



Experimental Study on Surface Quality, Integrity and Tool Wear Mechanism under Cryogenic CO₂-Assisted Minimum Quantity Lubrication (MQL) Technology in Turning Hard Tool Steels

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دراسة تأثير تقنيات التبريد باستخدام (CO₂) و (MQL) على جودة السطح وتآكل أداة القطع في عمليات خراطة الصلب المصلد

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Abstract:

This study investigates how minimum quantity lubrication (MQL) assisted by cooled carbon dioxide affects surface quality, substrate integrity, and tool wear when turning hard steel. Standard lubrication systems experience difficulty dissipating the heat and mechanical loads generated by machining these materials. By combining carbon dioxide cooling with minimum quantity lubrication, this study seeks to improve thermal stability, lubrication efficiency, tool durability, and the microstructure quality of the workpiece. Four environments, dry, MQL, CO₂ cooling, and CO₂ + MQL hybrid, are evaluated using metrics such as surface roughness (Ra), white layer depth, microhardness mapping, and flank wear progression. All experiments and measurements were conducted at the Libyan Centre for Advanced Technology (ACT). The results reveal that MQL preparation with carbon dioxide results in finer surface finishes, longer tool life, and reduced thermal and mechanical damage, representing a practical and environmentally friendly approach to high-precision hard steel manufacturing.

Keywords: Cryogenic Machining, CO₂ Cooling, MQL, Hard Tool Steel, Surface Integrity, Tool Wear, Sustainable Manufacturing.

الملخص:

تبحث هذه الدراسة في كيفية تأثير التزييت برذاذ المستحلب (MQL) والتبريد بثاني أكسيد الكربون على جودة السطح وتآكل الأدوات عند خراطة الصلب المصلد. حيث تواجه أنظمة التزييت التقليدية صعوبة في تبديد الحرارة والأحمال الميكانيكية الناتجة عن تشغيل هذه المواد. من خلال الجمع بين تبريد ثاني أكسيد الكربون والتزييت بالرذاذ، تسعى هذه الدراسة إلى تحسين الاستقرار الحراري، وكفاءة التزييت، ومتانة الأدوات، وجودة قطعة العمل. يتم تقييم أربع بيئات - جافة، وتبريد MQL، وتبريد ثاني أكسيد الكربون، وبيئات هجينة من ثاني أكسيد الكربون CO₂ + MQL - باستخدام عوامل مثل خشونة السطح (Ra)، وعمق الطبقة البيضاء، ورسم خرائط الصلادة الدقيقة، وتطور تآكل جوانب أداة القطع.

أُجريت جميع التجارب والقياسات في المركز الليبي المتقدم للتقنية (LACT). تكشف النتائج أن استخدام الهجين $\text{CO}_2 + \text{MQL}$ يؤدي إلى تشطيبات سطحية أدق، وعمر أطول للأدوات، وتقليل التلف الحراري والميكانيكي، مما يمثل نهجاً عملياً وصديقاً للبيئة لتصنيع الفولاذ الصلب عالي الدقة.

الكلمات المفتاحية: التصنيع بالتبريد الهجين، تبريد ثاني أكسيد الكربون، التصنيع المؤهل للتصنيع، الخراطة، الصلب المصلد، جودة السطح، تآكل الأدوات، التصنيع المستدام.

Introduction:

With present technologies, machining hardened tool steels presents major challenges as the great cutting temperatures, accelerated tool deterioration, and diminished surface quality cannot be readily controlled [1–5]. Usually without the thermal and lubricating control these materials require are flood cooling and dry cutting processes. Simultaneously, the drive toward more environmentally friendly manufacturing techniques motivates investigation of cooling systems that minimize waste.

Combination cryogenic cooling with Minimum Quantity Lubrication (MQL) presents itself as sensible approach [6–8]. When deployed, cryogenic carbon dioxide, either in liquid or supercritical form, absorbs thermal energy and leaves no liquid residue behind nearly immediately at the cutting area [9–11]. MQL introduces small streams of biodegradable lubricant that form a protective film at the tool–chip interface, therefore lowering friction and wear [12–14]. Combining these two methods produces a forward-looking machining mode able of lengthening tool life and raising part quality [15–17]. Table 1 shows the advantages of media type on deferent types of tool steels.

