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(Review Article)

Hard Turning and CNC Parameter Optimization: A Review of Cutting Force, Surface Roughness, Tool Wear, and Taguchi/RSM Approaches

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ABSTRACT

Hard turning, the single-point turning of steels hardened above about 45 HRC, is now an established alternative to grinding for finishing precision parts. Its success depends on selecting cutting speed, feed rate, depth of cut and tool geometry that balance cutting force, surface finish, surface integrity and tool life. This review first outlines the mechanics that set hard turning apart from conventional turning, namely segmented chip formation, a strongly negative effective rake and a dominant thrust force, and the demands these place on tools and machines. It then surveys experimental and statistical work on cutting force, surface roughness and integrity, and tool wear, with emphasis on CBN, ceramic and coated-carbide tools cutting bearing, die, alloy and high-speed tool steels (AISI 52100, H13, D2, 4340 and M2). The optimization methods most used in this field are compared in terms of their assumptions, data needs and limitations: Taguchi designs with signal-to-noise ratios and ANOVA, response surface methodology (RSM) with desirability functions, multi-criteria methods such as grey relational analysis, TOPSIS and WASPAS, and neural-network and other machine-learning models. Across the literature, feed rate and nose radius usually dominate surface roughness, while workpiece hardness, feed and depth of cut dominate forces; however, reported rankings vary with tool, material and the tested parameter window, and for AISI M2 at 62–64 HRC cutting speed has been found to lead for both force and roughness. A synthesis section explains why such rankings conflict and how studies can be made more comparable. The review closes with research gaps, including the scarcity of tool-wear-aware and integrity-aware optimization, limited data on very hard (above 60 HRC) high-speed steels, the need for in-process monitoring and hybrid physics–data models, and better statistical and reporting practice.

Keywords: *hard turning; CNC turning; cutting force; surface roughness; tool wear; Taguchi method; response surface methodology; CBN tools; AISI M2*

I. INTRODUCTION

Hard turning replaces grinding for many finishing operations on hardened steel parts such as bearings, gears, shafts, dies and cutting tools. It allows higher material removal rates, several features in one setup, flexible part geometry and, in many cases, dry cutting without grinding sludge [1, 2]. It became practical with the commercial availability of polycrystalline cubic boron nitride (PCBN) and ceramic inserts, which keep their hardness at the high temperatures generated at the cutting zone [1].

Typical applications include bearing rings and rollers, transmission gears and shafts, constant-velocity joint components, fuel-injection parts, and the finishing or repair of dies, moulds and cutting tools [1, 27, 28]. In these parts the finishing step usually follows case hardening or through hardening, and removing it from a grinding line can shorten the process chain, reduce the number of fixtures and cut work-in-progress. The environmental case is also important: dry hard turning avoids the disposal of grinding sludge contaminated with coolant and abrasive, which has become a significant cost in many plants [2, 29].

The process is also demanding. High workpiece hardness raises cutting forces, cutting temperatures and tool wear, and small changes in parameters can shift the surface finish and the integrity of the machined layer [2, 3]. Because CBN tools are expensive and brittle, the choice of cutting speed, feed rate, depth of cut and nose radius matters both technically and economically.

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Hard turning does not replace grinding in every case. Grinding remains preferable for very tight form and size tolerances on long or slender parts, for surfaces that must be free of the periodic feed marks left by a single-point tool, and where the machine tool lacks the static and dynamic stiffness that hard turning needs [1, 27, 30]. The two processes also leave different surface layers. König et al. showed that turned and ground surfaces of comparable roughness can differ in residual stress profile and surface texture, so the choice between them depends on the functional demands of the part rather than on roughness alone [27]. Understanding how process parameters govern force, finish, integrity and wear is therefore central to extending the range of parts that can be hard turned reliably.

This has produced a large body of parametric studies, most of which follow a similar pattern: a designed experiment on a CNC lathe, measurement of force, roughness, wear or vibration, statistical analysis, and a set of optimum parameters. Earlier overviews summarized this work in general terms [2, 3, 5] and for hard materials at 62–64 HRC in particular [4]. The present review updates that picture and organizes it around three responses — cutting force, surface roughness and tool wear — and around the optimization methods used to control them.

The scope of this review is single-point turning of ferrous workpieces hardened to roughly 45 HRC and above, using PCBN, ceramic and coated-carbide tools. Related CNC turning studies on other difficult-to-cut materials, such as Inconel 718 [25], are included where their experimental and statistical methods transfer directly. Priority is given to studies that use designed experiments and report statistical analysis, because these make up most of the parameter-optimization literature and allow factor effects to be compared. Quantitative results are quoted as reported by the original authors. Since machines, tool grades, workpiece batches and measurement procedures differ between studies, these values indicate trends rather than transferable settings.

The review is organized as follows. Section II outlines the fundamentals of the process, including chip formation, cutting mechanics and machine requirements. Section III covers tool and workpiece materials and the role of edge preparation and insert geometry. Sections IV, V and VI review cutting forces, surface roughness and integrity, and tool wear. Section VII compares the optimization methods used to select cutting conditions, and Section VIII synthesizes the reported factor effects and discusses why they differ between studies. Section IX identifies research gaps and Section X draws conclusions.

