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# Tool Wear, Surface Integrity and Sustainability Assessment in Minimum Quantity Lubrication Machining of Inconel 718 Using Nanofluid-Based Cutting Fluids

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## Abstract

***Inconel 718, a nickel-based superalloy widely used in aerospace turbine components, presents severe machinability challenges arising from its low thermal conductivity, high work-hardening tendency, and chemical affinity for cutting tool materials at elevated temperature, conditions under which conventional flood cooling is both environmentally costly and only partially effective at controlling tool-chip interface temperature. This study evaluates minimum quantity lubrication (MQL) machining of Inconel 718 using nanofluid-enhanced cutting fluids — vegetable-oil-based MQL, Al2O3 nanofluid MQL, and MoS2 nanofluid MQL — benchmarked against dry cutting and conventional flood coolant across tool flank wear progression, surface roughness, cutting force and cutting-zone temperature, specific cutting energy, tool-chip interface temperature distribution, tool life, machining cost per component, and cutting fluid consumption with associated $CO_2$-equivalent emissions, using coated carbide inserts on a CNC turning centre across a cutting speed range of 40-120 m/min and feed rates of 0.05-0.25 mm/rev. MQL with MoS2 nanofluid achieves the lowest flank wear rate among all five conditions tested, extending tool life to 31.5 minutes against 11.2 minutes for dry cutting and 18.6 minutes for flood coolant, while reducing surface roughness to 0.78-1.05 µm across the tested speed range compared to 1.85-2.85 µm for dry cutting. Cutting force and cutting-zone temperature under MoS2 nanofluid MQL are reduced by 42% and 46% respectively relative to dry cutting, and the MQL nanofluid conditions reduce cutting fluid consumption to under 1 litre per 1000 components against 42 litres for flood coolant, with a corresponding 90% reduction in associated $CO_2$-equivalent emissions and a 55% reduction in machining cost per component relative to dry cutting. These findings establish nanofluid-enhanced MQL as a machinability and sustainability improvement strategy for Inconel 718 turning operations.***

**Keywords:** *Inconel 718, minimum quantity lubrication, MQL, nanofluid, tool wear, surface roughness, specific cutting energy, sustainable machining, superalloy machining, MoS2 nanofluid*

## 1. Introduction

Nickel-based superalloys such as Inconel 718 are extensively used in gas turbine discs, blades, and casings owing to their retained strength and corrosion resistance at elevated service temperature, but these same metallurgical properties make Inconel 718 notoriously difficult to machine: low thermal conductivity concentrates heat at the cutting zone rather than dissipating it through the chip, rapid work hardening increases cutting forces as deformation proceeds, and the alloy's chemical affinity for common tool coatings accelerates diffusion and adhesion wear mechanisms that shorten tool life relative to machining of conventional steels at equivalent material removal rates.

Flood coolant has historically been the default strategy for managing the thermal and tribological challenges of superalloy machining, but large-volume cutting fluid use carries substantial procurement, storage, and disposal cost, generates occupational health concerns from fluid mist inhalation and dermal contact, and imposes wastewater treatment burdens that conflict with increasingly stringent environmental regulation of metalworking fluid discharge in Indian manufacturing clusters. Minimum quantity lubrication (MQL), which delivers cutting fluid at flow rates of milliliters per hour rather than litres per minute via a compressed-air-atomised spray directed at the cutting zone, has emerged as a near-dry alternative capable of substantially reducing fluid consumption while retaining meaningful lubrication and cooling benefit relative to fully dry cutting.

The lubricating and cooling performance of base MQL fluids can be further enhanced by dispersing nanoparticles — commonly Al2O3, MoS2, CuO, or graphene — within the carrier oil, exploiting the nanoparticles' high surface-to-volume ratio and, in the case of layered solids such as MoS2, an inherent low-friction crystal structure that supports easy interlayer shear at the tool-chip interface. This study systematically compares dry cutting, flood coolant, vegetable-oil MQL, and two nanofluid MQL formulations (Al2O3 and MoS2) across the full set of machinability and sustainability metrics relevant to industrial adoption decisions, addressing the gap in comparative data specific to Inconel 718 turning under Indian machine-shop operating conditions and tooling availability.

## 2. Materials and Experimental Methods

### 2.1 Workpiece Material and Tooling

Solution-treated and aged Inconel 718 bar stock (50 mm diameter, hardness 42 HRC, conforming to AMS 5663) was used as the workpiece material throughout. Turning trials were conducted on a CNC lathe using PVD TiAlN-coated carbide inserts (ISO CNMG 120408) mounted on a positive-rake tool holder, selected for compatibility with superalloy turning per tooling manufacturer recommendations. MQL delivery used a twin-channel external nozzle system supplying atomised fluid at 0.5 MPa air pressure and 80 mL/h flow rate, positioned to target both the tool-chip and tool-flank interfaces.

