

Ecofriendly Cutting Fluids for Turning Hard to Cut Materials: A Review

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ABSTRACT

The machining of hard-to-cut materials such as high-strength steels, nickel-based super alloys, titanium alloys, and ceramic composites presents significant tribological challenges due to high cutting forces, rapid tool wear, elevated temperatures, and poor thermal conductivity. The choice and performance of cutting fluids significantly influence machining quality, tool life, and sustainability outcomes. Traditional mineral-oil-based fluids, although effective for lubrication and cooling, pose environmental and health hazards due to toxicity, poor biodegradability, and waste disposal concerns. In response, eco-friendly cutting fluids based on vegetable oils, synthetic esters, nanofluids, and biodegradable agents have emerged to meet the dual demands of machining performance and environmental stewardship. This review critically examines the mechanisms, classifications, performance metrics, and applications of eco-friendly cutting fluids specifically in the turning of hard-to-cut materials. Comparisons with conventional fluids, environmental impact assessments, and insights into challenges and future research directions are also provided to guide sustainable machining practices.

Keywords:- Eco-friendly cutting fluid,s Sustainable machining Turning process, Hard-to-cut materials, Green manufacturing

1. INRODUCTION

Turning is one of the most common machining processes used to form cylindrical parts from a range of engineering materials. In turning operations involving hard-to-cut materials—which include high tensile strength alloys, hardened steels, and heat-resistant superalloys—the process is often limited by high cutting temperatures and poor heat dissipation. The interactions at the tool–chip–workpiece interface produce intense friction and rapid wear, severely affecting surface integrity, dimensional accuracy, and production cost.

Turning hard-to-cut materials such as nickel-based superalloys (e.g., Inconel), titanium alloys (e.g., Ti-6Al-4V), and hardened steels is challenging because of high cutting temperatures, excessive tool wear, and poor thermal conduction at the tool–workpiece interface. Traditionally, machining relies on petroleum-based cutting fluids for cooling and lubrication; however, these fluids pose environmental risks, toxicity concerns, and disposal problems. Consequently, the machining community is prioritizing eco-friendly cutting fluids with enhanced biodegradability, lower toxicity, and comparable or better machining performance than conventional fluids.

.MECHANISMS OF ECO-FRIENDLY CUTTING FLUIDS

A detailed understanding of how eco-friendly fluids function in the turning zone is essential to assess and optimize their performance.

1.1 Lubrication Mechanism

Lubricity reduces friction at the tool–chip and tool–workpiece interfaces. Eco-friendly fluids commonly contain long hydrocarbon chains in vegetable oils or ester groups that form adsorbed boundary films, lowering boundary friction.

1.2 Cooling Mechanism

Cooling reduces the thermal load on both tool and workpiece. Techniques include:

- Conventional flood cooling
- MQL (very low volume application)
- Cryogenic or hybrid cooling (when blended with eco-friendly agents)

Water has high specific heat capacity but low lubricity; eco-friendly fluids often balance these properties to optimize cooling and lubrication.

1.3 Chip Formation and Evacuation

Better lubrication and controlled heat at the shear zone influence chip segmentation, reduce built-up edge formation, and facilitate smoother chip flow—critical in hard material turning.

2. PERFORMANCE EVALUATION IN TURNING HARD-TO-CUT MATERIALS

The assessment of cutting fluids is based on their influence on cutting performance, tool wear, surface integrity, and environmental impact.

2.1 Tool Wear Reduction

Eco-friendly fluids enhance tool life through lubrication and lower cutting temperatures. Specific mechanisms include:

- Formation of boundary films that minimize adhesion
- Reduction in crater and flank wear
- Delaying onset of thermal cracking

Studies have shown that vegetable oil and ester based formulations significantly outperform mineral oils in reducing flank wear during turning of superalloys, especially under MQL conditions.

2.2 Surface Finish and Integrity

Surface roughness and integrity affect fatigue life and dimensional accuracy. Eco-friendly fluids:

- Improve surface quality due to better lubrication
- Reduce built-up edge formation
- Maintain stable cutting forces

In high-precision turning, enhanced lubrication from nanofluid additives further refines surface texture.

2.3 Cutting Temperature

Monitoring cutting temperatures is essential. Eco-friendly fluids show:

- Improved heat extraction compared to dry machining
- Variable performance based on fluid composition and delivery method

Nano-enhanced fluids improve thermal conductivity, lowering temperature peaks—even in turning of titanium alloys where heat management is difficult.

2.4 Cutting Forces

Lower cutting forces imply reduced energy consumption and better tool life. Eco-friendly lubricants:

- Reduce frictional component of cutting forces
- Produce more stable cutting dynamics
- Facilitate smoother chip separation

2.5 Environmental and Health Metrics

Eco-friendly fluids are evaluated on:

- **Biodegradability:** rapid breakdown in environment
- **Toxicity:** reduced dermal and respiratory hazards
- **Disposal:** easier wastewater treatment
- **Worker safety:** minimized irritation and allergic risks

3. APPLICATION CASES IN HARD-TO-CUT MATERIALS

3.1 High-Strength Steels

Characterized by high hardness, turning operations benefit from:

- MQL with vegetable oil to reduce flank wear
- Water-based biodegradable fluids with extreme pressure (EP) additives

Eco-friendly fluids match or exceed performance of mineral oils in tool life and surface finish.

3.2 Titanium Alloys

Titanium's low thermal conductivity makes cooling difficult. Effective strategies include:

- Nano-enhanced eco-fluids to improve heat transfer
- High lubrication from natural esters to reduce chip adhesion

Studies show significant reduction in cutting temperature and tool wear rates in Ti-6Al-4V turning with MQL biodegraded lubricants.

3.3 Nickel-Based Superalloys

Used in aerospace, tight tolerances demand excellent lubrication. Solutions:

- Synthetic ester fluids with high film strength
- Combined cryogenic cooling (e.g., CO₂ or LN₂) with biodegradable lubricants

Wear reduction and enhanced surface integrity make these fluids suitable for precision turning.

3.4 Ceramic and Composite Materials

These materials wear tools through abrasion and thermal shock. Approaches include:

- Hybrid formulations with nano-additives
- Pulse MQL for targeted lubrication

4. CONCLUSIONS

The machining of hard-to-cut materials presents inherent thermal and tribological challenges that necessitate effective cooling and lubrication. Traditional mineral oil-based cutting fluids, while effective, pose considerable environmental, health, and disposal issues.

Eco-friendly cutting fluids—including vegetable-oil-derived lubricants, biodegradable synthetic esters, nanofluid-enhanced formulations, and water-based systems—represent a sustainable alternative that often matches or surpasses conventional fluids in performance metrics such as tool wear reduction, surface finish, and cutting temperature control.

Successful application of eco-friendly fluids depends on appropriate selection, delivery methods (such as MQL), and formulation adjustments for specific materials and cutting conditions. While challenges in high-temperature stability and nanoparticle management persist, ongoing research and innovations in hybrid cooling strategies, smart additives, and real-time control systems are paving the way for broader adoption.

By aligning machining performance with environmental responsibility, eco-friendly cutting fluids offer a viable and compelling solution for modern manufacturing of hard-to-cut materials.

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