion and diffusion leads to the wear of PVD coated tool. Gaitonde et al. (2009) studied the relationships between the cutting parameters (cutting speed, feed rate, and machining time) on tool wear. They used RSM to analyze the effects of process parameters on machinability during turning of high chromium AISI D2 cold work tool steel using CC650WG wiper ceramic inserts. They found that the maximum tool wear occurs at a cutting speed of 150 m/min for all values of feed rate and the tool wear increases with the increase in machining time. Dogra, Sharma, Sachdeva, Suri, and Dureja (2011) made comparison between the performance of CBN inserts with coated carbide and cryogenically treated coated/uncoated carbide inserts in terms of flank wear during finish turning of hardened AISI H11 steel (48–49 HRC). They indicated that the flank wear of CBN is lower than that of other inserts.

4. Summary

Hard machining including hard turning is widely used by several manufacturing industries such as ball bearings, automotive, gear, and die-making industries, since it offers numerous advantages when compared with traditional methodology based on finish-grinding operation after heat treatment of workpieces. This technology possesses immense potential to machine very hard materials to produce near net shape components and also to contribute to a great extent to the sustainable manufacturing. In the recent past, this technology has created interest among researchers and attracted their attention, and consequently, many research studies have been conducted and the results have been reported which are available in the literature. This paper has presented an overview focusing mainly on turning of hardened steels that are used by ball bearings, automotive, gear, and die-making industries. On the basis of the research findings reported in the available literature reviewed and presented in this paper, following conclusions can be drawn:

- Hard turning offers a number of potential benefits over traditional form grinding, including lower equipment costs, shorter setup time, fewer process steps, greater part geometry flexibility, and elimination of the use of cutting fluid.
- During hard turning, the cutting tool is subjected to heavy mechanical loads and also it is exposed to very high temperature due to excessive heat generation, and therefore, cutting tools made of superhard materials such as coated cemented carbide, ceramic, PCD, CBN, etc. must be used as they perform well under severe machining conditions.
- The cutting tool geometry, workpiece hardness, and cutting parameters significantly affect the cutting forces, surface residual stress, surface roughness, surface integrity, tool wear, and tool life.
- The information gained through study and prediction of the tool wear during machining can be used as a basis for the effective design of cutting tools and determination of cutting conditions that will lead to the formulation of the tool change strategies.
• The complex phenomena involved in hard turning can be studied through simulation and modeling using techniques such as FEM, ANN, etc. and the results of the models can be validated with experimental results.

Thus, it is concluded that the information gathered through extensive literature review has been presented in a modular way in this paper. The review has been organized in terms of role of machining parameters on machining of hard steel, cutting force, heat generation, and temperature evolution during machining, surface integrity, and tool wear during hard machining, etc. The information presented are immensely useful to the researchers in identifying solutions to the several machining problems to mention some: (i) to identify strategies with regard to tool edge geometry, cutting parameters, etc. for specific work material hardness so as to obtain better surface integrity and surface finish; and (ii) to identify prevalent wear mechanisms and appropriate tool material for specified machining situations.

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Major findings of the researches presented in this review are summarized in the following table.

