

Review Of Cryogenic Machining: Effect on Tool Wear and Tool Life in Turning and Milling

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Abstract — High-performance engineering alloys, including titanium alloys (Ti-6Al-4V), nickel-based superalloys (Inconel 718), and hardened bearing/tool steels (AISI 52100, AISI D2), are vital for aerospace, automotive, petrochemical, and biomedical industries due to their high mechanical strength, fatigue endurance, and corrosion resistance. However, their low thermal conductivity, high hardness, severe chemical affinity, and work-hardening tendencies lead to extreme cutting zone temperatures exceeding 800 °C to 1000 °C, rapid flank/crater wear, and poor surface integrity. Traditional flood cooling methods rely on petroleum-derived mineral oil emulsions that create hazardous airborne aerosols, environmental disposal hazards, and significant recycling costs. Cryogenic cooling utilizing liquid nitrogen (LN₂, boiling point: -195.8 °C) and liquid carbon dioxide (LCO₂, delivered under saturation pressure) has emerged as a premier sustainable thermal management strategy. This review provides a comprehensive analysis of cryogenic machining mechanisms, heat transfer dynamics, tool wear evolution, process forces, surface roughness, and techno-economic sustainability. Fundamental phenomena such as the suppression of the Leidenfrost vapor barrier via high velocity jet impingement, temperature-dependent surface heat transfer coefficients, and speed-sensitive tool wear regimes are examined. Furthermore, hybrid lubrication-cooling synergies, life-cycle carbon emissions, and finite element modelling uncertainties are evaluated to establish an authoritative roadmap for green manufacturing.

Keywords: Cryogenic Machining, Liquid Nitrogen (LN₂), Liquid Carbon Dioxide (LCO₂), Tool Wear Mechanisms, Heat Transfer Rate, Minimum Quantity Lubrication (MQL), Sustainable Manufacturing, Specific Cutting Energy

I. INTRODUCTION

Modern manufacturing across the aerospace, automotive, petrochemical, and biomedical sectors demand materials that can withstand severe thermal, corrosive, and mechanical environments [1]. Primary representatives include alpha-beta titanium alloys (e.g., Ti-6Al-4V), nickel-based superalloys (e.g., Inconel 718), and high-carbon chromium bearing/tool steels (e.g., AISI 52100, AISI D2) [1,2,7]. Despite their indispensable utility in safety-critical components, machining these alloys using conventional subtractive methods induces extreme thermomechanical loading on cutting tools [1,2]. In metal cutting, over 90% of mechanical cutting energy converts directly into thermal energy across the primary shear, secondary tool-chip, and tertiary tool-workpiece contact interfaces [1,8]. Consequently, localized temperatures frequently exceed 800 °C to 1000 °C under dry conditions, accelerating thermal softening, severe plastic deformation, cobalt binder depletion, and premature tool failure [1,2,5].

For decades, the global manufacturing sector has relied heavily on conventional flood cooling, consuming billions of litres of petroleum-derived mineral oil emulsions [1,6]. High-pressure flood lubrication facilitates bulk cooling and chip evacuation at low upfront capital costs; however, it poses severe environmental and human health challenges [1,3,6]. Vigorous fracturing of fluid jets generates hazardous polydisperse aerosols linked to occupational asthma, chronic bronchitis, dermatitis, and various forms of toxicity documented by the National Institute for Occupational Safety and Health (NIOSH) [1,5]. Furthermore, spent cutting fluids require biocide monitoring and costly post-treatment disposal, contributing 10% to 17% of total manufacturing operating costs while polluting soil and aquatic ecosystems [1,3,7].