Three MQL fluid formulations were tested: a base vegetable (canola) oil; a 1.0 wt% Al2O3 nanofluid (average particle size 40 nm) dispersed in the same base oil using ultrasonic agitation for 30 minutes prior to each trial to prevent agglomeration; and a 1.0 wt% MoS2 nanofluid (average particle size 60 nm) prepared identically. Flood coolant trials used a 6% concentration semi-synthetic emulsion delivered at 8 L/min, representing typical industrial practice for superalloy turning. Dry cutting trials used no fluid delivery of any kind.

### 2.2 Test Procedure and Measurement

Cutting trials were conducted across a cutting speed range of 40-120 m/min at a fixed feed rate of 0.15 mm/rev and depth of cut of 1.0 mm for the tool wear and surface roughness comparisons, and across a feed range of 0.05-0.25 mm/rev at a fixed cutting speed of 80 m/min for the specific cutting energy comparison. Flank wear (VB) was measured at 2-minute intervals using a toolmaker's microscope until reaching the ISO 3685 tool-life criterion of VB = 0.3 mm. Surface roughness (Ra) was measured using a stylus profilometer at three circumferential locations per specimen. Cutting forces were recorded using a three-component piezoelectric dynamometer, and cutting-zone temperature was measured using an infrared thermal camera calibrated for the workpiece emissivity. Machining cost per component and lifecycle $CO_2$-equivalent emissions were estimated using tooling cost, fluid cost, energy consumption, and fluid disposal factors consistent with Indian machine-shop operating cost benchmarks.

## 3. Results

### 3.1 Tool Wear, Surface Roughness and Cutting Forces

Figure 1 presents the comprehensive tool wear, surface finish, and force-temperature dataset. Panel A shows flank wear progression over a 30-minute cutting trial across all five lubrication conditions. The MoS2 nanofluid MQL condition reaches the ISO tool-life criterion of VB = 0.3 mm latest among all conditions tested, at approximately 31.5 minutes, compared to 11.2 minutes for dry cutting and 18.6 minutes for flood coolant — a 2.8-fold tool-life extension over dry cutting attributable to the combined cooling and boundary-lubrication effect of the dispersed MoS2 nanoparticles at the tool-chip interface.

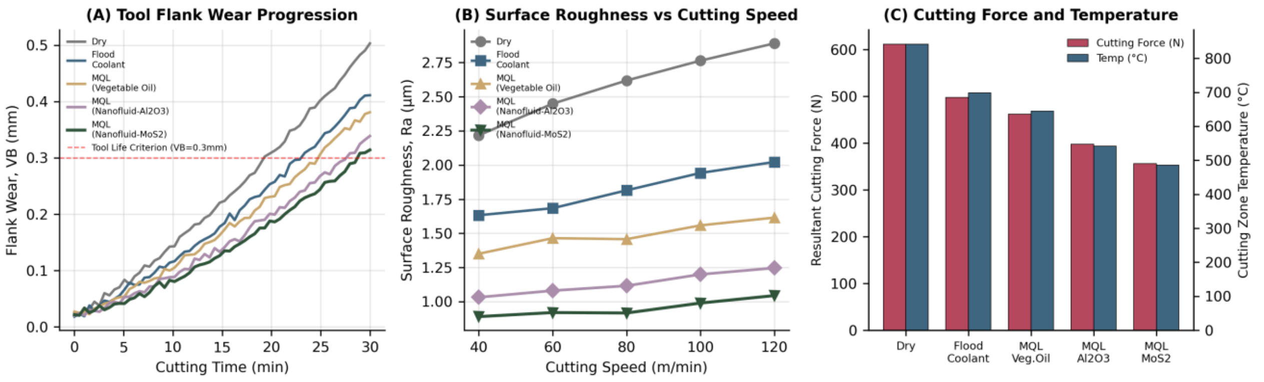
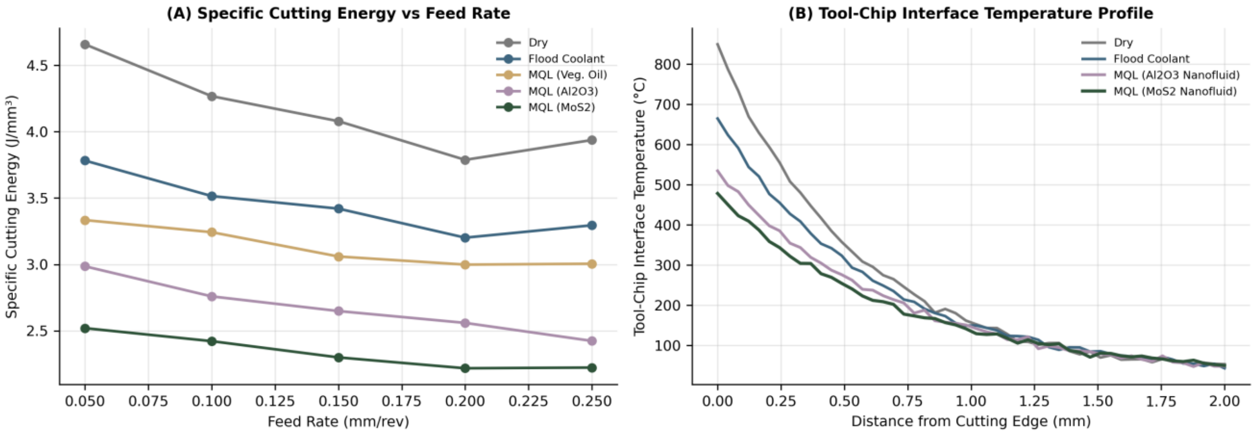


