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Dry Machining: Strategies and Advances for Sustainable Manufacturing – A Review

Harshal Balasaheb Wagh[1], Devendra Bhimraoji Sadaphale[2]
[1]*Assistant Professor, Department of Automation and Robotic, MET's BKC IOT, Nashik, Maharashtra, India.*
[2] *Associate Professor, Department of Mechanical Engineering, SSBT's College of Engineering & Technology, Jalgaon, Maharashtra, India*

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ABSTRACT

In recent years, dry machining has emerged as a critically important approach for advancing sustainability in manufacturing processes. This review paper provides a comprehensive introduction to dry machining, highlighting its benefits while consolidating recent technological innovations that facilitate its implementation. The primary objective is to deliver a concise overview of the current state of the art in dry machining, with a particular focus on its role in promoting sustainable industrial practices. By critically examining and consolidating findings from the existing literature, this study summarizes the principal methodologies and tooling strategies employed in dry machining. It also addresses the major challenges and limitations; alongside potential solutions aimed at enhancing its efficiency. The paper concludes by identifying key future research directions essential for scholars and researchers to further advance the field. The major findings of this review are as follows: (1) The application of textured or patterned cutting tools significantly improves machining performance under dry conditions across various materials; (2) Tool coatings offer a cost-effective means of achieving the requisite functional properties without compromising the core characteristics of the substrate; (3) Alumina-based mixed ceramic tools reinforced with silicon carbide (SiC) whiskers exhibit superior fracture toughness, thermal shock resistance, and self-crack-healing capabilities; (4) The integration of external energy sources to assist dry machining represents an effective strategy for enhancing the processing of engineering materials that are particularly advantageous for dry machining applications.

Keywords:- Sustainability, Dry Machining, Textured tools, Tool Coatings, Energy-Assisted Machining

1. INTRODUCTION

Energy and materials are essential resources for the global economy, yet their extraction from natural sources causes severe environmental impacts, including pollution, deforestation, biodiversity loss, and climate change. These issues threaten planetary life and drive the pursuit of sustainable development defined as meeting present needs without compromising future generations' ability to meet theirs [1]. As illustrated in Figure 1, sustainability encompasses the capacity to sustain activities indefinitely across environmental, social, and economic dimensions [1]. The manufacturing sector fuels economic growth as a major consumer of energy and materials, offering significant potential for sustainable practices. As the backbone of industrialized economies, it faces sustainability challenges. Today, sustainable manufacturing is not merely a regulatory requirement but a pathway to global competitiveness and societal benefits [2].

Machining, a critical process for producing precision components, underpins global economic expansion [3]. Amid rising demands for eco-friendly methods, machining innovation prioritizes systems that integrate research and industry expertise to conserve energy, resources, and the environment [4]. In the United States alone, manufacturing and machining generate over $100 billion annually, underscoring the urgency of sustainable practices given the scale of operations and associated environmental risks [5]. Machining removes material from a workpiece using a cutting tool to achieve specified geometry, generating substantial heat from intense deformation at the tool-workpiece interface [6]. This heat elevates temperatures, promotes built-up edges, and shortens tool life. Traditionally, cutting fluids mitigate these effects but contribute heavily to waste and environmental harm [7]. While fluids enhance heat dissipation, tool life, and surface finish, they account for ~17% of machining costs, pose disposal challenges, and degrade rapidly at high temperatures [8]. In the U.S., over 30 million gallons of cutting fluids are discharged yearly, with retreatment costs around $15 per gallon [9]. These fluids are hazardous, causing skin irritation, inflammation, cancer risks upon contact, and toxic vapours from evaporation that harm respiratory health [9], [10]. High-speed machining exacerbates issues like poor fluid penetration and thermal shocks that reduce tool life [11].

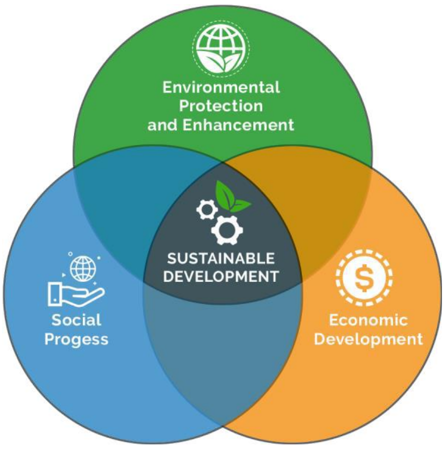

Fig -1: Pillars of Sustainable Growth

Growing environmental awareness and cost pressures have prompted scrutiny of cutting fluids [12]. Dry machining performed without fluids has surged in popularity and research, especially over the past five years [13]. As a green, cost-effective alternative to fluid-based methods, it minimizes waste, energy use, and health risks, positioning it as a vital strategy for future manufacturing [7].