To overcome these ecological and economic limitations, cryogenic machining has emerged as a state-of-the-art sustainable thermal management alternative [1,3]. Cryogenic cooling utilizes expendable, chemically inert, non-toxic liquefied gases—primarily Liquid Nitrogen (LN₂, boiling point: -195.8 °C / 77 K) and Liquid Carbon Dioxide (LCO₂, sublimating at -78.5 °C)—delivered directly into the cutting zone [1,2,3]. Upon absorbing cutting heat, cryogens undergo endothermic phase transformation and flash cleanly into ambient air, leaving zero chemical residue on machined workpieces, machine tools, or chips [1,2,5,6]. This eliminates secondary solvent cleaning, degreasing, and fluid recycling while significantly reducing life-cycle carbon emissions [2,5,6].

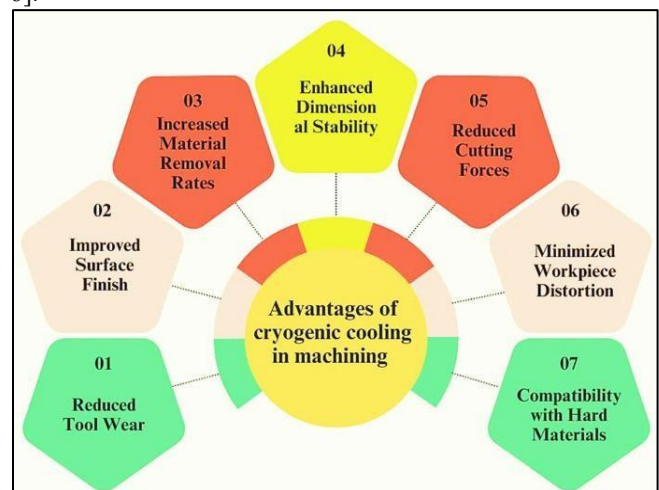


Fig. 1: Comprehensive overview of advantages provided by cryogenic cooling in sustainable machining [1].

II. FUNDAMENTALS AND THERMODYNAMIC PRINCIPLES OF CRYOGENIC COOLING

Cryogenic thermal management fundamentally departs from conventional flood cooling in its physical mode of heat evacuation [2,3]. Conventional water-oil emulsions operate

almost exclusively through sensible heat transfer governed by convective heat exchange: Q (Sensible) = $m_{\text{dot}} * c_p * (T_{\text{surf}} - T_{\text{inlet}})$, where total heat absorption depends entirely on the temperature differential between the hot surface and the ambient-temperature liquid [2,3]. Because emulsions remain liquid, they provide excellent bulk surface wetting over extended contact areas [2,3]. In contrast, cryogenic media dissipate high localized heat fluxes through endothermic phase transformations [2,3].

Liquid Nitrogen (LN2): Stored in vacuum-jacketed cryogenic Dewars at nominal temperatures of -195.8°C (77.35 K) under moderate storage pressure (nominally 3 to 10 bar) [1,2,3,6]. Delivered to the cutting tool through insulated pipelines, LN2 absorbs sensible heat and rapidly vaporizes into gaseous nitrogen via latent heat of vaporization ($Q_{\text{latent}} = m_{\text{dot}} * h_{\text{evap}}$) [1,2,3]. Because nitrogen comprises $\sim 78\%$ of ambient air, the evaporated gas is non-toxic and displaces oxygen at the cutting zone, shielding tool carbides and workpieces from high-temperature oxidation [1,2,5].

– Liquid Carbon Dioxide (LCO2): Stored in pressurized bottles at ambient room temperature ($\sim 20^{\circ}\text{C}$) under saturation pressures of 50 to 60 bar [2,3]. When throttled through a micro-nozzle into atmospheric pressure, LCO2

experiences rapid Joule-Thomson isenthalpic expansion and flash vaporization, creating an ultra-cold dual-phase jet containing solid dry-ice crystals (sublimating at -78.5°C) and high-velocity gaseous CO_2 [2,3]. The sublimation of solid CO_2 extracts significant latent heat while providing a powerful pneumatic kinetic blast for chip clearing [2,3]. A major practical advantage of LCO2 over LN2 is that it does not require vacuum-insulated piping and can be routed through standard CNC spindle and tool-holder hardware [2,3].

