A REVIEW OF INSIGHTS AND RESEARCH PROGRESS ON HARD TURNING

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ABSTRACT

Of late, due to the launch of improved machine tool designs and extremely hard cutting tools, "Hard Turning" (HT) or "Hard Finish Turning" (HFT) has turned out to be an innovative, cost-effective, and smart alternative to the traditional grinding and subsequent superfinishing processes. As a result, HT clenches the potential to produce excellent part quality in very little time along with negligible additional costs, which is considered to be a boon for the manufacturing industries. Hence, an attempt was made to review the development, key insights, and research progress in the HT process. So, a huge pool of HT studies has been reviewed to achieve a better understanding of the evolution and key insights namely process, workpiece materials, cutting inserts, machine tools, and machining parameters. Additionally, the effectiveness of HT using CBN (Cubic Boron Nitride) insert under different machining conditions is briefed. The review highlights the growing potential of HT in modern manufacturing and outlines the challenges and future research direction.

KEYWORDS: hard turning, materials, cutting inserts, machine tools, cutting parameters, cutting conditions

1. INTRODUCTION

The HT process has become a viable and intelligent alternative to traditional grinding, offering both technical and financial advantages. The technique provides dry machining capabilities, which contribute to improved surface integrity and eco-friendliness. Adopting HT in manufacturing processes can ensure higher dimensional accuracy, better geometrical tolerances, and surface precision. Materials such as superalloys and hardened steels are especially appealing for HT applications due to their exceptional mechanical properties, including high hardness, toughness, wear resistance, and fatigue strength. Hardened steel parts, in particular, are essential in critical load-bearing applications across various industries, further emphasizing the importance of HT in achieving efficient and sustainable machining.

These materials are essential in engineering applications, such as transportation, machine tool manufacturing, energy generation, and power transmission. Rotary bearings, for instance, are used in a wide range of settings, from heavy-duty automotive axles to precision watch components. These elements are often subjected to loads approaching their physical limits, necessitating thermal treatment to attain the desired mechanical properties. To ensure optimal dimensional accuracy, geometric precision, and surface tolerance in the hardened state, traditional grinding and superfinishing processes have become indispensable.

The grinding process is often time-consuming and not cost-effective for processing materials like AISI D2, M2, H13, 4340, 52100, and various superalloys, including Nitinol, Waspaloy, Hastelloy, and other exotic materials. These materials are crucial for applications where the performance, reliability, and safety of components are of utmost importance. In contrast, the HT process has proven to be a highly advantageous alternative, offering significant technical and economic benefits along with environmental advantages. From its inception, HT has been a breakthrough for the machining community, promising efficiency, reduced costs, and eco-friendliness, making it a valuable and effective solution.

2. EVOLUTION AND SIGNIFICANCE OF HT

Cost-effective, time-efficient, and innovative machining solutions are highly valued by the machining specialists' community to meet ever-evolving manufacturing demands. The HT process emerged as a groundbreaking and efficient machining method in the late 1970s [1] for processing hardened steel parts. Named for its ability to handle materials with high hardness, HT stands out as a competitive

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alternative to traditional grinding processes. The progression of HT, illustrated in Fig. 1a, contrasts traditional methods such as forming, annealing, soft-turning, hardening, form grinding, and abrasive-based superfinishing, marking a significant advancement in manufacturing technologies [2].

Subsequently, the HT process chain was streamlined by removing steps such as annealing, soft-turning, and disk grinding, as illustrated in Fig. 1b [3]. Recent advancements are shown in Fig. 1c, which highlight the replacement of abrasive processes with high-precision super-finish HT. This optimized approach enables complete part production using turning operations within a single machining setup, eliminating the need for abrasive finishing [4]. Achievements in this domain have been made possible through advanced CNC lathes, high-speed turning centres, and precision lathes that incorporate enhanced vibration damping, structural rigidity, increased spindle power, and superior tool motion control [5]. These improvements, coupled with the use of ceramic inserts, have allowed the HT to achieve exceptional surface finishes and dimensional precision.

When machining is conducted using setups with insufficient stiffness, cutting inserts can suffer rapid failure due to micro-fractures along their cutting edges [6]. To address this, modern machine tool designs have significantly enhanced stiffness. Improvements include the use of polymeric composite materials for machine bases, the reduction of joints to increase structural integrity, and the development of advanced slide ways, such as hydrostatic designs, which provide superior support and vibration damping [7, 8]. Additionally, advancements in machine control systems have enhanced the precision and stability of these tools. The HT has played a crucial role in transforming traditional machining operations for challenging-to-cut materials, offering a cost-effective balance between achieving high part quality and reducing production expenses, even for small production runs [9].

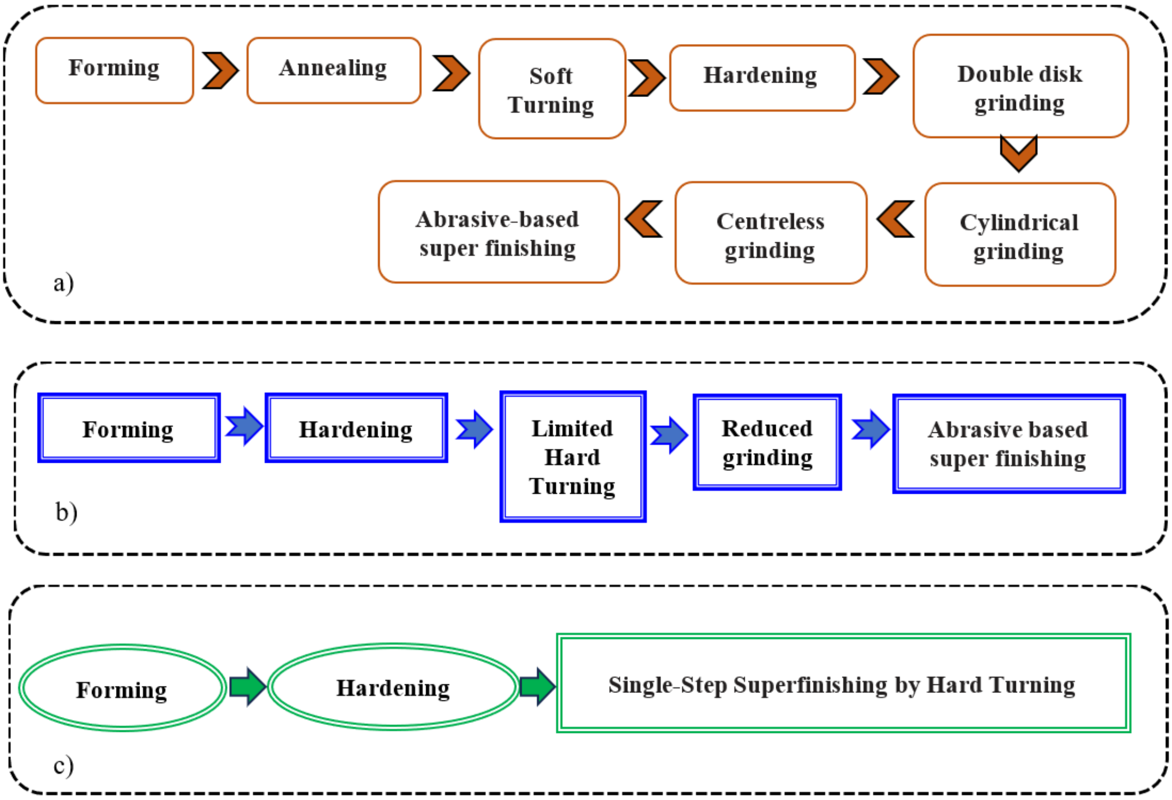


Fig. 1. Evolution of super finish HT: a) age-old method in production; b) advanced method followed in industries; c) single-step super finish HT pursued recently

HT is a single-point cutting process designed for machining hard-to-cut materials, particularly hardened steels with a hardness exceeding 45 HRC [10]. HT has proven highly advantageous by reducing lead times, setup costs (eliminating the need for costly fixtures), tool costs (removing the need for form grinding wheels), energy consumption (due to the efficiency of single-point cutting), and coolant expenses (as it often uses dry machining techniques) [11]. As a result, HT has created new revenue opportunities, even for small production batches, compared to traditional grinding. Since its introduction to the industrial sector, HT has effectively replaced grinding processes, offering considerable benefits such as lower production costs, reduced cycle times, fewer processing steps, and greater flexibility in machining complex geometries.

These advantages make HT a compelling choice for manufacturers aiming to achieve high efficiency and precision while maintaining cost-effectiveness.

In the present context, the HT process has emerged as a viable alternative to traditional grinding, thanks to its versatility in machining under various cooling methods, including dry, near-dry, minimum volume of oil (MVO), flood cooling, and even cryogenic cooling [12]. Dry machining, in particular, stands out as an environmentally friendly, "green" manufacturing process by eliminating the need for hazardous cutting fluids. Despite this, dry HT still yields superior surface integrity compared to grinding. Technological assessments of HT indicate that it enables the production of parts with complex geometries at significantly lower costs and in shorter time frames than traditional grinding [13]. For example, HT reduces machining times substantially, with notable reductions in both setup and run times. As shown in Table 1 [14], setup time can be reduced by up to 340%, and run time by up to 575%, demonstrating the efficiency and cost-effectiveness of HT in comparison to grinding processes. It is interesting to note that the drive shafts of the Mercedes Benz Sprinter (Daimler Chrysler Power Systems Achsen), which were traditionally machined by grinding, saw a significant reduction in production costs when the process was shifted to HT. This transition utilized a PCBN insert and a single machining setup, which drastically minimized time and costs. Previously, the flange required soft turning for normal finishing, while other finishing processes, such as the bearing seat, thrust ring, sealing ring seat, and thread, were completed using CBN grinding wheels.

