International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V73I2P107

Volume 73 Issue 2, 73-91, February 2025

Review Article

Enhancing Hard Turning Performance: The Crucial Role of Cutting Parameters and Tool Geometry

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Received: 23 September 2024 Revised: 13 January 2025 Accepted: 23 January 2025 Published: 21 February 2025

Abstract *- Hard turning has emerged as a prominent alternative to traditional grinding due to its advantages, including improved productivity, flexibility, and cost efficiency. However, conventional machining techniques are ineffective for hard turning because of their unique challenges, rendering traditional turning theories inapplicable. Although numerous studies have explored the effects of cutting parameters and tool materials on hard-turning performance, a comprehensive understanding of this process remains limited. This paper provides a comprehensive and systematic analysis of how cutting conditions and tool geometry affect key performance characteristics in hard turning. It also discusses recent advancements in achieving smooth surfaces and compares the effectiveness of hard turning versus grinding, highlighting both economic and technical benefits. Additionally, the paper reviews advanced modeling and optimization techniques used in various studies. These insights offer valuable references for researchers and practitioners to optimize hard-turning processes, enhancing manufacturing efficiency and product quality.*

Keywords *- Hard turning, Cutting forces, Cutting temperature, Tool wear, Surface roughness.*

1. Introduction

Hard turning is a technique for machining parts made from ferrous materials with hardness greater than 45 HRC, including hard steels, bearing steels, high-speed steels, alloy cast iron, various alloy steels, and die steels. Hardened steels are favored in engineering applications due to their enhanced strength, fatigue strength, and wear resistance [1]. In the United States, the annual demand for hardened steel components, such as transmission shafts, roller bearings, crankshafts, gears, cutting tools, dies, molds, and various automotive parts, is valued at 30-35 billion USD [2].

These components are extensively utilized in energy generation, transportation, and other engineering applications. Hard turning is considered a highly promising technique for manufacturing hard materials. It has become popular for its ability to produce parts more quickly and cost-effectively by eliminating several steps typically required in traditional machining methods [3]. Figure 1 compares the process chains of conventional machining with hard turning. As shown in Table 1, hard-turning operations offer several advantages over traditional grinding. Hard machining provides more flexibility than grinding and can produce complex geometries in a single setup. Huang et al. [4] suggest that using hard turning to manufacture intricate parts can decrease production costs by up to 30%. The material removal rate in hard turning is 4–6 times higher than in grinding, which reduces the machining time by approximately 60% [5]. Additionally, hard turning is a more environmentally friendly process. Unlike grinding, which produces sludge that requires costly separation processes, hard turning generates chips that can be easily recycled. Moreover, hard turning is typically performed without coolants. The elevated temperatures in the cutting zone can cause immediate coolant boiling, which reduces tool life and can deteriorate the machined surface due to thermal distortions. Dry cutting in hard turning offers a distinct advantage, as the substantial heat generated leads to thermal softening of the workpiece material, making shear deformation easier. Consequently, coolant is generally not used in most hard turning operations, although its absence can reduce tool life and slightly diminish surface finish [6]. Despite these benefits, the limitations are often not highlighted in documents or research papers.

However, it is important for end-users to have a clear understanding of these aspects [7]. These are some limitations of hard turning: (1) Tooling costs are significantly higher than grinding costs, (2) Chatter can occur, especially when turning long and thin parts; the length-to-diameter (L/D) ratio generally should not exceed 4:1 for unsupported workpieces, (3) Specialized rigid machinery is often necessary for effective hard machining, (4) Surface quality declines as the tool wears, even when the tool is still within its operational lifespan, (5) The formation of residual stress, and white layers on the workpiece surface can negatively impact the overall machining performance. Turning hard materials requires techniques that differ significantly from those used in conventional turning. Much of the existing knowledge related to conventional machining may not be directly applicable to hard turning [7].

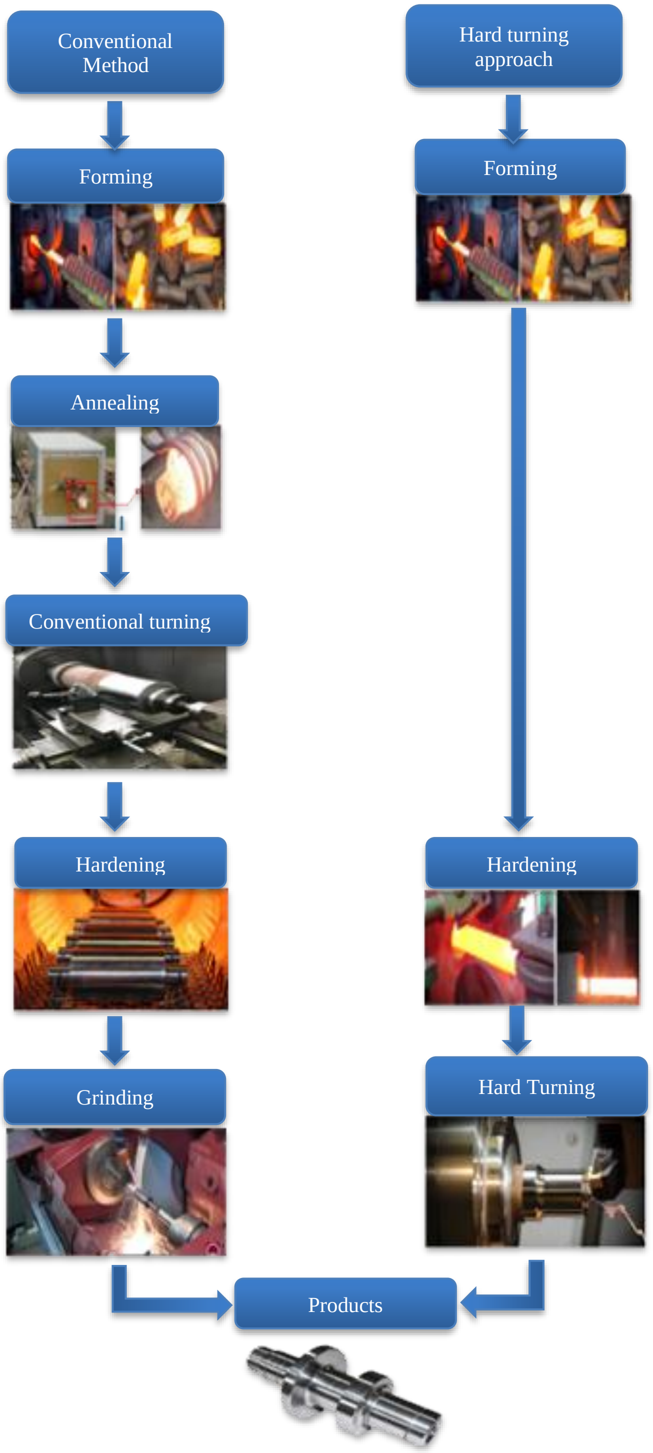


Fig. 1 Visual representation distinguishes between conventional and hard-turning machining methods

Table 1. Hard turning versus grinding

Parameter	Grinding	Hard Turning
Productivity	Comparatively Low	Comparatively High
Set-Up Time	More	Relatively Less
Operational Cost	High	Low
Flexibility	Low (Specialized Wheel Configuration Needed)	More Flexible
Accuracy	Better	Can Achieve Ra = 0.2 µm or less
Environment-Friendliness	Processing without lubrication is not viable	Machining Without the Use of a Cooling Fluid is Possible.
Maintenance	Cumbersome	Simple

Cutting tools used in hard turning must withstand the rigors of machining hardened materials, which involves high specific cutting forces and elevated cutting temperatures. These tools must possess exceptional hardness, thermal conductivity, wear resistance, and thermal stability. The primary tool materials employed in hard machining include sintered carbides, ceramics, and CBN. CBN is the most commonly used material among these materials due to its exceptional hardness, superior chemical stability, high thermal conductivity, and wear resistance at high cutting temperatures [8,9]. However, the high cost of CBN inserts has become a significant factor in assessing their economic viability. To establish hard turning as a viable alternative to grinding, it is essential to select process parameters (Figure 2) that are appropriate for the specific operation. The acceptable range of these parameters is narrower compared to conventional turning. Inadequate optimization of these parameters may result in reduced tool life, poor surface roughness, and other negative effects [10].