| Author(s)                              | Tool material                      | Cutting parameters                                      | Remarks                                                                                                                                 |
|----------------------------------------|-------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Thiele and Melkote (1999)              | CBN tools                           | Tool edge geometries, workpiece hardness, and feed rate | Large edge hone of CBN tools result in higher forces in the axial, radial, and tangential directions as compared to the tools with small edge hone during turning AISI 52100 steel |
| Ramesh et al. (2005)                   | CBN                                 | Cutting speed                                           | The grains of white layers are smaller than the grains of the bulk material. Machining at higher speeds results in the formation of coarser grains |
| Diniz et al. (2005)                    | CBN                                 | Two different kinds of CBN cutting tools (high CBN content material and CBN content material), cutting speed, three cutting operations continuous, semi-interrupted surfaces interrupted cutting | Low CBN content tool is more suitable for continuous and semi-interrupted surfaces, whereas the high CBN content tool presents a slightly longer life during interrupted cutting |
| Adesta et al. (2009)                   | Cermet tools                        | Rake angles, cutting speed                              | Increase in negative rake angles causes higher wear, shorter duration of tool life, and poor surface finish. Further, high cutting speed turning gave shorter tool life, high wear rate but finer surface finish than conventional one |
| Gaitonde et al. (2009)                 | Ceramic inserts with TiN coating (CC650, CC650WG, and GC6050WH) | Depth of cut and machining time                         | CC650WG wiper insert performs better with reference to surface roughness and tool wear. The surface roughness is minimal at lower values of depth of cut and machining time in case of CC650 and CC650WG inserts machining, while the minimum surface roughness occurs at 0.4 mm depth of cut for hard turning with GC6050WH insert. Finally, the CC650 conventional insert is useful in reducing the cutting force |
| Fnides et al. (2009)                   | Mixed ceramic tool(insert CC650)    | Cutting speed, feed rate, depth of cut                  | Statistical models of surface roughness criteria were developed |
| Author(s)            | Tool Material                                                                 | Conditions                        | Remarks |
|----------------------|-------------------------------------------------------------------------------|-----------------------------------|---------|
| Meyer et al. (2012)  | CBN content of 56%                                                           | Geometrical contact conditions    | It was suggested that by applying a load-specific tool and process design, the tool operation behavior and the productivity of the process can be enhanced in a beneficial way. |
| Aslan (2005)         | TiCN coated tungsten carbide, TiCN + TiAlN coated tungsten carbide, TiAlN coated cermet, mixed ceramic with Al₂O₃ + TiCN and CBN | Different cutting tool materials  | TiAlN coated carbide and cermet tools perform slightly better than TiCN coated carbide tool which can be attributed to better high-temperature properties of TiAlN compared to TiCN. CBN tool exhibits the best cutting performance in terms of both flank wear and surface finish and the highest volume of metal removal is obtained with CBN. |
| Lima et al. (2007)   | Coated carbide                                                                | Workpiece hardness, cutting speed, feed rate, depth of cut, cutting time | The abrasion is the principal wear mechanism and catastrophic failure takes place when attempting to machine the AISI 4340 steel with 525 HV. |
| Chowdhury and Dhar (2011) | Coated carbide insert                                                        | Tool geometry                     | The application of MQL technique significantly helps to obtain better performance of coated carbide insert in comparison to dry condition. |
| Hwang and Lee (2010) | Coated carbide insert                                                         | Cutting speed, Feed rate, Depth of cut, Supplied air pressure, Nozzle diameter | Turning of AISI 1045 with coated carbide inserts under MQL results in better surface finish than wet turning. |
| Luo et al. (1999)    | CBN Ceramic Carbide P10                                                       | Cutting speed, feed rate, depth of cut | A protective layer formed on the chip–tool interface plays an important role in wear behavior of CBN and ceramics tools. |
| Kumar et al. (2003)  | Ti[C,N] mixed alumina ceramic and zirconia toughened alumina ceramic          |                                    | Ti[C, N] mixed alumina ceramic cutting tool produces the best surface finish during turning of EN 24 steel (HRC 40 and HRC 45). |

(Continued)
### Appendix (Continued).