These operations, previously carried out in four separate setups, consumed considerable time. By switching to HT, all these operations were completed in a single setup, which led to a substantial reduction in setup time and overall cycle time, without compromising quality [15].

This shift has sparked considerable research into HT for hard-to-cut materials, with numerous studies conducted by individual researchers and research groups. Notably, the CIRP (International Academy for Production Engineering) collaborative working group conducted an extensive study on surface integrity during the machining of difficult-to-cut materials [16]. Their work highlighted key issues related to surface characteristics, particularly during HT processes. More recently, research has focused on enhancing surface integrity through the elimination of the WL using gas mixture coolants [17], further improving the machining process. Undoubtedly, HT has garnered significant attention from both engineers and scholars, driven by its potential to provide an effective machining solution globally.

Table 1. Evaluation of time for machining a part

S. No.	Grinding Process		HT Process	
	Operation	Time [min]	Operation	Time [min]
1	Set up OD &Face	15	Set-up Lathe Tools	25
2	Grind OD & Face	5	Hard Turn & Face	88
3	Set-up ID	30	-	-
4	Grind ID	10	Bore ID	42
5	Set-up Taper	40	-	-
6	Grind Taper	4	Turn Angle	65

3. INSIGHTS OF HT PROCESS

The key insights into the HT process are centred around several critical factors, including the process itself, workpiece materials, cutting inserts, machine tools, machining parameters, and machining conditions [11], as illustrated in Fig. 2.

These factors play a significant role in optimizing HT, offering improvements in machining efficiency and surface integrity. The insights derived from various research studies are summarized in the following sections, with appropriate references provided to highlight the findings of other researchers in this field.

3.1. Process

The HT process represents a significant advancement in high-speed machining, particularly for hardened steels with high indentation hardness [18-20]. This process utilizes cutting tool materials such as coated carbides [21-23], ceramics [24, 25], and CBN [26, 27], typically at higher machining parameters [28, 29], with or without coolant application [30-33]. Analyzing the chip formation during HT reveals essential process characteristics. Specifically, when dry HT is employed, chip configuration becomes crucial for understanding the overall process dynamics [34]. It has been observed that turning materials above 45HRC at high processing parameters under dry conditions results in elevated thermal stress intensities at the machined surface. In contrast, moderate processing parameters generate moderate to high thermo-mechanical stress intensities, influencing chip formation [11]. When lower processing parameters are used, the resulting mechanical stress intensities at the machined surface are lower to medium, also affecting the chip configuration.

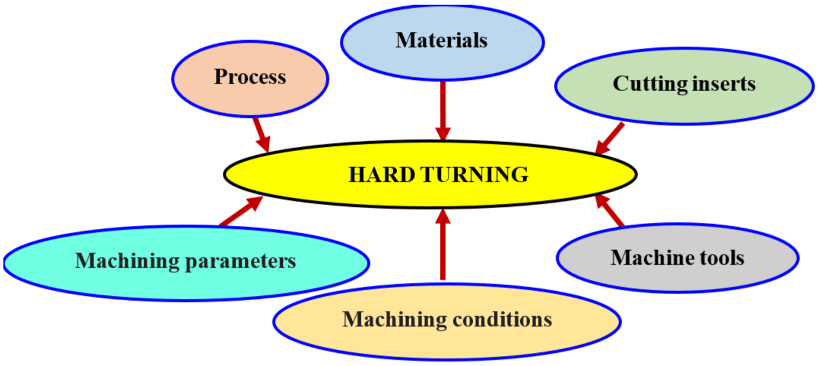


Fig. 2. Key insights of the HT

As shown in figure 3, the chip configuration during dry HT varies from partially continuous to continuous, with moderate to large saw-tooth edges. This variation in chip formation is influenced by factors such as workpiece material hardness, machining conditions, and cutting parameters. Specifically, it has been observed that the hardness of the workpiece material, along with the cutting parameters, plays a key role in shaping the chip configuration. Additionally, the content of CBN in the cutting insert, the micro-cutting edge geometry, and the rigidity of the machine tool further contribute to the overall process characteristics. These factors collectively enhance the HT process, improving the quality and efficiency of machining operations [35].

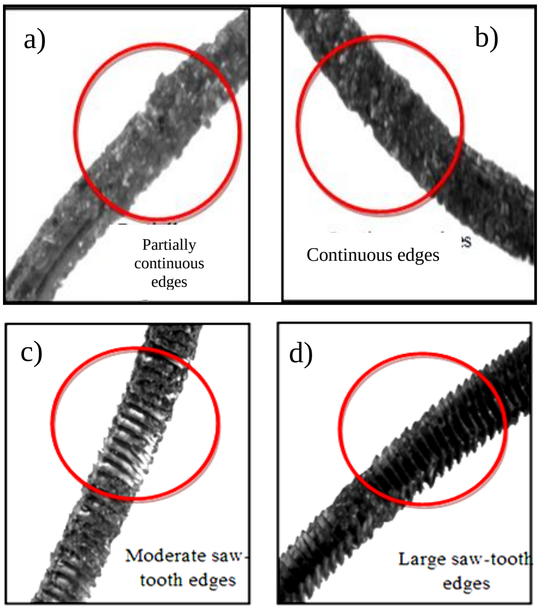


Fig. 3. a-d) Chip configurations obtained during the dry HT

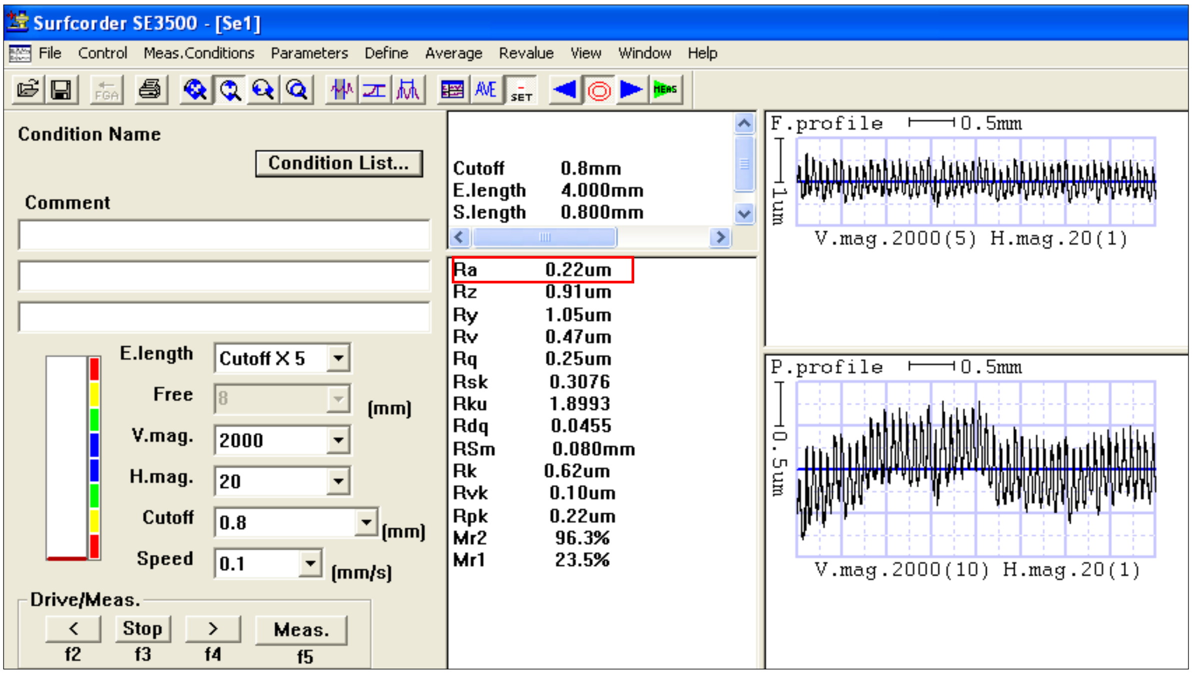
3.2. Materials

Hardened steels are commonly used for critical machine components such as bearings, cams, spindles, gears, and punches due to their enhanced strength and wear resistance [36]. These parts often operate close to their physical limits, making it essential for the workpiece materials to possess high indentation hardness (greater than 45 HRC), superior wear resistance, and excellent toughness to ensure reliable functionality [37]. Additionally, the dimensions of these parts are significant, as in certain cases, achieving the required hardness through HT may not be feasible. For optimal HT process, parts should ideally have a small length-to-diameter (L/D) ratio. According to ISO 3685, the L/D ratio should not exceed 4:1 for unsupported workpieces and 8:1 for supported workpieces [9]. Generally, an aspect ratio of 10:1 is recommended for effective HT [38]. In the recent study, AISID2 steel workpieces with a length of 150 mm and a diameter of 30 mm (L/D ratio of 5:1) were selected and air-hardened to a hardness of 61±1 HRC, as shown in Figure 4a [17]. For effective HT, the workpiece material must have a minimum hardness of 45 HRC. The HT is commonly performed on hardened steels with hardness levels around 60 HRC or even higher. From a metallurgical perspective, materials with a hardness within ±2 HRC deviations are essential for achieving predictable process outcomes [11]. Therefore, AISI 52100 bearing steel, with a hardness of approximately 58±2 HRC, was selected to investigate the resulting temperature effects [39]. Similarly, the impact of surface integrity was studied for AISI 5140 steel with a hardness of around 57±1 HRC [40]. Variations in workpiece material hardness can lead to differences in the shearing process and chip formation during HT [41]. Heating metals to high temperatures often results in rapid oxidation, which is undesirable. To prevent this, it is preferable to use a vacuum furnace, which removes oxygen by evacuating the loading chamber. This method also ensures uniform heating and controlled cooling. The high-performance vacuum furnace was deemed suitable for the study, as it supports a wide range of heat treatments, as shown in figure 4b [17].