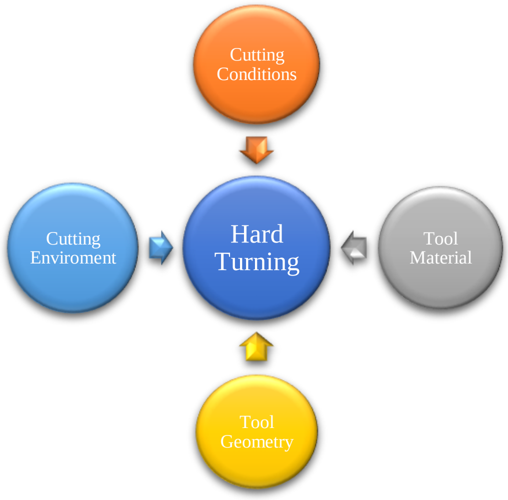


Fig. 2 Various process parameters in hard turning

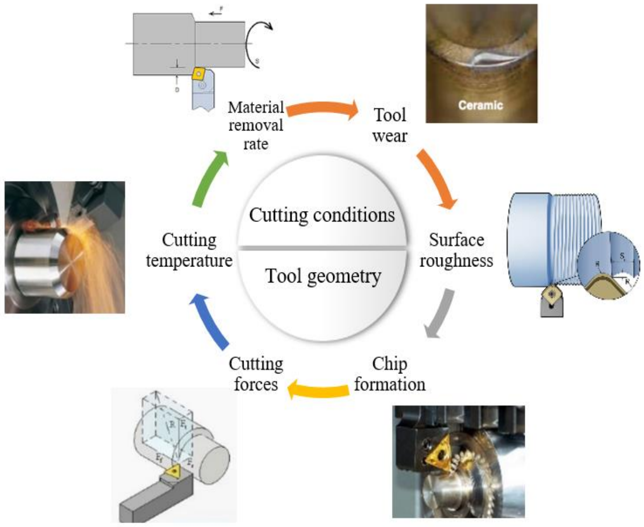


Fig. 3 The responses affected by cutting conditions and tool geometry

The effects of cutting conditions and tool geometry in hard turning are demonstrated in Figure 3. A comprehensive understanding of the impact of these parameters and their interactions on critical performance characteristics in hard turning is essential. These characteristics include cutting forces, cutting temperature, tool wear, surface roughness, and Material Removal Rate (MRR).

These are crucial for optimizing processes to achieve high productivity, good product quality, and low costs. In the turning process, MRR is calculated by multiplying the Cutting Speed (CS), Feed Rate (FR), and Depth of Cut (DOC). Consequently, it is essential to increase these three cutting conditions to enhance productivity. However, increasing these parameters is constrained because they significantly affect machining characteristics.

2. The Influence of Cutting Conditions for Hard-Turning

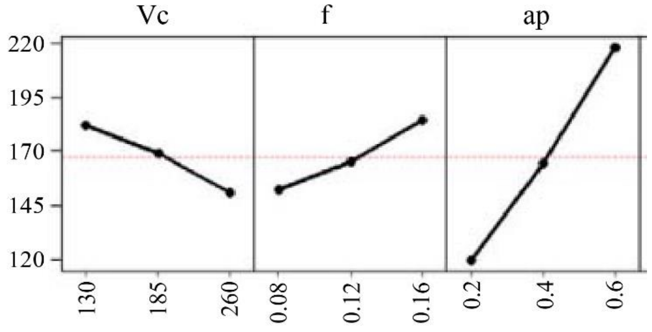
The selected cutting conditions significantly impact the efficiency of hard turning. Various aspects of hard turning have been examined by researchers, leading to the establishment of specific guidelines. Hard turning is a finishing operation that involves high-speed cutting with low FR and DOC.

Reported CSs typically range from 100 to 250 m/min [11-13]. Although some studies have reported even higher speeds [14], most adhere to this range to avoid stability issues. The recommended FRs range between 0.05 and 0.2 mm/rev, and the DOC does not exceed 0.2 mm.

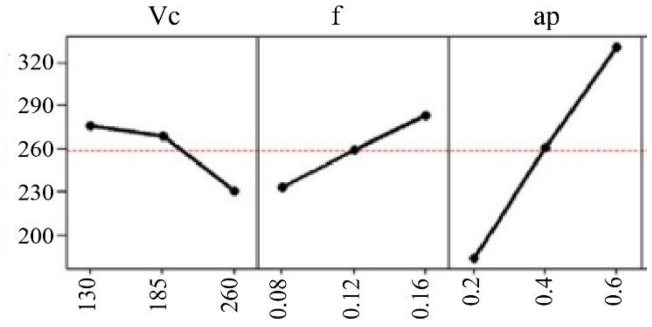
2.1. Influence of Cutting Conditions on Cutting Forces

Analyzing cutting forces can offer deeper insights into the machining process. In hard turning, radial (thrust) force was typically the largest force, followed by tangential (cutting) force, and then axial (feed) force [15-18]. This is due to the small DOC and the negative rake angle employed, which cause the majority of the cutting action to occur at the tool nose radius. Higher CSs often lead to lower cutting forces due to thermal softening of the workpiece material, reducing its shear strength. Conversely, increasing the DOC and FR expands the cutting area, resulting in higher resistance on the tool and greater cutting forces (Figure 4) [15,16], [19-21].

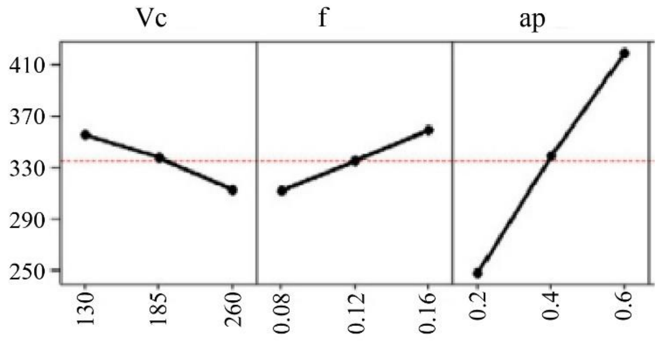
The DOC was identified as the most influential factor in cutting forces, followed by FR and CS [15,16]. Kumar et al. [21] concluded that cutting forces tend to escalate with higher workpiece hardness and that workpiece hardness significantly influences cutting forces, along with DOC and FR, while CS has a less pronounced effect.



(a) Feed force



(b) Tangential force



(c) Radial force

Fig. 4 The main effect of CS, FR and DOC on average force components [15]

2.2. Effects of Cutting Conditions on Cutting Temperature

Most of the energy from cutting forces during machining is converted into thermal energy [22,23]. This heat is mainly generated in three distinct regions: the shear zone (primary zone) due to plastic deformation of the workpiece material, the rake face (secondary zone) due to friction between the tool and chip, and the flank face (tertiary zone) due to friction between the tool and workpiece (Figure 5). Several factors influence heat generation in metal cutting, including the physical and chemical properties of the workpiece and tool materials, cutting conditions, and tool geometry. The elevated temperatures in the cutting zone, resulting from this heat generation, negatively impact the tool's strength, hardness, and wear resistance. Additionally, these high temperatures can reduce the ability to control dimensional accuracy and maintain desired surface integrity. Higher CSs result in more material being removed per unit of time, leading to increased friction and, consequently, higher cutting temperatures [24]. Moreover, high CSs lead to a higher strain rate in the shear zone, generating more heat and causing a temperature rise [25]. Although the influence of FR and DOC on cutting temperature is relatively minor, an increase in either will still lead to a rise in cutting temperature (Figure 6) [24], [26-29]. Elsadek et al. [26] examined the effect of workpiece hardness on cutting temperature. Their findings revealed workpiece hardness as the dominant factor (63.77%), followed by CS (16%), FR (4.78%), and DOC having the least influence. Additionally, Abrao et al. [27] and Kishawy [29] found that the heat generation correspondingly increased with tool wear progression.

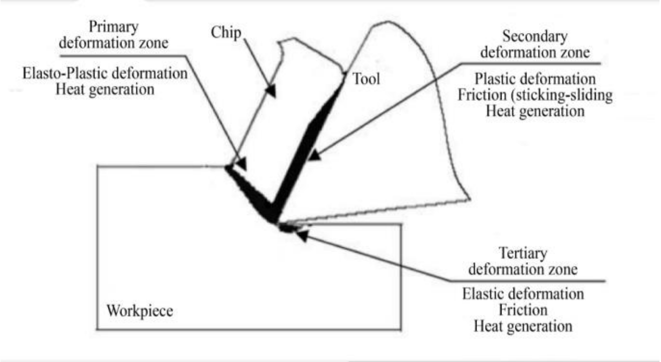


Fig. 5 Mechanisms of heat generation in the machining process [22]

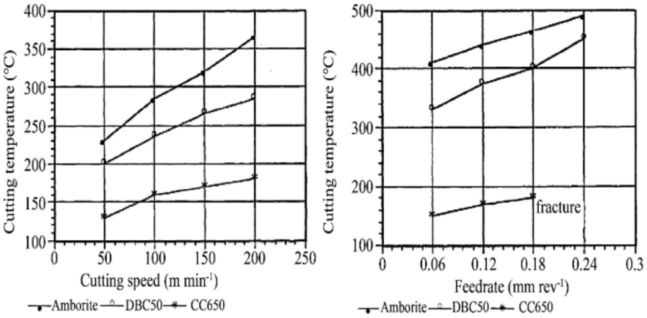


Fig. 6 Effect of cutting conditions on temperature [27]

2.3. Effects of Cutting Conditions on Tool Wear

Tool wear directly impacts dimensional accuracy, surface roughness, and tool life. Tools are subjected to intense forces and elevated temperatures during machining, contributing to tool wear. The primary mechanism driving tool wear in hard turning is the abrasion of the binder material by the hard particles in the workpiece [30-32]. Figure 7 illustrates the main types of tool wear observed in the hard-turning process, including flank wear, crater wear, and notch wear. In finishing hard turning, to ensure surface roughness, tool wear is typically restricted to a very narrow range, and flank wear criterion (VB=0.2 mm) is commonly used to assess tool life [31], [33].

