

Surface quality and Tool Wear Analysis in AISI D2 Tool Steel Hard
Turning: A Comprehensive Review of Cooling Techniques
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Surface quality and Tool Wear Analysis in AISI D2 Tool Steel Hard Turning: A Comprehensive Review of Cooling Techniques

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Abstract:

Due to its low heat conductivity and strong resistance to wear, AISI D2 tool steel, recognized for its high level of hardness (58-62 HRC) and complex structure with tough carbides, poses significant challenges in machining. A review of 106 freely available studies from 2020 to 2026 examines hard turning operations on D2 steel, focusing on surface roughness, surface quality, and tool wear. The study evaluates various cooling and lubrication methods including dry cutting, flood coolant, minimum quantity lubrication (MQL), nanofluid-MQL, cryogenic cooling, hybrid techniques, and high-pressure coolant. The research identifies feed rate as the primary factor influencing surface roughness, explaining a substantial portion of the observed variations. It highlights the effectiveness of hybrid cryogenic-MQL and Nanofluid-MQL treatments in increasing tool lifespan by 80-400% compared to dry cutting while enhancing surface finish. The article also identifies seven critical research gaps such as the need for a deeper understanding of white layer formation during cryogenic cooling and the stability evaluation of nanofluids.

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Keywords: AISI D2 tool steel; hard turning; surface roughness;
surface integrity; tool wear; MQL; nanofluid; cryogenic cooling;
white layer; residual stress; CBN;

دراسة تحليلية لجودة السطح وتآكل العدة عند خراطة المواد الصلبة لفولاذ العدد AISI D2: مراجعة شاملة لتقنيات التبريد

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الملخص:

نظراً لانخفاض موصليته الحرارية ومقاومته العالية للتآكل، يُمثل فولاذ الأدوات AISI D2، المعروف بصلابته العالية (58-62 HRC) وبنيته المعقدة الغنية بالكربيدات الصلبة، يمثل تحدياً كبيراً في عمليات التشغيل الآلي. وتستعرض هذه الدراسة 106 دراسات متاحة، نُشرت بين عامي 2020 و2026، تتناول عمليات الخراطة الصلبة على صلب العدد D2. مع التركيز على خشونة السطح وجودته وتآكل الأداة. تقيم الدراسة طرق التبريد والتشحيم المختلفة، بما في ذلك القطع الجاف، والتبريد بالغمر، والتبريد بكميات قليلة (MQL)، والتبريد باستخدام السوائل النانوية، والتبريد السريع. والتقنيات الهجينة، والتبريد بالضغط. وقد بين البحث معدل التغذية كعامل رئيسي يؤثر على خشونة السطح، مُفسراً جزءاً كبيراً من التباينات الملحوظة. كما يُبرز فعالية المعالجات الهجينة بالتبريد المبرد والتشحيم بكمية قليلة، والتبريد بكميات قليلة باستخدام السوائل النانوية، في زيادة عمر الأداة بنسبة تتراوح بين 80% و400% مقارنةً بالقطع الجاف، مع تحسين جودة السطح النهائي. وتُحدد الدراسة أيضاً سبع ثغرات بحثية هامة، منها الحاجة إلى فهم أعمق لتكوّن الطبقة البيضاء أثناء التبريد المبرد، وتقييم استقرار الموائع النانوية.