The evaluation clearly shows that the hardness of the material significantly impacts the surface integrity of the parts produced [42, 43]. Additionally, the material's hardness influences the residual stresses generated during processing [44, 45]. Hardness also plays a critical role in the material's flow stress properties [46]. Beyond material hardness, factors such as cutting speed and feed rate have a considerable effect on surface finish, as demonstrated in Figure 4c, and contribute to reducing surface roughness to below 1 µm, as shown in Figure 5 [47]. Furthermore, the influence of hardness on microstructural changes has been studied extensively [48].


a) b) c)

Fig. 4. a) Air-hardened AISI D2 workpieces; b) COFI SPA Vacuum furnace; c) hard-turned AISI D2 punches [9]



E.length Cutoff X 5
Free 8 (mm)
V.mag. 2000
H.mag. 20
Cutoff 0.8 (mm)
Speed 0.1 (mm/s)

Cutoff 0.8mm
E.length 4.000mm
S.length 0.800mm

Ra	0.22um
Rz	0.91um
Ry	1.05um
Rv	0.47um
Rq	0.25um
Rsk	0.3076
Rku	1.8993
Rdq	0.0455
RSm	0.080mm
Rk	0.62um
Rvk	0.10um
Rpk	0.22um
Mr2	96.3%
Mr1	23.5%

Fig. 5. Surface roughness measured by Surfcorder SE3500
(Part = AISI D2 Punches, R_a=0.22µm, Cutoff length = 0.8mm)

Recently, high-hardness, tough hot-working tool steel (approximately 62±1 HRC) was investigated to assess its mechanical properties under the influence of deep cryogenic treatment [49].

Deep cryogenic treatments reduce the content of retained austenite in H13 steel, promoting the formation of homogeneously dispersed carbide precipitates. This distribution of carbides significantly enhances the toughness of the steel.

Additionally, the cryogenic treatment, combined with more severe quenching, increases the overall volume fraction of carbides, contributing further to the improvement in the material's mechanical properties.

Most studies emphasize that material hardness is just as critical as other mechanical properties [50-52]. Additionally, for effective HT, the aspect ratio of the workpiece should be carefully considered.

3.3. Cutting Inserts

The development of cutting tool materials is a critical aspect of metal-cutting processes [53]. However, this area also faces significant challenges and limitations that must be addressed to improve efficiency and performance. The materials developed should be wear-resistant, tough, and chemically stable. Super-hard materials, such as CBN, have been identified as key factors in the success of the HT process. When selecting a cutting tool for hardened steels, it is essential to consider characteristics like high hot hardness, thermal conductivity, wear resistance, and both physical and chemical stability [54]. As a result, cemented carbide tools [55], ceramics [56], PCBN [57], and CBN inserts [58] are commonly used in HT. Generally, hot hardness and wear resistance are directly proportional, while toughness is inversely proportional for most cutting tool materials [59].

In HT, high-speed steel (HSS) is generally unsuitable for machining hard materials due to its poor hot hardness, with a maximum working temperature of around 500°C [60]. Cemented carbide tools, on the other hand, are sintered to achieve superior hot hardness and toughness. Despite these advantages, degradation of cemented carbide begins at the cobalt binder, as the cohesion between tungsten carbide and cobalt increases brittleness, leading to edge chipping [61]. As a result, the use of cemented carbide tools in HT is limited due to premature tool failure. Polycrystalline diamond (PCD) is known for its exceptional hardness, but it is not suitable for HT of ferrous alloys. At elevated temperatures, carbon atoms from the PCD can diffuse and deposit onto the removed chips, as illustrated in figure 6.

As the hardness of the workpiece material increases, the hot hardness of the tool material tends to decrease, making the machining process more vulnerable over time [62]. Ceramics, while not as tough as CBN, are typically not preferred for applications requiring high precision, such as those with tolerances around ±0.025 µm. Additionally, ceramics are unsuitable for discontinuous cuts and cannot be used with coolants due to the risk of thermal shock and subsequent thermal damage. However, ceramics perform better than CBN for continuous cuts when machining case-hardened materials. Although ceramics do not offer the same level of wear resistance as CBN, they tend to wear gradually over time, rather than chipping or breaking [11].

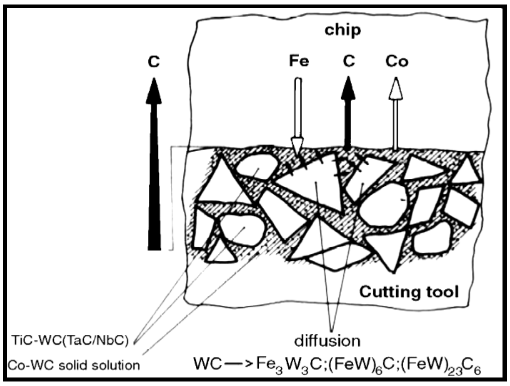


Fig. 6. Material diffusion at the interface tool-workpiece [62]

CBN is recognized as a highly effective tool material compared to other common cutting tool materials [63]. Metal-cutting industry trends have consistently focused on achieving continuous improvements in part performance and reducing processing costs, all while adhering to environmental regulations [64]. Since its introduction in the late 1970s [65], CBN tools have undergone significant advancements. Known for their superior mechanical, thermal, physical, and chemical properties, these tools have transformed HT machining. CBN is produced by synthesizing Boron and Nitrogen into a ceramic compound called Boron Nitride (BN), which in its hexagonal form is known as Hexagonal Boron Nitride (HBN). Through high-temperature and high-pressure processes, Hexagonal Boron Nitride (HBN) is transformed into its cubic form, known as CBN [66]. CBN stands out in HT applications, as it can be customized using a diverse range of mono-crystalline grains. This versatility is achieved by varying factors such as grain size, solvent or catalyst types, binder phase conditions, sintering grades, and particle size distribution.

CBN can be synthesized with or without the addition of inert ceramics and metallic or non-metallic fillers. These compositional variations significantly influence the mechanical, physical, chemical, and thermal properties of CBN tools [54]. Polycrystalline Cubic Boron Nitride (PCBN) tools are produced by sintering polycrystalline CBN grains, which are combined with metallic binders like cobalt and ceramics such as TiC, TiN, or other materials [67]. As the second hardest material after natural diamond [68], CBN outperforms coated and uncoated carbide inserts in machining hardened steels with the HT process. Additionally, CBN inserts have demonstrated superior performance compared to cryogenically treated coated and uncoated carbide tools. Consequently, both CBN-coated and non-coated inserts have become established and proven solutions for HT machining applications [69]. The physical properties of CBN are presented in Table 2 [70].

Table 2. Physical Properties of CBN [70]

S. no.	Properties	Values
1	Density [g/cm^3]	3.12
2	Young’s Modulus [GPa]	680
3	Modulus of Rigidity [GPa]	279
4	Poisson’s Ratio	0.22
5	Compressive Strength [MPa]	3,800
6	Transverse Rupture Strength [MPa]	800
7	Thermal Conductivity (W/m/K]	100
8	Thermal expansion [mm/°C]	4.9 x 10^{-6}

Consequently, CBN was chosen for precision HT in the recent study [71] due to its exceptional properties, including high hardness, superior wear resistance, excellent red-hot hardness (physical stability), and stable cutting performance without chemical diffusion [72]. High CBN content inserts, containing around 90% CBN, exhibit greater hardness and toughness compared to lower-content inserts with approximately 50% CBN. As a result, high CBN content tools are typically recommended for machining interrupted surfaces. In lower-content CBN inserts, part of the CBN is replaced with a ceramic phase, impacting their performance characteristics. As a result, lower-content CBN inserts, while sacrificing some hardness and toughness compared to high-CBN content inserts, gain enhanced chemical stability. This stability is critical in preventing diffusive wear that can occur at high cutting temperatures, especially during finishing operations on continuous surfaces.

As shown in figure 7a, different grades of CBN cutting tool materials play a crucial role in HT machining. Each grade has specific advantages and limitations; for example, CB7015 inserts are the preferred choice for finishing operations on continuous surfaces of hardened steels with hardness above 45 HRC. The CB7015 inserts contain approximately 50% CBN, with the remainder being a ceramic phase, whereas CB7025 inserts contain 60% CBN, and CB7525 inserts contain 90% CBN, with the rest also being ceramic [73]. Inserts with lower CBN content provide a superior surface finish compared to higher CBN content inserts, mainly due to their greater chemical stability [74]. Generally, CBN exhibits higher brittleness and lower toughness than most other cutting tool materials, except natural diamonds [59]. This brittleness makes CBN inserts prone to chipping or fracturing, which is a common issue in HT machining. To address this, it is essential to reinforce the micro-cutting edge geometry of CBN inserts to minimize tool wear and extend tool life. This requires specialized edge preparation to enhance the strength of the micro-cutting edges [42]. As depicted in Figure 7b, various forms of micro-cutting edge geometries commonly used in CBN inserts significantly influence the performance of the HT machining process.