- Controlled calorimetric experiments conducted by Pušavec et al. using integrated thermocouples revealed that while emulsion cooling capability increases strongly with heater temperature (driven by thermal gradients), cryogen cooling capability depends weakly on substrate temperature and is governed primarily by mass flow rate and phase change [2,3]. Consequently, cutting interface temperatures under cryogenic cooling can be dynamically controlled and optimized by modulating cryogen mass flow rates [2,3].

Cooling Strategy	Delivery Temp. ($^{\circ}\text{C}$)	Supply Pressure	Primary Heat Removal Mechanism	Residue & Environmental Impact
Conventional Emulsion	$\sim 20^{\circ}\text{C}$ (Ambient)	5 – 70 bars	Sensible convective heat transfer [2, 3]	Hazardous biocide mist, high disposal cost [1,3]
Liquid Nitrogen (LN2)	-195.8°C	3 – 10 bars	Latent heat of vaporization (liquid-gas) [2, 4]	Zero residue, clean inert N_2 gas [1,5]
Liquid CO_2 (LCO2)	-78.5°C (J-T flash)	50 – 60 bars	Joule-Thomson expansion & sublimation [2, 3]	Zero residue, recycled industrial CO_2 [2, 8]
CryoMQL Hybrid	Sub-zero spray/mist	5 – 8 bars	Combined phase cooling + boundary lubrication [2, 9]	Near-zero aerosol mist, biodegradable ester [2, 9]

Table 1: Physical, thermodynamic, and ecological comparison of conventional, cryogenic, and hybrid cooling media [1,2,3].

III. LITERATURE REVIEW ACROSS MACHINING OPERATIONS

Over the past decade, extensive experimental and numerical studies have evaluated cryogenic cooling across diverse subtractive processes, cutting tools, and engineering alloys [1]. This section synthesizes landmark research across turning, milling, and grinding operations [1].

A. Cryogenic Turning Investigations

Turning represents the most widely documented cryogenic operation [1]. Basten et al. investigated the face turning of AISI 304 austenitic stainless steel with LN2 supplied at 1.2 kg/min (-196°C) [10]. Embedded instrumentation revealed that LN2 reduced maximum cutting tool temperatures from 249°C in dry cutting down to 168°C , whereas flood emulsion reached 121°C [10]. Interestingly, near-surface XPS analysis demonstrated that steep thermal gradients under LN2 increased workpiece surface oxidation within the first 4 nm, highlighting the complex surface chemistry induced by cryogenic quenching [10]. Juho Ratava et al. demonstrated that unmitigated dry turning of alloy steels promotes chatter instability and friction spikes, which can be detected in real time via spindle power and acoustic sensors [10].

Agrawal et al. conducted comprehensive cutting trials on Ti-6Al-4V turning across five cutting speeds (70 to 110 m/min) comparing LN2 cryogenic cooling against semi-

synthetic flood emulsion [5]. They discovered a critical speed-sensitivity threshold: at low cutting speeds (70 to 90 m/min), cryogenic turning shortened tool life by up to 17% relative to wet machining [5]. This was attributed to workpiece overcooling; low heat generation at low speeds allowed prolonged LN2 exposure to overcool the titanium alloy, elevating shear strength and inducing abrasive microchipping [5]. Conversely, at elevated cutting speeds (100 and 110 m/min), cryogenic cooling extended tool life by 116% to 125% over wet machining, suppressed crater wear, lowered total machining power by up to 23.4%, and improved surface roughness (R_a) by 22.1% [5].

In the hard turning of hardened AISI 52100 bearing steel (62 HRC), Kim et al. evaluated alumina ceramic (KY4400) and cubic boron nitride (CBN KB5625) inserts under dry, wet, and LN2 jet cooling [6]. Cryogenic flank jets extended ceramic tool life by 5.6 times (from 3.85 min dry to 21.49 min) and CBN tool life by 3.0 times (from 7.16 min dry to 25.07 min) while eliminating premature tool chipping [6]. In comparative studies by [Demirpolat et al.] on AISI 52100 turning, MQL delivered substantial lubricity by reducing tool tip temperatures from 410°C (dry) to 348°C and producing uniform washer-type helical chips instead of tangled ribbon-type chips [11].

