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Effect of minimum quantity lubrication (MQL) on hob cutter wear in sprocket hobbing of T12.7, S45C steel

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Abstract
This study experimentally investigates the effect of Minimum Quantity Lubrication (MQL) on the wear behavior of CVD-TiN-coated P5M6 high-speed steel (HSS) hob cutters during the hobbing of T12.7 sprockets made of S45C steel under industrial cutting conditions. The study evaluates the advantages and limitations of MQL compared with conventional flood cooling based on wear mechanisms, crater wear, and flank wear characteristics of the cutting tool. Experimental observations obtained from scanning electron microscopy (SEM) indicate that MQL significantly reduces adhesive and abrasive wear, improves chip evacuation, stabilizes cutting temperature, and prolongs tool life. The results also demonstrate the potential applicability of environmentally friendly vegetable-based lubricants in sustainable gear and sprocket manufacturing.

Keywords: *Minimum Quantity Lubrication (MQL); Gear hobbing; Hob wear; P5M6 HSS; TiN coating; S45C steel; Sustainable machining.*

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I. INTRODUCTION

Flood cooling lubrication has been widely applied in gear machining processes based on the generating method. However, conventional flood cooling exhibits several limitations, including insufficient lubrication and cooling efficiency, excessive cutting fluid consumption, high operational cost, and environmental pollution [1–3]. Consequently, the development of environmentally sustainable machining technologies has become an important research direction in modern manufacturing.

Minimum Quantity Lubrication (MQL) technology has emerged as a promising alternative to conventional flood cooling. MQL employs a very small amount of lubricant, typically ranging from 50 to 500 ml/h, which is atomized and delivered directly into the cutting zone using compressed air. This approach significantly reduces cutting fluid consumption while improving lubrication performance and environmental sustainability.

Several studies have demonstrated the effectiveness of MQL in gear machining operations. Lierath [4] and Tokawa et al. [5] reported that MQL substantially improved the wear resistance and productivity of TiAlN-coated powder metallurgy HSS hob cutters during gear hobbing. Fratila [6] investigated MQL-assisted gear hobbing using coated and uncoated HSS cutters and concluded that MQL reduced tool wear and maintained cutting edge integrity more effectively than flood cooling.

In Vietnam, studies related to the application of MQL in gear hobbing remain limited. Previous investigations by Tran Minh Duc et al. [7–9] primarily focused on the use of vegetable-oil-based lubricants and nanofluids in hard machining processes. However, detailed studies concerning the wear mechanisms of hob cutters during sprocket hobbing under MQL conditions are still insufficient.

Vegetable-based lubricants available in Vietnam have demonstrated favorable lubrication performance, low toxicity, biodegradability, and low cost. Considering the large-scale production of motorcycle sprockets in Vietnam, the replacement of conventional flood cooling with MQL may provide considerable economic and environmental benefits.

Therefore, this study experimentally evaluates the influence of MQL using vegetable-based lubricant on the wear characteristics and wear mechanisms of CVD-TiN-coated P5M6 HSS hob cutters during the hobbing of T12.7 sprockets made of S45C steel under industrial cutting conditions.