2. DRY MACHINING: BENEFITS AND CHALLENGES

The transition from conventional flood coolant machining to near-dry and dry processes represents a fundamental shift toward sustainable manufacturing practices. This progression tackles environmental demands and economic constraints while overcoming key technical challenges. Dry machining, defined as the complete elimination of cutting fluids, emerges as a cornerstone technology for future manufacturing systems [8], [13], [14].

2.1 Advantages of Dry Machining

Dry machining delivers multifaceted benefits across environmental, health, and economic domains, as summarized in Figure 2(a)

- Elimination of liquid waste streams and associated pollution liabilities [15]
- Removal of worker exposure to hazardous cutting fluid constituents responsible for dermatological and respiratory disorders [16]
- Prevention of thermally-induced cracking in cutting tools [13]
- Substantial cost reductions through elimination of fluid procurement, storage, maintenance, and disposal expenditures [15]

These advantages position dry machining as both a regulatory compliance strategy and a competitive differentiator.

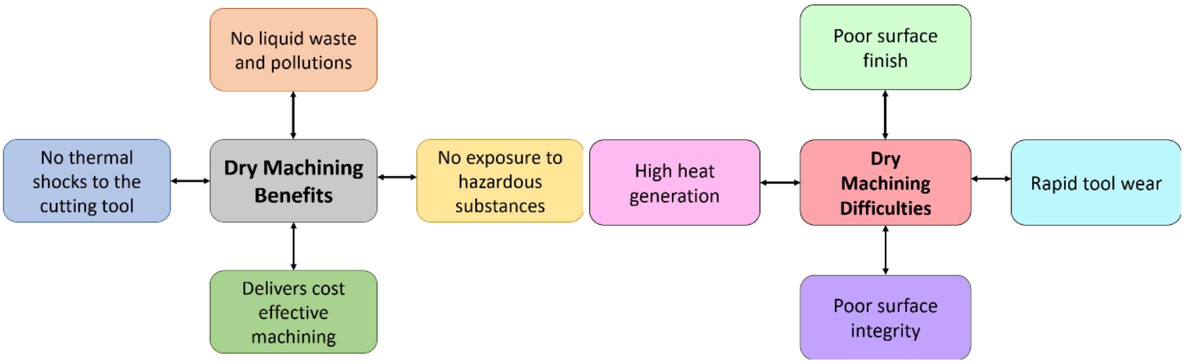

Fig -2: Dry machining (a) Benefits and (b) Difficulties

2.2 Technical Challenges

Absence of cutting fluids fundamentally alters tribological conditions at the tool-chip-workpiece interface, generating several critical challenges as shown in figure 2(b)

- Intensified frictional heating due to elevated adhesion and friction coefficients, producing cutting zone temperatures exceeding 1000°C [7]
- Thermal softening of cutting tools, compromising hot hardness and accelerating wear mechanisms [17]

- Surface integrity degradation manifested as increased roughness (Ra), dimensional deviations, and subsurface microstructural alterations [9]
- Generation of respirable metal fines posing occupational health risks.

2.3 Material-Specific Dry Machining Challenges L

Engineering alloys exhibit distinct behavioral responses under dry cutting specified in table 1.

Table -1: Material-specific challenges in dry machining

Material	Thermal Conductivity (W/mK)	Primary Failure Mode	Tool Wear Characteristics
Aluminium	237	Severe built-up edge formation	Adhesive wear, edge chipping [16], [18]
Stainless Steel (SS316L)	16	Adhesive chip-tool interaction	Built-up edge, crater wear [18], [19]
Titanium Alloys	22	Extreme interface temperatures	Diffusion wear, notching [8], [15], [20]
Nickel Superalloys	11	Work hardening + thermal fatigue	Abrasive wear, thermal cracking [14], [21]

High-speed dry machining amplifies these effects, particularly for low thermal conductivity materials where MORE THAN 90% of generated heat accumulates at the tool tip.