II. FUNDAMENTALS OF HARD TURNING

A. Process Window and Productivity

Hard turning is usually a finishing operation. Depths of cut are small, commonly about 0.05–0.3 mm, feeds are low, about 0.05–0.2 mm/rev, and cutting speeds with PCBN tools typically lie between roughly 100 and 250 m/min, although wider ranges are reported [1–3]. Because the depth of cut is often smaller than the tool nose radius, the chip is formed almost entirely by the curved nose, and the uncut chip thickness along most of the engaged edge is only a fraction of the nominal feed. The productivity of a given setting is commonly expressed through the material removal rate:

$$\mathrm{MRR} = 1000 \cdot v_c \cdot f \cdot a_p \tag{1}$$

where MRR is in mm^3/min, v_c is the cutting speed in m/min, f is the feed in mm/rev and a_p is the depth of cut in mm. Equation (1) shows the basic conflict that optimization must resolve. Feed and depth of cut raise MRR linearly, but they also raise forces and, in the case of feed, roughness; higher speed raises MRR at the cost of temperature and tool wear. Several of the studies reviewed here therefore treat MRR as a response to be maximized alongside roughness [10].

B. Chip Formation and Cutting Mechanics

The chips produced in hard turning differ in kind from those in conventional turning. Above a certain hardness, the continuous chip gives way to a segmented or saw-tooth chip in which shear localizes periodically in narrow bands [1, 31]. Two mechanisms are usually proposed: thermoplastic instability, in which local heating softens the material faster than strain hardening strengthens it, leading to adiabatic shear; and periodic crack initiation at the free surface of the chip, followed by sliding along the crack [1, 32]. Both may contribute, and the dominant one depends on hardness, cutting speed and microstructure. Segmentation makes the cutting force fluctuate at high frequency, which raises the cyclic load on the edge and can contribute to chipping of brittle tool materials.

Classical shear-plane analysis, beginning with Merchant's model of orthogonal cutting [33], assumes a continuous chip, a single shear plane and a sharp tool. These assumptions are poorly met in hard turning. Inserts are normally mounted with a negative rake, often about −6°, and are chamfered or honed, while the uncut chip thickness can be of the same order as the edge radius or chamfer width. Under these conditions the effective rake angle becomes strongly negative, part of the material is ploughed under the edge rather than removed as chip, and the specific cutting energy rises as the uncut chip thickness falls, the so-called size effect [30, 31]. This is the main reason why the thrust force is often larger than the tangential force in hard turning, as discussed in Section IV.

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Workpiece hardness also changes the state of the machined surface. Matsumoto et al. showed that the residual stress produced by turning AISI 4340 depends strongly on hardness, with a marked change in the stress profile as the steel became harder [34]. Hardness therefore cannot be treated as a passive property of the workpiece: it shapes chip formation, force, temperature and integrity together, which is one reason why studies that include hardness as a design factor often find it among the most significant [11, 14].

C. Machine Tool and Setup Requirements

Because thrust forces are high and depths of cut small, hard turning is sensitive to the stiffness of the machine, toolholder and workpiece clamping. Deflection under the thrust force directly changes the diameter produced, and insufficient damping allows chatter that degrades finish and can chip a brittle CBN edge [1, 2]. Machines designed for hard turning address this with high static stiffness, well-damped beds, precise guideways and thermal compensation, so that size tolerances of a few micrometres can be held over long runs [29]. Workpiece slenderness matters as well; a common rule of thumb is that length-to-diameter ratios above about 3–4 need tailstock or steady support. Vibration measurements made during hard turning of AISI M2 show that the dynamic response of the system is itself sensitive to the cutting parameters, with feed rate having the largest effect on the resultant vibration signal [8, 9]. These machine-related factors are seldom reported in parametric studies, yet they influence the absolute values of force and roughness and may explain part of the variation between laboratories.

III. CUTTING TOOLS AND WORKPIECE MATERIALS

A. Tool Materials

PCBN remains the reference tool for hard turning, with ceramics and coated carbides as lower-cost options at lower hardness or speed [1, 2]. PCBN grades are broadly divided by CBN content. Low-content grades, with roughly 40–65% CBN in a ceramic binder such as TiN or TiC, offer greater chemical stability and are preferred for continuous finishing cuts, where crater and chemical wear dominate. High-content grades, with about 80–95% CBN, are tougher and more thermally conductive and are favoured for interrupted cuts and heavier sections [1, 35]. The CBN content and binder of a grade therefore change its behaviour: Kumar et al. compared three CBN grades on AISI H13 at 45, 50 and 55 HRC and found that forces and roughness depended on CBN percentage and alloying elements, with hardness, feed and speed all significant [11]. More et al. showed that CBN–TiN coated carbide inserts can be a competitive, cheaper alternative to solid PCBN compacts on hardened AISI 4340 [22].

Ceramic tools, chiefly alumina mixed with TiC or TiCN and alumina reinforced with SiC whiskers, cost much less than PCBN and keep their hardness at high temperature, but their lower fracture toughness makes them sensitive to edge chipping, vibration and interrupted cuts [1, 2]. They have nonetheless been used successfully at high hardness. Aslan et al. turned AISI 4140 hardened to 63 HRC with an Al_2O_3 + TiCN mixed ceramic tool and used a Taguchi design to select conditions that balanced flank wear and surface roughness [36], and Davim and Figueira showed with statistical techniques that ceramic tools can give finishes on hardened AISI D2 comparable to those of cylindrical grinding [37]. Coated carbides, with multilayer TiN, TiCN, TiAlN or Al_2O_3 coatings, are the least expensive option and perform acceptably at the lower end of the hardness range; Suresh et al. demonstrated this on AISI 4340 at 48 HRC, developing models for force, roughness and tool wear with multilayer coated carbide inserts [38]. As hardness rises, however, the wear rate of carbide grows quickly, and its use on the hardest steels is generally limited to light cuts and short tool lives [2]. The main characteristics of these tool groups are summarized in Table 1.

Table 1. Cutting tool materials used in hard turning.