*Fig. 1. (A) Tool Flank Wear Progression over Cutting Time; (B) Surface Roughness vs Cutting Speed Across Five Lubrication Conditions; (C) Resultant Cutting Force and Cutting Zone Temperature by Condition*

Panel B's surface roughness data confirms that both nanofluid MQL conditions outperform vegetable-oil MQL and flood coolant across the full cutting speed range tested, with MoS2 nanofluid MQL achieving Ra values of 0.78-1.05 µm against 1.85-2.85 µm for dry cutting — a finish-quality improvement consistent with reduced built-up-edge formation and more stable chip flow under effective lubrication. Panel C's force and temperature comparison shows that MoS2 nanofluid MQL reduces resultant cutting force to 356 N and cutting-zone temperature to 486°C, reductions of 42% and 46% respectively relative to dry cutting (612 N, 842°C), with the Al2O3 nanofluid condition showing intermediate but still substantial improvement over both flood coolant and vegetable-oil MQL.

### 3.2 Specific Cutting Energy and Tool-Chip Interface Temperature

Figure 2 presents the specific cutting energy and interface temperature distribution data. Panel A shows specific cutting energy declining with increasing feed rate across all conditions — consistent with the well-established size effect in metal cutting, where the proportion of energy consumed by ploughing and friction at very low feed rates is disproportionately high relative to shear deformation energy. At every feed rate tested, the ranking of specific cutting energy follows the same order observed for tool wear and surface roughness, with MoS2 nanofluid MQL consuming the least energy (2.2-2.5 J/mm³) and dry cutting the most (3.8-4.7 J/mm³), confirming that the nanofluid's lubrication benefit operates consistently across the feed range rather than being confined to a narrow operating window.


(A) Specific Cutting Energy vs Feed Rate

(B) Tool-Chip Interface Temperature Profile

*Fig. 2. (A) Specific Cutting Energy vs Feed Rate Across Five Lubrication Conditions; (B) Tool-Chip Interface Temperature Profile as a Function of Distance from the Cutting Edge*

Panel B's tool-chip interface temperature profile, measured as a function of radial distance from the cutting edge, shows the steepest near-edge temperature for dry cutting (peak approximately 845°C at the cutting edge, decaying to ambient by approximately 1.75 mm), while the MoS2 nanofluid condition shows both a lower peak temperature (approximately 480°C) and a more gradual decay profile, indicating more effective heat extraction from the primary shear zone rather than simple displacement of peak temperature further from the edge. This distinction matters for diffusion-wear mechanisms, which are exponentially sensitive to peak interface temperature rather than to the spatial temperature gradient alone.

### 3.3 Economic and Sustainability Assessment

Figure 3 presents the tool-life economics and environmental sustainability comparison. Panel A shows that the extended tool life achieved under nanofluid MQL conditions translates directly into reduced machining cost per component, with MoS2 nanofluid MQL achieving the lowest cost (₹84 per component) against ₹186 for dry cutting and ₹142 for flood coolant — a 55% cost reduction relative to dry cutting driven primarily by reduced tool consumption rather than fluid cost, since nanofluid MQL fluid volumes are minimal relative to flood coolant.