2.4 Mitigation Strategies

Contemporary research addresses dry machining limitations through four primary technology vectors:

1. **Advanced Tool Substrates:** Ceramic and cermet compositions offering superior hot hardness (>1400°C)
2. **Multilayer PVD Coatings:** TiAlN/AlCrN/Al_2O_3 stacks providing tribological optimization and thermal barrier effects [21]
3. **Surface Micro texturing:** Dimple/pocket patterns reducing contact area by 20-40% and improving chip evacuation [22]
4. **Hybrid Energy Assistance:** Ultrasonic vibration (20-40 kHz) reducing cutting forces by 15-30% [23]; Laser-assisted heating doubles the machining speed [24]

3. COMPREHENSIVE REVIEW STUDIES

A systematic literature survey reveals several review articles addressing dry machining, either exclusively or alongside complementary near-dry techniques such as minimum quantity lubrication (MQL). This section critically evaluates key contributions, identifies coverage gaps, and positions the present study within the research.

Sreejith and Ngoi [25] presented one of the earliest reviews focused exclusively on dry machining, analyzing current trends and emphasizing the critical need for technological innovations to achieve practical viability. Weinert et al. [12] examined minimal quantity lubrication (MQL) alongside dry machining, highlighting advancements in tool development, coating technologies, and machine tool optimization essential for near-dry processes. Zhang et al. [26] conducted a specialized systematic review on high-speed dry milling of hard-to-cut materials, documenting the performance impacts of auxiliary energy fields such as laser assistance, ultrasonic vibration, and cryogenic MQL.

Goindi and Sarkar [7] delivered a targeted critique of dry machining challenges and limitations, discussing recent progress in advanced tool materials and coatings, laser- or modulation-assisted variants, and MQL integration, yet notably omitted coverage of emerging surface texturing solutions. Complementary surveys by Chetan et al. [27] evaluated diverse eco-friendly machining alternatives, demonstrating performance often comparable to conventional wet methods, although their broad scope resulted in insufficient depth on pure dry machining dynamics.

4. STRATEGIES FOR ENHANCING DRY MACHINING PERFORMANCE

4.1 Cutting Tool Surface Structuring: Pattern or Texturing

Friction at the tool-chip interface governs heat generation and plastic deformation during machining, fundamentally controlling machinability [28]. Micro/nano-scale surface texturing represents a proven strategy for friction reduction, enabled by advancements in micromanufacturing technologies including laser beam machining and electrical discharge machining [29]. Surface-textured cutting tools constitute a next-generation tribological solution that has received considerable attention for its potential to improve machining process performance [30]. One of the earliest works presenting the concept was by Kawasegi et al. [28], who demonstrated that texture direction significantly influences cutting force reduction.

Fundamental Mechanisms and Benefits

Applying textures to cutting tool surfaces demonstrably reduces friction by 13-26% during machining processes by decreasing the contact area between the tool and chip [22], [31]. Textured cutting tools can reduce cutting force and feed force by 10-30% [32]. The primary documented benefits include:

- Cutting and feed forces reduction by 10-30% [29], [32], [33]
- Friction coefficients reduction by 13-26% across rake and flank surfaces [22], [31]
- Reduced contact area between tool and chip, minimizing heat generation [34]
- Reduced built-up edge formation and adhesive wear [29], [33]

Texturing Location and Geometry Effects

Researchers have explored various texturing locations on cutting tool surfaces to reduce friction, including rake surfaces [35]-[37], flank surfaces [38], and both surfaces simultaneously to form dual-textured cutting tools [32], [39].

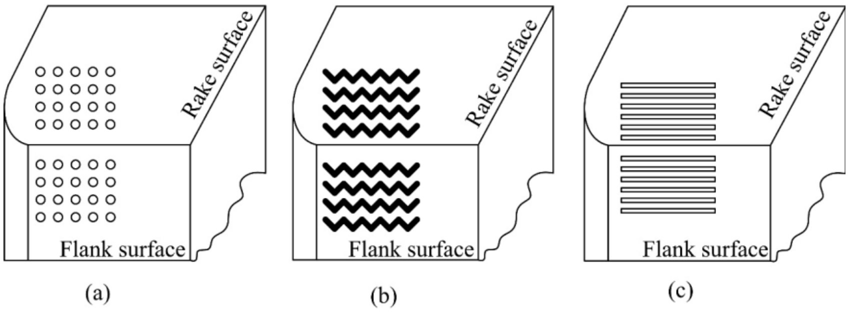

Fig -3: Rake and flank face textured tool (a) dimples, (b) waves, and (c) channels [32]