II. EXPERIMENTAL SETUP

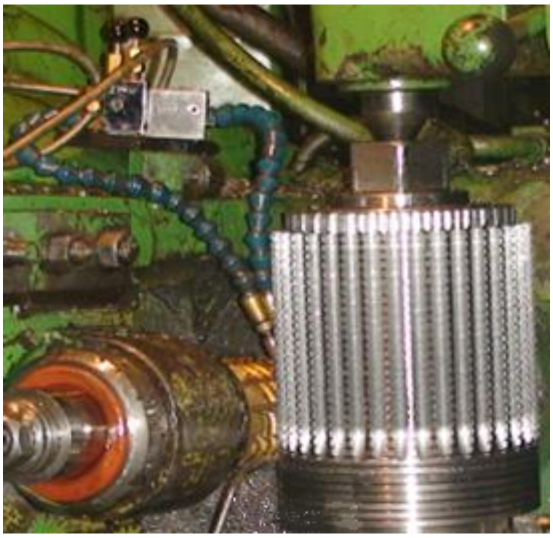


Figure 1. Experimental setup

2.1 Machine Tool and Cutting Conditions

The experiments were conducted on a 50A50H gear hobbing machine manufactured in Russia. The cutting tool was a T12.7 sprocket hob cutter made of P5M6 high-speed steel coated with CVD-TiN.
The workpiece material was S45C medium-carbon steel.
Cutting Parameters
Cutting speed: V = 25.13 rpm
Feed rate: S = 1.5 mm/rev
Depth of cut: t = 6.35 mm

2.2 Lubrication Conditions

MQL Conditions
Lubricant: Vegetable-based soybean oil
Air pressure: 8 KG/cm²
Lubricant flow rate: 30 ml/h through two nozzles
Flood Cooling Conditions
Cutting fluid: Industrial oil D32
Flow rate: 10 l/min

2.3 Measurement Equipment

Tool wear observations were performed using a TESCAN scanning electron microscope (SEM), Czech Republic.

III. EXPERIMENTAL PROCEDURE

The experiments were carried out under industrial machining conditions for a machining duration of 240 minutes. Tool wear on both rake and flank faces was examined and compared under MQL and flood cooling conditions.
SEM images were used to evaluate wear morphology and identify dominant wear mechanisms.

IV. RESULTS AND DISCUSSION

4.1 Rake Face Wear

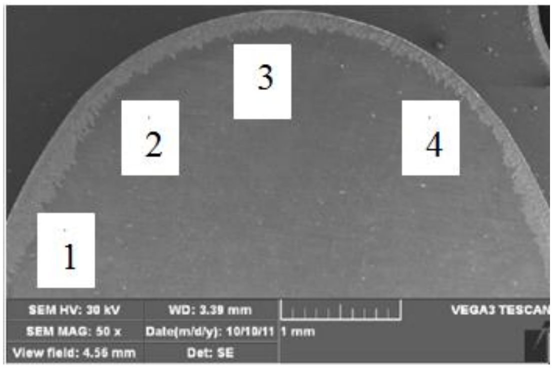


Figure 2. Rake face wear under MQL condition (50×1 mm)

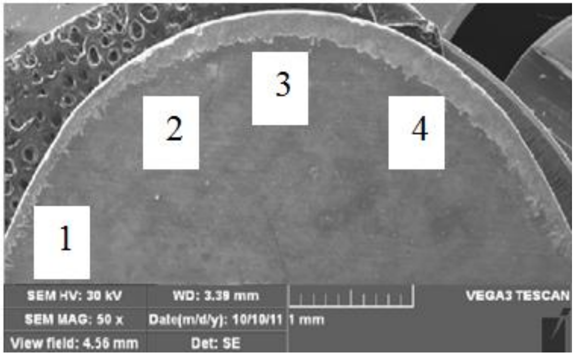
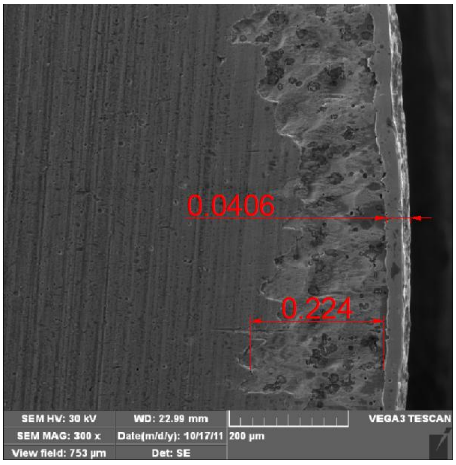


Figure 3. Rake face wear under flood cooling condition (50×1 mm)

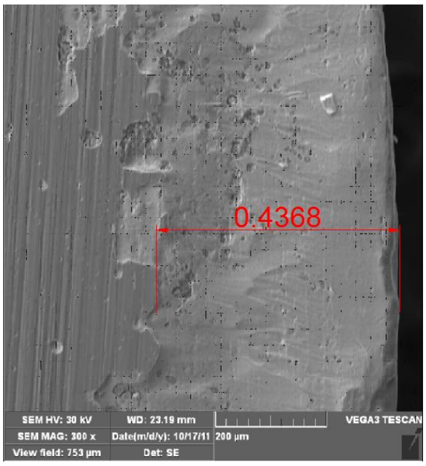
SEM observations reveal that both lubrication methods produced wear on the rake face and flank face of the hob cutter. However, significant differences in wear morphology were observed.