| Author(s)          | Tool material                                                                 | Cutting parameters                                      | Remarks                                                                                                                                                                                                 |
|--------------------|-------------------------------------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gaitonde (2009)    | CC650, CC650WG, and GC6050WH ceramic inserts                                  | Cutting speed, feed rate, machining time                | CC650WG wiper insert performs better with reference to surface roughness and tool wear, while the CC650 conventional insert is useful in reducing the machining force, power and specific cutting force during turning of high chromium AISI D2 cold work tool steel |
| Elmunafi (2012)    | Wiper coated ceramic                                                           | Cutting speed, feed rate                                 | Wiper inserts produce better surface finish when turning ASSAB DF-3 grade hardened steel with hardness 55 HRC                                                                                                                                              |
| Maňková et al. (2011) | Mixed oxide ceramic inserts (70% Al₂O₃ + 30% TiC)                                           | Cutting speed, feed rate                                 | Ceramic cutting tools have an advantage in the machining of hard work piece materials at high speed                                                                                                                                                 |
| Fnides et al. (2011)| Mixed ceramic tool                                                             | Cutting speed, feed rate, depth of cut                   | Statistical models of cutting force components for turning of AISI H11 grade steel treated at 50 HRC, with a mixed ceramic tool (insert CC650) was developed                                                                                       |
| Zhao et al. (2010) | The Al₂O₃-based composite ceramic tool material reinforced with WC microparticles and TiC nanoparticles | Cutting speed, depth of cut                             | The tool life of the Al₂O₃/WC/TiC ceramic tool increases when the cutting speed increases to 170 m/min. The longer tool life of the Al₂O₃/WC/TiC composite ceramic tool is attributed to its synergistic strengthening/toughening mechanisms induced by the WC microparticles and TiC nanoparticles |
| Oliveira et al. (2009) | PCBN and alumina-based ceramic reinforced with silicon carbide tools                        | Continuous and interrupted surfaces                     | The longest tool life is achieved using PCBN in continuous turning, but similar tool longevity is attained in interrupted turning using both PCBN and ceramic. PCBN tools result in lower roughness for continuous and interrupted surfaces |
| Sahin (2009)       | Mixed alumina ceramic with that of Al₂O₃ (70%):TiC (30%) matrix and CBN cutting tools    | Cutting speed, feed rate, tool hardness                 | The CBN cutting tool has the best performance as compared to the ceramic based cutting tool                                                                                                      |
| Authors            | Tool Material | Workpiecepecified as                            | Study Conditions/Additional Details |
|--------------------|---------------|-------------------------------------------------|--------------------------------------|
| Poulachon et al.   | PCBN cutting tool | Workpiece hardness                              | TiN coated PCBN improves the tool-wear and hence the tool-life by reducing the diffusion wear between workpiece and tool rake face. Surface roughness in all three cutting conditions i.e. dry cutting, wet cutting, and minimum volume of oil cutting is the lowest at the highest cutting speed. A large variation in tool wear occurs in the machining of these steels. At low feed rates PCBN compact tool gives best results in terms of the tool life followed by the mixed alumina tool. However, as feed rate is increased tool life of the whisker reinforced alumina tool is better. The generated tool flank grooves are correlated with the hard carbide content of the workpieces. |
| Diniz et al. (2003)| CBN           | Cutting speed, and under three cutting conditions: dry cutting, wet cutting, and minimum volume of oil i.e. MVO (oil flow of 10 ml/h) |                                       |
| Poulachon et al.   | PCBN          | Steel workpiece with different hardness         |                                       |
| Benga and Abrao (2003)| Mixed alumina, whisker reinforced alumina, and PCBN inserts | Cutting speed, feed rate |                                       |
| Poulachon et al. (2004)| CBN          | Different steels (AISI D2 cold work steel, AISI H11 hot work steel, 35NiCrMo16 hot work steel and AISI 52100 bearing steel), cutting speed, and feed rate | Chamfer angle significantly affects the cutting forces and the tool stress. CBN insert with a wiper geometry presents longer tool life compared to no coated tools. |
| Kurt and Seker (2005)| PCBN          | Chamfer angle                                   |                                       |
| Galoppi et al.     | Different types of CBN inserts with wiper geometry, coated with TiAlN and TiN as well as with no coated ones | Cutting speed, and feed rate |                                       |
| Remadna and Rigal (2006)| CBN          | Cutting speed                                   | The wear of CBN does not directly or appreciably affect the manufactured surface. The crater wear of the CBN–TiN coated inserts is less than that of the PCBN inserts because of the lubricity of TiN capping layer on the CBN–TiN coating. The highest acceptable values of tool life and volume of material removal is obtained at low speed. |
| More et al. (2006) | CBN–TiN coated carbide inserts and PCBN compact inserts | Cutting speed, and feed rate |                                       |
| Arsecularatne et al. (2006)| PCBN tools | Cutting speed, and feed rate |                                       |