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الكلمات المفتاحية: فولاذ الأدوات AISI D2 ؛ الخراطة الصلبة؛ خشونة السطح؛ سلامة السطح؛ تآكل الأداة؛ الحد الأدنى من التزييت والتزييت؛ الموائع النانوية؛ التبريد المبرد؛ الطبقة البيضاء؛ الإجهاد المتبقي؛ تبريد البورون المكعب.(CBN)

1. Introduction

The global precision manufacturing industry is increasingly shifting towards hard turning of hardened tool steels as a more eco-friendly and effective alternative to grinding. AISI D2 cold-work tool steel, with a hardness of 58-62 HRC, remarkable compressive strength, wear resistance, and dimensional stability post heat treatment, is widely used in die, punch, and precision tooling applications. Hard turning, when conducted optimally, can achieve surface finishes (R_a 0.4 μ m) comparable to or better than grinding, simplifying setup and enabling the production of intricate geometries in a single operation. The primary challenge lies in the high proportion (15-25%) of large, angular Cr₇C₃ and Cr₂₃C₆ carbides (1600-2100 HV), imposing severe mechanical and thermal loads at the tool-chip-workpiece interface. This leads to accelerated tool wear, induced detrimental residual stresses, and the formation of white layers (WL) at cutting temperatures ranging from 800-1100°C. Hence, selecting the most suitable lubrication and cooling method is crucial for optimal performance. Modern options offering improved performance sustainability trade-offs include MQL, nanofluid-MQL (NFMQL), cryogenic LN₂, and hybrid combinations, contrasting with conventional flood coolant which can cause environmental harm and thermal shock.

Despite a growing body of research, there is a lack of a comprehensive review encompassing surface integrity, surface roughness, and tool wear mechanisms for AISI D2 across various cooling technologies. This study fills that void utilizing only open-access publications from 2020 to 2026. The analysis is structured around six objectives: (1) metallurgical characterization of AISI D2; (2) mechanisms and factors influencing surface roughness; (3) phenomena impacting surface integrity; (4) classification of tool wear; (5) comparison of cooling technologies systematically; and (6) review of process optimization and modeling.

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Inclusion criteria involved experimental or modeling data on hard turning of tool or bearing steels (45 HRC) from peer-reviewed journals with verified DOIs and CC BY licenses. Studies on surface roughness, surface integrity, tool wear, cooling technology, or optimization were eligible. Out of an initial pool, 106 studies met all criteria. This narrative review synthesizes findings qualitatively without formal meta-analytical pooling, supplemented by tables providing quantitative summaries.

2. Characterization of the mechanical and metallurgical properties of AISI D2 tool steel.

2.1 Microstructure and chemical composition

The wear resistance of AISI D2 stems from its chemical composition (Table 1) and the microstructural features resulting from heat treatment. Following austenitization at 1000–1050°C and double tempering at 150–200°C, a tempered martensitic matrix forms, containing 15–25 vol. % of undissolved M7C3-type carbides (2–15 µm; 1600–2100 HV). These carbides are reported to be harder than any commercial tool coating and are the primary reason for abrasive wear on both the flank and rake faces.

Table 1. Nominal chemical composition of AISI D2 tool steel (wt.%)
[5,6,7]

Element	C	Cr	Mo	V	Si	Mn	Fe
Min (%)	1.40	11.00	0.70	0.10	0.10	0.20	Bal.
Max (%)	1.60	13.00	1.20	1.10	0.60	0.60	Bal.
Typical (%)	1.50	11.50	0.80	0.90	0.30	0.40	Bal.

2.2 Mechanical and Thermal Characteristics

- Hardened D2 possesses the following attributes:
- Hardness: 58-62 HRC
- Ultimate compressive strength: 2300-2700 MPa
- Transverse rupture strength: 3100-3500 MPa
- Thermal conductivity: 17-21 W/m•K
- Young's modulus: around 210 GPa

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- Due to its low thermal conductivity, heat accumulates at the tool-chip interface, leading to higher temperature spikes than those seen in steels with lower alloy content under similar cutting conditions.
 - White layer formation starts at around 800°C, determined by the Ac1 austenitisation threshold.
- D2 falls into the category of challenging-to-machine materials, with a machinability index of 30–45% compared to AISI 1212.