The flank wear results in an enlarged contact zone with the workpiece, thereby increasing friction acting on the machined surface. This leads to a poorer surface finish. The relationship between cutting conditions and tool wear is complex. Generally, increasing these parameters leads to greater tool wear (Figure 8) due to elevated temperature and friction [15], [30-32], [35-44]. Among these factors, CS has the most significant impact because of the high CS and the small DOC and FR required in hard turning [30], [32], [36]. A study by Khamel et al. [32] identified that CS was the most influential factor, accounting for 89.83% of the variation in tool wear, followed by FR at 5.69% and DOC at 1.26%.

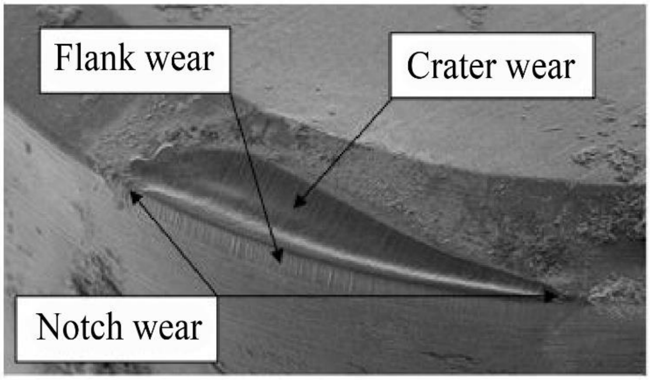


Fig. 7 The typical tool wear in hard turning [34]

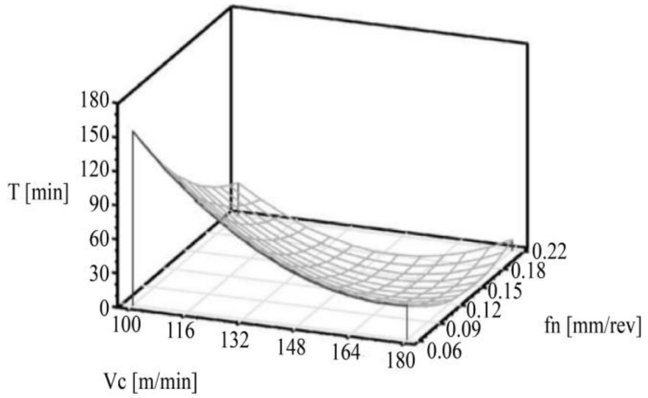


Fig. 8 Tool life response surface based on CS and FR [36]

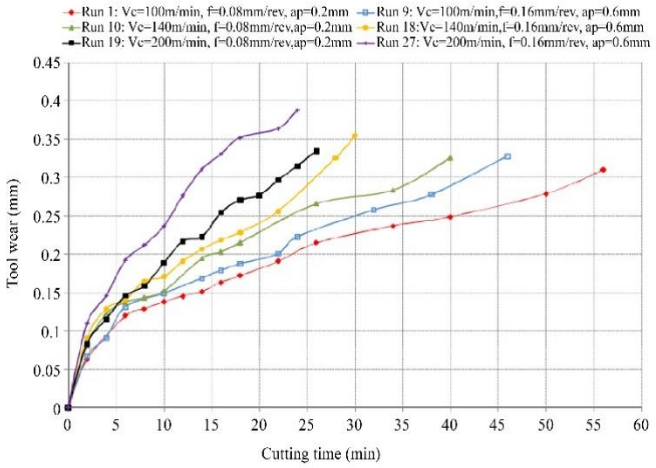


Fig. 9 CBN flank wear results when hard turning of AISI 52100 bearing steel [32]

The interactive effects between cutting parameters on tool wear were found to be insignificant. Additionally, tool wear increased with cutting time (Figure 9). Benga et al. [36] reported that PCBN offers an extended tool life compared to ceramics.

2.4. Effects of Cutting Conditions on Surface Roughness

The surface integrity of a machined component is characterized by residual stresses, surface roughness, and a white layer. Among the factors, surface roughness is the most crucial factor influencing the performance of a machined component, making it a critical quality attribute in hard turning. Research indicates that surface quality is enhanced by high CS, low FR, and shallow DOC (see Figure 10), with the FR being the primary influencing factor [15], [17,18], [32], [39], [41-45]. Increased CS reduces surface roughness in hard turning by lowering cutting forces and providing smoother cutting action. However, excessively high speeds can lead to increased tool wear and thermal effects, potentially degrading surface quality. Conversely, high FRs result in a rougher surface finish due to the creation of helicoid furrows on the workpiece's surface as the cutting tool moves along it. These furrows become deeper and broader with higher FRs, leading to decreased surface quality [44]. Moreover, larger depths of cut contribute to increased tool deflection and vibrations, resulting in a rougher surface finish. However, in hard turning, the DOC is usually very small (0.1-0.2 mm), so its impact is minimal. Bensouilah et al. [18] observed that FR had the greatest impact on surface roughness, contributing 84.39% and 54.19% for the CC6050 and CC650 inserts, respectively, followed by CS at 11.96% and 30.35%, while DOC contributed only 0.35% and 7.37%, respectively. The study also revealed that the interaction between these parameters on surface finish was insignificant. Das et al. [40] also demonstrated that the DOC is not statistically significant for surface roughness. Various investigations related to the cutting conditions have also been reported by the researchers, as shown in Table 2.

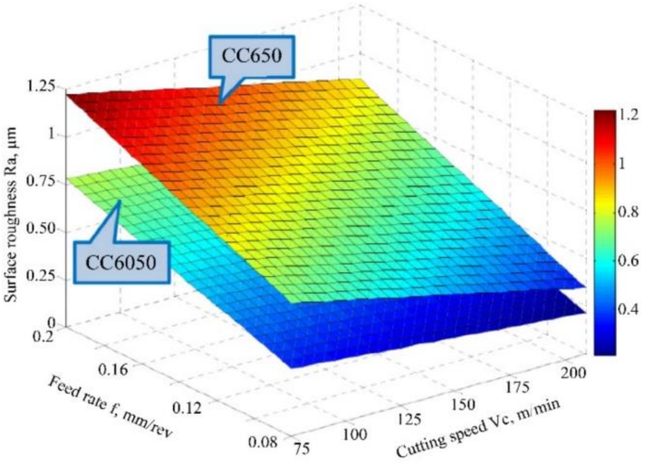


Fig. 10 Effect of FR and CS on surface quality for CC6050 and CC650 [18]

Table 2. Overview of various studies on cutting conditions in hard turning

Authors	Methods	Workpiece Material	Tool Material	Cutting Parameters			Machining Characteristics
				CS (m/min)	FR (mm/rev)	DOC (mm)	
Azizi et al. [46]	CCD, RSM, ANOVA, DFA	EN19 (50 HRC)	Coated Carbide	40, 80, 120	0.08, 0.16, 0.24	0.04, 0.08, 1.2	Surface Roughness, Tool Vibration, MRR
Zerti et al. [47]	Taguchi (L25) design, RSM, ANN, ANOVA, DFA	AISI 420 (59HRC)	Coated Ceramic	80, 120, 170, 240, 340	0.08, 0.12, 0.16, 0.2, 0.24	0.1, 0.2, 0.3, 0.4, 0.5	Cutting force, Surface Roughness, MRR
Arfaoui et al. [48]	CCD, RSM, FEM, ANOVA, DFA	AISI 52100 (62 HRC)	PCBN	100, 200, 300	0.05, 0.1, 0.15	1, 2.5, 4	Cutting Force, White Layer
Suresh et al. [49]	CCD, RSM, ANOVA, DFA	AISI H13 (55HRC)	Coated Mixed Ceramic	80, 140, 200	0.1, 0.14, 0.18	0.2, 0.4, 0.6	Cutting Force, Tool Wear (VB)
Arsene et al. [50]	FFD, ANOVA	AISI D2 (55 HRC)	Mixed Ceramic	120, 150, 180	0.1, 0.15, 0.2	0.1	Surface Roughness, Tool Wear (VB)
Tiwari et al. [51]	Taguchi (L9) Design, ANOVA, RSM	AISI 4340 (56HRC)	Coated Cermet	70, 140, 210	0.05, 0.1, 0.2	0.1, 0.30, 0.50	Surface Roughness, MRR