Table -2: Comparative performance of textured tool configurations

Texturing Location	Performance Improvements	Materials Tested
Rake surface only [29], [33], [35]-[37]	14% force reduction; 24% shorter chip-tool contact [33]; 13% cutting force reduction at lower speeds [29]	Al alloys, steels, Inconel 718
Flank surface only [38], [40]	Superior flank wear resistance at high speeds; 10% cutting force reduction [40]	AISI 4140
Dual (rake + flank) [22], [32], [39], [41]	16-31% force reduction; 56% flank wear reduction [39]; 14% friction reduction [32]	Ti6Al4V, AISI 420

Hole textures consistently outperform linear grooves in force and contact length reduction [33], while bio-inspired micro-crescent patterns on both tool surfaces have demonstrated exceptional performance in hard martensitic steels, reducing flank wear by 56% and feed force by 29% compared to conventional tools [39].

Material-Specific Performance

- Inconel 718: Micro-textured channel cutting tools extend tool life by 60% compared to micro-textured dimple tools at low cutting speeds [37].
- Ti6Al4V: Dual-textured tools reduce cutting force by 16%, thrust force by 31%, and friction by 18% compared to plain tools [22]. Textured inserts perform better at low cutting velocities [41].
- Aluminum Alloys: Textured tools prevent chip adherence and reduce cutting forces by 13% at lower speeds [29].

4.2 Cutting Tool Coatings

The fundamental challenge in cutting tool design lies in simultaneously achieving conflicting material properties: the tool core requires toughness and strength, while the surface demands hardness and wear resistance [42]. Coatings resolve this by depositing thin functional layers on cemented carbide substrates [21], [43]. In dry machining, uncoated carbide tools suffer accelerated cobalt binder diffusion at cutting zone temperatures exceeding 1000°C, causing premature failure [44]. Coatings provide a cost-effective solution, with research demonstrating their dominant influence on friction coefficients [45].

Table -3: Key coating systems evaluated for dry machining

Coating Type	Deposition Technique	Materials Tested	Key Performance Metrics
TiAlN [21], [46]	PVD	Inconel 718	Optimal Al content ($Ti_{0.41}Al_{0.59}N$): longest life [21]
TiN [46], [47]	PVD	Al alloys, steels	Best surface finish [48]; adhesion strength limits [47]
Al_2O_3 [49]	CVD	Inconel 718	Superior thermal barrier; CVD outperforms PVD [49]
TiCN-Al_2O_3-TiOCN [11]	CVD	Ti6Al4V	Multilayer excels at high speeds (>80 m/min) [11]

Coatings function as thermal barriers with conductivities 5-10 times lower than carbide substrates, confining more than 80% of generated heat within the chip [43]. For nickel-based superalloys, TiAlN variants with optimized Al content maximize tool life through stable Al_2O_3 phase formation at 900-1100°C [21]. Aluminium alloys benefit from TiAlN's hardness for wear minimization and TiN's smooth chip flow for superior finish [48]. Self-lubricating innovations include Ag-doped TiSiN doubling Ti6Al4V tool life via BUE suppression [8], TiSiVN forming lubricating V_2O_5 leading to ~18-23% adhesion reduction [50], and nc-TiAlSiN achieving 50% force reductions [44]. Graphite-PTFE outperforms MoS_2 against aluminum adhesion in humid conditions [16]. Multilayers like TiN/TiCN/Al_2O_3/ZrCN extend tool life across cutting speeds [42], with 4 µm TiN optimal for load balance [51]. The primary failure modes for coatings are delamination in CVD and cracking in PVD [43].

4.3 Advancement in Cutting Tool Material

While cemented carbide has dominated for decades due to its superior properties, its hardness degradation above 800°C limits dry and high-speed applications [52]. Global research now targets novel tool materials that maintain hot hardness (>1000°C) to enable fluid-free machining of difficult alloys [53].