Under MQL conditions, the wear regions in areas 2, 3, and 4 were considerably smaller than those observed under flood cooling conditions. Conversely, wear in area 1 was relatively larger under MQL due to the limited spray coverage of the lubricant mist.



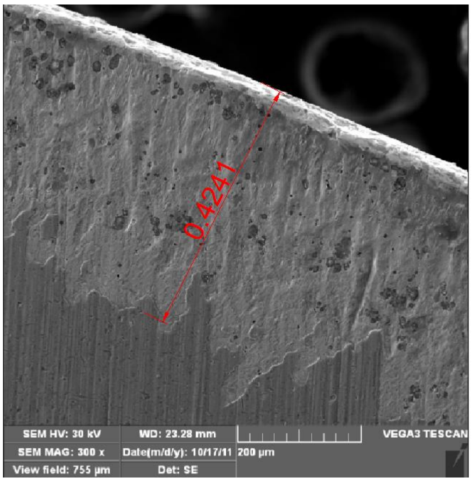
300x200µm

Figure 4. Rake face wear in region 3 under MQL condition



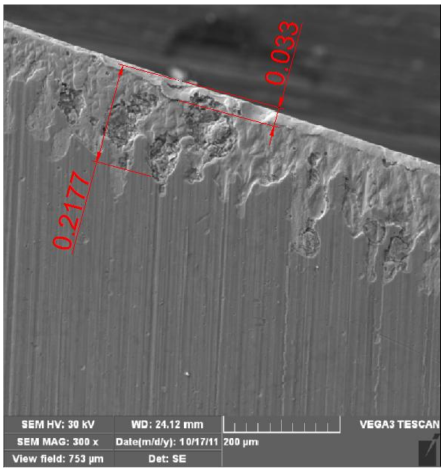
300x200µm

Figure 5. Rake face wear in region 3 under flood cooling condition



300x200µm

Figure 6. Rake face wear in region 1 under MQL condition



300x200µm

Figure 7. Rake face wear in region 1 under flood cooling condition

Wear Mechanisms

Two dominant wear mechanisms were identified:

1. Coating fracture and delamination of the TiN layer.
2. Wear of the substrate material caused by adhesion and abrasion.

Stage I: Coating Failure

Under the combined effects of normal stress, frictional stress, and elevated temperature beneath the coating layer, plastic deformation occurred in the substrate material. Consequently, the TiN coating cracked and fractured, and coating fragments were removed by the chip flow, exposing the substrate material.

As friction and temperature increased further, crater wear developed on the rake face. The softened substrate near the wear region accelerated coating fracture and progressive enlargement of the crater wear zone.

Stage II: Adhesive and Abrasive Wear

Adhesive wear subsequently occurred when material detached from the tool surface and was carried away by the chips. The crater depth gradually increased and propagated toward the cutting edge, weakening the cutting edge and leading to chipping and fracture. These observations are consistent with the findings reported by Hedenqvist et al. [10].

Under MQL conditions, the lubricant mist was directly delivered into the cutting zone. The high-pressure air stream facilitated lubricant penetration into the tool–chip interface and reduced friction between the rake face and flowing chips. In addition, the lubricant formed an oil film that minimized direct metal-to-metal contact.