Bonfá et al. [52]	ANOVA	AISI D6 (59 HRC)	Coated PCBN	160, 190, 250, 310, 340	0.05, 0.1, 0.15, 0.2, 0.25	0.05	Surface Roughness, Tool Wear
Tang et al. [53]	Not Defined	AISI D2 (40, 45, 50, 55, 60 HRC)	PCBN	250	0.1	0.2	Tool Wear
Nayak et al. [54]	FFD, RSM, ANOVA	AISI D6	CBN	54.03, 93.62, 132.92	0.08, 0.133, 0.21	0.15	Cutting forces, Cutting Temperature, Surface Roughness
Kam et al. [55]	Not Defined	AISI 4140 (45 HRC, 52 HRC)	Ceramic	120, 160, 200, 240	0.05, 0.1, 0.15	0.2	Surface roughness, Vibration
Shalaby et al. [56]	Not Defined	AISI 4340 (52 HRC)	Mixed Ceramic	150, 250, 700, 1000	0.1	0.125	Cutting Force, Tool Wear
Rath et al. [57]	Taguchi (L25) design	AISI D3 (58-64 HRC)	Mixed Ceramic	80, 140, 190, 245, 320	0.04, 0.05, 0.06, 0.07, 0.08	0.1, 0.3, 0.5, 0.7, 0.9	Cutting Temperature, Surface Roughness, Cutting Forces,
Padhan et al. [58]	BBD, RSM	AISI 4140 (51 HRC)	Coated Carbide	100, 140, 200	0.06, 0.12, 0.18	0.2, 0.3, 0.4	Surface Roughness
Mallick et al. [59]	Taguchi (L27) Design, ANOVA	AISI D2 (57 HRC)	Coated Carbide	100, 175, 250	0.06, 0.12, 0.18	0.15, 0.25, 0.35	Surface Roughness, Tool wear, Cutting temperature, etc.
Karthik et al. [60]	Taguchi (L9) Design, ANOVA, Taguchi Analysis	EN 31 (60HRC)	CBN	100, 200, 300	0.04, 0.08, 0.12	0.1, 0.2, 0.3	Surface Roughness

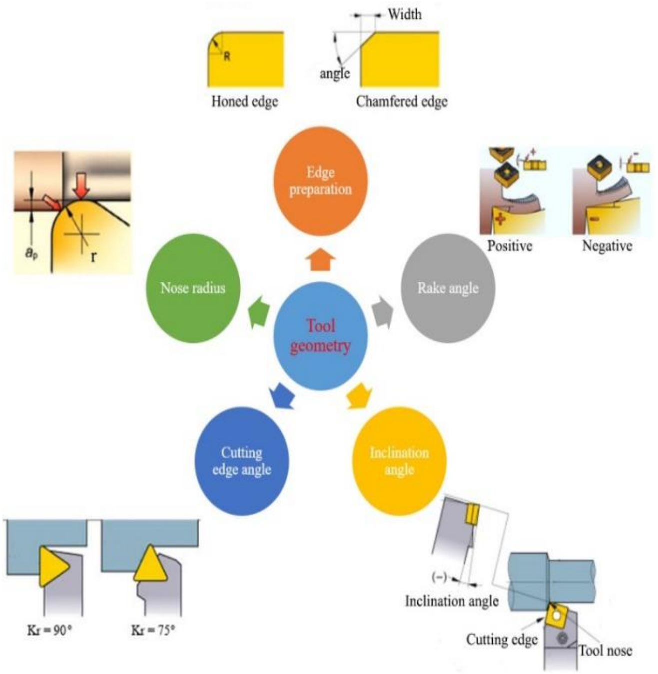


Fig. 11 Tool geometry parameters

3. The Effects of Cutting Tool Geometry for Hard Turning

Cutting tool geometry (Figure 11) is a crucial factor in the hard-turning process. Due to the high hardness of the workpiece, the cutting tool needs to be distinctively designed to enhance the durability of the tool edge.

3.1. Effects of Cutting Tool Geometry on Cutting Forces

In hard turning, a negative rake angle is commonly used to withstand extreme compressive stresses, resulting in a larger tool-chip contact area and greater chip volume, which together increase cutting forces (Figure 12) [61-66]. Harisha et al. [67] and Saglam et al. [63] demonstrated that increasing the cutting-edge angle results in an increase in axial force but a decrease in radial force.

Furthermore, the tool nose radius significantly influences cutting forces [70]. A larger nose radius increases the cutting area, thereby leading to higher cutting forces (Figure 13) [44], [67-70].

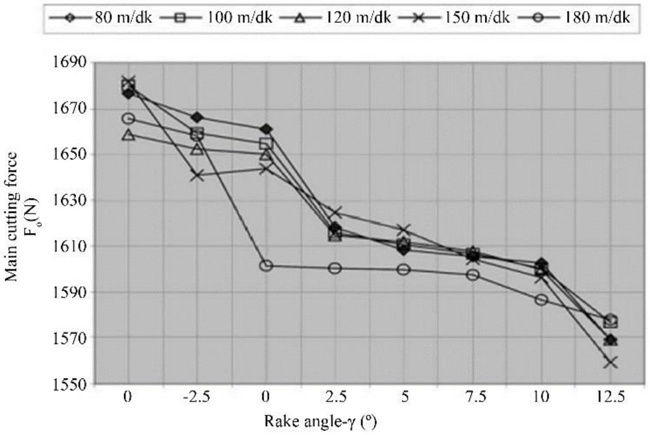


Fig. 12 Variation in cutting force (Fc) with changes in rake angle at various CSS [64]

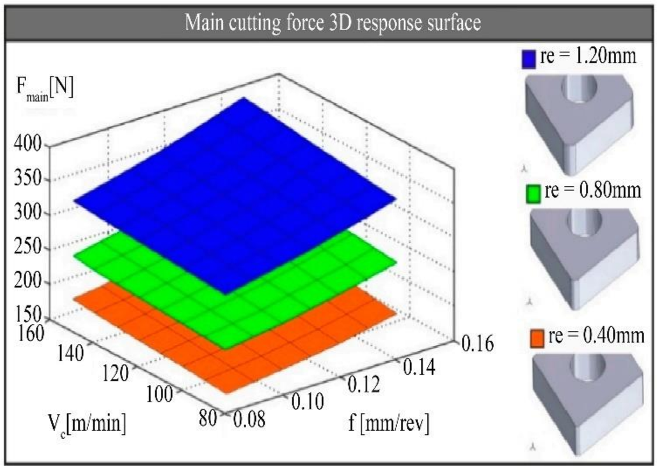


Fig. 13 The cutting force corresponding to each nose radius [70]

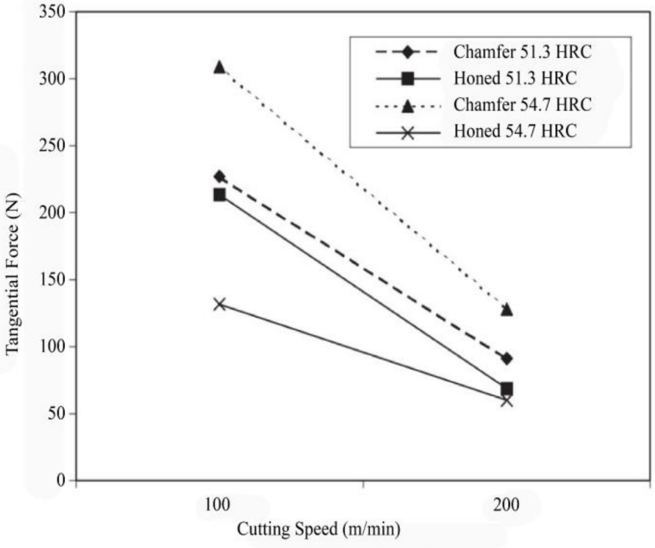
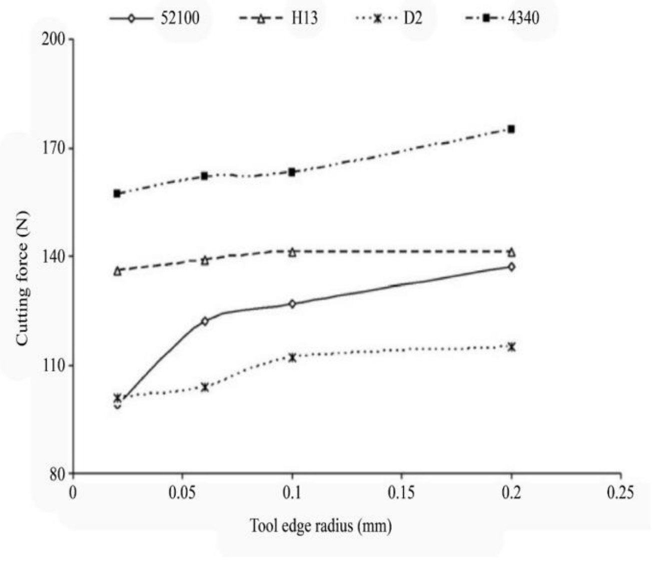
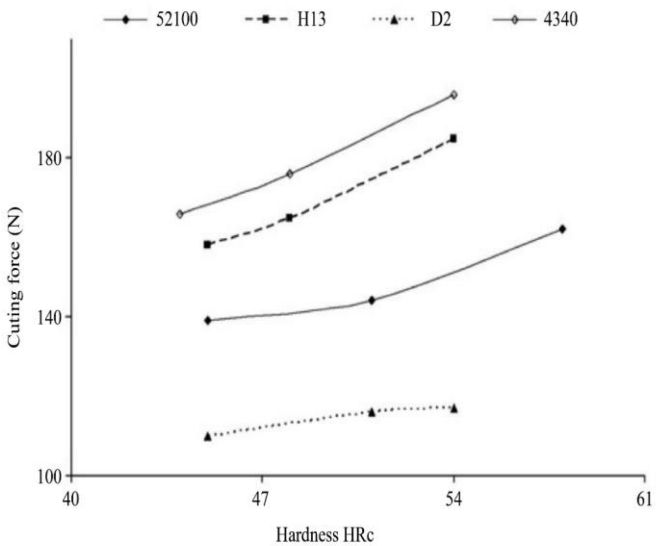