B. Cryogenic Milling Operations

Milling is an interrupted cutting process characterized by severe cyclic thermal and mechanical shocks as cutter flutes engage and exit the workpiece [2,3]. Dry milling of titanium alloys or superalloys generates interface temperatures past 800 °C, inducing thermal fatigue comb-cracks and edge flaking [2]. Race et al. observed that while flood coolant reduced surface tensile residual stresses in milling SA516 pressure vessel steel, severe quenching caused premature insert failure at 16.5 minutes via thermal cracking [3]. In contrast, MQL roughly halved operating costs and reduced machine power by 20% by eliminating high-pressure pumps [3]. Pušavec et al. established that orthogonal (90°) nozzle jet delivery of LN2 or LCO2 maximizes stagnation pressure, directing cryogen deep into the tool-chip interface gap [2,3]. Furthermore, hybrid LCO2 + MQL milling of Inconel 718 demonstrated a 21% reduction in cutting forces and a 57% tool life extension over wet milling [1, 2].

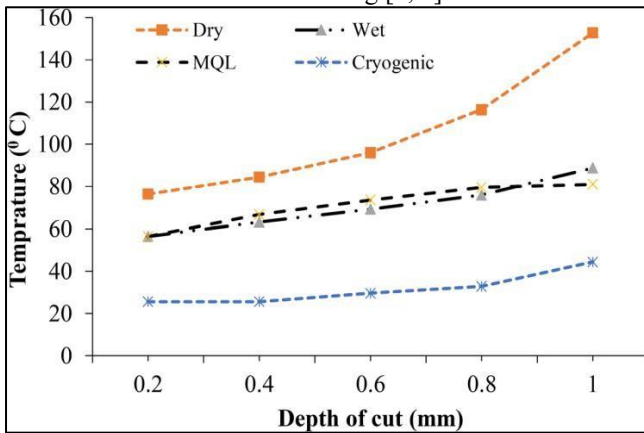


Fig. 2: Schematic of cryogenic fluid delivery in turning operations featuring a phase separator for 100% liquid LN2 delivery [1].

IV. TOOL WEAR MECHANISMS AND CUTTING PERFORMANCE

Tool degradation in machining high-strength alloys involves interactive mechanical abrasion, thermal softening, chemical dissolution-diffusion, adhesion, and microchipping along the

flank and rake faces [1,5,7]. Unchecked flank wear (VB) deteriorates machined surface finish, escalates dynamic cutting forces, and alters part tolerances, with ISO 3685 establishing an average wear criterion of VB = 0.3 mm (or maximum wear VBB max = 0.2 mm) as the end of tool life [5,7].

On the tool rake face, extreme temperatures and contact pressures accelerate crater wear through dissolution diffusion, wherein tool binder elements (e.g., cobalt in WC-Co tools) dissolve into exiting chips [1,5]. By maintaining interface temperatures below critical diffusion thresholds, LN2 suppresses binder depletion and retains tool substrate hardness [1,5,6]. In hard turning of AISI D2 steel (610 HV), Khan et al. evaluated novel A-type prime inserts with a 27.5° major cutting-edge angle compared to conventional and wiper inserts [7]. ANOVA established that cutting speed exerted the dominant influence on tool life (55.38% contribution), followed by feed rate (13.72%) and depth of cut (11.43%) [7]. At 125 m/min, prime inserts achieved stable tool wear progression and a remarkable tool life of 19 minutes (removing 252.6 cm³ of material), outperforming wiper and conventional inserts by over 50% [7].

In interrupted milling of titanium Ti-6Al-4V, Pušavec et al. proved that maximum bulk cooling does not inherently yield maximum tool life [2,3]. While flood emulsion extracted superior bulk heat (insert temperatures 40 °C to 90 °C), excessive cooling caused thermal shock in cemented carbides [2,3]. Hybrid Cryo-MQL (LCO2 or LN2 combined with vegetable ester oil mist) yielded superior tool longevity by establishing an optimal equilibrium between thermal suppression and boundary lubrication [2,9].