3. Surface Roughness in Hard Turning of AISI D2 Steel

3.1 Possible Measurements and Key Factors

- Standard methods for measuring surface roughness include Ra (ISO 4287) and Rz, with reported ranges between 0.10 and 1.20 m depending on the process settings.
- Traditional grinding achieves a finish range of 0.20–0.80 µm, which can be improved to below 0.40 µm by optimizing CBN or ceramic tooling.
- Ultra-precision CBN turning at specific speeds and feeds has shown surface roughness values as low as 0.08–0.32 µm.
- While advancements have been made in 2D profiling, the exploration of three-dimensional areal parameters for hard-turned D2 surfaces remains limited.

3.2 Impact of Parameters

- Feed rate (f) is the most crucial factor affecting surface roughness, contributing to 45–90.53% of Ra ANOVA variation, with the highest impact observed in D2 hard turning.
- Decreasing the feed rate from 0.20 to 0.05 mm/rev typically results in a significant reduction in surface roughness.
- The relationship between cutting speed and surface roughness is complex, with an initial decrease in Ra followed by deterioration as cutting speed increases.
- Depth of cut has minimal influence on surface roughness except for very shallow cuts.

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- Optimal conditions for improving both surface roughness and tool life simultaneously have been identified through multi-objective studies.

3.3 Cooling Strategy Effects on Surface Roughness

- Various cooling methods have been explored to reduce surface roughness in hard turning.
- Hybrid NFMQL+cryogenic strategies have shown the lowest Ra values, while NFMQL strategies using specific materials have demonstrated significant reductions in Ra compared to dry cutting.

Table 2. Comparative surface roughness (Ra) under different cooling strategies in hard turning of D2 and related tool steels — OA literature 2020–2026

Cooling Strategy	Ra Range (μm)	Reduction vs. Dry	Key OA Refs.
Dry cutting	0.25–0.95	Baseline	[5],[6],[11],[31]
Flood/wet coolant	0.22–0.80	5–20%	[41],[42]
MQL (vegetable/ester)	0.18–0.65	15–35%	[11],[12],[43],[44]
NFMQL – Al ₂ O ₃ /ZrO ₂ /MgO	0.12–0.50	30–50%	[13],[14],[45],[46]
NFMQL – MoS ₂ /Graphene/hBN	0.10–0.48	40–60%	[14],[15],[47],[48],[49]
Cryogenic (LN ₂ /CO ₂)	0.18–0.70	15–40%	[17],[18],[50],[51],[19]
Hybrid NFMQL + Cryogenic	0.10–0.42	45–65%	[20],[21],[22],[23],[52]
High-Pressure Coolant (HPC)	0.18–0.72	15–35%	[53],[42]

4. Hard turning of AISI D2 steel and its impact on surface integrity

4.1 Residual Stress State

The development of residual stress is influenced by a combination of thermal (tensile, driven by temperature differences) and mechanical (caused by plastic deformation, compressive) processes. According to XRD sin²psi tests, under Sharp-tool conditions, residual stresses vary from -200 to -800 MPa in the feed direction

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and between -100 to -500 MPa in the cutting direction [8,10,27]. When the flank wear VBmax exceeds 150-200 μm , thermal effects become more significant, changing the stress state to a damaging tensile condition (+200 to +600 MPa) and adversely affecting the fatigue life of the part [9,10,26]. Studies on bearing steels with similar structures demonstrate that during initial tool use, VB is the primary factor affecting subsurface WL thickness and microhardness, with Vc becoming more important as wear progresses—a shift in mechanisms that is directly relevant to D2. By reducing peak thermal loads at the cutting interface, cryogenic LN2 cooling maintains compressive residual stresses across wider VB ranges [17, 18, 23, 50].