Fig. 14 Effect of edge preparation on tangential force [71]



(a)



(b)

Fig. 15 Influence of (a) tool edge radius and (b) workpiece hardness on force [66]

Edge preparation, including honing and chamfering, provides higher edge strength, reducing the likelihood of tool chipping and fracture. However, they also increase cutting forces. Ozel et al. [71] indicated that a rounded cutting edge produces lower cutting forces compared to a chamfered cutting edge (Figure 14). Qian et al. [66] compared turning hardened steels with CBN inserts and found that cutting forces increase with larger workpiece hardness and tool edge radius. (Figure 15).

3.2. Effects of Cutting Tool Geometry on Cutting Temperature

The geometry of the cutting tool significantly influences heat generation. The larger negative rake angle increases the contact area between the tool chip, leading to higher frictional heat generation [65], as shown in Figure 16 (a-d). The findings reveal that the maximum cutting temperature is around 900°C for negative rake tools, 750°C for neutral rake tools, and 700°C for tools with a positive rake angle (Figure 16 (d)).

Meanwhile, the tool nose radius moderately affects the cutting temperature, with the cutting temperature rising as the nose radius increases (Figure 17) [69,72]. Chamfered and honed edges improve edge strength and raise cutting temperature due to the increased contact area.

Karpat et al. [73] demonstrated that the cutting temperature increases with a larger edge radius and that tools with chamfered edges exhibit lower efficiency compared to honed edge tools when subjected to higher cutting temperatures on the rake face (Figure 18) [74]. This reduction in efficiency is attributed to the increased effective negative rake angle, which consequently elevates friction in chamfered inserts.

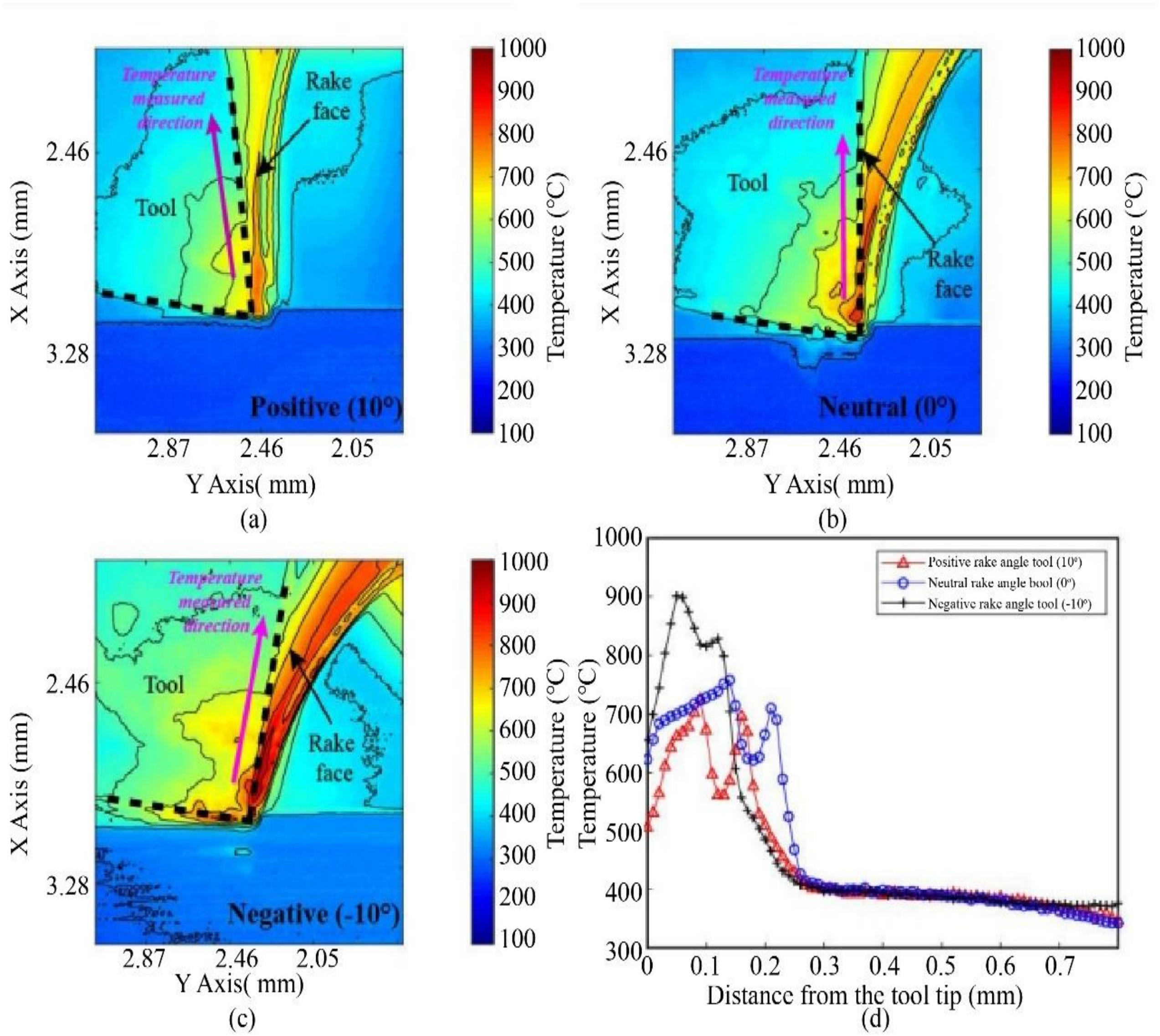


Fig. 16 Thermal distribution for different rake angle tools [66]: (a) Positive rake angles, (b) Neutral rake angles, (c) Negative rake angles, (d) The temperature gradient along the rake face of different geometry tools

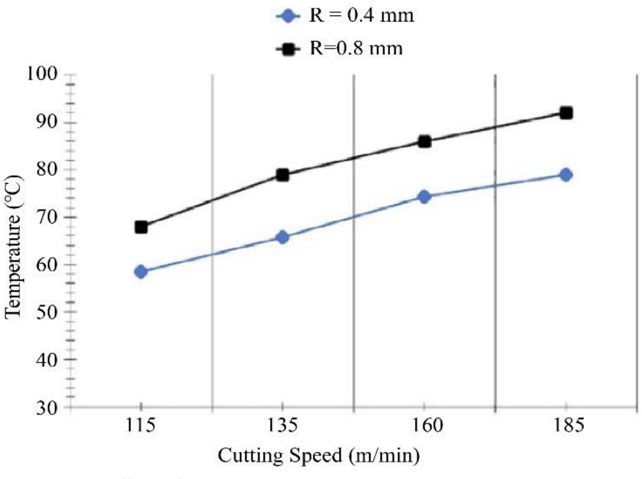
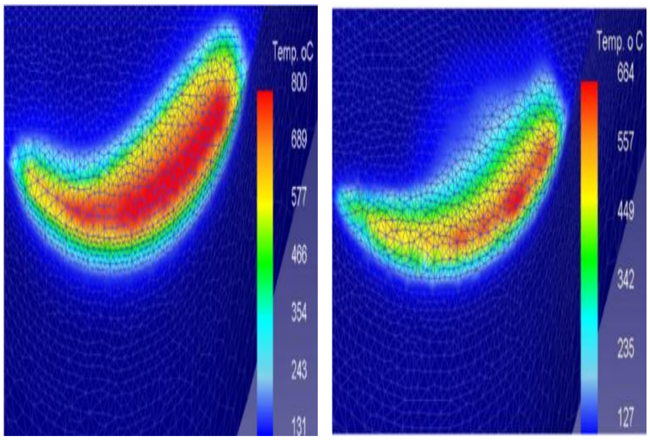