V. COMPARATIVE ASSESSMENT AND DISCUSSION

A rigorous synthesis of machining literature demonstrates that cooling and lubrication performance must be evaluated across multiple dimensions: thermal control, tool wear, surface finish, energy efficiency, and lifecycle economics [1,5,9]. Table 2 presents a comprehensive comparison of dry, flood, MQL, and cryogenic cooling technologies based on synthesized experimental literature [1].

Parameter	Dry Machining	Flood Cooling	MQL	Cryogenic Cooling
Cutting Temperature	Very High (>800 °C)	Moderate (Bulk cooling)	Moderate (Limited cooling)	Very Low (Subzero quenching)
Lubrication Efficacy	None (High friction)	Good (Fluid film)	Excellent (Boundary film)	Limited (Cooling dominant)
Tool Wear Rate	High (Thermal + abrasion)	Moderate (Quenching risks)	Low to Moderate	Very Low (Suppressed diffusion)
Workpiece Surface Finish	Poor to Moderate	Good	Good	Excellent (Ra reduced 22–42%)
Chip Morphology	Irregular, snarled, adhesion	Controlled chip formation	Improved chip control	High breakability, clean dry
Environmental Impact	Very Low	High (Toxic mist & disposal)	Low (Biodegradable oils)	Very Low (Residue-free N2/CO2)
Operating / Capital Cost	Low capital & operational	High (Disposal & recycling)	Moderate	High initial setup; low speed penalty

Table 2: Critical comparison of cryogenic cooling against dry, flood, and MQL machining technologies [1].

To evaluate overall process viability, Agrawal et al. examined machinability, machining cost, and carbon emissions in Ti-6Al-4V turning [5]. As depicted in Figure 3, a holistic evaluation framework must encompass cutting mechanics, tool wear, electrical energy, cutting fluid consumption, and chip recycling economics [5].

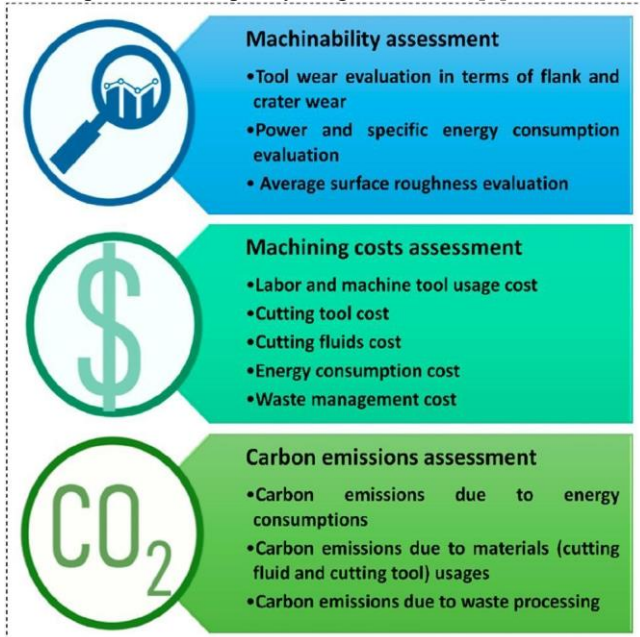


Fig. 3: Comprehensive framework evaluating machinability, machining costs, and carbon emissions in sustainable turning [5].

At elevated cutting speeds (110 m/min), Agrawal et al. demonstrated that cryogenic turning reduced total machining cost by 27.9% (\$12.7 vs \$17.6 per 5 cm³ material removed) and lowered life-cycle carbon emissions by 21.2% (2.6 kg CO₂ vs 3.3 kg CO₂) relative to flood wet turning [5]. A major contributor to emissions abatement is chip recycling: uncontaminated cryogenic titanium swarf requires only 23.25 kWh/kg to remelt into high-grade alloy, compared to 83.04 kWh/kg for chips contaminated with oil emulsions [5]. Similarly, in hybrid techniques evaluated by Agrawal et al., combining LN₂ with ultrasonic vibrations and MQL (CUMQLAT) reduced active cutting energy by 1.8% to 3.6% and surface roughness by 32% to 42%, yielding the highest Relative Sustainability of Process (RSP) rating [9].