4.2 Changes in Microhardness

In the hard machining of D2, the subsurface microhardness profile displays three distinct regions: (1) a hardened surface layer (15–80 μm , +20 to +120 HV higher than the bulk) resulting from intense plastic deformation; (2) a thermally softened area (50–200 μm , 15 to 40 HV) caused by excessive tempering of martensite; and (3) a return to bulk hardness in deeper material. As spindle speed decreased from 8000 to 2000 rpm in D2 ball-end milling, the percentage of work-hardening increased from 12.5% to 38.4% [24], demonstrating that lower speeds prolong exposure to mechanical strain. Due to better heat dissipation, the dual-nozzle NFMQL decreases the thickness of the thermally softened zone by 30-45% compared to dry cutting at Vc = 150 m/min [11].

4.3 White Layer Generation and Prevention

4.3.1 Mechanisms of Formation

The white layer (WL) - a hard, nanocrystalline/untempered martensitic surface layer (900-1300 HV in D2) - forms through two simultaneous mechanisms: (1) localized austenitization triggered by heat above Ac1 800°C followed by rapid cooling ($>104^\circ\text{C/s}$), and (2) severe plastic deformation due to mechanical stress ($>200\%$ shear strain) [10, 24, 26]. Grinding studies on AISI D2 [7] highlight the primary role of peak thermal load: workpiece speed has minimal impact, while grinding speed controls the transition from the outer hard white layer to a softer, over-tempered dark layer underneath. This finding directly affects hard turning: the cutting speed (Vc)

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significantly influences the thickness of the WL more than the depth of cut or feed rate. The thickness of the WL can range from 1-3 μm (under optimized conditions and sharp tools) to 15-35 μm (with severe wear and high-speed dry cutting). Retained austenite can be 25-45 vol. % in the WL compared to 3–8 vol.% in the bulk material [8,10].

4.3.2 Impact of Cooling Strategy

A comparative study of MQL/LN2 on AISI 4340 [17] in 2025 (similar to D2 hard turning) showed that LN2 leads to a thinner WL and smaller plastic deformation zones with both sharp and worn tools, with the most significant advantage seen at advanced wear stages. Table 3 summarizes the performance of various methods in controlling WL.

Table 3. White layer thickness under representative tool-wear state and cooling strategy combinations in D2 hard turning (synthesised from [7,9,10,17,21–23,52])

Strategy	Thermal Mitigation Mechanism	WL Thickness (New Tool)	WL Thickness (Worn, VB = 0.2 mm)	Key Refs.
Dry	None	2–5 μm	12–35 μm	[7],[10],[26]
Flood coolant	Bulk heat removal	1.5–4 μm	9–28 μm	[41],[42]
MQL	Tribological film; modest cooling	1.2–3.5 μm	7–22 μm	[11],[17]
NFMQL	Enhanced thermal conductivity + lubrication	1.0–3.0 μm	6–18 μm	[13],[14],[17]
Cryogenic LN2	Extreme heat extraction; sub-Ac1 maintenance	0.8–2.5 μm	5–15 μm	[17],[18],[50]
Hybrid NFMQL+Cryo	Synergistic cooling + lubrication	0.5–2.0 μm	3–12 μm	[17],[21]–[23],[52]

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4.4 Phase Alterations

When D2 is hard turned, secondary carbide dissolution and reprecipitation occur, along with the transformation of retained austenite to new martensite due to strain under operational loads (which may lead to dimensional instabilities), as well as thermal overtempering of the heat-affected zone, in addition to white layer formation. For the thermomechanical planning of D2 hard turning procedures, research on grinding [7] has identified critical temperature limits, like approximately 800°C for re-austenitization and between 400 and 600°C for sub-critical overtempering, which are essential reference points.

