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A REVIEW PAPER ON EXPERIMENTAL INVESTIGATION AND LIFE-CYCLE ASSESSMENT (LCA) OF CRYOGENIC MACHININGVS. MINIMUM QUANTITY LUBRICATION (MQL) FOR TITANIUM ALLOYS: A "CLOSING THE LOOP" APPROACH TO SUSTAINABLE MANUFACTURING

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ABSTRACT

Sustainable manufacturing of difficult-to-cut titanium alloys, such as Ti-6Al-4V, necessitates a shift from conventional flood cooling to advanced clean cutting technologies. This review synthesizes findings from recent experimental investigations comparing cryogenic machining and Minimum Quantity Lubrication (MQL) across technical, economic, and environmental dimensions. While both techniques offer significant advantages over dry machining, cryogenic methods consistently demonstrate superior perform ancein tool life extension, surface integrity improvement, and reduction of hazardous oil mist emissions. Integrating these results into a life-cycle assessment (LCA) framework reveals that while cryogenic systems introduce higher embodied energy from specialized infrastructure, they achieve a more balanced"closed-loop" sustainability profile through enhanced productivity and reduced long-term environmental burden.

1. INTRODUCTION

TitaniumalloyslikeTi-6Al-4Varecriticaltoaerospaceandmedicalindustries due to their high strength and thermalst ability, yetthey present extreme machining challenges including rapid tool wear and high heat generation. Traditional flood coolingis increasingly rejected due to its environmental toxicity and high disposal costs. In response, clean cutting technologies—Dry, MQL, and Cryogenic—aim to reconcile machining efficiency with ecological sustainability.

2. Technical Performance: Surface Integrity and Tool Life

Cryogenictechniques,includingliquidnitrogen(LN_2)andcarbondioxide(CO_2),significantly outperform MQL in thermal management.

- **Tool Life**: Cryogenic cooling (CMQL) extends tool life by approximately 40% compared to dry milling and remains superior to MQL by suppressing cutting-zone temperatures and reducing adhesivewear. Inturning HastelloyX, LN_2cooling reducedtoolwearby21.11% over dry conditions.
- **Surface Roughness**: Cryogenic machining consistently yields smoother surface finishes. CMQL reduced surface roughness by about 25% compared to dry milling. For Hastelloy X, LN_2 and CO_2 cooling achieved roughness reductions of up to 25% and 22.22%, respectively.
- **Microhardness**: Cryogenic environments lead to strain hardening on the surface and subsurface, inducing higher microhardness values than MQL, which is critical for the functional performance of high-stress components.

3. Environmental and Social Impact Assessment

A"closingtheloop"approachrequiresevaluatingthefulllife-cycleburdenbeyondthemachine tool.

- **Energy Consumption**: Specific energy consumption (SEC) generally decreases as cutting speed increases due toimproved material removalefficiency. While MQL saves energyby reducing friction, cryogenic cooling further lowers energy demand by reducing cutting forces. However, CMQL involves substantial embodied energy from upstream processes like refrigerant production and delivery.
- **Carbon Emissions**: Trend-wise, carbon emissions mirror energy consumption. Coated tools paired with cryogenic systems can reduce carbon emissions by nearly 30% versus uncoated end mills in dry environments.
- **Occupational Health**: A critical social advantage of cryogenic machining is the drastic reductionin inhalable particulate matter. MQL generates high concentrations ofPM_2.5oil mist (often >2.19 g/m^3), whereas cryogenic systems utilize condensation effects to aggregate and sediment oil mist, significantly improving

workplace air quality.

4. Economic Analysis

Cost-effectivenessisdrivenbyproductionefficiencyandresourceconsumption.

- **Unit Cost**: For Hastelloy X turning, LN_2 cooling resulted in parts that were 7.37% and 26.67%lessexpensivethan those produced with MQL and dry machining, respectively.
- **Trade-offs**: Cryogenic systems involve higher initial capital investment for storage and delivery infrastructure. However, these are often offset by higher material removal rates (MRR) and reduced machine downtime for tool changes.

5. Multi-Objective Optimization and Decision Support

Modern sustainability assessment uses models like Nash Equilibrium to balance conflictingenvironmental, economic, technical, and social goals.

- **WeightAllocation**:Analysisshowsthatsubjectiveexpertpreferenceoftenfavorenvir onmental indicators (e.g., lifecycle carbon), while objective data weighting highlightsproductivity (MRR) and health (PM_2.5).
- **Optimal Configurations**: For Ti-6Al-4V ball-end milling, cryogenic cooling combined with high cutting speeds and feed rates represents the optimal sustainable configuration.

6. CONCLUSION

Thecomparativeanalysisconfirmsthatwhile MQLisaviablenear-drymachiningalternative, **cryogenic machining** offers a more robust path toward sustainable manufacturing for titaniumalloys. Byminimizingtoolwear, improving surfaceintegrity, and protectingoperator health through PM_2.5 reduction, cryogenic systems effectively "close the loop" on manufacturing waste and inefficiency. Future research must expand system boundaries to include the full lifecycle impact of cryogenic infrastructure to ensure long-term ecological viability.