VI. ADVANTAGES AND LIMITATIONS OF CRYOGENIC MACHINING

While cryogenic thermal management provides decisive environmental and metallurgical advantages, industrial implementation requires addressing key technical constraints [1,2,5].

A. Major Industrial Advantages

- Substantial Tool Longevity: Delivers up to 125% tool life improvement in titanium alloys at elevated cutting speeds and extends ceramic cutting tool life by 5.6 times in hard turning of AISI 52100 [5,6].
- Complete Elimination of Hazardous Mist: Replaces petroleum coolants with inert gases that vaporize instantaneously into ambient air, eliminating toxic

airborne aerosols, biocide handling, and occupational respiratory/skin diseases [1,5].

- Residue-Free Dry Workpieces: Produces completely dry, clean workpieces and chips, abolishing expensive post-machining ultrasonic washing, degreasing solvents, and contaminated fluid disposal [1,2,6].
- Reduced Specific Cutting Energy: Self-pressurized cryogenic Dewars eliminate continuous high-power fluid circulation pumps, reducing total machining electrical power consumption by up to 23.4% [5].
- High-Purity Chip Recycling: Dry, unpolluted metallic swarf commands premium scrap value and slashes recycling energy from 83.04 kWh/kg (wet) down to 23.25 kWh/kg [2,5].

B. Operational Limitations and Challenges

- Absence of Boundary Lubricity: Pure LN₂ and LCO₂ provide intense cooling but lack intrinsic hydrodynamic lubrication, leading to high rubbing friction in operations dominated by sliding contact [1, 2,9].
- Workpiece Overcooling at Low Cutting Speeds: At low cutting speeds (70 to 90 m/min in Ti-6Al-4V), prolonged cryogen exposure increases workpiece shear strength and flow stress, causing insert microchipping and shortening tool life by up to 17% [5].
- Thermal Shock in Interrupted Cutting: Steep thermal gradients during intermittent milling can induce micro-cracking and brittle fracture in fragile tool substrates like ceramics and PCD [2,3,12].
- High Consumable Costs & Infrastructure: Cryogenics are open-loop consumables (\$7.56/h for LN₂ vs \$0.11/h for wet emulsions) requiring vacuum-jacketed piping, phase separators, and cryogenic safety valves [1,4,5].
- Workplace Safety Hazards: Extreme cold poses frostbite hazards upon contact, while high-volume vaporization in confined machine enclosures creates severe oxygen-depletion and asphyxiation risks requiring automated oxygen/CO₂ monitoring [1,2].

VII. RESEARCH GAPS

Despite substantial progress in cryogenic machining, several critical research gaps remain unaddressed in the reviewed literature [1,3]:

- 1) Lack of Standardized Heat-Removal Metrics: Current studies report inconsistent thermal indicators (infrared thermometry, thermocouple telemetry, qualitative post-process readings) without unified metrics for convective heat flux (W/m²) and cooling rate (°C/s) across different cryogens and delivery setups [3, 4].
- 2) Sub-Ambient Constitutive Flow Stress Modelling: Predictive digital modelling (FEA and mechanistic force models) relies on Johnson-Cook constitutive equations calibrated at ambient to elevated temperatures [2,3]. Propagating parameter scatter through FE simulations reveals severe sensitivity in force prediction, while low-temperature flow stress data below 0 °C remains critically scarce [2,3].
- 3) Speed-Sensitive Overcooling Boundaries: The exact thermodynamic crossover boundary between workpiece overcooling (tool life degradation) and beneficial heat

dissipation (tool life extension) remains unmapped across alloy grades and cutting geometries [5].