5. Tool Wear Mechanisms in Hard Turning of AISI D2 Steel

5.1 Tool Material Performance and Categorization

The selection of tool material governs the main wear mechanisms and tool longevity. The primary categories consist of: (1) ceramic-binder CBN with low CBN content (45–65 vol.%), suitable for continuous finishing due to its exceptional chemical stability; (2) metallic-binder CBN with high CBN content (85–95 vol.%), preferred for interrupted cuts; (3) blended ceramics ($\text{Al}_2\text{O}_3 + \text{TiCN/TiC}$); and (4) PVD/CVD-coated carbides (TiAlN , TiSiN , AlCrN , AlN-TiN) [6,25,26,41]. In a Taguchi L36 evaluation comparing ceramic and CBN inserts with two different nose radii, CBN was found to be more effective for all R_a and F_c measurements; the tool nose radius ranked second after the feed rate (f) in terms of managing R_a [6]. By altering the Xcel insert geometry for roughing, a R_a of 0.38 μm can be achieved with a 150 μm depth and one-step sustainable D2 machining without any subsurface structural harm. Tools with novel AlN-TiN hybrid coatings [41] deliver performance similar to commercial CBN in D2 finishing at a significantly reduced cost.

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Table 4. Comparative classification of cutting tool materials used in hard turning of AISI D2 tool steel [6,25,26,28,41]

Tool Class	Hardness	Primary Advantage	Key Limitation	Key Refs.
Low-CBN (ceramic binder)	≈ HV 3200–3800	Optimal chemical stability	Ra; Unsuitable for interrupted cuts	[6,25,26]
High-CBN (metallic binder)	≈ HV 4200–4700	High toughness; tolerates interruption	Higher cost; coarser Ra	[6,25,26]
Mixed ceramics (Al ₂ O ₃ +TiCN)	≈ HV 2000–2200	Lower cost than CBN	Higher abrasive wear rate	[6,25,26]
PVD/CVD coated carbide	Substrate + ≈ HV 3000–3300	Cost-effective; adhesion resistance	Coating breakdown at high T	[25,26,41]
Novel hybrid (AlN-TiN)	Comparable to CBN in trials	CBN-competitive at reduced cost	Limited industrial validation	[41]
Modified geometry (Xcel/wiper)	Substrate-dependent	One-step sustainable roughing-to-finish	Geometry-specific availability	[28]

5.2 Key Wear Mechanisms

Across different cutting speeds, abrasive wear caused by Cr₇C₃ carbide micro-ploughing on the flank and rake surfaces is the main wear mechanism. The evaluation of tool life using ISO 3685 (VB_{max} = 0.30 mm) is referenced in [6,11,25,26,33]. As proven in [6], CBN (HV 4700) shows significantly superior resistance to abrasion compared to Al₂O₃ ceramics (HV 2000–2200). At cutting speeds below V_c = 80 m/min, adhesive wear (built-up edge formation) is prevalent; minimum quantity lubrication (MQL) reduces the friction coefficient from 0.35–0.55 (in dry conditions) to 0.20–0.35, thus preventing built-up edge formation [12,13,61], while the inclusion of graphene nanoplatelet and MoS₂ additives achieves a coefficient of friction of 0.15–0.22 through lamellar

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lubrication [15,47,48,62]. Rake surface crater wear [17,25,26] indicates diffusion wear, which initiates at temperatures around 700°C ($V_c > 150$ m/min) and results in the removal of B from CBN and Ti/Al from TiAlN coatings. The use of LN2 cryogenic cooling decreases interface temperatures by 150–300°C, thereby reducing diffusion wear and enhancing tool life by 200–400% compared to dry cutting [17,18,19,23]. By maintaining tool temperatures below oxidation thresholds, cryogenic cooling eliminates notch wear, which arises from oxidation wear at the depth-of-cut boundary [17,18,51]. A compilation of comparative tool wear performance data can be found in Table 5.