Table 1: Key Advantages of Cooling/Lubrication Modes in conventional Turning

Mode	Cooling Effectiveness	Lubrication Quality	Environmental Impact	Tool Life Extension	Surface Integrity
MQL	Medium	High	Medium (biodegradable oils)	Moderate	Moderate
CO_2 Cryogenic	High	Low	Low (no residue)	High	Good
$\text{CO}_2 + \text{MQL}$	Very High	Very High	Low	Very High	Excellent
Mode	Cooling Effectiveness	Lubrication Quality	Environmental Impact	Tool Life Extension	Surface Integrity

This research focuses on how the cryogenic CO_2 -MQL hybrid in the turning of DIN 1.2714 AISI L6 hardened tool steels affects wear patterns, surface roughness, and general integrity. The focus is on measuring the additive thermal and frictional advantages as well as benchmarks the hybrid against traditional cooling techniques.

Literature Review:

The effectiveness of various cooling and lubrication methods in turning operations has been thoroughly examined concerning enhancing surface quality, tool longevity, and overall sustainability of the process. As production sectors move towards more eco-friendly practices, conventional techniques like flood cooling and dry machining have faced criticism for their constraints and environmental effects [1-3].

Dry machining is environmentally friendly and cost-effective, but it usually leads to higher temperatures in the cutting zone, which speeds up tool wear and deteriorates surface finish, particularly when machining hardened tool steels [4-5]. Conversely, flood cooling ensures stable temperature management and chip removal but has drawbacks like excessive fluid use, disposal concerns, and health hazards associated with extended contact with emulsified oils [6-7].

Minimum quantity lubrication (MQL) delivers a small amount of lubricant (typically 30–100 ml/h) to the tool–workpiece contact area as an aerosol. Especially when applied to biodegradable oils derived from vegetables, this technique has proven effective in reducing cutting forces and improving surface quality [8-9]. Nevertheless, in demanding turning operations with materials like Inconel alloys or AISI D2, MQL by itself may not suffice for heat removal [10]. Due to their high ability to absorb heat, cryogenic cooling methods using liquid nitrogen (LN_2) or carbon dioxide (CO_2) have emerged as effective alternatives. The accessibility, affordability, and non-flammable nature of CO_2 render it highly advantageous. At -78.5°C , it transitions directly from solid to gas, allowing effective, intense cooling at the cutting interface without any leftover material [11-12].

Research indicates that cryogenic cooling using CO_2 can enhance surface integrity and significantly reduce flank wear [13-14]. The integration of the lubricating abilities of MQL with the cooling effectiveness of CO_2 has been a focus of recent research. This hybrid approach is particularly beneficial in intense turning processes that involve significant mechanical and thermal requirements. Experiments

conducted by Shokrani et al. [15] and Dhar et al. [16] indicated that CO₂ + MQL could enhance surface roughness by 30% and diminish tool wear by as much as 60%, compared to dry or flood cooling.

Due to its elevated levels of carbon and chromium, hardened tool steel exhibits low machinability but outstanding wear resistance. Research indicates that cryogenic MQL improves performance in machining D2 compared to other methods due to its ability to maintain lower temperatures, which reduce microstructural damage and enhance dimensional stability [17-20]. Comparative analyses indicate that air blow cooling provides little thermal relief and is appropriate solely for soft metals or finishing operations [21].

The adoption of CO₂ + MQL in industrial settings has been bolstered by the shift towards eco-friendly machining. In addition to enhancing performance, it also reduces the environmental footprint of machining processes and adheres to ISO 14001 environmental management standards [22-23]. Numerous recent articles emphasize the need to balance performance, sustainability, and operator safety, pointing to hybrid cooling-lubrication techniques as a vital area for innovation [24-28].