- 4) Microstructural Subsurface Alterations: Detailed understanding of near-surface phase transformations, cryogenic oxidation layers (such as the 4 nm oxide detected in stainless steel), and white layer suppression across varied feed-speed-nozzle regimes is incomplete [7,10,11].
- 5) Comprehensive Life-Cycle Cost Accounting: Most economic evaluations focus on localized tooling and energy expenses, neglecting the full cradle-to-grave life-cycle inventory of cryogenic liquefaction, bulk cryogenic transport, and Dewar boil-off losses [3,5,6].

VIII. FUTURE SCOPE AND EMERGING HORIZONS

The future development of cryogenic manufacturing is advancing toward smart, hybrid, and digitally integrated machining platforms [1,2]. Figure 4 outlines key strategic directions for future cryogenic research [1].

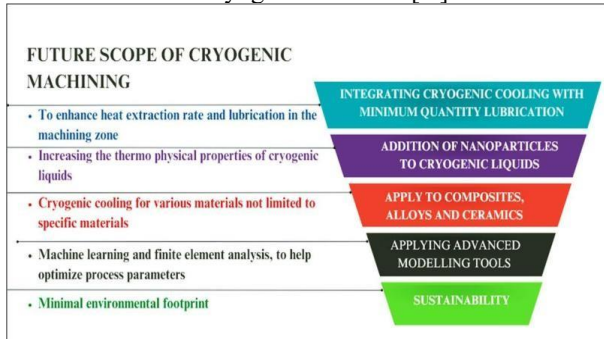


Figure 4: Strategic future scope and emerging horizons of cryogenic machining technology [1].

- Hybrid Cryo-MQL and Nanofluid Integration: Coupling cryogenic carriers (LN₂ or LCO₂) with vegetable-based MQL containing advanced nanoparticles (graphene, MoS₂, Al₂O₃, copper oxide) to simultaneously deliver maximum latent heat dissipation and boundary tribological lubrication [1,2,9].
- Smart Tooling with Conformal Internal Micro-Channels: Additive manufacturing of cutting tool holders equipped with internal conformal micro-nozzles directed precisely at the tool-chip interface, eliminating chip deflection while slashing LN₂ consumption below 10 kg/h [1,2,4].
- Closed-Loop Adaptive Cryogen Metering: Integrating real-time acoustic emission, piezoelectric force dynamometers, and IoT temperature sensors with machine learning algorithms to dynamically adjust cryogen mass flow rates based on instantaneous tool wear state [1,10,11].
- Low-Temperature Constitutive Database & Digital Twins: Formulating cryogenic Johnson-Cook and modified Zerilli-Armstrong flow stress models calibrated via split-Hopkinson pressure bar tests at subzero temperatures, enabling reliable digital twin force predictions [2,3].
- Expansion to Advanced Composites and Ceramics: Optimizing cryogenic parameters for difficult-to cut material stacks, including carbon fibre reinforced polymers (CFRP), metal matrix composites (MMCs), and structural ceramics [1].

IX. CONCLUSION

Cryogenic thermal management using liquid nitrogen (LN₂) and liquid carbon dioxide (LCO₂) offers a clean, highly effective alternative to traditional cutting fluids by absorbing heat through rapid phase transformations governed mainly by flow rate and jet pressure. High-velocity LN₂ jets sweep away insulating vapor blankets to achieve extraordinary heat transfer rates, while placing nozzles close to the tool (such as 2 cm at a 45° angle) ensures deep fluid penetration and slashes cutting forces by up to 48%. The process is especially powerful at high cutting speeds, where it prevents tool overheating, improves tool life by up to 125%, and enhances workpiece smoothness. These gains lower total machining power by up to 23.4%, reduce net costs by 27.9%, and cut overall carbon emissions by 22% largely through clean chip recycling. Ultimately, combining cryogenics with minimum quantity lubrication (Cryo- MQL), ultrasonic vibration, and smart flow control overcomes friction limits to establish an economical standard for modern sustainable manufacturing.

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