Tool material	Typical role in hard turning	Main limitation
PCBN (low and high CBN content)	Finishing of 45–65 HRC steels; best wear resistance and finish	High cost; brittle edge sensitive to vibration
Mixed / whisker ceramics (Al_2O_3–TiC, Al_2O_3–SiCw)	Finishing at moderate hardness and speed	Lower toughness; chipping under interrupted cuts
Coated carbide (TiN, TiAlN, Al_2O_3)	Lower-hardness range and light cuts	Faster wear as hardness rises
Cermet (TiCN-based, Ni/Co binder)	Semi-finishing and finishing at the lower end of the hardness range	Limited toughness and thermal-shock resistance; rarely used on the hardest steels

B. Edge Preparation and Insert Geometry

The geometry of the cutting edge is a process variable in hard turning, not merely a tool specification. PCBN and ceramic inserts are almost always given a protective edge preparation, either a chamfer (T-land), a hone, or a chamfer combined with a hone, to strengthen the brittle edge against chipping [1, 39]. The preparation, however, changes the effective rake angle and the volume of material ploughed under the edge. Thiele and Melkote found that edge geometry and workpiece hardness both affected surface roughness and forces in finish hard turning of

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AISI 52100, with large hones raising the thrust force markedly [40]. Özel modelled the effect of edge preparation in CBN tools by finite elements and showed that it alters the stresses and temperatures on the tool and the stress state in the workpiece [39], a result consistent with the experimental work of Özel et al. on AISI H13 [14].

Nose radius involves a similar trade-off. A larger radius lowers the theoretical roughness for a given feed (Section V) and strengthens the tool corner, but it lengthens the engaged edge, raises the thrust force and makes the process more prone to vibration. Pawar and Palhade found nose radius to be among the most significant factors for both roughness and material removal rate in turning M2 [10], and a comparative study of insert geometries on M2 reached a similar conclusion [26]. Wiper inserts, whose nose is formed from several blended radii, offer a way around the feed–roughness conflict by smoothing the feed marks left by the primary radius. Grzesik and Wanat showed that wiper ceramic inserts gave substantially lower roughness than conventional inserts at the same feed on hardened alloy steel [41]. Gaitonde et al. reported on hardened AISI D2 that wiper ceramic inserts performed better in roughness and tool wear, while the conventional insert gave lower machining force, power and specific cutting force [42]. Wiper geometry therefore allows higher feeds for a given finish, at the cost of higher forces.

C. Workpiece Materials

The workpiece materials studied most often are bearing steel AISI 52100, hot-work die steel AISI H13 and H11, cold-work steels AISI D2, D3 and D6, and alloy steel AISI 4340 [11–14, 19–22]. High-speed steel AISI M2 at 62–64 HRC is less studied. Pawar's work fills part of that gap, with Taguchi-based studies of dry CNC turning of hardened M2 using 0.8 mm nose-radius PCBN inserts for force [6], roughness [7] and vibration [8, 9], plus earlier work on M2 with TiN-coated carbide inserts [10]. The hardness chosen matches that of M2 drill tools in service [9].

The machinability of these steels at a given hardness differs considerably, mainly because of the type, size and volume fraction of their carbides. AISI 52100 has a fine dispersion of spheroidized chromium carbides in tempered martensite and is the most extensively studied hard-turning material. AISI H13 and H11 are hot-work steels with comparatively low carbide content, normally hardened to about 45–55 HRC. AISI D2 and D3 are high-carbon, high-chromium cold-work steels containing a large volume fraction of coarse chromium carbides, which act abrasively against the tool [15]. AISI M2 is a tungsten–molybdenum high-speed steel whose microstructure contains very hard vanadium-rich MC carbides and tungsten- and molybdenum-rich M_6C carbides. In its fully hardened state of 62–64 HRC it combines high hardness, high hot hardness and abrasive carbides, which makes it one of the most demanding materials for hard turning [4, 6]. Table 2 summarizes these differences. Because carbide content affects force, wear and finish together, results obtained on one steel cannot be assumed to hold for another at the same nominal hardness.

Table 2. Workpiece materials commonly studied in hard turning.

Material	Type	Typical hardness in reviewed studies	Features relevant to hard turning
AISI 52100	Bearing steel	About 58–64 HRC	Fine spheroidized Cr carbides; most widely studied; benchmark for PCBN finishing
AISI H13, H11	Hot-work die steel	About 45–55 HRC	Low carbide content; hardness strongly affects force and chip form
AISI D2, D3, D6	Cold-work tool steel	About 58–62 HRC	Large volume of coarse Cr carbides; highly abrasive to tools
AISI 4340, 4140	Low-alloy steel	About 45–63 HRC	Few primary carbides; suited to ceramics and coated carbide at lower hardness
AISI M2	W–Mo high-speed steel	62–64 HRC	Hard MC and M_6C carbides and high hot hardness; least studied at full hardness

IV. CUTTING FORCES IN HARD TURNING

In hard turning the thrust (radial) force is often as large as or larger than the tangential force. This follows from the negative rake, chamfered or honed edges and small depths of cut used with CBN tools [1, 2]. A high thrust force deflects the tool and workpiece, which harms dimensional accuracy and can excite vibration, so force control matters beyond power and tool load.

Three force components are usually measured with a dynamometer: the tangential or main cutting force F_c, acting in the direction of cutting speed and determining power; the feed force F_f, along the feed direction; and the thrust or radial force F_t, normal to the machined surface. Many studies report the resultant force:

$$F_R = \sqrt{F_c^2 + F_f^2 + F_t^2} \tag{2}$$

The resultant is convenient for single-response optimization, as in the M2 studies [6], but it hides the balance between the components. Since dimensional error and vibration are driven mainly by the thrust force, and power

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mainly by the tangential force, a setting chosen on the resultant may not be the best for accuracy. Reporting the components separately, even when the resultant is optimized, would make studies easier to compare.