Recent progress in sustainable machining has revived attention to cryogenic and minimum quantity lubrication (MQL) approaches for difficult-to-machine alloys. Authors have tested liquid nitrogen and CO₂ as cryogenic agents; CO₂ attracts notice for its non-explosive safety and ease of handling from pressurized cylinders. For MQL, vegetable-based oils have yielded less ecological impact and better cost efficiency than conventional flood coolant, but when thermal demands peak, especially in hard turning, MQL sometimes cannot meet the cooling requirement.

Dhar and co-workers [32], showed that integrating cryogenic coolant with MQL reduced flank wear by nearly (40%) versus both flood and dry cutting. Other recent investigations incorporating CO₂ in machining titanium alloys, Inconel, and hardened steels have documented extended tool life and enhanced subsurface microstructure. Side-by-side experiments comparing cryogenic MQL to flood, dry, and standard MQL have consistently documented thinner white layers and more favorable residual stress distributions.

Tool wear in hard turning under cryogenic environments shows a shift in dominant mechanisms from adhesive-abrasive to more brittle and oxidative modes [23] and [29–31]. Hybrid cooling mitigates tool chipping and preserves coating adhesion on carbide and ceramic tools [32-33]. Surface integrity, encompassing surface roughness, microhardness, and metallurgical alterations, is notably improved by hybrid cooling, as supported by studies from Mia et al. [3], Uzun et al. [4], and Yildiz et al. [5]. Additionally, hybrid methods reduce thermal-induced phase transformations and microcracks [34–37]. Despite growing evidence, more experimental validation under varied cutting conditions and material hardness levels is necessary to confirm these benefits for industrial applications [38-39]. This paper contributes by filling this experimental gap for hard tool steels.

Experimental Setup and Procedure:

Workpiece Material: The turning tests were performed on DIN 1.2714 AISI L6 tool steel, heat-treated to a hardness of 45 HRC. The material was selected for its wide industrial use in die and mold manufacturing.

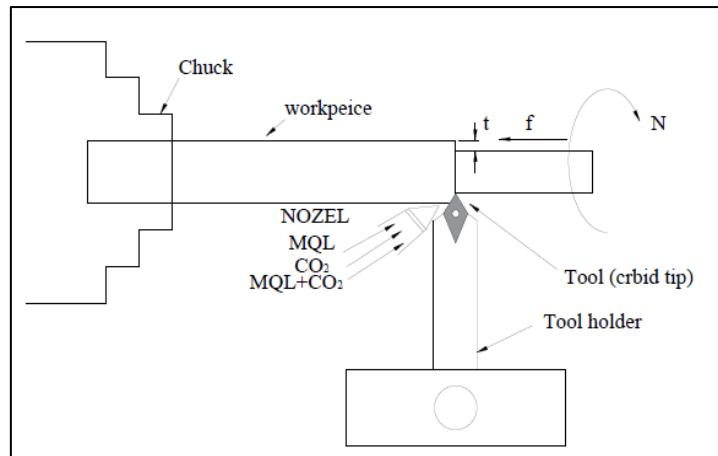
Cutting Tool: A VBMT 16 04 04-UM 525 un-coated carbide insert (SANDVIK) was used. The tool holder (PCLNR2525M12) and insert geometry were selected for high heat resistance and wear stability.

Machine Setup: Experiments were conducted on a CNC lathe (HAAS ST-10) with a constant cutting speed. The lathe provides stability and precision required for repeatable results in turning operations.

The experiments on Din1.2714 and st37 were conducted using a conventional lathe (manufacturer: Biglia; model: B131/52) under all machining circumstances. The obtained workpiece was fixed on the headstock prior to the real trials, and the overhang issue was resolved by center drilling and facing operation. The produced material has wobbles and surface microcracks, which can significantly impair the quality of processing. Consequently, 1 mm of the top layer was taken off of the resultant material in order to remove these impacts. The cutting insert from sandvik coromant was chosen in accordance with the manufacturer's suggestion. A fresh cutting edge was chosen for every experiment in order to track tool wear over a fixed time frame of roughly five minutes.