4.3.1 New Cutting Tool Material Advancement

Iron-based cermets offer non-toxic, cost-effective alternatives to conventional binders. Canteli et al. [54] demonstrated M2 HSS reinforced with 50 vol.% TiCN doubling tool life during Steel35 steel dry machining. Ti(C,N)-based cermets deliver high-temperature hardness, enhanced by Al_2O_3 reinforcement and microwave sintering [55]. Zhang et al. [55] reported 64.5 min tool life on 40Cr steel with 15.9% improved surface finish. β-SiAlON ceramics exhibit exceptional thermal shock resistance. Yin et al. [56] achieved productivity five times over TiAlN-coated tools during high-speed Inconel 718 turning. Al_2O_3-YAG composites provide high fracture toughness through YAG dispersion. de Sousa et al. [57] confirmed superior tool life on nodular cast iron. Si_3N_4/TiC micro/nanocomposites leverage nanoscale refinement for crack inhibition. Lu et al. [58] outperformed conventional tools on 61 HRC steel. SiC whisker-toughened $Al_2O_3/SiC^W/TiC$ self-heals cracks via SiO_2 formation at 1200°C. Zhao et al. [59] achieved 50% longer life on Inconel 718 at 400 m/min.

4.3.2 Recent Advances in Tooling Materials

Advances in dry machining increasingly rely on intelligent tool architectures rather than material improvements alone. Following are the three representative innovations:

a. **Variable-Length Restricted Contact Tools (VRCT):** Pang et al. [19] developed VRCTs for AISI 316L stainless steel dry turning, achieving 20% cutting force reduction, 17% temperature decrease, and 44% flank wear reduction.
b. **Heat-Pipe Embedded Cooling Systems:** Quan and Mai [60] demonstrated ~40% heat extraction from tool rake faces, reducing maximum temperatures by 200°C.

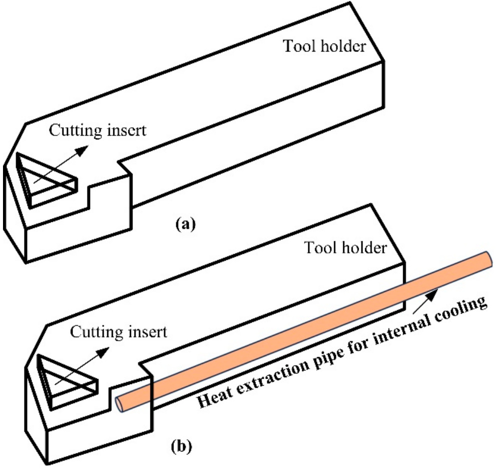

Fig -4: (a) Conventional cutting tool. (b) Schematic arrangement for the internally cooled cutting [60]

c. **Liquid Metal Embrittlement:** Sugihara et al. [61] introduced liquid gallium application to selectively remove aluminium-chip adhesion without substrate damage.

4.4 Energy-Assisted/Hybrid Dry Machining

Hybrid energy-assisted processes combine conventional machining with ultrasonic vibration or laser preheating to overcome dry machining limitations [24], [62].

a. **Ultrasonic Vibration-Assisted Machining (UVAM):** UVAM applies high-frequency vibrations creating intermittent chip-tool separation that reduces forces by 15-30% [23], [62]. Amplitude variation improves Ti6Al4V performance by 14-35% [62].
b. **Laser-Assisted Machining (LAM):** LAM preheats workpiece shear zones, reducing flow stress by 20-50% [26], [63]. LAM of Inconel 718 delivers 25% better finish and 800% higher material removal rates [63].
c. **Advanced Hybrid Systems:** Modulation-assisted machining segments continuous cutting, reducing wear at high speeds [64]. Laser-ultrasonic hybrids combine thermal softening with vibration-induced gaps for synergistic benefits [65].