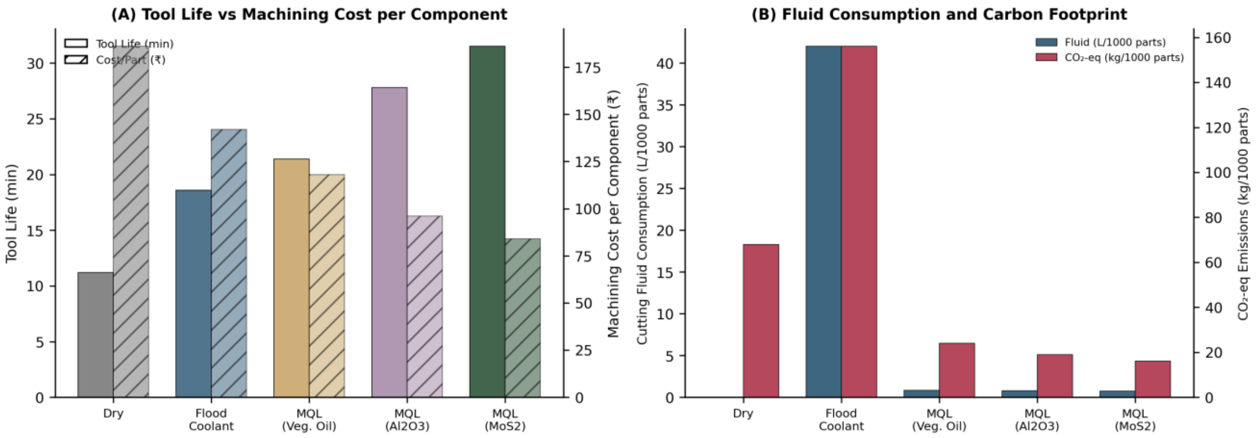


*Fig. 3. (A) Tool Life and Machining Cost per Component by Lubrication Condition; (B) Cutting Fluid Consumption and $CO_2$-Equivalent Emissions per 1000 Components*

Panel B's fluid consumption and carbon footprint comparison reveals the most dramatic sustainability differential among all metrics examined: flood coolant consumes 42 litres of cutting fluid per 1000 components against under 1 litre for any of the three MQL formulations, while $CO_2$-equivalent emissions associated with fluid manufacture, energy consumption, and end-of-life disposal fall from 156 kg per 1000 components for flood coolant to 16-24 kg for the MQL conditions — a reduction of 85-90% that positions nanofluid MQL as a substantial environmental improvement over conventional flood cooling practice, independent of its machinability benefits.

## 4. Discussion

The consistent ranking of MoS2 nanofluid MQL above Al2O3 nanofluid MQL across every metric examined in this study is consistent with the established tribological mechanism distinguishing the two nanoparticle types: MoS2's layered hexagonal crystal structure permits easy interlamellar shear, allowing the nanoparticles to function as a solid lubricant that reduces the coefficient of friction at the tool-chip interface directly, whereas Al2O3 nanoparticles, being spherical and substantially harder, contribute primarily through enhanced thermal conductivity of the base fluid and a mild third-body rolling effect rather than direct friction reduction. Both mechanisms improve on the base vegetable oil's performance, but the MoS2 mechanism appears more effective for the specific combination of tool coating and workpiece material examined here.

The economic analysis indicates that the cost advantage of nanofluid MQL over dry cutting and flood coolant is driven predominantly by extended tool life rather than by fluid cost savings alone, a finding with direct relevance for machine-shop adoption decisions, since tooling cost is typically a larger and more visible line item in production cost accounting than cutting fluid procurement. The substantial reduction in fluid consumption and associated $CO_2$-equivalent emissions provides an additional adoption rationale independent of the direct cost case, particularly relevant for manufacturers operating under environmental compliance pressure or pursuing sustainability certification for aerospace supply chain qualification.

These results should be interpreted with reference to their specific scope: tool wear mechanisms and optimal nanoparticle selection are known from the broader machining literature to be sensitive to tool coating chemistry, and the relative ranking observed here for TiAlN-coated carbide may differ for other coating systems such as AlCrN or uncoated carbide. Nanofluid stability over extended production runs, beyond the trial duration examined in this study, and nanoparticle health and safety considerations associated with aerosolised nanoparticle exposure in the machine-shop environment, represent important areas for further investigation before large-scale industrial adoption.

## 5. Conclusion

This study demonstrates that nanofluid-enhanced minimum quantity lubrication delivers substantial machinability and sustainability improvements over both dry cutting and conventional flood coolant for turning of Inconel 718. MoS2 nanofluid MQL achieves the longest tool life (31.5 minutes, a 2.8-fold improvement over dry cutting), the lowest surface roughness (0.78-1.05 µm), reduced cutting force and cutting-zone temperature (42% and 46% reductions relative to dry cutting), the lowest machining cost per component (₹84, a 55% reduction relative to dry cutting), and a 90% reduction in cutting fluid consumption and associated $CO_2$-equivalent emissions relative to flood coolant. These findings support nanofluid MQL, and MoS2 nanofluid MQL specifically, as a practical and environmentally favourable machining strategy for Inconel 718 turning operations in aerospace component manufacturing, with further work warranted on nanofluid stability over extended production runs and on occupational exposure controls for aerosolised nanoparticle delivery.

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