Table 5. Comparative tool wear behaviour under different cooling/lubrication strategies in D2 and related tool steel hard turning — OA literature 2020–2026

Cooling Strategy	Dominant Mechanism	Typical Tool Life	Key OA Refs.
Dry	Abrasion Diffusion Oxidation	+ + 5–18 min	[11],[6],[28],[5]
Flood/wet coolant	Abrasion Adhesion (reduced)	+ 12–30 min	[41],[42]
MQL (vegetable/ester)	Abrasion reduced Adhesion	+ 18–42 min	[11],[12],[43],[74]
NFMQL (Al ₂ O ₃ /MoS ₂ /Graphene)	Abrasion (reduced)	28–65 min	[13],[14],[15],[48],[46]
NFMQL (ZrO ₂ /MgO/hBN/hybrid)	Abrasion (minimised)	30–70 min	[16],[75],[47],[49]
Cryogenic LN ₂ /CO ₂	Abrasion dominant (slow rate)	(slow 22–70 min	[17],[18],[51],[19]

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Cooling Strategy	Dominant Mechanism	Typical Tool Life	Key OA Refs.
Hybrid NFMQL + Cryogenic	Abrasion only (very slow)	40–90+ min	[20],[21],[22],[23],[52]
High-Pressure Coolant	Abrasion + Fatigue	25–55 min	[53],[76]

6. Cooling and Lubrication Technologies: Mechanisms and Performance

Table 6 provides a structured overview of all cooling technologies evaluated. The following subsections address each strategy mechanistically.

Table 6. Overview of cooling/lubrication technologies evaluated for hard turning of AISI D2 and related tool steels

Technology	Delivery	Primary Benefit	Primary Drawback	Key OA Refs.
Dry cutting	No external fluid	Zero coolant cost; simplest setup	Highest T°, wear, and Ra	[5,6,28]
Flood/wet coolant	Continuous liquid flood	Bulk heat removal	Thermal shock; disposal burden	[41,42]
MQL (vegetable/ester)	5–200 mL/h aerosol, 3–8 bar	Reduced friction/forces at low volume	Limited bulk cooling capacity	[11,12,43,74]
Nanofluid-MQL (NFMQL)	Nanoparticle-enhanced aerosol, 0.1–2.5 vol. %	Enhanced conductivity + tribofilm	Agglomeration/stability risk	[13–16,77,78]

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Technology	Delivery	Primary Benefit	Primary Drawback	Key OA Refs.
Cryogenic (LN ₂ /CO ₂ /vortex)	Cryogenic jet at -196 to -78°C	Large ΔT ; suppresses diffusion/oxidation	No lubrication; equipment cost	[17–19,50]
Hybrid NFMQL + Cryogenic	Simultaneous cryo jet + nanofluid aerosol	Addresses cooling and lubrication concurrently	Highest system complexity/cost	[20–23,52]
High-Pressure Coolant	High-pressure liquid jet, 50–200 bar	Effective chip control at high MRR	High energy/pump demand	[42,53]

6.1 Dry cutting

- Dry cutting at $V_c = 120$ m/min generates cutting temperatures ranging from 750–1000°C.
- A study conducted in 2021 on D2 dry-turning with CBN inserts identified optimal parameters: $V_c = 80$ –120 m/min, $f = 0.05$ –0.10 mm/rev, and $a_p = 0.10$ –0.15 mm.
- These settings resulted in $R_a = 0.30$ –0.80 μm and $VB_{\text{max}} = 0.30$ mm within a timeframe of 10–18 minutes.
- The enhanced Xcel insert geometry [28] broadened the operating range to $V_c = 225$ m/min, $a_p = 0.90$ mm, achieving 99.25% of the minimum specific energy target and fulfilling 100% of the tool life objectives compared to regular inserts.

6.2 Nanofluid MQL and MQL

- MQL reduces R_a by 15–35%, cutting forces by 10–25%, and the tool-chip friction coefficient from 0.35–0.55 (in dry conditions) to 0.20–0.35.
- Dual-nozzle MQL for D2 steel [11] decreased R_a by 28%, cutting temperature by 22%, and flank wear by 35% in comparison to single-nozzle systems by addressing both tool-chip and tool-workpiece interfaces simultaneously.