The current study compared the rotational performance characteristics at constant rotational speeds and constant feed rate. Machinability studies were conducted in various cooling environments, including MQL, CO₂ and hybrid MQL+ CO₂. Due to its proportionate relationship to both surface quality and material removal rate, coolant is a crucial metric. Thus, the machinability characteristics under various environments situations were examined in the current study.

Also, this study liquefied gases are typically directed into the cutting zone to cool the tool and/or workpiece. The coolant absorbs heat from the cutting zone and evaporates into the atmosphere. Images of the machining zone under various cutting cooling methods are displayed in Figure 1.



(a)



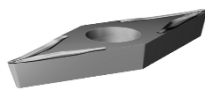
(b)

Figure 1: a) schismatic turning process and **b)** machining processes and cooling techniques

Cutting Parameters:

The following parameters were used: The workpiece and tip insert dimensions, material specifications, mechanical properties, processes parameters and cutting conditions were used experimentally as show in Table 2.

Table 2: Experimental conditions.

Workpiece material and size		Din1.2714 &st37 round bar and (Ø 30 mm × 250 mm)										
Chemical composition of DIN 1.2714 AISI L6 <table border="1"><tr><td>Hardness</td><td></td></tr></table>		Hardness		C	Si	Mn	P	S	Cr	Ni	Mo	V
		Hardness										
		0.50	0.10	0.65	0.	0.	1.00	1.50	0.45	0.07		
-	-	-	0	0	-	-	-	-				
		0.60	0.40	0.95	3	3	1.20	1.80	0.55	0.12		
		45 HRC										
Cutting inserts: VBMT 16 04 04-UM 525 VBMT 331-UM												
Turning process parameters		Cutting velocity (<i>v</i>): 1600 rpm; feed rate (<i>f</i>): 0.035 mm/rev; depth of cut (<i>d</i>): .5 mm										
Environments and coolants used Cutting fluid supply		- MQL (emulsion-based flood cooling: 1:20 soluble oil). - CO ₂ cooling - MQL+CO ₂										
Nozzle diameters used to spray coolant for different environments		The hybrid CO ₂ + MQL system and MQL: Ø5 mm, wet: Ø 10 mm										

Measurement Tools:

Figure 2 shows that an electronic balance (KERN) was utilized for weighing the tool both prior to and following machining. An optical microscope (NIKON) obtained the micrographs displayed in Figure 3 at a magnification of 100x. The Ra value of the treated sample was determined using the surface roughness tester "TIME@3221 Roughness Tester" depicted in Figure 4. The lengths for cutting were 0.08, 0.25, 0.8, and 2.5 mm and could be chosen for assessing average variations. The final result for further analysis is determined by averaging three measurements taken in different directions. The work surface's microhardness was evaluated using a digital microhardness tester (Model No. 005 – LEICA), as shown in Figure 5. Test Method: Every test was conducted three times to ensure consistency. The tool was assessed following every 100 mm of cutting length until the tool wear standard ($VB = 0.3$ mm) was attained. Metallographic samples were prepared for evaluating surface integrity.



Figure 2: Electronic balance



Figure 3: Optical Microscope



Figure 4: Surface Roughness Tester

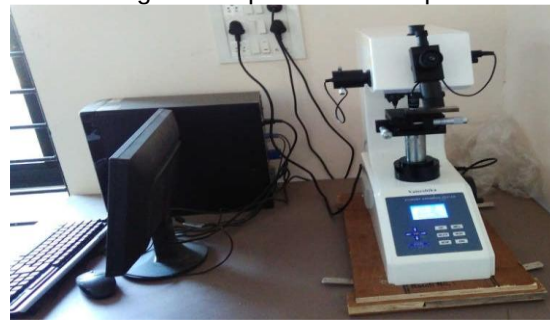


Figure 5: LEICA Vickers Microhardness Tester

Results and Discussion:

The Effect on Surface Roughness:

The test results are represented graphically as shown in the figure 6. Surface roughness values were significantly lower under hybrid MQL+CO₂ condition, achieving an average Ra of (0.84 μm) at optimal parameters, compared to (1.22 μm) in (CO₂) case, and (1.8 μm) in (MQL) case. This substantial improvement is attributed to the synergistic effect of efficient lubrication and rapid heat dissipation. The combined method prevented built-up edge formation and reduced smearing of material on the surface. Additionally, chip morphology under hybrid conditions showed more uniform curling and reduced adhesion to the cutting edge. **The Effect on Tool Wear:**

MQL conditions exhibited a more tool wear than other conditions cutting alone. microscopic imaging revealed minimal flank wear, smaller crater formations, and less nose rounding. Under CO₂ conditions, adhesive and abrasive wear mechanisms dominated, often accompanied by tool chipping. Under hybrid CO₂+MQL system cooling, oxidative wear mechanisms were more prevalent, which are generally less destructive.

Figure 7 illustrates the variations in cutting conditions and recorded average tool wear at the end of the processes. The MQL machining approach exhibited the most significant tool wear, followed by CO₂ machining. The MQL machining test, which demonstrated considerable flank wear, and edge chipping was occurred (Fig. 7a). Conversely, the CO₂ test had to be terminated while the lathe was in operation due to chips sticking in the flutes. The provided image shows the removed material (Fig. 7b). Despite ending the experiments, the wear on the tools' edges was quite noticeable. As expected, hybrid CO₂+MQL machining resulted in the least tool wear (Fig. 7c).