Fig. 17 Effect of insert nose radius on cutting temperature [69]



(a) Chamfered tool (20°, 0.1mm) (b) Rounded tool (r_e=40μm)

Fig. 18 Temperature distributions for (a) chamfered and (b) rounded inserts, as determined through 3D finite element modeling (FEM) [74]

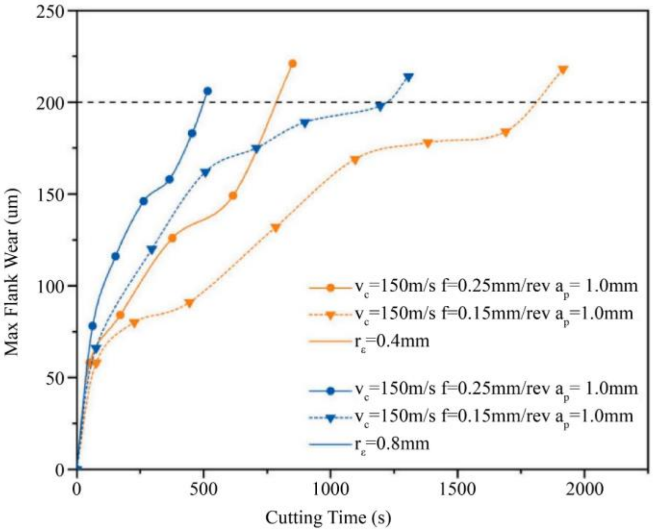


Fig. 19 A Comparison of the flank wear progression for inserts with varying nose radii [76]

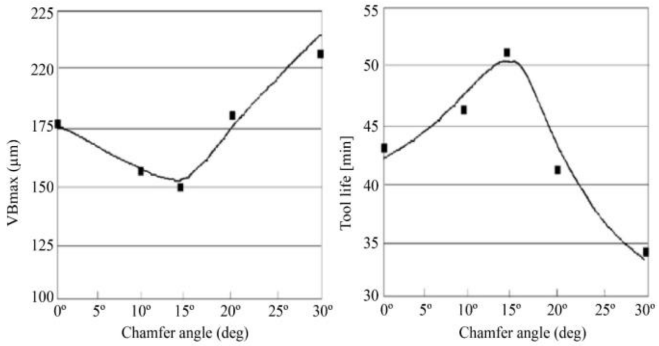


Fig. 20 Flank wear and tool life of PCBN tools at varying chamfer angles [80]

3.3. *Effects of Cutting Tool Geometry on Tool Wear*

Negative rake angles used in hard turning can lead to increased tool wear due to higher cutting forces and temperatures [37]. However, compared to the study by Kuhn et al. [75], the rake angle did not significantly affect tool wear when milling gears with ALCrN-coated carbide tools. Hossainy [37] found that increasing the cutting-edge angle increases tool wear. The tool nose radius also significantly affects tool wear; an increase in nose radius results in greater tool wear (Figure 19) [69], [76]. Tools with a larger nose radius enlarge the machining area [76] and cause more ploughing and extrusion of the tool nose in the cutting region [77, 78] due to the variation in chip thickness from zero to maximum [79]. Consequently, this leads to higher cutting forces and increased heat generation, both of which contribute to accelerated tool wear. Edge preparation plays a crucial role in tool life. Rounded and chamfered edges contribute to the durability of cutting tools, enabling them to withstand higher thermal-mechanical loads and extend their lifespan.

However, these preparations can also lead to increased wear due to higher frictional forces and temperatures. In the hard turning of 100Cr6 bearing steel, Zhou et al. [80] observed that increasing chamfer angles enhances tool life, with the maximum tool life seen at a 15° chamfer angle compared to a zero-chamfer angle. The tool life difference between cutting tools with 15° and 30° chamfer angles was found to be 53%. These findings imply the presence of an optimal chamfer angle that maximizes tool life. Figure 20 illustrates the flank wear for various chamfered edges under equivalent cutting times and tool life based on the same wear criterion (VB = 0.2 mm). Additionally, Ventura et al. [81] analyzed the performance of sharp, chamfered, and honed tools during interrupted turning. They found that chamfered inserts exhibited superior wear resistance compared to other types, even though sharp inserts experienced the lowest thermal-mechanical loads on the edge. Honed edges showed larger flank wear widths in comparison to chamfered tools. In a study by Zhao et al. [82], it was found that larger cutting-edge radii lead to better tool wear resistance.

3.4. *Effects of Cutting Tool Geometry on Surface Roughness*

Tool geometry significantly influences surface finish in hard turning. Positive rake angles typically result in improved surface finish, while negative rake angles, despite offering greater edge strength, can lead to increased surface roughness [37], [83-86]. This increase in roughness is primarily due to the longer contact length between the tool and chip and the higher chip compression ratio, both of which contribute to heightened vibrations. Meanwhile, increasing the cutting-edge angle resulted in decreased surface roughness [44], [87]. This effect is attributed to the shift in the cutting position on the tool nose radius, which reduces the local negative rake angle of the engaged cutting-edge elements on the tool nose radius. The tool nose radius is a critical geometric factor affecting surface roughness. A larger nose radius typically improves surface finish (Figure 21) [44], [69], [88] by increasing the contact length of the tool-workpiece, which reduces the residual height of feed marks [89].

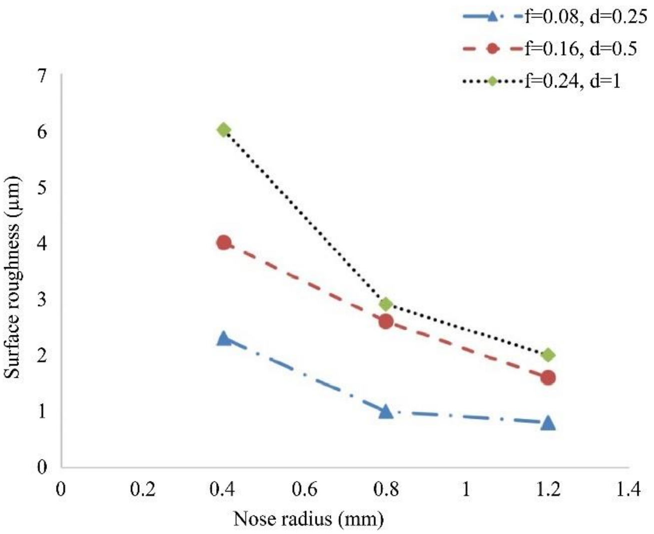
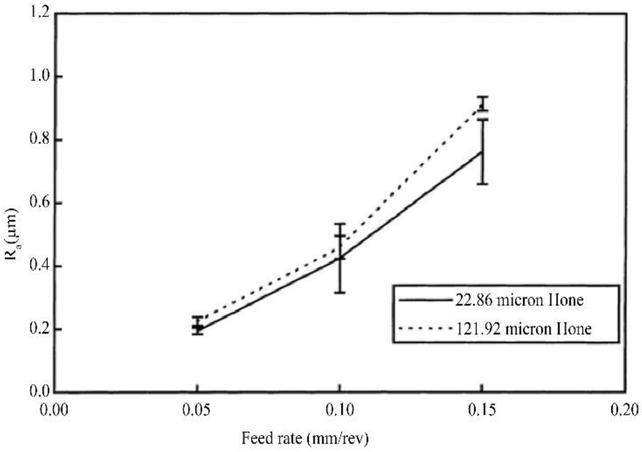
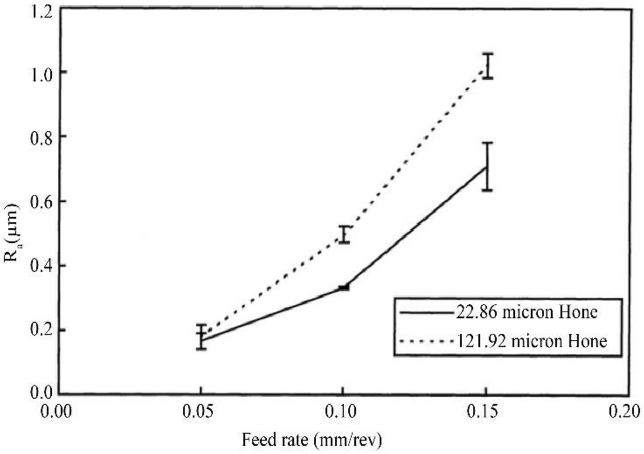


Fig. 21 Influence of nose radius on surface quality [89]



(a) 47 HRC workpiece



(b) 57 HRC workpiece

Fig. 22 Effect of cutting-edge radius on surface roughness [91]

In theory, surface roughness decreases as the nose radius increases. However, deviations from the theoretical prediction ($Ra=\frac{f^2}{32r}$) become significant at low FRs, likely due to plowing actions from smaller uncut chip thickness [69]. Ferreira et al. [90] performed a comparative analysis of the performance between multi-radii and conventional ceramic tools, revealing that multi-radii inserts yielded superior surface roughness compared to conventional tools.