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- MQL nanofluid enhances the base fluid by incorporating nanoparticles (10–100 nm, 0.1–2.5 vol.%), boosting thermal conductivity by 15–35%, and improving tribological performance through mechanisms like surface polishing, rolling/mending action, and increased thermal conduction.
- Cryogenic cooling techniques reduce cutting zone temperatures by 150–300°C compared to dry machining, offering advantages such as decreased cutting forces, lower cutting zone temperatures, and reduced Ra when compared to MQL.

6.3 Cryogenic Cooling

- Cryogenic methods (LN2 at 196°C; scCO2 at 78°C; vortex-produced cold air) decrease cutting zone temperatures by 150–300°C when compared to dry machining.
- LN2 has several benefits including reducing cutting forces, cutting zone temperature, and Ra in comparison to MQL.
- LN2 is advantageous due to its ability to reduce workpiece thermal softening, protect tools from oxidation, prevent built-up edge formation, and control thermal contraction.

6.4 Cryogenic and Hybrid NFMQL Strategies

- Combining MQL with cryogenic cooling enhances performance synergistically.
- Hybrid methods show improved tool life compared to dry cutting and individual methods.
- A study on additive-manufactured stainless steel demonstrated a synergistic interaction between MQL tribological film formation and cryogenic-induced compressive hardening.
- Hybrid cryo-lubrication was found to be superior to individual methods for D2 machining.

7. Predictive Modeling and Process Enhancement

7.1 Multi-Objective and Statistical Optimization

The standard approach to optimize D2 hard turning parameters is through Response Surface Methodology (RSM), utilizing Box-Behnken or central composite designs [5,11,24,29,32,34]. The feed rate in Ra ANOVA remains the predominant factor (45–90.53%) across all experiments [6,11]. Taguchi arrays (L9/L18/L27/L36) with Signal-to-Noise (S/N) analysis provide robust design capabilities [5,6,29,98], while various multi-criteria techniques

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(such as GRA [99], TOPSIS, VIKOR, WASPAS, and NSGA-II/III [34]) help in balancing conflicting objectives. In a 2024 GRA research [99], optimal conditions were identified that simultaneously reduced Ra and VB in heat-treated alloy steel during high-speed turning. Through adjustments in parameters alone, a 2024 NSGA-III investigation on tool steel for cold work accomplished 87.66% of its cost reduction goals, 80.94% of its carbon emission targets, and 99.25% of its specific energy objectives.

7.2 Machine Learning Models

Various machine learning algorithms like random forest, XGBoost, Artificial Neural Networks (ANN), Support Vector Regression (SVR), and gradient boosting models are utilized to predict the cutting temperature, Ra, Fc, and VBmax of D2 and related steels [30,98,100-103]. In a 2023 study on D2 ultra-precision turning using BRNN [30], Ra prediction demonstrated high accuracy with $R^2 = 0.99$ and MAPE close to 1%, marking it as the most precise prediction in the literature on D2 hard turning. A 2024 research [102] implemented supervised machine learning in powder-mixed Electrical Discharge Machining (EDM) of D2 and achieved $R^2 > 0.95$, indicating the broader potential of machine learning. By employing machine learning-guided parameter selection, a study on NFMQL turning for D3 steel [103] reduced the number of experimental trials needed to achieve $Ra \leq 0.20 \mu m$ by 60%. A comparison of optimization and modeling method performance can be found in Table 7.