The main influences reported are workpiece hardness, feed rate, depth of cut and edge geometry. Kumar et al. found hardness to be the primary driver of forces in AISI H13 [11]. RSM studies on AISI 52100 with CBN tools built quadratic force models in which feed and depth of cut dominate [12], and Aouici et al. reached a similar conclusion for hardened AISI H11 [13]. Özel et al. showed that edge preparation, hardness, feed and speed together shape both forces and roughness in finishing H13 [14].

Lalwani et al. found a similar pattern in finish hard turning of MDN250 steel at about 50 HRC with coated ceramic tools: feed and depth of cut had the main effect on the force components, while cutting speed had little influence within the range tested [43]. Depth of cut acts mainly on the tangential and feed forces because it lengthens the engaged edge, whereas feed acts on all three components by thickening the chip. Because the depth of cut in hard turning is often less than the nose radius, increasing it changes the shape of the chip cross-section as well as its area, which helps explain why its effect on the thrust force is sometimes weaker than expected.

The relation between hardness and force is less simple than it first appears. Higher hardness raises the flow stress and hence the force, but it also promotes chip segmentation, in which localized shear lowers the average force needed to form the chip. Some studies therefore report that force rises with hardness only up to a point, or that the rise is smaller than the change in flow stress would suggest [1, 2, 14]. Edge preparation interacts with hardness, since a honed or chamfered edge increases ploughing, and this interaction has been found significant in designed experiments [14, 40].

Cutting speed usually has a smaller effect on forces in these studies, but this is not universal. In dry turning of AISI M2 at 62–64 HRC with PCBN inserts, Pawar used an L27 orthogonal array with signal-to-noise ratios and ANOVA and found cutting speed to be the most influential factor on resultant cutting force, confirmed by verification runs [6]. A plausible reading is that at very high hardness, thermal softening at higher speed lowers the shear strength in the cutting zone enough to outweigh other effects within the tested window. This contrast shows why factor rankings should be read as specific to the material, tool and parameter range rather than as general rules.

Multi-response studies often treat force together with roughness and temperature. Umamaheswarrao et al. used a central composite design and TOPSIS for PCBN turning of AISI 52100, varying speed, feed, depth of cut, nose radius and rake angle, and reported an optimum machining force of about 561 N alongside roughness of about 0.51 µm [20].

Tool wear has a large effect on force, and its influence is strongest on the thrust component. As the flank wear land grows, the contact area between tool and machined surface increases and the thrust force can rise well above its fresh-tool value, while the tangential force changes less [15, 35]. This sensitivity makes thrust force a useful indirect indicator of wear for monitoring (Section VI), but it also means that force optima found with a fresh edge in each run may not hold over a tool's life.

Approaches to predicting force fall into four groups. Empirical models, mostly regression or RSM equations fitted to designed experiments, are the most common in the optimization literature [12, 13, 43]; they are accurate inside the tested region but carry no physical meaning outside it. Mechanistic models relate force to chip area through specific cutting coefficients that depend on edge geometry and material, and can account for the nose-radius chip geometry. Finite element models simulate chip formation directly and can predict force, temperature and stress fields together [39], but they need flow-stress and friction data at the high strains, strain rates and temperatures of hard turning, which are difficult to obtain. Finally, neural-network models have been used to estimate forces in hard turning directly from cutting conditions [44].

V. SURFACE ROUGHNESS AND SURFACE INTEGRITY

A. Surface Roughness

Hard turning can reach an arithmetic mean roughness below about 0.3 µm with size tolerances near 0.010 mm in one setup, which is why it competes with grinding [11]. The geometric starting point is the ideal roughness left by the tool nose, which depends on feed f and nose radius r:

$$R_a \approx \frac{f^2}{32\,r} \tag{3}$$

This explains why feed rate and nose radius dominate most roughness studies. Pawar and Palhade, turning M2 with TiN-coated carbide inserts of 0.4, 0.8 and 1.2 mm nose radius in an L9 Taguchi design, found feed rate and nose radius to be the most significant factors for both roughness and material removal rate [10]. A companion study compared insert geometries in CNC turning of M2 using the Taguchi method, reinforcing the role of nose radius [26]. The same design approach has been applied beyond hardened steels: in dry turning of Inconel 718, cutting speed was found to be the leading factor for roughness, followed by feed [25]. RSM work on AISI 52100 and H11 with CBN tools likewise places feed first [12, 13].

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Equation (3) gives a useful sense of scale: a feed of 0.1 mm/rev with a 0.8 mm nose radius gives a theoretical R_a of about 0.39 µm, and doubling the feed raises it about fourfold. The relation holds best at moderate feeds. At very low feeds the uncut chip thickness near the trailing edge falls below the minimum needed for chip formation, material is ploughed and pushed sideways rather than cut, and the measured roughness levels off or even rises above the theoretical value [45].

Real surfaces depart from the ideal model through edge wear, side flow of material, built-up material and vibration. These effects can make cutting speed more important than geometry alone predicts. In dry PCBN turning of M2 at 62–64 HRC, Pawar found cutting speed to be the most influential factor for roughness under an L27 design [7], while a related study identified feed rate as the dominant factor for resultant tool vibration [8, 9]. Linking vibration and roughness measurements in the same experiment is a useful direction that few studies have taken.

Side flow, in which material is squeezed out laterally under the worn or chamfered edge and left as ridges on the feed marks, is one of the main reasons that measured roughness in hard turning exceeds the geometric value. Kishawy and Elbestawi showed that side flow increases with tool wear, edge hone and negative rake and is aggravated at low feeds [45]. This mechanism also explains why roughness often deteriorates over a tool's life even though the nose radius is unchanged. Predictive models for roughness range from the geometric relation of Equation (3), through regression and RSM equations, to neural networks and other machine-learning methods. Benardos and Vosniakos reviewed these approaches and pointed out that roughness also depends on factors such as tool wear and vibration that models based only on cutting conditions do not capture [46]. In practice, roughness well below 0.4 µm is regularly achieved with PCBN tools, and ceramic tools can give grinding-comparable finishes on cold-work steel [37].