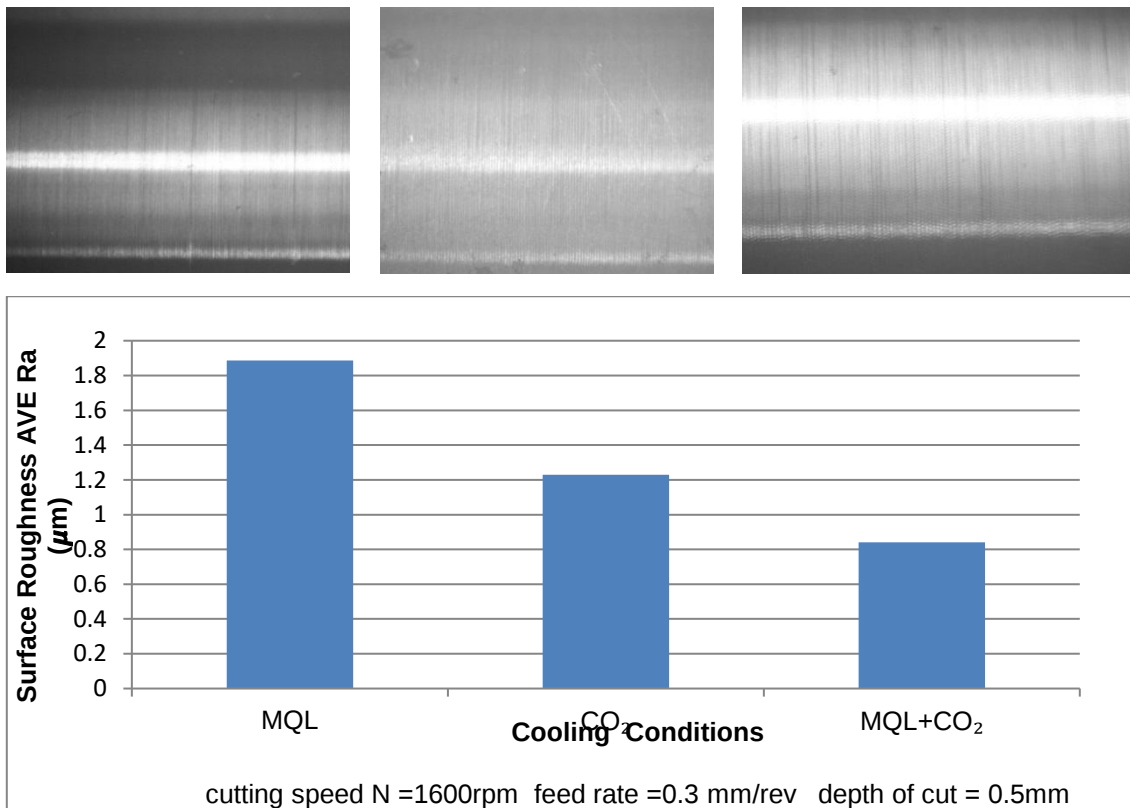


Figure 6: Surface Roughness vs. Cooling Conditions

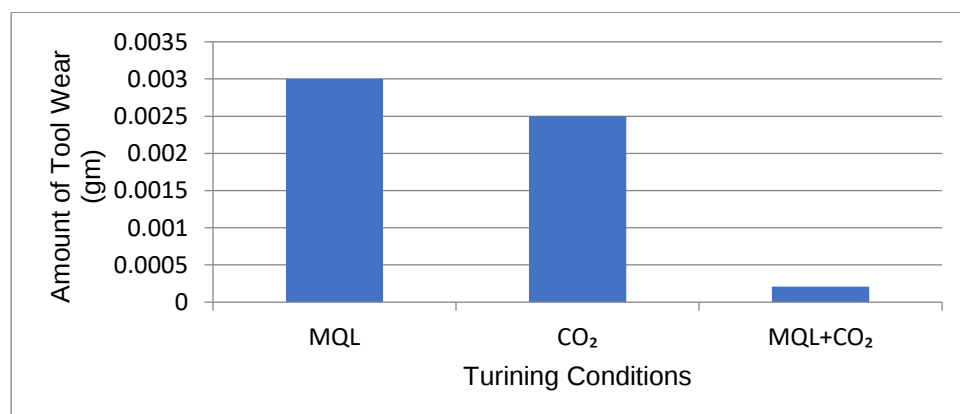
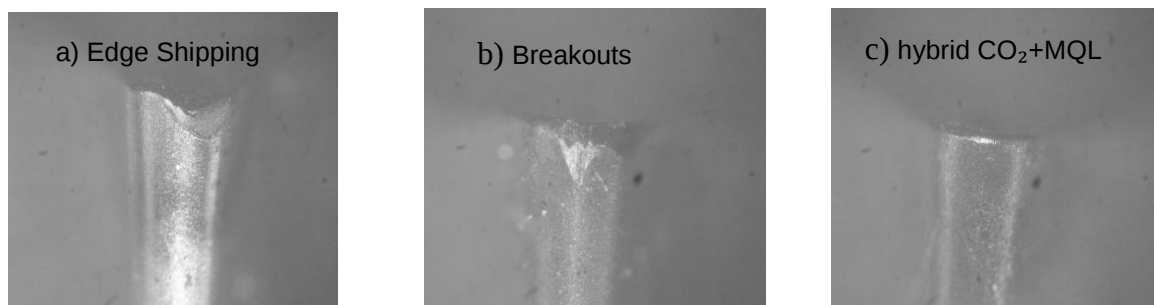


Figure 7: Tool Wear under Different Conditions

The Effect on White Layer Thickness:

Figure 8 shows microscopic white layer (WL) formation is a critical indicator of thermal and mechanical degradation. MQL turning produced white layers exceeding 12 μm in thickness, often containing untempered martensite and microcracks. MQL and CO₂ alone reduced this thickness

moderately, while hybrid MQL+CO₂ limited WL to less than 5 µm, indicating superior thermal control and lower energy deposition into the surface.

The Effect on Microhardness

Numerous factors in machining influence microhardness as a response parameter. The functionality of the material is affected by the amount and intensity of heat generated during machining. Therefore, an evaluation was conducted to assess how hybrid MQL+CO₂ impacts surface microhardness, with comparisons made to MQL and CO₂ cooling individually. Tests were carried out on steel subject of study, maintaining a hardness of ($\approx$ 45 HRC or $\approx$ 448 HV) during the hardening process. Figure 9 illustrates the microhardness trend below the machined surface of the workpiece, under consistent machining parameters and selective cooling environments.