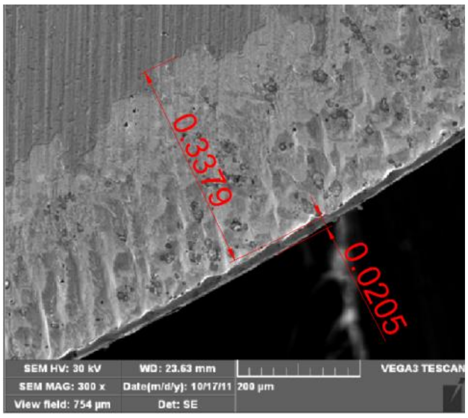
The compressed air also improved chip evacuation and reduced heat transfer from the cutting zone to the tool. Consequently, the cutting edge maintained higher hardness and wear resistance. SEM observations indicated that the TiN coating remained partially intact near the cutting edge with a coating width ranging from approximately 0.0205 mm to 0.0406 mm.

In contrast, flood cooling failed to penetrate deeply into the cutting zone. Cooling primarily occurred on the upper chip surface, while the contact region between the chip and rake face remained nearly dry. This intensified friction and cutting force, resulting in larger crater wear width and depth.

Severe thermal and mechanical loading under flood cooling caused plastic deformation, chipping, and fracture of the cutting edge. SEM images also revealed delamination of the HSS substrate and the formation of wear pits due to adhesive wear and material transfer between the tool and chips.

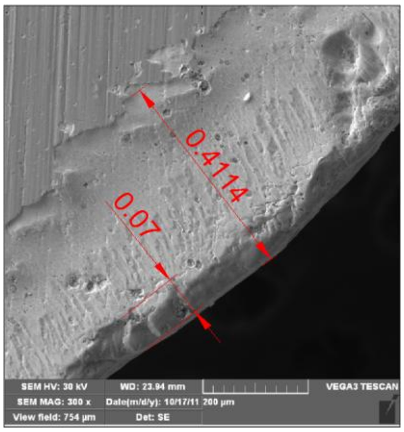
The larger wear region observed in area 1 under MQL was mainly attributed to the nozzle configuration and spray direction. The lubricant mist concentration was highest at the central regions of the cutting edge (areas 2, 3, and 4), whereas lubricant penetration in area 1 was relatively insufficient.

Nevertheless, despite the increased wear in this region, thermal deformation and severe edge chipping were not observed under MQL, indicating that the cooling efficiency of the compressed-air-assisted lubrication remained effective.



300x200µm

Figure 8. Rake face wear in region 4 under MQL condition



300x200µm

Figure 9. Rake face wear in region 4 under flood cooling condition

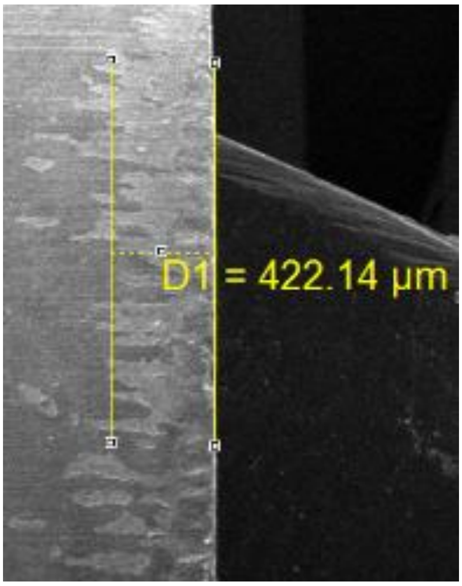
4.2 Flank Wear

SEM observations indicate that the flank wear mechanisms were generally similar to those observed on the rake face.

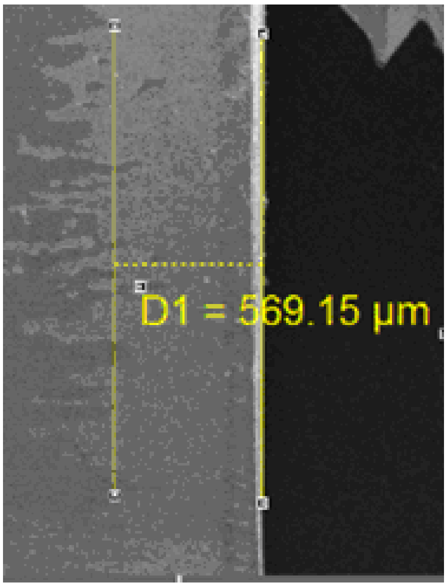
Measured flank wear widths in areas 2, 3, and 4 under MQL conditions were significantly smaller than those obtained under flood cooling. This result confirms that direct lubricant delivery to the flank face effectively reduced friction between the tool flank and the machined surface.