To strengthen edge geometry and minimize the risk of premature fracture or chipping, especially under higher cutting parameters, CBN inserts are typically designed with honed or chamfered edges. Additionally, nose radii are crucial, along with micro-cutting edge enhancements, to improve the overall strength of the insert. This results in satisfactory surface integrity of the machined parts [44]. For lower CBN content inserts, both chamfered and honed edges provide improved tool life. However, for higher CBN content inserts, honed cutting edges are preferred. The honed edge increases the contact area between the insert and the workpiece, enhancing tool life even in interrupted cutting conditions [75].

However, inserts with a larger honed edge radius tend to increase surface roughness due to the intensified ploughing effect. It has also been observed that inserts with a smaller honed edge radius generate lower cutting forces compared to those with chamfered edges [76]. Additionally, inserts with a larger honed edge radius can produce more compressive stresses and may lead to WL formation [25]. Generally, chamfered edges result in higher cutting forces than honed edges [77]. Furthermore, cutting speed has a more significant impact on flank wear than feed rate for both chamfered and honed-edge inserts. Inserts with a variable honed edge outperform standard honed edges (conventional) by reducing heat generation at the cutting edge, thanks to the increased contact area between the insert and the workpiece.

As a result, variable honed edge inserts help reduce tool wear and lower plastic strain on the machined surface [78]. However, they are more time-consuming and costly to produce compared to standard honed edges. Studies have shown that wiper edge inserts provide better-bearing properties to the machined surface than honed edge inserts, particularly at higher feed rates [79]. Despite this advantage, the tool life of wiper edge inserts is less favourable. In contrast, honed-edge inserts increase tool life, even though they generate higher friction at the secondary edge due to the unfavourable chip thickness-to-cutting-edge radius ratio [12]. Additionally, asymmetric honed edge inserts have been found to impact tool wear and overall tool life [80]. Nonetheless, honed edge inserts are generally preferred for HT machining, as they enhance both surface integrity and tool life [81].

Recent studies indicate that excellent surface integrity can be achieved using CB7015 grade, low-content honed edge CBN inserts with a 0.8 mm nose radius [17]. Coatings have played a crucial role in enhancing the performance of CBN inserts since their introduction. Commonly used coatings include TiN, TiCN (applied through both CVD and PVD methods), TiC, Al2O_3 (CVD), and TiAlN (PVD). These coatings have become essential in modern cutting tool materials, as depositing hard, wear-resistant layers significantly extend tool life by minimizing wear [72]. Effective hard coatings must exhibit strong adhesion to the substrate and maintain high chemical stability with the workpiece material, even under elevated temperatures.

Coatings are therefore considered one of the most critical factors in enhancing wear resistance, significantly extending the life of CBN inserts [82]. It has been observed that CBN-TiN-coated inserts exhibit reduced flank wear during dry and near-dry HT machining compared to wet conditions [83]. This improvement is attributed to the lubricity of the TiN capping layer, which reduces crater wear on the CBN substrate through its ceramic phase properties [84]. Additionally, low-content CBN inserts coated with TiN/Al2O3/TiCN have demonstrated reduced tool wear compared to high-content CBN inserts with the same coatings, especially at higher cutting speeds. This is because low-content CBN inserts have lower thermal conductivity, which helps in managing heat more effectively during machining.

The low thermal conductivity of low-content CBN inserts increases cutting temperatures, causing thermal softening of the work material. This softening makes material shearing easier at high cutting speeds. Additionally, low-content CBN inserts with the same coatings achieve a good surface finish due to their higher chemical stability, which prevents diffusion wear. Both low and high-content CBN inserts primarily experience abrasion and adhesion as the main wear mechanisms [85]. Recent studies have demonstrated that CBN-TiN coated inserts outperform uncoated CBN inserts in the HT of M2 die steels, proving to be more effective and cost-efficient [86]. Overall, factors such as CBN content and grade, micro-cutting edge geometry, nose radius, ceramic coatings, and machining parameters are critical in achieving efficient HT machining performance.

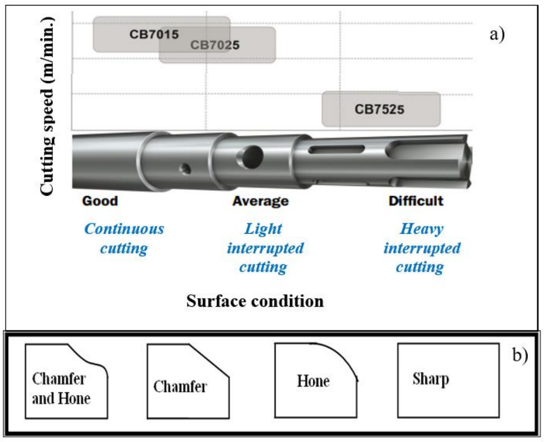


Fig. 7. a) Cutting speed vs. surface condition and appropriate insert grades [73]; b) Micro-cutting edge geometry of CBN Inserts [35]

3.4. Machine Tools

Achieving precise dimensional accuracy, geometric tolerances, and surface quality in HT is challenging, as these factors are heavily influenced by the rigidity of the machine tool [11]. This is often cited as one of the limitations of the process. It has been emphasized that improving rigidity and damping characteristics is crucial for turning centres, and this can be achieved by integrating additional features. Key features such as a polymeric composite reinforced machine base and direct-seating collected spindles significantly enhance system rigidity, as illustrated in Figure 8a and Figure 8b. A direct-seating collected spindle places the main spindle bearing as close as possible to the workpiece, minimizing overhangs and eliminating the need for shims and spacers. The goal is to ensure the entire setup remains stable and firmly supported by the turret, optimizing machining accuracy and stability [9].

The integration of a linear ball guide system and hydrostatic guideways is designed to improve anti-friction performance, eliminating the possibility of the stick-slip effect and ensuring precise positioning. The linear ball guide system is driven by a low-inertia, high-speed servo motor, controlled by a servo controller and linear transducer, which enables positional feedback control in the drive system [87]. Recent technological advancements have significantly enhanced the performance of existing machine tools. As a result, the accuracy and precision of the machining system have improved considerably, enhancing the effectiveness of HT [62]. A recent study has demonstrated that the stability and robustness of a high-precision prototype lathe greatly improve surface integrity, including surface roughness [88].

As previously discussed, a rigid, accurate, and precise machining system is essential for performing HT effectively. Therefore, machine tools that are exceptionally stiff, accurate, and precise are critical for HT. One such system is the JOBBERXL High-Speed CNC Turning Centre, as shown in Figure 9.

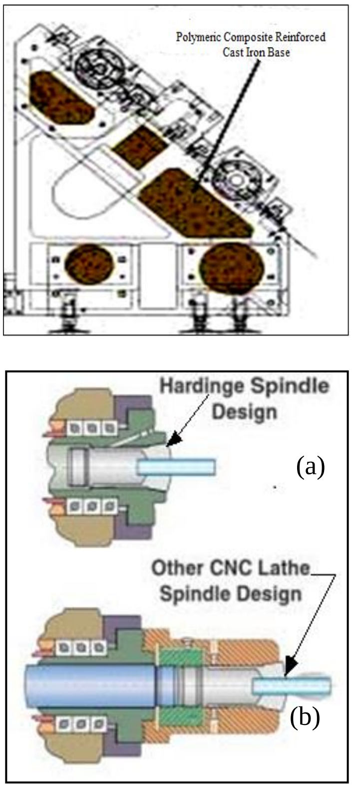


Fig. 8. a) Machine base with Polymer Composite Reinforced Cast Iron Base [9]; b) Direct-Seating Collected Spindle [9]

Since CBN cutting tools are brittle, tough, and prone to chipping, it is recommended that machine tools provide higher rigidity for both work holding and tool holding. Additionally, system vibrations and chatter marks are significant drawbacks, as they negatively impact part quality and the performance of the cutting tools [89]. Cutting tools are often identified as a major source of error in the machining process [90]. Significant issues, such as tool wear, elevated cutting temperature, and increased cutting force, are observed as key process outcomes, which adversely impact surface integrity. Consequently, these factors are believed to contribute to dimensional deviations, circularity errors, cylindricity errors, and parallelism issues in HT components [91]. Effective control over major error-driving factors has significantly improved the dimensional accuracy, geometric tolerance, and surface finish of the parts produced [92]. Enhanced surface finish and reduced tool wear are achieved with exceptional damping and extraordinary stiffness provided by the polymeric concrete bed [93]. However, it is important to note that residual stresses are influenced by high stiffness and spindle speeds [94]. Additionally, machining parameters, particularly extreme spindle speeds and power, have a direct impact on tool life and surface finish [95].