According to Yousefi et al. [88], FR and nose radius were the most significant factors affecting surface roughness, contributing 60%, followed by nose radius at 28%. Meanwhile, cutting-edge preparation can increase surface roughness by enhancing the plowing component of deformation relative to the shearing component. Davoudinejad et al. [31] investigated the microgeometries of ceramic tools and found that chamfered edges produced better surface roughness than honed inserts, particularly at low FRs.

Further research by Thiele et al. [91] and Ventura et al. [92] indicated that sharp tools yielded the smoothest surfaces, while an increase in edge radius resulted in higher surface roughness (Figure 22). Furthermore, the studies indicated that the interaction effects between factors on surface roughness were minimal. As reported in Singh's study [83], there was no significant interaction between the tool angle parameters and cutting conditions, except for a minor interaction between FR and nose radius. Zerti et al. [44] identified interaction effects between cutting edge angle and DOC at 3.82% and between cutting edge angle and CS at 1.16%. The influence of tool geometry in hard turning has been extensively studied, as summarized in Table 3.

Table 3. Overview of various studies on tool geometry in hard turning

Authors	Methods	Workpiece Material	Tool Material	Tool Geometry	Machining Characteristics
Singh et al. [93]	FFD, RSM, ANOVA, GA	AISI 52100 (58 HRC)	Mixed ceramic	Nose Radius: 0.4, 0.8, 1.2 mm Effective Rake angle: -6, -16, -26°	Surface Roughness
Meddour et al. [94]	BBD, RSM, ANN, ANOVA, DFA, NSGA-II	AISI 4140 (60 HRC)	Mixed Ceramic	Nose radius: 0.8, 1.2, 1.6 mm	Cutting Force, Surface Roughness, MRR
Kumar et al. [95]	Not Defined	AISI H13 (45, 50, 55 HRC)	CBN	Nose radius: 0.4, 0.8, 1.2 mm	Surface roughness, Cutting force
Rafighi et al. [96]	Taguchi (L36) design, ANOVA, RSM, ANN	AISI D2 (60 HRC)	CBN, Coated ceramic	Nose Radius: 0.4, 0.8, 1.2 mm	Surface Roughness, Cutting Force
Kumar et al. [97]	CCD, RSM, ANOVA, DFA	AISI 4340 (40, 45, 50, 55, 60 HRC)	Coated CBN	Nose Radius: 0.2, 0.4, 0.8, 1.2, 1.6 mm	Cutting Temperature, Cutting Force
Guddat et al. [98]	Not Defined	AISI 52100 (58-62 HRC)	PCBN	Chamfer angle: 15, 25, 35° Edge radius: 15, 25, 35 μm Nose radius: 0.4, 0.8, 1.2 mm	Surface Integrity

Anthony [99]	Taguchi (L27) Design, ANOVA	AISI D2 (55 HRC)	Coated carbide, Cermet, Ceramic	Rake angle: 0, 6, 18° Nose radius: 0.4, 0.8, 1.2 mm	Cutting force, Chip Morphology
Zhang et al. [100]	FEA	AISI 52100 (62 HRC)	CBN	Rake angle: -5, -20, -30° Lead angle: 0, 7° Nose radius: 0.4, 0.8 mm	Chip Morphology, Cutting Forces, Cutting Temperature
Caruso et al. [101]	Not Defined	AISI 52100 (56.5, 61 HRC)	PCBN	Edge radius: 0.015 mm Nose radius: 0.4, 0.8, 1.2 mm	Residual Stress
Gunnberg et al. [102]	CCD, Regression Model	18MnCr5 (550 HV)	CBN	Nose radius: 0.8, 1.6, 4.5 mm Rake angle: -6, -15, -21°	Residual Stresses, Surface Roughness
Gundarneeya et al. [103]	Taguchi (L9) Design, ANOVA, The S/N Ratio	EN24 (48HRC)	CBN	Nose radius: 0.4, 0.8 mm	Surface Roughness, Dimension Accuracy

4. Surface Quality in Hard Turning

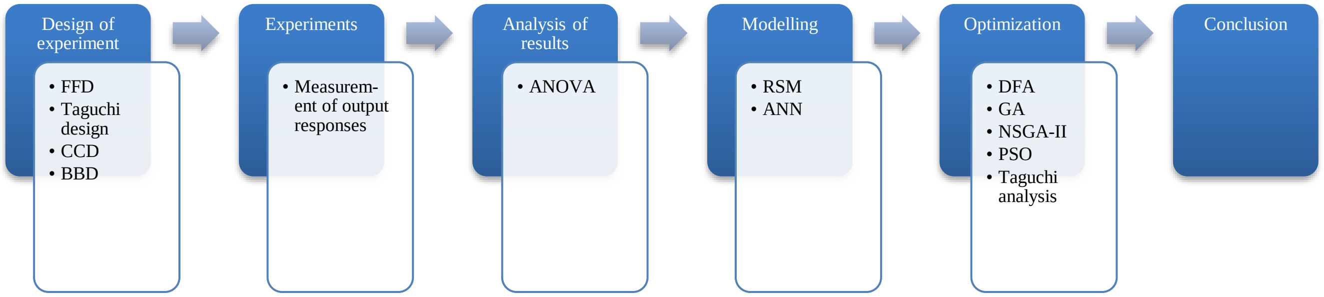
Turning Surface roughness serves as a key indicator for evaluating machining accuracy [104]. Generally, surface roughness exceeding 1.6 microns is considered unacceptable for grinding hard-to-cut metals [105, 106]. Puerto et al. [107] indicate that grinding operations can achieve surface roughness values between 0.1 and 2 µm. Rech [109] evaluated the surface roughness when turning 27MnCr5 steel using PCBN inserts and achieved a low surface roughness, with Ra = 0.2 µm. Abrão [27] focused on the impact of various insert materials on surface finish.

The study revealed low CBN content PCBN and mixed ceramics offered the best surface finish, achieving remarkably low Ra values of 0.14 µm. Benga [36] identified the optimal cutting conditions to minimize surface roughness in the hard turning of DIN 100Cr6 steel, achieving a minimum Ra of 0.25 µm. Arsene et al. [51] reported Ra values between 0.151 and 0.452 µm when hard-turning AISI D2 steel with ceramic wiper inserts. Similarly, Özel et al. [109, 110] found that optimal Ra values (0.18 – 0.2 µm) were achieved at low FRs and high CSs with wiper ceramic inserts. These studies clearly show that surface roughness in hard turning has not yet reached the Ra = 0.1 µm level typical of grinding processes. However, choosing the right machining parameters can achieve surface roughness values that satisfy the technical requirements of most mechanical products.

5. Mathematical Modeling and Optimization of the Hard Turning Process

Mathematical modeling and optimization play a crucial role in hard-turning research, enhancing both efficiency and product quality. The diagram in Figure 23 provides a detailed overview of the specific steps involved in machinability studies. The most commonly used Design of Experiment (DOE) techniques include FFD, CCD, BBD, and Taguchi Design.

Although FFD generally yields more reliable results, it can be costly and sometimes impractical to conduct. CCD and BBD are widely utilized experimental designs within the RSM framework. CCD requires five levels per factor, while BBD needs three levels per factor to adequately model quadratic responses. While Taguchi's design is ideal for two-level factorial experiments, it can also be applied to evaluate main effects when factors have more than two levels. Additionally, it can be adapted for mixed-level experiments, where independent variables have varying numbers of levels.