B. Surface Integrity

Surface integrity goes beyond roughness. Hard turning can leave a thin, hard 'white layer' and alters residual stresses and microhardness in the subsurface, all of which affect fatigue life [1–3, 47]. White layers appear featureless under optical microscopy after etching and are generally attributed to rapid heating above the austenitizing temperature followed by quenching, to severe plastic deformation, or to a combination of the two [48, 47]. Chou and Evans modelled the thermal conditions at the tool–workpiece interface and found that white-layer depth grows with tool flank wear and cutting speed, the wear land acting as the main heat source [48]. Beneath the white layer an over-tempered 'dark layer' of reduced hardness is often present.

Residual stress depends strongly on tool condition. Sharp or lightly honed tools generally leave compressive stress at or just below the surface, which benefits fatigue life, while worn tools shift the surface stress towards tension and move the compressive peak deeper [1, 47]. Workpiece hardness modifies this pattern [34], as do feed and edge preparation [40]. Residual stress can itself be the optimization target: Pawar and Mokshanatha used a Taguchi design with ANOVA and confirmation runs on hardened AISI M2 and reported a best-case compressive residual stress of about −230 MPa [24]. Because residual stress, white-layer thickness and microhardness are costly to measure, typically requiring X-ray diffraction, metallographic sectioning and microhardness traverses, they are measured far less often than roughness, and most optimization studies do not include them.

C. Cooling and Lubrication

Most hard turning is done dry, since PCBN performs well at high temperature and flood coolant can cause thermal shock in brittle tools, but several studies show benefits from small quantities of lubricant. Varadarajan et al. showed that minimal cutting fluid application gave better results than both dry and flood cooling [18], and Khatai et al. obtained low flank wear (0.027–0.095 mm) with a ZnO nanofluid in a dual-nozzle pulsed MQL system on AISI 52100 [19]. High-pressure coolant has also been applied to hard turning, and Mia and Dhar used it together with an artificial neural network to predict roughness [49]. Sharma et al. reviewed the wider range of cooling techniques in turning, including minimum quantity lubrication, high-pressure and cryogenic methods [50]. In hard turning the benefit of any fluid has to be weighed against the cost and environmental burden it adds, which is why dry cutting remains the reference condition.

VI. TOOL WEAR AND TOOL LIFE

A. Wear Mechanisms

Tool wear sets the economics of hard turning, because a worn CBN edge raises thrust force, degrades finish and alters the machined layer long before the tool fails outright. Flank wear and crater wear are the main modes. Poulachon et al. linked PCBN wear in several hardened steels to the hard carbide particles in the workpiece, which act abrasively, alongside chemical and diffusion wear at high temperature [15]. The carbide-rich microstructure of tool steels such as D2 and M2 therefore makes them harder on tools than bearing steels of similar hardness.

Huang et al. surveyed CBN tool wear in hard turning and identified abrasion, adhesion, diffusion and chemical wear as the main mechanisms, with their relative importance depending on CBN content, binder and cutting

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temperature [35]. Barry and Byrne related CBN wear in hardened steels to layers formed on the tool surface from the workpiece, which can either protect the tool or accelerate its wear depending on workpiece composition [51]. Low-CBN grades with ceramic binders resist chemical attack better in continuous cutting, which is consistent with their preference for finishing. Besides gradual flank and crater wear, brittle tools suffer edge chipping, notch wear at the depth-of-cut line and, under unstable conditions, fracture. Crater wear in PCBN tends to form close to the edge and can undermine the chamfer until it breaks away, so crater growth often limits tool life even when the flank wear land is still small [15, 35].

B. Tool-Life Criteria and Models

Tool life is usually defined by a limiting flank wear land. ISO 3685 sets a general criterion of an average flank wear of 0.3 mm for uniformly worn turning tools [52], but in hard turning a smaller limit is often used, or tool life is ended when roughness or size error exceeds the part tolerance, because finish and accuracy usually degrade before the wear land reaches 0.3 mm. The relation between cutting speed and tool life is commonly described by Taylor's equation [53]:

$$v_c T^n = C \tag{4}$$

where T is tool life, n is an exponent that depends mainly on the tool–workpiece pair and C is the cutting speed that gives a tool life of one unit of time. Extended forms add terms in feed and depth of cut. Taylor-type models are simple and widely used for economic speed selection, but in hard turning they must be fitted separately for each tool grade, edge preparation and workpiece hardness, and the scatter in PCBN tool life, caused partly by random edge chipping, can be large.

C. Wear Measurement, Monitoring and Prediction

Experimental studies track flank wear against cutting time or volume removed and relate it to roughness. Tamizharasan et al. analysed flank wear and finish together for different CBN tools [21], and More et al. compared the wear life of coated carbide and PCBN inserts [22]. Özel and Karpat built regression and neural-network models that predict both roughness and flank wear from cutting conditions, and found the neural networks more accurate [16].

Despite its importance, tool wear is the least-studied of the three responses in parameter-optimization work. Most Taguchi and RSM studies use a fresh edge for each run, so their optimum settings describe a new tool rather than the process over a tool's life. Signals such as vibration offer an indirect way to follow wear during cutting; the vibration studies on hardened M2 [8, 9] provide a baseline for this kind of monitoring.