Fig. 9. JOBBER$_{XL}$ High-speed CNC Turning Centre

Surface textures generated in HT are found to be superior to those produced by conventional grinding, especially when using a precision CNC turning centre such as the Genos L200E-M [96]. A recent study on surface integrity optimization has demonstrated that grinding can be replaced by HT using CBN tools. Moreover, the precision CNC lathe Romi Centre 30D, with a total power of 10/7.5 kW and spindle speeds ranging from 4 rpm to 4000 rpm, achieved significant reductions in machining time and costs [97]. Ultimately, it is crucial to have a machine tool with excellent stability, rigidity, overhang-free workpieces, and a table free from the stick-slip effect. Features such as precise position control, feedback control, and an appropriate range of spindle rotations and power are essential for ensuring high-quality parts.

3.5. Machining Parameters and Machining Conditions

The performance of Cubic Boron Nitride (CBN) cutting tools is significantly affected by various cutting parameters, including cutting speed, feed rate, and depth of cut [54]. Cutting speed and depth of cut have a pronounced impact on tool life, as higher speeds and greater depths can accelerate tool wear [98]. As cutting speed increases, the temperature at the machining zone rises, influencing tool durability and potentially affecting the material removal process [35]. Furthermore, increased depth of cut contributes to accelerated tool wear, reducing tool longevity [74]. Additionally, feed rate variations can alter the workpiece surface's residual stress state, transitioning from compressive to tensile stresses, which is a critical aspect of surface integrity. Feed rate is also a key determinant of surface finish quality [99]. Most research on HT has examined a cutting speed range of 100 m/min to 250 m/min [100]. Specific investigations, for example, have explored speeds from 50 m/min to 250 m/min and feed rates between 0.04 mm/rev to 0.2 mm/rev to study surface finish using solid lubricants [101]. Commonly researched combinations of machining parameters, workpiece materials, and tool materials for HT are presented in Table 3 [12], reflecting the standard setups used in experimental studies to optimize outcomes for high precision and efficiency.

The surface integrity characteristics of hardened steel have been analyzed using semi-worn CBN inserts across a cutting speed range of 30 m/min to 260 m/min, with a constant feed rate of 0.08 mm/rev and a depth of cut of 0.08 mm, under wet cooling conditions [102]. Similarly, research aimed at enhancing fatigue life was performed using gas cooling and dry conditions, employing cutting speeds between 110 m/min and 210 m/min, maintaining a feed rate of 0.15 mm/rev and a depth of cut of 0.1 mm [103]. Furthermore, certain studies have extended beyond these specified ranges, exploring the influence of even higher cutting speeds and their effects on the surface and subsurface properties of machined components.

Table 3. Workpiece materials, cutting tool materials and cutting parameters used in various investigations

Workpiece Materials	Tool Materials	Cutting Speed	Feed Rate	Depth of Cutting
AISI52100, AISI 4340, D2, D13 steels etc. hardened up to 60 HRC (approx.)	CBN (low and high content), Uncoated or coated CBN, ceramics. Coated ceramics and carbide are also used in some cases	100 m/min to 400 m/min	0.05mm/rev to 0.2 mm/rev	up to 0.2 mm

It is observed that cutting speeds in the range of 280 m/min to 350 m/min are typically not recommended for industrial applications due to several detrimental effects, including high tool wear rates, increased vibrations, excessive sparking, and overall instability in the machining system under dry conditions [104]. Consequently, HT often requires a lower feed rate and depth of cut to mitigate cutting resistance and ensure stable machining. Moreover, while an increase in cutting speed tends to improve the surface finish, the feed rate remains the most significant factor influencing surface quality. The depth of cut, on the other hand, has the least impact on surface finish when dry machining is employed [105]. In recent studies, the Taguchi method has been used to determine optimal cutting parameters, with selected ranges for cutting speed between 55 m/min and 122 m/min, feed rates from 0.1 mm/rev to 0.3 mm/rev, and depths of cut from 0.05 mm to 0.15 mm. These parameters were chosen to optimize surface finish while maintaining efficiency and tool longevity.

The approach using optimized cutting parameters was found effective, showing satisfactory results in terms of surface roughness, cutting force, and cutting temperature under dry machining conditions [106]. A central composite design methodology was also applied to select suitable cutting parameters, with cutting speeds ranging from 129.55 m/min to 230.45 m/min, feed rates from 0.05 mm/rev to 0.18 mm/rev, and depths of cut between 0.05 mm and 0.25 mm. This method identified that lower cutting parameter values optimized surface integrity for AISI 4317 steel in dry conditions [97]. In a similar study aimed at enhancing surface integrity and eliminating the WL, researchers experimented with cutting speeds from 90 m/min to 280 m/min, feed rates between 0.08 mm/rev and 0.20 mm/rev, while maintaining a constant depth of cut of 0.1 mm. These investigations highlight the importance of carefully selecting cutting parameters to improve machining performance and achieve desired surface characteristics.

Recent studies have demonstrated that surface integrity can be significantly enhanced, with the effective elimination of WL formation, when using gas coolant [107, 108]. More recently, an optimization and cost analysis compared the performance of TiCN-coated and cryogenically treated uncoated CBN inserts under dry conditions. These investigations were conducted with cutting speeds ranging from 150 m/min to 250 m/min, and feed rates between 0.05 mm/rev and 0.30 mm/rev, while maintaining a constant depth of cut of 0.1 mm [109]. The cutting parameters in these studies were carefully selected to remain within optimal ranges, which minimized issues like high tool wear rates, system vibration, excessive sparking, and instability. The research has offered comprehensive insights into crucial factors affecting HT, including cutting force, temperature, chip morphology, tool wear, surface roughness, microhardness, microstructure evolution, residual stress profiles, compositional changes, and effective WL removal. Collectively, these findings deepen the understanding of hard-turning complexities and underscore its significant impact on the quality and performance of machined components.

4. OPTIMISING HT PROCESS FOR SUPERIOR PERFORMANCE: A COMPREHENSIVE PERSPECTIVE

a) Process perspective: Traditionally, turning operations are executed from right to left. However, in HT, this conventional method can lead to severe chip jamming, reducing surface reliability and tool life. To overcome this, Prime HT recommends machining from left to right. This approach minimizes chip jamming, thereby improving surface finish reliability and extending tool life.

b) Work material perspective: Heating metals to high temperatures often causes rapid oxidation, which is undesirable. Vacuum furnaces are preferable for heat treatment since they remove oxygen from the chamber and provide uniform heating and controlled cooling. High-performance vacuum furnaces are particularly suitable, as they support a wide range of heat treatments and enhance material performance.

c) Cutting tool materials perspective: CBN is the preferred cutting tool material for HT due to its superior hardness, wear resistance, red hot hardness, and chemical stability. High-content CBN inserts (around 90% CBN) offer enhanced toughness and durability, making them ideal for turning interrupted surfaces. In contrast, lower-content CBN inserts (around 50% CBN) incorporate a ceramic phase that improves chemical stability, essential for avoiding diffusive wear at elevated temperatures, but these inserts sacrifice some hardness and toughness.

d) Cutting parameters perspective: for optimized HT performance, cutting speeds ranging from 100 m/min to 400 m/min, feed rates between 0.05 mm/rev and 0.2 mm/rev, and depths of cut from 0.05 mm to 0.2 mm are recommended. These parameters have been widely adopted by researchers to ensure safe and effective machining operations, providing a balance between productivity and tool longevity.

e) Machine tool perspective: The effectiveness of HT depends on using rigid, precise, and highly accurate machine tools. Examples include JOBBERXL, Hardinge CNC turning centres, and Okuma Genos L200E-M. These machines are engineered to deliver exceptional stiffness and precision. Recent studies have shown that using high-quality CBN tools on precision CNC lathes, such as the Romi Centre 30D, can optimize surface integrity and minimize machining time and costs, effectively replacing traditional grinding.

f) Machining conditions perspective: HT can be performed under a variety of conditions, including dry, near-dry, MVO, flood cooling, cryogenic cooling, and minimum volume cryogenics. Recent research has explored advanced cooling methods, such as using gas coolants and mixed gas coolants (e.g., Argon, CO_2, Helium, and combinations like Argon with CO_2 or Argon with Helium), promoting eco-friendly manufacturing practices.

g) Material hardness perspective: Select hardness levels and minimal deviations according to ISO standards, ensuring proper support to avoid instability. Hardness significantly affects outcomes like tool wear and surface finish.

This multi-faceted approach to HT ensures enhanced efficiency, reduced environmental impact, and improved overall machining performance.

5. CONCLUSIONS

This review comprehensively examines the research progress, and critical factors influencing the HT process, a sustainable and efficient alternative to traditional grinding for machining hardened steels. HT has shown transformative potential in reducing cycle times, costs, and energy consumption while maintaining exceptional part quality. Continued research focusing on innovations in cutting tool materials, real-time monitoring systems, and advanced cooling strategies will further refine the process and broaden its industrial applicability. The success of HT hinges on a well-orchestrated balance among material properties, cutting tool composition, machine tool stability, and optimized machining parameters. Selecting appropriate workpiece hardness, adhering to ISO standards, and minimizing deviations are pivotal for predictable performance. The use of CBN inserts, particularly with varying content levels tailored to either interrupted or continuous cuts, has demonstrated significant benefits in terms of wear resistance, stability, and tool life. Equally, machine tool rigidity, power stability, and precision controls are essential to counteract vibrations and ensure high-quality finishes. Optimal cutting parameters—such as cutting speed, feed rate, and depth of cut—must be carefully calibrated to manage forces, heat, and chip formation, ultimately affecting surface integrity. Moreover, adopting the right machining conditions, including dry, near-dry, flood cooling, or cryogenic techniques, enhances performance while promoting environmental sustainability. Some of the points are given below:

- HT demands machines with high rigidity, minimal overhangs, superior control features, and adequate spindle power.
- Variations in cutting parameters impact chip morphology, affecting tool life and part quality.
- Material hardness variations substantially influence machining outcomes, including surface integrity.
- Coatings such as TiN, Al_2O_3, and TiCN enhance tool life, particularly at higher speeds.
- Asymmetric honed edges can influence wear mechanisms, impacting tool performance.
- The use of gas coolants, such as mixed gases, enhances fatigue life and prevents WL formation, supporting advanced, environmentally friendly machining practices.