(Continued)
### Author(s) Tool material Cutting parameters Remarks

| Author(s)          | Tool material                  | Cutting parameters                              | Remarks                                                                                                                                                                                                 |
|--------------------|--------------------------------|--------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Lin et al. (2008)  | CBN tools which contained 50% and 45% of CBN | Cutting speed                                   | At high cutting speed a protective layer is formed on the chip–tool interface which prolongs life of the CBN tool. With further increase in the cutting speed (i) cutting temperature becomes the dominant factor instead of the cutting force which causes inhomogeneous shear strain, and a transition from continuous chip to saw-tooth chip, (ii) the friction force increases because of the very irregular chip–tool contact and it results in the removal of the protective layer, and (iii) the bond between tool particles gets weakened due to serious diffusion between the work material and the cutting tool. Subsequently, hard particles of the tool get detached from it and the tool life is reduced. |
| Özel (2009)        | PCBN                            | Different edge micro-geometry, cutting speed, and feed rate | Micro-geometry insert edge design improves surface integrity, the tool life, and reduces tool wear depth and wear rate. At very high cutting speed the machining system becomes unstable and produces significant sparks and vibrations after only a few minutes of work and causes tool wear. |
| Yallese et al. (2009) | CBN                            | Cutting speed, feed rate, and depth of cut       |                                                                                                                                           |
| Godoy and Diniz (2011) | CBN and ceramic tools           | Continuous and interrupted cutting, cutting speed | The CBN tools exhibit a much better performance with respect to both tool life and workpiece surface roughness than the ceramic tools. Turning with PCBN tools can produce a very smooth and uniform surface. |
| Zawada-Tomkiewicz (2011) | PCBN coated and uncoated tools |                                                                                     | The wedge’s wear is almost unnoticeable for PCBN coated tool material.                                                                                                                                   |
| Authors                  | Tool Material          | Processing Parameters | Characteristics |
|--------------------------|------------------------|-----------------------|------------------|
| Deepakkumar and Sadaiah  | CBN                    | Cutting speed, feed rate, depth of cut, and different cutting environments (dry, wet, and MQL) | The tool wear increases with increase in the cutting speed and feed rate |
| Panzera et al. (2012)    | Coated carbide inserts | Cutting speed, feed rate, and depth of cut | The three components of the turning force decrease slightly as cutting speed increases and also they increase linearly with feed rate and depth of cut |
| Aouici et al. (2010)     | CBN tool (57% CBN and 35% Ti(C, N)) | Cutting speed, feed rate, and depth of cut | Tangential cutting force is very sensitive to the variation in cutting depth |
|                         |                        |                       | Thrust force is dominating compared to both others cutting forces |
|                         |                        |                       | Surface roughness is very sensitive to the variation of the feed rate |
|                         |                        |                       | The temperature is greatly influenced by the cutting speed |
| Amritkar et al. (2012)   | Uncoated tungsten carbide tool | Cutting speed and feed rate | The tool-work thermocouple technique is the best method for measuring the average chip–tool interface temperature during metal cutting |
| Sutter et al. (2003)     | Carbide tools TiCN coated | Cutting speed and depth of cut | The temperature at the chip increases with the increase in both cutting speed as well as the depth of cut |
| Ren et al. (2004)        | PCBN                   |                       | The average cutting temperature increases with increase in both the cutting speed and feed rate |
| Abukhshim et al. (2005)  | Uncoated cemented carbide | Cutting speed | The maximum temperature at the tool–chip contact increases with cutting speed but not linearly and this could be attributed to the trend of the heat fraction flowing into the tool |