Tool condition monitoring offers a way to follow wear during cutting rather than after it. Signals from force dynamometers, accelerometers, acoustic emission sensors and spindle power meters have all been correlated with flank wear [54, 55]. Dimla reviewed sensor signals for wear monitoring and found that no single signal is reliable under all conditions, which favours combining several sensors [54], and Teti et al. surveyed the wider field of machining monitoring, including signal processing and decision-making methods [55]. In hard turning the thrust force is especially informative because of its sensitivity to the wear land, but dynamometers are costly and difficult to fit to production machines, which has encouraged the use of vibration and power signals. Prediction models complement monitoring: Özel and Karpat used neural networks to predict flank wear from cutting conditions [16], and Sharma et al. applied neural networks to forces and roughness [44]. Linking such models to on-line signals is a natural next step, but few studies have yet done so for very hard tool steels.

VII. OPTIMIZATION METHODS

Taguchi designs and RSM are the two workhorses of hard-turning optimization, with multi-criteria and machine-learning methods added when several responses must be balanced.

All of these methods share a common sequence: choose factors and levels, run a designed or historical set of experiments, build a model or ranking of the responses, select the best setting and confirm it experimentally. They differ in the type of model they build, the number of runs they need and the way they combine several responses, as summarized in Table 3 at the end of this section.

A. Taguchi Method with ANOVA

Orthogonal arrays (L9, L18, L27) cut the number of runs, signal-to-noise ratios pick the best level of each factor, and ANOVA gives each factor's percentage contribution. Yang and Tarng's application to turning is a standard early reference [17]. The method is quick and robust, and most of the M2 studies cited here use it [6–10]. Its limits are that it finds the best tested level rather than a true optimum between levels, handles interactions only partly, and optimizes one response at a time unless combined with another method.

The signal-to-noise (S/N) ratio converts replicated measurements at each trial into a single figure that rewards both a good mean and low variation. For responses to be minimized, such as force, roughness, wear and vibration, the smaller-the-better form is used:

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$$\mathrm{S/N} = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{5}$$

and for responses to be maximized, such as MRR or tool life, the larger-the-better form:

$$\mathrm{S/N} = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right] \tag{6}$$

where y_i is the i-th measured value and n the number of replicates [17, 56]. The level of each factor with the highest mean S/N ratio is selected, and ANOVA on the S/N ratios or raw data gives the percentage contribution of each factor. A confirmation experiment at the predicted optimum then checks the additive model; agreement within the confidence interval suggests that interactions are small.

Two practical points deserve attention. First, the design must leave enough degrees of freedom to estimate error. An L9 array has eight degrees of freedom, all of which are used by four three-level factors, so the error term can then only be estimated by pooling the smallest effects, which can inflate the apparent significance of the others. Second, an L27 array allows selected two-factor interactions to be estimated if the factors are assigned to the correct columns, which is one advantage of the L27 designs used in the M2 studies [6–8]. Percentage contributions are also specific to the factor levels chosen: widening the range of a factor tends to raise its contribution, so contributions from studies with different windows cannot be compared directly.

B. Response Surface Methodology

Central composite or Box–Behnken designs fit second-order models of force, roughness or temperature, which can then be optimized, often with a desirability function for several responses [11–13, 20]. RSM captures curvature and interactions, but its models are valid only inside the tested region.

The usual second-order model for k factors is

$$y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii}x_i^2 + \sum_{i<j}\beta_{ij}x_i x_j + \varepsilon \tag{7}$$

where x_i are the coded factor levels, the β terms are regression coefficients and ε is the error [57, 58]. A central composite design for three factors typically needs about 20 runs, including six centre points, while a Box–Behnken design needs about 15. Both support the full quadratic model, and the Box–Behnken design avoids extreme corner combinations, which is useful where these would risk tool fracture. Model adequacy is checked with the coefficient of determination and its adjusted value, the lack-of-fit test and residual plots [58]. When several responses must be optimized together, each is converted into an individual desirability d_j between 0 and 1, and these are combined into a composite desirability [59]:

$$D = (d_1 d_2 \cdots d_m)^{1/m} \tag{8}$$

The setting that maximizes D is taken as the compromise optimum. Kumar et al. used this approach for force and roughness on AISI H13 [11]. The result depends on the targets, limits and weights chosen for each response, which should therefore be reported alongside the optimum.

C. Multi-Criteria Methods

Grey relational analysis, TOPSIS and WASPAS rank experimental runs across several responses at once [19, 20]. They are simple to apply, but the result depends on the weights assigned to each response.

Grey relational analysis, based on Deng's grey system theory [60], first normalizes each response and then computes, for each run i and response k, a grey relational coefficient:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{0i}(k) + \zeta\Delta_{\max}} \tag{9}$$

where $\Delta_{0i}(k)$ is the deviation of the normalized value from the ideal, $\Delta_{\min}$ and $\Delta_{\max}$ are the smallest and largest deviations, and ζ is a distinguishing coefficient, usually 0.5. The coefficients are averaged, with or without weights, into a grey relational grade that ranks the runs. TOPSIS ranks alternatives by their relative closeness to an ideal solution and distance from a negative-ideal one [61], and WASPAS combines weighted-sum and weighted-product scores [62]. These methods are attractive because they need no model beyond the experimental table, but they normally choose among the tested runs or levels rather than predicting an untested optimum, and their rankings can change with the normalization method and the weights. Objective weighting schemes, such as entropy weights, and sensitivity checks on the weights make the conclusions more robust.

D. Neural Networks and Machine Learning

Neural-network models can predict roughness and wear more accurately than regression [16] and can be linked to search algorithms for optimization. They need more data and give less physical insight than designed-experiment models.