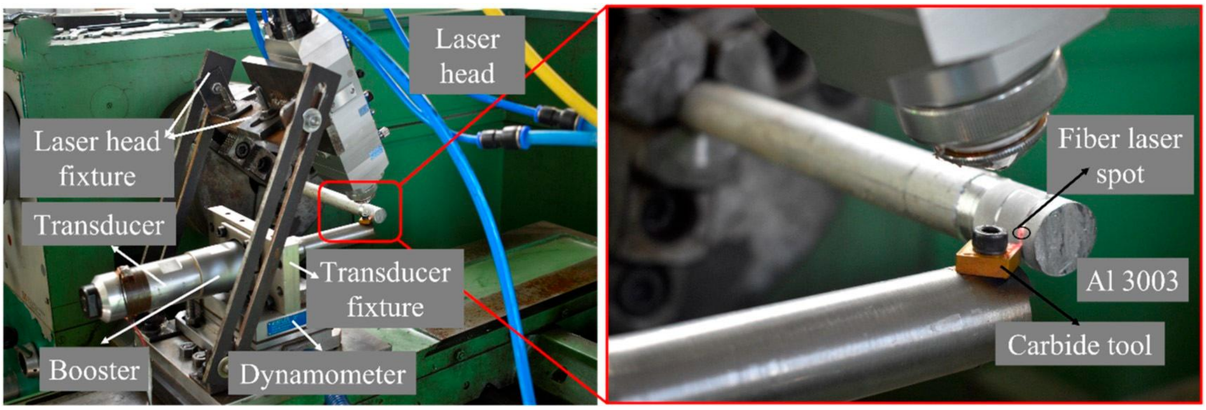

Fig -5: LUAM Assisted Setup [65]

Table -4: Energy-assisted dry machining performance

Method	Mechanism	Key Benefits	Target Materials
UVAM [23], [62]	Intermittent contact	15-35% force reduction	Ti6Al4V
LAM [26], [63]	Thermal softening	800% MRR increase	Inconel 718
MAM [64]	Low-frequency segmentation	High-speed wear resistance	Cast iron
UVLAT [65]	Synergistic hybrid	Widest parameter window	Multiple alloys

5. DISCUSSION

The previous sections highlight significant progress in various dry cutting processes and strategies aimed at promoting sustainability in metal cutting. Nevertheless, each approach presents its own set of benefits and limitations regarding ease of implementation, cost efficiency, and environmental impact.

Table -5: Overview of various Dry machining approach

Dry Machining Approach	Implementation Complexity	Economic Considerations	Environmental Considerations
Cutting Tool Surface Structuring	Comparatively easy to apply, as modern machining technologies enable precise surface texturing on tools.	Requires advanced equipment such as EDM, ECM, or laser machining. Although initial costs may be high, the technology is gradually becoming more affordable.	Does not generate toxic emissions. Textured tools enhance durability, reduce tool replacement frequency, and conserve resources.

Dry Machining Approach	**Implementation Complexity**	**Economic Considerations**	**Environmental Considerations**
Cutting Tool Coatings	Straightforward to implement using commonly adopted methods like PVD and CVD.	Coating processes are costly due to the need for specialized and expensive machinery.	PVD is environmentally harmless, whereas CVD may cause chemical pollution. Despite energy use during deposition, coated tools reduce energy and material consumption during service.
Advancements in Tool Materials	Challenging to implement; demands expertise in material science and extensive experimental validation.	Involves significant costs related to material development, manufacturing, and comparative performance evaluation.	Environmental effects vary depending on material type and processing route. Improved wear resistance and thermal stability extend tool life, reducing long-term environmental burden.
Energy-Assisted / Hybrid Dry Machining	Moderately difficult; requires integration of conventional machining with energy-assisted systems.	High setup costs due to additional equipment such as laser or ultrasonic systems.	No direct environmental hazards apart from increased electricity consumption.

6. CONCLUSIONS AND FUTURE SCOPE

This comprehensive review has systematically evaluated advanced dry machining strategies that enable sustainable metal cutting while eliminating cutting fluid dependency. Despite inherent challenges such as elevated friction, thermal loads, and accelerated tool wear, these technologies deliver substantial environmental, economic, and performance benefits for modern manufacturing

Key Findings

1. Textured tools enhance dry machining performance, yet flank and dual textures remain largely unexplored compared to rake surface texturing.
2. Tool coatings (e.g., TiN, TiAlN, AlCrN) improve dry machinability without sacrificing substrate integrity.
3. Advanced coatings (self-lubricating, multilayered, nanocomposite) show potential but require further study at higher cutting speeds.
4. Dry machining offers environmental and economic advantages over flood cooling, despite challenges such as elevated temperatures and friction.
   Future work should focus on hybrid strategies combining surface texturing, advanced coatings, and energy-assisted methods for difficult-to-cut materials. Need to set standardized criteria for selecting texture geometry, necessitating optimized guidelines based on material and process parameters.

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