The impact of MQL (Minimum Quantity Lubrication) operates through an independent mechanism: MQL reduces friction and temperature compared to other conditions by directing a small mist of oil droplets (usually vegetable-based) at the tool-chip interface. However, this mist is insufficient to prevent heat buildup in hard steels and results in surface softening about (18–20%) reduction in HV due to localized martensitic structure heat tempering. Additionally, before stabilizing at bulk hardness, the subsurface ($\sim$ 0–150 µm) may exhibit a gradient of decreased hardness. The effect of CO₂ cryogenic cooling alone significantly reduces cutting temperature and minimizes heat dispersion into the workpiece. The results indicate that it preserves or even slightly improves hardness near the surface. Furthermore, the subsurface region (0-100 µm) maintains its hardening degrees and preserves its martensitic structure.

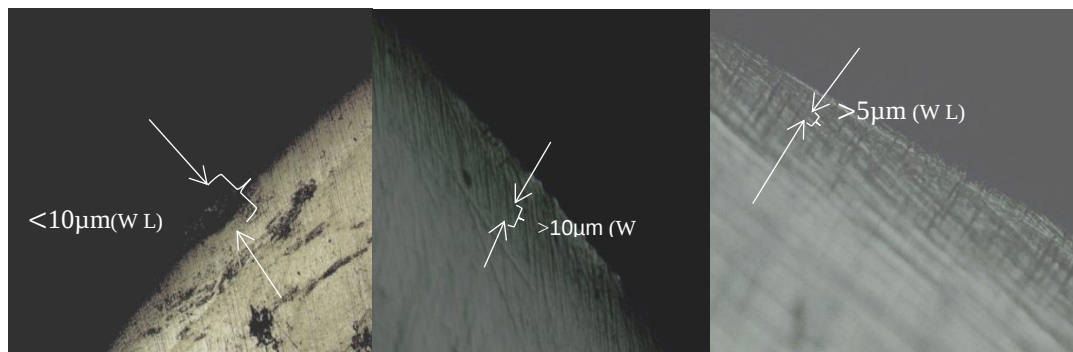


Figure 8: Microstructure Comparison Showing White Layer Thickness

The impact of Cryo-MQL (Hybrid MQL + CO₂) involves MQL oil creating a thin lubricating film that reduces adhesion and frictional heating, while cooling CO₂ rapidly dissipates heat. Among the three systems, the one with the lowest overall temperature and the highest lubrication efficiency had the most significant effect on temperature and stress. The best maintenance of surface hardness (no softening) is achieved through microhardness. Additionally, the surface hardness (<400 HV) remains nearly the same as that of the base material. Stable thermal-mechanical conditions are indicated by a smooth gradient. The findings reveal fine martensite without the development of a white layer or over-tempering.