6. FUTURE RESEARCH DIRECTIONS

The research in HT may focus on several crucial areas to advance the understanding and performance of this process. Firstly, the development of novel cutting tool materials, coatings, and geometries will be essential for enhancing tool life and surface finish, especially when machining hard-to-cut materials. Researchers could explore advanced ceramics, hybrid coatings, and optimized cutting-edge designs that resist wear and thermal degradation. Furthermore, the implementation of intelligent machining systems, leveraging real-time monitoring and data-driven approaches like machine learning, could be explored to predict tool wear, optimize process parameters, and ensure consistent part quality.

REFERENCES

[1] **Stier J. H.,** *The Rewards & Demands of Hard-Part Turning,* Modern Machine Shop, 1988, pp. 495-502.

[2] **Salah R.A., Richard L. C.,** *Experimental study on the performance of super finish hard turned surfaces in rolling contact*, Wear, vol. 244, no. 1-2, 2000, pp. 52–59.

[3] **Matsumoto, Y., Barash, M.M., Liu, C.R.,** *Residual stress in the machined surface of hardened steel*, High-Speed Machining ASN, 1984, pp.193–204.

[4] **Liu, C.R., Mittal, S.,** *Single step super-finish hard machining, feasibility & feasible cutting conditions*, Robotics & Computer-Integrated Manufacturing, vol. 12, no. 1, 1999, pp.15-27.

[5] **Tonshoff H. K., Hetz F.,** *Surface integrity of difficult to machine material*, 2nd IMEC Session II, 1986, pp. 120-136.

[6] **Chryssolouris G.,** *Effects of machine-tool-workpiece stiffness on the wear behavior of super hard cutting materials*, Annals of the CIRP; vol. 31, no. 1, 1982, pp. 65-69.

[7] **Sheehy T.,** *Taking the hard out of hard turning,* Manufacturing Engineering SME, vol. 118, no. 3, 1997, pp. 100-106.

[8] **Devitt A. J.,** *Sliding-way design primer*, Manufacturing Engineering SME, vol.119, 1998, pp. 68-74.

[9] **Soroka D. P.,** *Hard Turning and the Machine Tool,* Hardinge Inc., One Hardinge NY, 2011, 14902607378-4423.

[10] **Konig W., Komanduri R., Tonshoff H. K., Ackershott G.,** *Machining of hard material,* Annals of the CIRP, vol. 33, no. 2, 1984, pp. 417-427.

[11] **Derek, K.,** *Hard-turning-might-not-be-as-hard-as-you-think,* Modern Machine Shop, 2004, Article: 8-16-2004.

[12] **Bartarya, G., Choudhury, S.K .,** *State of the art in hard turning,* Int J Machine Tools & Manuf, vol.53, no. 1, 2012, pp.1-14.

[13] **Steven, Y.L., Morris, M.B.,** *The Technology Assessment on Current Advanced Research Projects in the area of Hard Turning,* The George. W. Woodruff School of Mechanical Engineering Georgia Institute of Technology, Atlanta, USA, The Association for Manufacturing Technology, 2006.

[14] **Hardinge Inc.,** available at http://www.superprecision.com/hardturn_grind.html, 2005.

[15] **Reisner S.,Vogt B.,** *Process converted from grinding to hard fine turning,* Industrial Diamond Review A, vol.3, no. 62, 2003, pp. 63-65.

[16] *Jawahir, I.S. Brinksmeier, E. M'Saoubi, R. Aspinwall, D.K. Outeiro, J.C. Meyer, D. Umbrello, D., Jayala, A.D., Surface integrity in material removal processes: Recent advances,* CIRP Annals-Manufacturing Technology vol.60, 2011, pp. 603–626.

[17] **Girisankar S., Omkumar, M.,** *A Study on the Efficacy of Hard Turning (HT) Process in enhancing the Surface Reliability by White Layer elimination using CBN inserts under Protective gas mixture atmosphere,* Journal of the Chinese Society of Mechanical

Engineers, Vol.39, no. 2, 2018, pp. 233-244.

[18] **Meyer R. Köhler J., Denkena B.,** *Influence of the tool corner radius on the tool wear & process forces during hard turning,* Int J Adv Manuf Tech, vol. 58, 2012, pp. 933– 940.

[19] **Hu H. J., Huang W. J.,** *Studies on wears of ultrafine-grained ceramic tool & common ceramic tool during hard turning using Archard wear model,* Int J Adv Manuf Tech, vol. 69, 2013, pp.31–39.

[20] **Sridhar A. Palanikumar, K., Durgaprasad B.,** *Experimental Investigation & Surface roughness Analysis on Hard turning of AISI D2 Steel using Coated Carbide Insert,* Procedia Engineering, vol. 97, 2014, pp. 72 – 77.

[21] **Chowdhury N. T., Dhar, N. R.,** *Experimental analysis & modelling of tool wear & surface roughness in hard turning under minimum quantity lubricant environment,* International Conference on Industrial Engineering & Operations Management, 01- 22.2011, Kuala Lumpur, Malaysia, pp. 326-330.

[22] **Bordin A., Bruschi S., Ghiotti A.,** *The effect of cutting speed & feed rate on the surface integrity in dry turning of CoCrMo alloy,* Procedia CIRP, vol.13, 2014, pp. 219 – 224.

[23] **Diniz A.E., Micaroni R.,** *Influence of the direction & flow rate of the cutting fluid on tool life in turning process of AISI 1045 steel,* Int J Machine Tools & Manuf, Vol.47, 2007, pp. 247-254.

[24] **Ghosh R., Zurecki Z., Frey J.H.,** *Cryogenic machining with brittle tools & effects on tool life,* Proceedings of ASME IMECE 11-2003, 42232, pp. 201-209.

[25] **Bushlya V., Zhou J. M., Lenrick F., Avdovic P., Ståhl J. E.,** *Characterization of White Layer Generated when Turning Aged Inconel 718,* 1st CIRP Conference on Surface Integrity (CSI), Procedia Engineering, Vol.19, 2011, pp. 60 – 66.

[26] **Javidi A., Rieger U., Eichlseder W.,** *The Effect of Machining on the Surface Integrity & Fatigue Life,* International Journal of Fatigue, vol.30, 2008, pp. 2050–2055.

[27] **Umbrello D.,** *Investigation of surface integrity in dry machining of Inconel 718,* Int J Adv Manuf Technol, vol. 69, no. 2, 2013, pp. 2183–2190.

[28] **Aramcharoen A., Mativenga P. T.,** *White layer formation and hardening effects in hard turning of H13 tool steel with CrTiAlN and CrTiAlN/MoST-coated carbide tools,* The International Journal of Advanced Manufacturing Technology, vol. 36, 2008, pp. 650-657.

[29] **Attanasio A., Umbhrello D., Capppellini C., Rotella G., M’Saoubi R.,** *Tool wear effects on white & dark layer formation in hard turning of AISI 521000 steel,* Wear, vol. 286-287, 2012, pp. 98-107.

[30] **Kaynak Y., Lu T., Jawhir I. S.,** *Cryogenic Machining-Induced Surface Integrity: A Review & Comparison with Dry, MQL, & Flood-Cooled Machining,* Machining Science & Technology, vol. 18, no.2, 2014, pp. 149-198.

[31] **Nath C., Kapoor S. G., DeVor R. E., Srivastava A. K., Iverson J.,** *Design & evaluation of an atomization-based cutting fluid spray system in turning of titanium alloy,* Journal of Manufacturing Processes, vol. 14, no. 4, 2012, pp. 452-459.

[32] **Klocke F., Settineri L., Lung D., Priarone C., Arft M.,** *High performance cutting of gamma titanium aluminides: Influence of lubricant strategy on tool wear & surface integrity,* Wear, vol. 302, no. 2, 2013, pp. 1136-1144.

[33] **Dureja J. S., Ranjit S., Talwinder S., Pargat, S., Dogra M., Manpreet S. B.,** *Performance Evaluation of Coated Carbide Tool in Machining of Stainless Steel (AISI202) under Minimum Quantity Lubrication (MQL),* International, Journal of Precision Engineering & Manufacturing-Green Technology, Vol.2, no. 2, 2015, pp. 123-129.

[34] **Ke Y. I., Dong H. Y., Liu G., Zhang M.,** *Use of nitrogen gas in high-speed milling of Ti-6Al-4V,* Transactions of Nonferrous Metals Society of China, Vol.19, no. 3, 2009, pp. 530-534.

[35] **Ozel T., Hsu T. K., Zeren E.,** *Effects of cutting edge geometry, workpiece hardness, feed rate & cutting speed on surface roughness & forces in finish turning of hardened AISI H13 steel,* Int J Adv Manuf Tech, vol. 25, no. 3, 2005, pp. 262-269.