Full Factorial Design (FFD); Central Composite Design (CCD); Box-Behnken Design (BBD); Analysis of Variance (ANOVA); Response Surface Method (RSM); Artificial Neural Network (ANN); Desirability Function Approach (DFA); Genetic Algorithms (GA); Non-dominated Sorting Genetic Algorithm (NSGA-II); Particle Swarm Optimization (PSO)

Fig. 23 Steps in hard turning studies

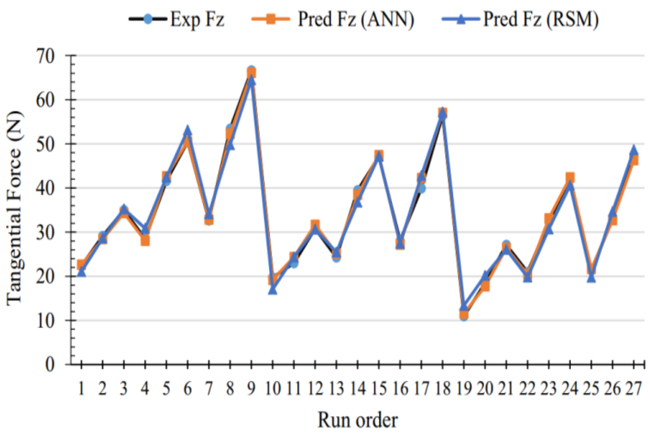


Fig. 24 Comparison of experimental and predicted results [118]

The optimization of process parameters in hard turning generally involves a systematic process comprising experimentation, analysis of experimental data, and the construction of precise mathematical models. RSM, ANN, and fuzzy modeling are among the modeling techniques proposed for hard turning [111]. In the optimization of hard turning, popular techniques include the Taguchi method [112], DFA coupled with RSM [113], GA [114], and PSO [115]. Parida et al. [116] utilized CCD, RSM, ANOVA, and DFA to study the hot turning of Monel-400 steel. Their findings demonstrated the high accuracy of the RSM model, with coefficients of determination (R^2) of 94.72% for tool wear and 86.17% for surface roughness. Laghari et al. [117] also employed RSM and DFA in their turning study, achieving high accuracy with R^2 values of 99.3%, 99.2%, and 92.56% for the cutting force models. Laouiss et al. [17] used the L27 Taguchi design and ANOVA to analyze the influence of cutting conditions. ANN and RSM were utilized to develop predictive models for optimization, which was then performed using GA. The accuracy of the models was assessed using MAD, MAPE, RMSE, and R^2, with both models demonstrating high predictive capability ($R^2 = 0.95$ to 0.99).

While the ANN model provided more accurate predictions, the RSM model offered additional insights by quantifying each factor's contribution to the variation in responses, a feature not available with the ANN approach. Chabbi et al. [118] also utilized RSM, ANN and DFA. They found that the ANN model had higher correlation coefficients ($R^2 = 0.99$) compared to the RSM model ($R^2 = 0.98$). Despite this, the prediction results of both models were nearly equivalent (Figure 24). Tang et al. [119] investigated cutting forces using both RSM and Orthogonal Regression Methodology (ORM) to model the machining process. Their findings indicated that the RSM provided superior accuracy compared to the ORM model.

Additionally, RSM has been widely used in many other studies, including those by Bagaber et al. [120], Xiao et al. [121], Santhosh [122], and Aslan [123].

6. Recent Advancements in Hard-Turning

Hard turning has seen significant advancements due to emerging technologies to improve process efficiency, surface quality, and tool life. The shift towards Industry 4.0 and the integration of smart manufacturing technologies transform traditional hard-turning practices, making them more adaptive, efficient, and sustainable [124]. One key development is the implementation of real-time monitoring systems. Traditional hard-turning operations often rely on indirect measurements and estimation methods to track machining parameters such as cutting forces, temperatures, and tool wear. However, recent innovations in sensor- and AI-based technologies (e.g., neural networks, image recognition, fuzzy logic, adaptive neuro-fuzzy inference systems) now enable continuous real-time monitoring of these parameters, providing immediate feedback on machining performance [125]. This advancement enhances process control and allows for predictive maintenance, thereby reducing unexpected tool failures and downtime. For instance, sensor technologies integrated with machine tools can measure cutting forces and vibration levels, providing critical data that can be used for in-process adjustments to maintain optimal cutting conditions and improve surface finish. Among these approaches, tool condition monitoring systems have emerged as a primary focus for many researchers [126-129].

7. Conclusion

This comprehensive review has elucidated the significant influence of cutting conditions and tool geometry on critical performance characteristics in hard turning (Figure 25). Understanding these effects is important for optimizing hard turning to enhance machining performance and achieve desired outcomes.

The following conclusions have been drawn from the reviewed literature:

- In hard turning, cutting tools are subjected to exceptionally high mechanical loads and temperatures. Consequently, superhard materials like coated cemented carbide, ceramic, and CBN are well-suited for these demanding conditions.
- Radial force is the dominant force in hard turning, distinguishing it from conventional machining.
- Higher CSs generally reduce cutting forces and improve surface finish but also increase tool wear and cutting temperature. Conversely, increased FRs and DOCs tend to increase cutting forces, temperature, tool wear, and surface roughness.
- Negative rake angles enhance the strength of the cutting edge but also increase cutting forces, temperature, and surface roughness. While increasing the cutting-edge angle can reduce surface roughness, it may also lead to greater tool wear. A larger nose radius typically improves surface finish but may result in higher cutting forces,

temperature, and tool wear. Appropriate edge preparation can extend tool life and maintain surface quality, although it may also increase cutting forces and temperature.

- Surface roughness is primarily influenced by FR and tool nose radius.
- CS is the most significant factor affecting cutting temperature and tool wear.

- The interaction effects of process parameters are typically minor or statistically insignificant.
- Selecting optimal cutting parameters can achieve surface roughness values that meet the technical specifications of most mechanical products.
- Advanced modeling and optimization techniques such as RSM, ANN, DFA, and GA can assist in identifying the optimal machining parameters for specific hard-turning applications, leading to more efficient and cost-effective machining processes.

Acknowledgments

The authors acknowledge the HCMC University of Technology and Education for supporting this study.

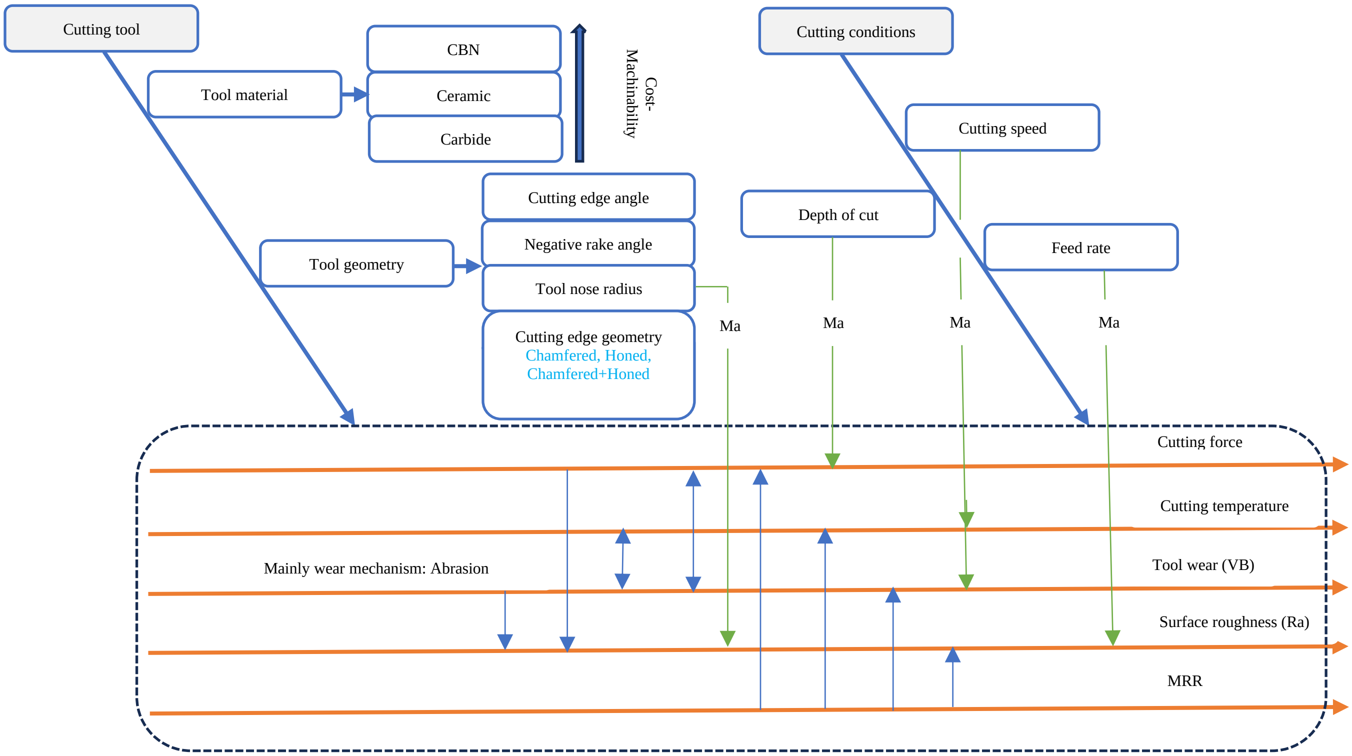


Fig. 25 A flowchart depicting the interrelationships among factors in the hard-turning process

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