Multilayer perceptrons are the most common architecture, trained on data from designed experiments; support vector regression, Gaussian process regression and tree-based ensembles are increasingly applied to machining

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data as well. Neural networks have been used to estimate forces and roughness in hard turning [44] and to predict roughness under high-pressure coolant [49]. A recurring weakness is data size. A network with dozens of weights trained on 27 or fewer points is prone to overfitting, and accuracy reported on the training data, or on a handful of confirmation runs, says little about generalization. Cross-validation, independent test sets and comparison with a simple regression baseline should be standard practice. Once validated, such models can be coupled to search algorithms, such as genetic algorithms or particle swarm optimization, to locate optima between the tested levels.

E. Comparison and Selection of Methods

No method is best in every case. Taguchi designs suit early screening, when many factors must be ranked cheaply, and cases where robustness to noise matters. RSM suits refinement around a known good region, where curvature and interactions must be modelled and a predictive equation is wanted. Multi-criteria methods suit the selection of a compromise among several conflicting responses from an existing data set, and machine-learning models suit large or historical data sets and strongly non-linear responses. Sequential combinations are common and sensible: Taguchi screening followed by RSM on the significant factors, or RSM models feeding a desirability or metaheuristic search. Table 3 summarizes these trade-offs, and Table 4 lists representative studies.

Table 3. Comparison of optimization methods used in hard turning.

Method	Typical design or data	Strengths	Limitations
Taguchi + S/N + ANOVA	L9, L18, L27 orthogonal arrays	Few runs; robust to noise; simple factor ranking	Best tested level only; interactions only partly estimated; one response unless combined
RSM + desirability	CCD or Box–Behnken (about 15–20 runs for three factors)	Predictive quadratic model; curvature and interactions; multi-response compromise	Valid only inside the design region; more runs; quadratic form may be too simple
GRA, TOPSIS, WASPAS	Any experimental table	No model needed; many responses at once; easy to apply	Ranks tested runs only; sensitive to normalization and weights
ANN and other machine learning	Larger designed or historical data sets	Captures strong non-linearity; can combine process and sensor data	Needs more data; risk of overfitting; limited physical insight
Metaheuristics (GA, PSO)	Fitted model as objective function	Searches the continuous space; handles constraints and several objectives	Only as good as the underlying model; algorithm settings need tuning

Table 4. Summary of selected hard-turning optimization studies.

Study	Material (hardness)	Tool	Method	Responses	Key reported finding
Pawar 2017 [6]	AISI M2 (62–64 HRC)	PCBN, r = 0.8 mm	Taguchi L27 + ANOVA	Resultant cutting force	Cutting speed most influential
Pawar 2017 [7]	AISI M2 (62–64 HRC)	PCBN, r = 0.8 mm	Taguchi L27 + ANOVA	Surface roughness	Cutting speed most influential
Pawar 2017 [8]; 2022 [9]	AISI M2 (62–64 HRC)	PCBN, r = 0.8 mm	Taguchi + ANOVA	Resultant vibration	Feed rate most influential
Pawar and Palhade 2015 [10]	HSS M2	TiN-coated carbide, r = 0.4–1.2 mm	Taguchi L9 + ANOVA	Roughness, MRR	Feed rate and nose radius most significant
Bouacha et al. 2010 [12]	AISI 52100	CBN	RSM	Roughness, forces	Quadratic models; feed and depth of cut dominant
Kumar et al. 2019 [11]	AISI H13 (45–55 HRC)	Three CBN grades	CCD + desirability	Forces, roughness	Hardness, feed, speed significant; CBN grade matters
Umamaheswarrao et al. 2021 [20]	AISI 52100	PCBN	CCD + TOPSIS	Force, roughness, temperature	Multi-response optimum identified
Khatai et al. 2023 [19]	AISI 52100	—	WASPAS	Wear, roughness, temperature, power, noise	Nanofluid pulse-MQL kept flank wear low
Aslan et al. 2007 [36]	AISI 4140 (63 HRC)	Al_2O_3 + TiCN mixed ceramic	Taguchi L27 + ANOVA	Flank wear, roughness	Compromise setting balancing wear and finish
Davim and Figueira 2007 [37]	AISI D2 (hardened)	Ceramic	Orthogonal array + ANOVA	Wear, roughness, specific cutting pressure	Grinding-comparable roughness attainable

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Lalwani et al. 2008 [43]	MDN250 (about 50 HRC)	Coated ceramic	RSM	Forces, roughness	Feed and depth of cut dominate forces; speed minor
Gaitonde et al. 2009 [42]	AISI D2 (hardened)	Conventional and wiper ceramic	Designed experiments + quadratic models	Force, power, roughness, wear	Wiper better for finish and wear; conventional lower force
Suresh et al. 2012 [38]	AISI 4340 (48 HRC)	Multilayer coated carbide	RSM	Force, power, roughness, wear	Coated carbide viable at moderate hardness
Pawar and Mokshanatha 2025 [24]	AISI M2 (hardened)	—	Taguchi + ANOVA	Residual stress	About −230 MPa compressive at best setting

VIII. SYNTHESIS OF REPORTED FACTOR EFFECTS

Table 5 summarizes the direction and typical significance of the main factor effects reported in the studies reviewed. The general picture is consistent. Feed and nose radius govern roughness through the geometry of the tool nose; feed, depth of cut, hardness and edge preparation govern force; and cutting speed and hardness, acting through temperature and abrasive carbides, govern wear. Yet individual studies frequently disagree on which factor ranks first. The M2 studies are the clearest example, with cutting speed leading for force and roughness [6, 7], whereas most studies on bearing and die steels place feed or depth of cut first [12, 13, 43].

Table 5. Summary of reported factor effects in hard turning.