(Continued)
| Author(s)          | Tool material                      | Cutting parameters                                                                 | Remarks                                                                 |
|-------------------|-----------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Rech et al.       | PCBN                              | Cutting speed, feed, depth of cut, tool geometry (all fixed values), and subsequent belt finishing | Belt finishing process improves the surface integrity by the induction of strong compressive residual stresses in the external layer and due to reasonable improvement in the surface roughness Lubrication used in the belt finishing technique is a key parameter to get compressive stresses to improve surface roughness |
| Caruso et al.     | PCBN                              | Tool geometry, workpiece hardness, cutting speed                                     | Tool geometry, workpiece hardness, and cutting parameters significantly affect the surface residual stress The feed rate significantly affects the surface roughness |
| Asilturk and Akkus| Coated carbide                    | Cutting speed, feed rate, and depth of cut                                            | The feed rate significantly affects the surface roughness                |
| Aouici et al.     | CBN which is essentially made of 57% CBN and 35% TiCN | Workpiece hardness, cutting speed, feed rate, and depth of cut Under dry and cryogenic conditions, cutting speed | The feed rate and workpiece significantly affect the surface roughness Cryogenic coolant significantly affects the surface integrity and improves product's functional performance |
| Umbrello et al.   | CBN                               |                                                                                      |                                                                         |
| Grzesik et al.    | CBN tools containing about 60% CBN| Under dry and cryogenic conditions, feed rate                                         |                                                                         |
| Abhang and Hameedullah| CNMA 120404, CNMA 120408, CNMA 120412, and diamond-shaped carbide | Cutting speed, feed rate, tool nose radius, and concentration of solid–liquid lubricants (MQL) | The surface roughness and the chip thickness in the turning process can be improved effectively through application of MQL |
| Authors                  | Type of Inserts                                                                 | Parameters                                                                 | Findings                                                                                                                                                                                                 |
|-------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Islam (2013)            | Cooling method, blank size, and work material                                   |                                                                             | The effect of these parameters on surface roughness is relatively low Dimensional accuracy and surface roughness of different work materials get influenced differently by the cooling methods, and in most cases the best result is achieved by MQL                                                                 |
| Grzesik and Zalisz (2008)| Mixed ceramic                                                                   | Feed rate                                                                  | The wear mechanisms involve abrasion, fracture, plastic flow, material transfer and tribochemical                                                                                                        |
| El Hakim et al. (2011)  | PCBN (CBN + TiN), TiN coated PCBN (CBN + TiN), mixed alumina ceramic (Al$_2$O$_3$ + TiC), coated tungsten carbide (TiN coated over a multilayer coating (TiC/TiCN/ Al$_2$O$_3$)) | Tool materials                                                              | The mixed alumina ceramic and coated carbide tool materials have longer tool life than PCBN tools                                                                                                         |
| Chinchanikar and Choudhury (2013) | Coated cemented carbide inserts                                                 | Workpiece hardness, cutting speed, feed rate, depth of cut, and type of coating for coated cemented carbide inserts | Flank wear is dominant wear form for CVD coated tool and crater wear is dominant wear form for PVD coated tool                                                                                           |
| Gaitonde et al. (2009)  | CC650WG wiper ceramic inserts                                                   | Cutting speed, feed rate, and machining time                                | The maximum tool wear occurs at a cutting speed of 150 m/min for all values of feed rate and the tool wear increases with the increase in machining time                                                                 |
| Dogra et al. (2011)     | CBN with coated/uncoated carbide                                               | Cutting speed under cryogenic cooling                                       | The flank wear of CBN is lower than that of other inserts                                                                                                                                              |