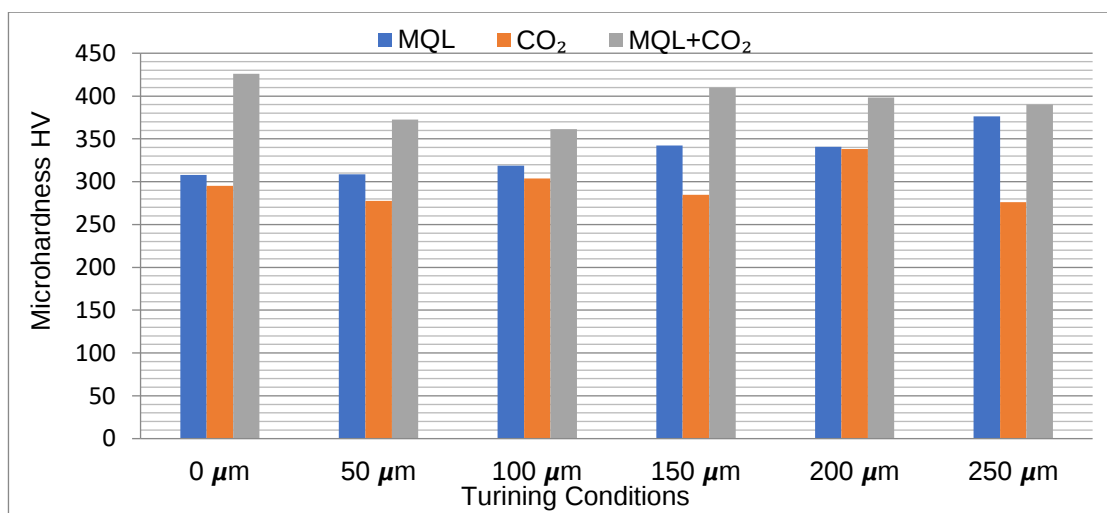


Figure 9: Subsurface Microhardness under Different Conditions

The Effect on Chip Morphologies:

Chip formation is crucial in cutting technology. Chip breakage occurs due to high friction and lower material ductility. Figure 10 presents MQL cooling causes long and yellowish chips. Using cryogenic (CO_2) cooling significantly improves chip breakage, but most chips are longer. The MQL+ CO_2 cooling-lubricating technique is most effective in reducing chip breakage, as it decreases friction and workpiece ductility, and aids in chip separation.

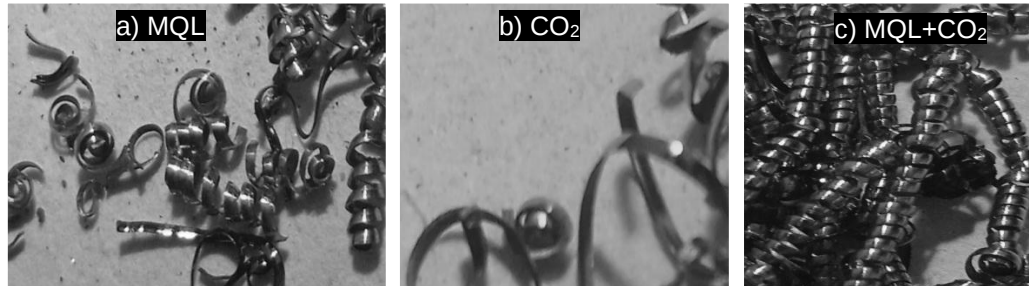


Figure 10: Chip formation for varying cooling conditions

Conclusion:

This experimental study demonstrates the significant advantages of using Cryogenic CO_2 -assisted Minimum Quantity Lubrication (MQL) in the turning of hardened tool steels. The key findings can be summarized as follows:

- MQL alone reduces friction but cannot prevent thermal softening. CO_2 effectively maintains hardness by preventing overheating. The combination of MQL and CO_2 offers optimal surface integrity, preserving or slightly enhancing microhardness due to a balance between low temperature and effective lubrication.
- Surface Roughness: The CO_2 + MQL method achieved the lowest surface roughness ($R_a \approx 0.84 \mu\text{m}$), surpassing dry, MQL, and CO_2 -only methods because of improved chip evacuation and lubrication.
- Tool Wear: Tool life was increased and the main wear mechanisms under hybrid cooling shifted from adhesive–abrasive to more stable oxidative wear, thereby reducing catastrophic tool failures.
- Surface Integrity: The hybrid cooling method minimized the formation of white layers ($WL < 5 \mu\text{m}$), preserved surface hardness ($\sim 730 \text{HV}$), and maintained favourable compressive residual stresses, factors that are crucial for enhancing fatigue resistance and service life.
- Sustainability: The hybrid method significantly decreases the use of cutting fluids while enhancing machining outcomes, aligning well with green manufacturing objectives. These results position CO_2 + MQL as a highly effective and environmentally friendly cooling/lubrication strategy for the precision machining of hardened steels. Future research may investigate real-time adaptive control, economic modeling, and integration with digital manufacturing systems.

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