Table 7. Comparison of optimisation and modelling methods applied to hard turning of D2 and related tool steels [5,6,8,11,24,27,29,30,32,34,98–103]

Method	Type	D2/Tool-Steel Application		Performance Reported	Key Refs.
RSM (CCD/BBD)	Statistical DOE	Ra, Fc, VBmax	Fc, VBmax modelling	$R^2 > 0.90$; feed rate dominant	[5,11,24,29,32,34]

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Method	Type	D2/Tool-Steel Application	Performance Reported	Key Refs.
Taguchi L9–L36	Robust statistical DOE	Optimal parameter sets	90.53% feed rate ANOVA (D2) [6]	[5,6,29,98]
GRA / TOPSIS / VIKOR	Multi-criteria decision	Ra + tool life trade-offs	Identifies Pareto-efficient sets	[32,34,99]
NSGA-II / NSGA-III	Evolutionary multi-objective	Cost, carbon, energy, Ra	87.66% cost reduction goal [34]	[34]
ANN / BRNN	Machine learning regression	Ra, T°, VBmax prediction	R ² = 0.99 for D2 Ra [30]	[30,98,100,101]
SVR / RF / XGBoost	Machine learning ensemble	Ra, VBmax prediction	R ² > 0.95 [102,103]	[102,103]
FEM (DEFORM-3D, ABAQUS)	Physics-based simulation	Residual stress profiles	R ² > 0.93 vs. XRD [27]	[8,27]

8. Urgent Research Gaps and Future Directions

Analysis of 106 OA publications reveals seven critical research priorities:

1. Priority Gap:

- Investigation of white layer suppression in cryogenically processed D2 steel, which contains a distinctive high-volume Cr₇C₃ carbide population and Ac₁ ≈ 800°C. This area lacks synchrotron XRD or TEM studies, unlike AISI 4340 and 52100 where LN₂ WL suppression has been established.

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2. Nanofluid Stability and Occupational Health:

- Understanding the long-term stability of ZrO₂, GO, and MgO nanofluids under recirculating MQL conditions, as well as the ecotoxicological effects of nanoparticle aerosols produced during D2 hard turning.

3. Correlation Between 3D Surface Texture and Functional Performance:

- Emphasizing the importance of three-dimensional parameters (Sa, Ssk, Sku, Smr, Sxp) in predicting tribological performance and contact fatigue resistance, which are currently lacking in hard-turned D2 literature.

4. Study on Tool Wear and Surface Integrity Evolution:

- The need for research that links tool wear development with changes in residual stress, white layer thickness, and microhardness over multiple tool life cycles under hybrid NFMQL+cryogenic conditions.

5. Assessment of Cooling Strategies in D2 Hard Turning:

- Lack of comprehensive life-cycle assessment studies evaluating the energy consumption, disposal burden, and operational costs associated with various cooling methods for D2 hard turning.

6. Development of Finite Element Models for D2 Steel:

- The absence of finite element models that consider D2's Cr₇C₃ carbide population, calibrated Johnson-Cook parameters, and carbide dissolution kinetics during white layer formation.

7. Implementation of In-Process Monitoring for White Layer Formation:

- Exploring real-time monitoring techniques like acoustic emission, cutting force signals, and thermographic imaging for detecting white layer formation and tool wear state during D2 hard turning under hybrid cooling conditions.

9. Conclusions

This review synthesized 106 peer-reviewed open-access publications from 2020 to 2026, providing an in-depth analysis of surface roughness, surface integrity, and tool wear in hard turning of AISI D2 tool steel across eight cooling/lubrication strategies. Key findings include:

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- Feed rate significantly influences surface roughness across all cooling strategies and tool materials.
- Tool wear progression affects subsurface residual stress, impacting the fatigue performance of D2 tooling components.
- Cutting temperature plays a crucial role in white layer formation, influencing subsurface layer characteristics.
- Cr7C3 carbides contribute to abrasive wear in D2 hard turning, with cryogenic cooling effectively suppressing wear.
- Nanoparticle-based lubrication reduces surface roughness and extends tool life, with hybrid formulations showing superior performance.
- Hybrid NFMQL+cryogenic strategies are at the forefront, offering extended tool life and effective white layer suppression.
- Machine learning models demonstrate high predictive accuracy for surface roughness and tool wear, pointing towards future modeling directions integrating explicit carbide microstructure and dissolution kinetics.

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