[36] **Zhang J. Y.,** *Process Optimization for Machining of Hardened Steels,* Ph.D. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, USA, 2005.

[37] **Nakayama K., Arai M., Kanda T.,** *Machining characteristics of hard materials,* CIRP Annals, vol. 37, no. 1, 1998, pp. 89-92.

[38] **Dogra M., Sharma V. S., Sachdeva A., Suri N. M., Dureja J.S.,** *Performance evaluation of CBN, coated carbide, cryogenically treated uncoated /coated carbide inserts in finish-turning of hardened steel,* The International Journal of Advanced Manufacturing Technology, vol. 57, no. 5, 2011, pp. 541-553.

[39] **Shihab S. K., Khan Z. A., Mohammad A., Siddiquee A. N.,** *RSM Based Study of Cutting Temperature during Hard Turning with Multilayer Coated Carbide Insert,* Procedia of Materials Science, vol. 6, 2014, pp. 1233 – 1242.

[40] **Grzesik W., Zak K., Prażmowski M., Storch B., Pałka T.,** *Effects of cryogenic cooling on surface layer characteristics produced by hard turning,* Archives of Materials Science & Engineering, vol. 54, no. 1, 2012, pp. 5-12.

[41] **Konig W., Berktold A., Koch F.K.,** *Turning versus grinding – a comparison of surface integrity aspects & attainable accuracies,* Annals of the CIRP, vol. 42, no. 1, 1993, pp. 39-43.

[42] **Hodgson T., Trendler P. H. H., Michelletti G.F.,** *Turning hardened tool steels with Cubic Boron Nitride inserts,* Annals of CIRP, vol. 30, no. 1, 1981, pp. 63-66.

[43] **Chou Y. S., Barash M. M.,** *Review on hard turning & CBN cutting tools,* SME Technical Paper 1st International Machining Conference, 1995, vol. 95-214, pp. 951- 962.

[44] **Matsumoto Y., Hashimoto F., Lahoti G.,** *Surface integrity generated by precision hard turning,* CIRP Annals - Manufacturing Technology, vol. 48, no. 1, 1999, pp. 59-62.

[45] **Thiele J. D., Melkote S. N., Peascoe R. A., Watkins T. R.,** *Effect of cutting-edge geometry & workpiece hardness on surface residual stresses in finish hard turning of AISI 52100 steel,* ASME Journal of Manufacturing Science & Engineering, vol. 122, no. 4, 2000, pp. 642-649.

[46] **Guo Y. B., Liu C. R.,** *Mechanical properties of hardened AISI 52100 steel in hard machining processes,* ASME Journal of Manufacturing Science and Engineering, vol. 124, 2002, pp. 1-9.

[47] **Dureja J. S., Gupta V.K., Sharma V. S., Dogra M.,** *Design optimization of flank wear & surface roughness for CBN-TiN tools during dry hard turning of hot work die steel,* International Journal of Machining & Machinability of Materials, vol. 7, 2010, pp. 129-147.

[48] **Hongtao D., Shin Y. C.,** *Multi-Physics modelling & simulations of surface microstructure alteration in hard turning,* Journal of Materials Processing Technology, vol. 213, 2013, pp. 877-886.

[49] **Pérez M., Belzunce F. J.,** *The effect of deep cryogenic treatments on the mechanical properties of an AISI H13 steel,* Journal of Materials Science & Engineering A, vol. 624, 2015, pp. 32– 40.

[50] **Sampaul P., Varadarajan A. S., Mohanasundaram S.,** *Effect of magneto rheological fluid on tool wear during hard turning with minimal fluid application,* Archives of civil & mechanical engineering, vol. 5, no. 1, 2015, pp. 124 – 132.

[51] **Amad E. I .E., Mohammed H., Norizah R., Noordin M. Y., Kurniawan D.,** *Performance comparison between Dry & Nitrogen gas cooling when Turning Hardened Steel with Coated Carbide,* Applied Mechanics and Materials, vol. 735, 2015, pp. 65-69.

[52] **Pal A., Choudhury S. K., Chinchanikar S.,** *Machinability Assessment through Experimental Investigation during Hard & Soft Turning of Hardened Steel,* Procedia Materials Science, vol. 6, 2014, pp. 80 – 91.

[53] **Huang Y., Chou Y. K., Liang S.Y.,** *CBN tool wears in hard turning: a survey on research progresses,* Int J Adv Manuf Tech, vol. 35, no. 5, 2007, pp. 443-453.

[54] **Tonshoff H.K., Arendt C., Ben A. R.,** *Cutting of hardened steel,* Annals of the CIRP, vol. 49, no. 2, pp.1-19, 2000.

[55] **Buchkremer S., Klockea F., Döbbelera B., Abouridouanea M., Meurera M.,** *Thermodynamics-based interpretation of white layer formation in metal cutting,* Procedia CIRP vol. 58, 2017, pp. 370 – 374.

[56] **Varaprasad B. H., Srinivasarao C. H., Vinay P.V.,** *Effect of Machining Parameters on Tool Wear in Hard Turning of AISI D3 Steel,* Procedia Engineering, vol. 97, 2014, pp. 338 – 345.

[57] **Tao C., Suyan L., Bangxin H., Guangjun L.,** *Study on cutting force & surface micro-topography of hard turning of GCr15 steel,* Int J Adv Manuf Technol, Vol.72, no. 9, 2014, pp.1639–1645.

[58] **Umbrello D., Micari F., Jawahir I. S.,** *The effects of cryogenic cooling on surface integrity in hard turning; A comparison with dry machining,* CIRP Annals - Manuf Tech, vol. 61, no. 1, 2012, pp. 103-106.

[59] **Boothroyd G., Winston A. K.,** *Fundamentals of machining &*

machine tools, Marcel Deckor Inc, Second Edition, ISBN: 0-8247-7852-9 (Online), 1989.

[60] ****HSS Smart Guide*, available at www. hssforum. Com, 2010.

[61] **López de lacalle L. N., Lamikiz A., Fernández J., Azkona I.,** *Machining of hard materials- Advanced cutting tools,* http://www. Springer. com/ 978-1-84996-449-4, 2007, pp. 33-86.

[62] **Galoppi G. D. S., Filho M. S., Batallha G. F.,** *Hard turning of tempered DIN100Cr6 steel with coated & no coated CBN inserts,* Journal of Materials Processing Technology, vol. 179, no. 1, 2006, pp. 146-153.

[63] **Anuja B. B., Kirubakaran E., Ranjit J. T., Leo D. W. K.,** *Surface Roughness Prediction using Artificial Neural Network in Hard Turning of AISI H13 Steel with Minimal Cutting Fluid Application,* Procedia Engineering vol. 97, 2014, pp. 205-211.

[64] **Cook M. W., Bossom P.K.,** *Trends & recent developments in the material manufacture & cutting tool application of polycrystalline diamond & polycrystalline cubic boron nitride,* International Journal of Refractory Metals & Hard Materials, vol. 18, no. 2-3, 2000, pp. 147-152.

[65] **Chou Y. K., Evans C. J., Barash M. M.,** *Experimental investigation on CBN turning of hardened AISI 52100 steel,* Journal of Materials Processing Technology, vol. 124, no. 3, 2002, pp. 274-283.

[66] **Dogra M., Sharma V. S., Sachdeva A., Suri N. M., Dureja J. S.,** *Tool Wear, Chip Formation & Workpiece Surface Issues in CBN Hard Turning: A Review,* International Journal of Precision Engineering & Manufacturing, vol. 11, no. 2, 2010, pp. 341-358.

[67] **Xiaomin C.,** *Experimental & Numerical Approaches for Improving Rolling Contact Fatigue of Bearing Steel through Enhanced Compressive Residual Stress,* Ph.D. Thesis, Graduate School of The Ohio State University, Ohio, USA, 2007.

[68] **Lin Z. C., Chen, D. Y.,** *A study of cutting with a CBN tool,* Journal of Materials Processing Technology, vol. 49, no. 1, 1995, pp. 149-164.

[69] **Dogra M., Sharma V. S., Sachdeva A., Suri N. M., Dureja J. S.,** *Performance evaluation of CBN, coated carbide, cryogenically treated uncoated /coated carbide inserts in finish-turning of hardened steel,* Int J Adv Manuf Tech, vol. 57, no. 5, 2011, pp. 541-553.

[70] **Harish T. K., Brookes E. J., Taylor, C. J.,** *The effect of temperature on the hardness of polycrystalline cubic boron nitride cutting tool,* Journal of Refractory metals & hard materials, vol. 22, no. 2, 2004, pp. 105-110.

[71] **Jouini N., Revel P., Mazeran M., Bigerelle M.,** *The ability of precision hard turning to increase rolling contact fatigue life,* Tribology International 59, 2013, pp. 141–146.

[72] **Venkatesh V. C., Izman S.,** *Precision Engineering,* Tata Mc-Graw Hill Publishing Company Limited, New Delhi, 2007.

[73] **Sandvik Coromant,** *Main Catalogue,* www.coromant. sandvik.com, 2012.

[74] **Chou Y.K., Evans C. J., Barash M. M.,** *Experimental investigation on CBN turning of AISI 52100 steel*, Journal of Materials Processing Technology, vol. 134, 2003, pp. 1- 9.