The lubricant formed a thin oil film that prevented direct contact between the tool and workpiece surfaces, thereby reducing adhesive and abrasive wear.

Furthermore, the high-pressure compressed air improved heat dissipation by disrupting the thermal barrier generated in the cutting zone. Faster heat removal reduced heat transfer into the cutting tool and maintained a favorable hardness ratio between the cutting tool material and workpiece material.



46x1mm



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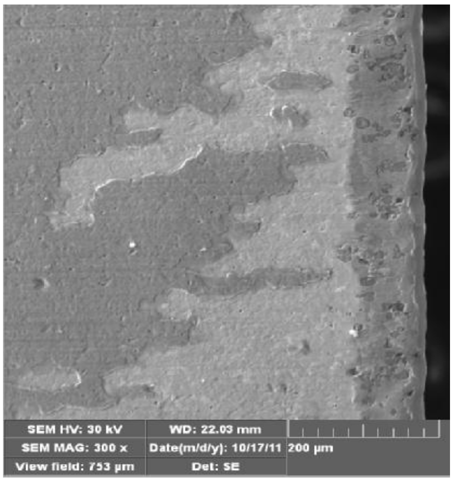
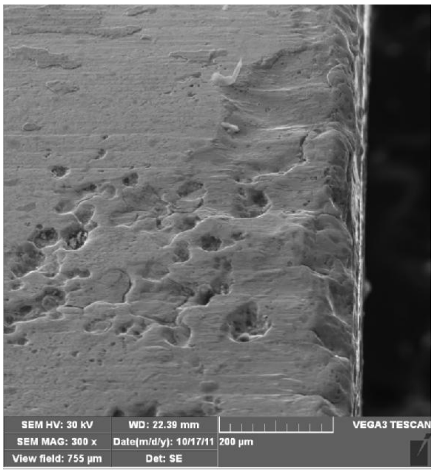


300x200μm

Figure 10. Flank wear under MQL condition



300x200μm

Figure 11. Flank wear under flood cooling condition

Under flood cooling conditions, limited lubricant penetration intensified direct friction between the flank face and the workpiece surface. Abrasive wear occurred due to hard carbide particles, fragmented tool material, and workpiece debris. Elevated temperatures softened the contact surfaces and accelerated abrasive wear.

Distinct grooves and scratches parallel to the sliding direction were observed on the flank face under flood cooling conditions. Wear propagation toward the cutting edge caused severe edge deformation, cracking, and chipping, which adversely affected the dimensional accuracy and profile quality of the machined sprocket.

V. CONCLUSIONS

The following conclusions can be drawn from this study:

1. MQL-assisted sprocket hobbing significantly reduced abrasive wear and suppressed adhesive wear compared with conventional flood cooling.
2. Vegetable-based lubricants available in Vietnam demonstrated excellent lubrication performance, low toxicity, biodegradability, and environmental compatibility.
3. MQL improved chip evacuation, reduced cutting temperature, preserved coating integrity, and prolonged hob cutter life.
4. The successful application of MQL in sprocket hobbing provides a scientific basis for extending sustainable lubrication technologies to other machining processes.

VI. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Although MQL exhibited superior performance compared with flood cooling, several limitations remain.

1. Further optimization of nozzle geometry, spray direction, lubricant flow rate, and air pressure is necessary to improve lubrication efficiency in poorly lubricated regions such as area 1.
2. Additional studies should investigate bio-based lubricants, multifunctional vegetable oils, and nanoparticle-enhanced lubricants for sustainable gear machining applications.

Acknowledgments

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