Factor	Cutting force	Surface roughness	Tool wear	Remarks
Cutting speed	Little effect or slight decrease in most studies; leading factor for M2 at 62–64 HRC [6]	Usually minor; leading factor for M2 [7] and Inconel 718 [25]	Strong increase through temperature	Effect depends on hardness and tool grade
Feed rate	Strong increase in all components	Strong increase, roughly with f^2	Moderate increase	Most consistent factor across studies
Depth of cut	Strong increase, mainly tangential and feed forces	Usually minor	Moderate increase	Often smaller than nose radius in finishing
Nose radius	Increase, mainly thrust force	Decrease (geometric), but vibration risk	Stronger corner; less chipping	Interacts with feed
Workpiece hardness	Generally increase; may be non-monotonic with chip segmentation	Variable	Strong increase, especially in carbide-rich steels	Often the top factor when included
Edge preparation	Increase with hone or chamfer size, mainly thrust force	Variable; can raise side flow	Reduces chipping	Seldom included as a design factor

Several reasons, mostly methodological, account for the disagreement. The first is the parameter window. ANOVA contributions measure the variation caused by moving a factor across its chosen levels, so a factor tested over a narrow range will appear less important than the same factor tested over a wide one. Second, interactions are often ignored or only partly estimated, so effects that depend on the level of another factor, such as speed on hardness or feed on nose radius, can be misattributed. Third, response definitions differ: the resultant force combines components with different sensitivities, and roughness values depend on the cut-off, evaluation length and position of the measurement. Fourth, tool condition varies, since some studies use a fresh edge for each run while others use one edge across several runs, letting wear enter as an uncontrolled factor. Fifth, the machine and setup, including stiffness, tool overhang and workpiece support, affect absolute values and the role of vibration. Finally, in very hard materials such as M2 at 62–64 HRC there may be a genuine physical difference, since thermal softening at higher speed may lower the flow stress in the shear zone enough to outweigh geometric effects within the tested window [6, 7].

These observations lead to some practical guidance. Factor rankings should be read as conditional on the material, tool, edge preparation and window studied, and when results are reported the factor levels, measurement details and tool condition should be stated with the ranking. For a new material–tool combination, a screening design across a wide window followed by model-based refinement is more reliable than adopting another study's optimum. Because roughness, force, wear and integrity respond differently to the same factors, a setting chosen for one response should be checked against the others before it is adopted in production.

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IX. RESEARCH GAPS AND FUTURE DIRECTIONS

1. **Wear-aware optimization.** Most optimum settings are found with fresh edges. Studies that optimize over the tool's life, or treat flank wear as a response alongside force and roughness, would give settings closer to production reality.
2. **Very hard high-speed and tool steels.** Data for M2 and similar steels above 60 HRC are limited compared with AISI 52100 and H13 [6–9]. Differences in reported factor rankings between these materials need systematic comparison under common conditions.
3. **Surface integrity as an objective.** Residual stress, white-layer thickness and microhardness govern fatigue life [1–3], yet only a few studies, such as recent Taguchi work on M2 residual stress [24], treat them as optimization targets. Multi-objective studies combining integrity with force, roughness and wear are still needed.
4. **In-process monitoring.** Vibration, force and acoustic signals can track wear and finish during cutting. Building on vibration baselines [8, 9], sensor-based models could adjust parameters in real time.
5. **Data-driven expert systems.** Neural networks already predict roughness and wear well [16]. Frameworks combining machine learning with process knowledge, of the kind proposed for extrusion processes [23], could be adapted to hard turning for parameter selection and defect detection.
6. **Sustainable cooling.** MQL and nanofluid approaches [18, 19] need longer tool-life tests and cost comparisons against dry cutting.
7. **Reporting standards.** Many studies omit edge preparation, CBN grade, machine stiffness or measurement details, which makes results hard to compare or combine.
8. **Statistical rigour and reproducibility.** Few studies report replication, confidence intervals on the predicted optimum or the degrees of freedom used to estimate error, and machine-learning studies often lack independent test data. Publishing raw data with the design would allow meta-analysis across laboratories.
9. **Interrupted and profiled hard turning.** Most studies turn plain cylindrical bars. Interrupted surfaces, such as splined or keyed shafts, and profiled parts with changing engagement load the tool differently and need dedicated studies [1, 35].
10. **Hybrid physics–data models.** Combining mechanistic or finite element models of force and temperature [39] with data-driven correction could give models that extrapolate better than purely empirical ones and support virtual process planning and digital twins of the hard-turning cell.
11. **Economic and environmental objectives.** Cost per part, energy consumption and carbon footprint are rarely optimized together with technical responses, although they decide whether hard turning replaces grinding in practice [2, 29].

X. CONCLUSIONS

Hard turning with CBN tools is a mature alternative to grinding, and statistical design of experiments has made parameter selection systematic. Its distinctive mechanics, namely segmented chips, a strongly negative effective rake, a dominant thrust force and a narrow process window, explain both its sensitivity to machine stiffness and edge geometry and the particular pattern of factor effects reported in the literature.

Feed rate and nose radius control surface roughness in most studies, following the geometry of the tool nose, while workpiece hardness, feed, depth of cut and edge geometry dominate cutting forces. Tool wear is governed mainly by cutting speed, hardness and the carbide content of the workpiece, and in turn drives the rise of thrust force, the deterioration of finish through side flow, and the formation of white layers and tensile residual stress. Work on AISI M2 at 62–64 HRC shows that cutting speed can become the leading factor for both force and roughness at very high hardness, a reminder that optimum settings do not transfer freely between materials and that factor rankings depend on the window tested.

Taguchi methods remain the fastest route to good settings, RSM gives predictive models and desirability-based compromises, and multi-criteria and neural-network methods handle several responses together; used in sequence, they are often more effective than any one alone. The main open needs are wear-aware and integrity-aware optimization, more data on very hard tool steels, monitoring-based and hybrid physics–data control, and stronger statistical and reporting practice so that results from different laboratories can be compared and combined.

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