[75] **Diniz A. E., DeOliveira A. J.,** *Hard turning of interrupted surfaces using CBN tools,* Journal of Materials Processing Technology, vol. 195, 2008, pp. 275-281.

[76] **Jeffrey D., Thiele J. D., Melkote S. N.,** *Effect of cutting edge geometry & workpiece hardness on surface generation in finish hard turning of AISI 52100 steel,* Journal of Materials Processing Technology, vol. 94, 1999, pp. 216–226.

[77] **Ozel T., Karpat Y., Srivastava A.,** *Hard Turning with Variable micro geometry PCBN tools,* CIRP Annals- Manufacturing Technology, vol. 57, no. 1, 2008, pp.73-76.

[78] **Karpat Y., Ozel T.,** *3D FEA of HT investigation of PCBN cutting tool micro geometry effect,* Transactions of NAMRI/SME, vol. 35, 2007, pp. 1–8.

[79] **Grezesik W., Wanat T.,** *Surface finish generated in HT of quenched alloy steel parts using conventional & wiper ceramic inserts,* Int J Machine Tools & Manuf, vol. 46, 2006, pp. 1988–1995.

[80] **Ventura C. E. H., Kohler J., Denkara B.,** *Cutting edge preparation of PCBN inserts by means of grinding & its application in hard turning,* CIRP Journal of Manufacturing Science & Technology, Vol.6, no. 4, 2013, pp. 246 – 253.

[81] **Hosseini S.B., Beno T., Klement U., Kaminski J., Ryttberg K.,** *Cutting temperatures during hard turning—Measurements & effects on white layer formation in AISI 52100,* Journal of Material Processing Technology, vol. 214, 2014, pp.1293–1300.

[82] **Quinto D.T.,** *Technology perspective on CVD & PVD coated metal-cutting tools,* International Journal of Refractory Metals & Hard Materials, vol. 14, 1996, no. 1–3, pp. 7- 20.

[83] **Diniz A. E., Ferreira J.,R., Filho F. T.,** *Influence of refrigeration /lubrication condition on SAE 52100 hardened steel turning at several cutting speeds,* Int J Machine Tools & Manuf, vol. 43, no. 3, 2003, pp. 317-326.

[84] **More A.S., Jiang W., Brown W. D., Malshe A. P.,** *Tool wear & machining performance of cBN–TiN coated carbide inserts & PCBN compact inserts in turning AISI 4340 hardened steel,* J Mat Process Technol, vol. 180, no. 1, 2006, pp. 253-262.

[85] **Kamely M.A., Noordin M. Y., Ourdjini A., Venkatesh V.C., Razali M. M.,** *Alternative low cost cutting tools for Hard turning of AISI D2,* Journal of Advanced Manufacturing Technology, vol. 2, 2008, pp. 29-37.

[86] **Girisankar S., Omkumar M.,** *Performance evaluation of hard turning for AISI M2 Die steel with coated and non-coated CBN inserts.* Applied Mechanics and Materials, vol. 766-767, 2015, pp. 594-599.

[87] **McKeown P. A.,** *The Role of Precision Engineering in Manufacturing of the Future,* CIRP Annals - Manufacturing Technology, vol. 36, no. 2, 1987, pp. 495-501.

[88] **Revel P., Jouini N., Thoquenne G., Lefebvre F.,** *High precision hard turning of AISI 52100 bearing steel,* Journal of Precision Engineering, vol. 43, 2016, pp. 24-33.

[89] **Davies M. A., Burns T. J., Evans C. J.,** *On the dynamics of chip formation in machining hard metals,* Annals of the CIRP, vol. 46, no. 1, 1997, pp. 25-30.

[90] **Zhou J. M., Andersson M., Sta°hl J. E.,** *Identification of cutting errors in precision hard turning process,* Journal of Materials Processing Technology, vol. 153–154, 2004, pp. 746–750.

[91] **Kundrak J., Karpuschewski B., Gyani K., Bana V.,** *Accuracy of hard turning,* Journal of Materials Processing Technology, vol. 202, 2008, pp. 328–338.

[92] **Bana V., Karpuschewski B., Kundrak J., Hoogstrate A. M.,** *Thermal distortions in the machining of small bores,* Journal of Materials Processing Technology, vol. 191, no. 3, 2007, pp. 335–338.

[93] **Bruni C., Forcellese A., Gabrielli F., Simoncini M.,** *Hard turning of an alloy steel on a machine tool with a polymer concrete bed,* Journal of Materials Processing Technology, vol. 202, 2008, pp. 493–499.

[94] **Caruso S., Umbrello D., Outeiro J. C., Filice L., Micari F.,** *An experimental investigation of residual stresses in hard machining of AISI 52100 steel,* 1st CIRP Conference on Surface Integrity (CSI), Procedia Engineering, vol. 19, 2011, pp. 67 – 72.

[95] **Suresh R., Basavarajappa S.,** *Effect of process parameters on tool wear and surface roughness during turning of hardened steel with coated ceramic steel,* International Conference on Advances in Manufacturing & Materials Engineering (AMME), Procedia Materials Science, vol. 5, 2014, pp.1450 – 1459.

[96] **Grezesik W., Zak K., Kiszka P.,** *Comparison of surface textures generated in hard turning & grinding operations,* 2nd CIRP Conference on Surface Integrity (CSI), Procedia CIRP, vol. 13, 2014, pp. 84 – 89.

[97] **Brancoa F. K., Delijaicova S., Bordinassia É. C., Bortolussia R.,** *Surface Integrity Analysis in the Hard Turning of Cemented Steel AISI 4317,* Materials Research. vol. 21, no. 5, 2018, e20171032.

[98] **Barry, J., Byrne, G.,** *Cutting tool wear in the machining of hardened steels,* Part II: CBN cutting tool wear, Wear, vol. 247, 2001, pp. 152-160.

[99] **Thiele, J.D., Melkote, S.N.,** *Effect of cutting edge geometry & workpiece hardness on surface generation in the finish hard turning of AISI 52100 steel,* Journal of Materials Processing Technology, vol. 94. no. 2, 1999, pp. 216-226.

[100] **Dessoly, V. Melkote, S.N., Lescalier, C.,** *Modelling and verification of cutting tool temperature in rotary tool turning of hardened steels,* International Journal of Machine Tools and Manufacture, vol. 44, 2004, pp. 1463–1470.

[101] **Singh D., Rao P.V.,** *Performance improvement of hard turning with solid lubricants,* The International Journal of Advanced Manufacturing Technology, vol. 38, no. 5, 2008, pp. 529 –535.

[102] **Hosseini S. B., Ryttberg K., Kaminski J., Klement U.,** *Characterization of the Surface Integrity induced by Hard Turning of Bainitic & Martensitic AISI 52100 Steel,* 5th CIRP Conference on

High-Performance Cutting, Procedia CIRP, vol. 1, 2012, pp. 494 – 499.

[103] **Kalam S. A., Azad A., Omkumar M., Giri S., Vajubunnisa Begum S. R.,** *Elimination of white layer formation during hard turning of AISI D3 steel to improve fatigue life,* IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) 12 (3), 07-14, 2015.

[104] **Yallese M. A., Chaoui K., Zeghib, N., Boulanouar L., Rigal J.,** *Hard machining of hardened bearing steel using cubic boron nitride tool,* Journal of Material Processing Technology, vol. 209, no. 2, 2009, pp. 1092–1104.

[105] **Suresh R., Basavarajappa S., Gaitonde V. N., Samuel G. L., Paulo Davim J.,** *State-of-the-art research in machinability of hardened steels,* Proc I Mech E Part B: J Engineering Manufacture, vol. 227, no. 2, 2018, 191–209.

[106] **Rajesh S., Veerapandian R., Madhan Kumar S., Hari Krishnan M., Vignesh T.,** *Experimental Determination and Optimization of Hard Turned Austempered Ductile Iron (ADI) With AL-TI-N Coated Carbide Insert,* International Journal of Applied Engineering Research ISSN 0973-4562, vol. 13, no. 11, 2018, pp. 9596-9600.

[107] **Girisankar S., Omkumar M.,** *Investigation on the hard turning in enhancing the surface reliability by white layer elimination using CBN semi-worn-out inserts under protective gas atmosphere,* Journal of the Mechanical Science and Technology, Vol.33, no. 5, 2019, pp. 2345-2352.

[108] **Girisankar S., Murugan S. S., Srinivasan S. P., Shankar E., Rajkumar A.,** *Hard Turning of AISI D4 Steel Under Dry Machining and Gas Cooling Attempt is made for the Elimination of White Layer and enhancement of Surface Finish,* National Academy Science Letters, vol.47, 2004, pp. 539–546.

[109] **Girisankar S., Dhandapani S., Rajkumar A., Muthiah C. T.,** *Optimization and cost comparison of Hard Turning with TiCN Coated and Cryogenically treated un-coated CBN Inserts,* AIP conference Proceedings, vol. 2395, no. 1, 2021, 040004-1 to 11.

ABBREVIATIONS

AISI: American Iron and Steel Institute
HT: Hard turning
HFT: Hard Finish Turning
DM: Dry machining
WL: White layer
CBN: Cubic boron nitride
GMC: Gas mixture cooling
MDPT: Mechanically driven phase-transformation
TMDPT: Thermo-mechanically driven phase-transformation
TDPT: Thermally driven phase-transformation
TMAZ: Thermally mechanically affected zone