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Cooling and Lubrication Strategies for Internal Grinding of Ti-6Al-4V: A Review with Emphasis on MQL-Cold CO_2 Hybrid Cooling

Nguyen Thi Thu Dung
Department of Mechanical, Electrical and Electronic Technology, Thai Nguyen University of Technology
666, 3/2 str., Phu Xa ward, Thai Nguyen, Vietnam, 250000

ABSTRACT

Ti-6Al-4V is a difficult-to-machine material due to its low thermal conductivity, low elastic modulus, and high chemical reactivity at machining temperatures. These characteristics lead to significant heat generation during grinding, increased friction, material adhesion to the wheel (clogging), and degradation of surface integrity. These challenges become even more severe in internal grinding, where the confined machining zone restricts the delivery of coolants/lubricants to the contact area and complicates local thermal control. This paper provides a comprehensive review of cooling and lubrication strategies for the internal grinding of Ti-6Al-4V, with a focus on MQL/SQL (Minimum/Small Quantity Lubrication), cryogenic cooling, and hybrid configurations. Experimental results indicate that liquid nitrogen (LN2) cooling can reduce tangential grinding forces by 8–27%, normal grinding forces by 3–12%, surface roughness by up to 38%, and grinding zone temperatures by 55% when machining Ti-6Al-4V. Furthermore, research on titanium grinding demonstrates that SQL combined with liquid CO2 improves grindability more effectively than dry grinding or the use of CO2 alone. Based on the published literature, a single optimal method for the internal grinding of Ti-6Al-4V has not yet been definitively established. However, the integration of MQL with chilled CO2 represents a promising solution due to its potential to provide simultaneous lubrication and effective heat dissipation.

Keywords: Ti-6Al-4V; internal grinding; MQL; cryogenic cooling; liquid CO2; hybrid cooling; surface integrity.

1. INTRODUCTION

Ti-6Al-4V is a titanium alloy widely utilized in aerospace, biomedical, and high-load component manufacturing due to its high strength-to-weight ratio, excellent corrosion resistance, and high reliability [1]. However, this material is also notorious for its poor machinability, characterized by low thermal conductivity, a low modulus of elasticity, high strength retention at elevated temperatures, and high chemical reactivity. These properties lead to excessive heat accumulation in the cutting zone and promote material adhesion (clogging) onto the cutting tool [2, 3].

In finishing operations, grinding is employed when high precision and superior surface quality are required. For Ti-6Al-4V, the grinding process is particularly sensitive to thermal effects due to the high specific energy and friction generated at the interface between the grinding wheel and the workpiece [4, 5]. Sadeghi et al. [4] indicated that MQL (Minimum Quantity Lubrication) is a suitable approach for Ti-6Al-4V grinding, while Elanchezhian et al. [5] demonstrated that cryogenic cooling with liquid nitrogen can significantly reduce grinding forces, surface roughness, and grinding zone temperatures.

Despite these advancements, results obtained in surface grinding or general grinding cannot be directly applied to internal grinding. Unlike open-surface operations, internal grinding occurs within a confined machining zone where the delivery of fluids to the contact area, chip evacuation, and local thermal control are severely restricted [8–10, 15]. Consequently, the effectiveness of cooling in internal grinding depends not only on the type of medium used but also heavily on the delivery configuration—whether external, internal, or hybrid—and the fluid's ability to penetrate the grinding zone [8, 15, 16].

Among the strategies investigated, MQL combined with chilled CO2 has emerged as a particularly noteworthy solution for the internal grinding of Ti-6Al-4V. Mechanistically, this approach integrates the boundary lubrication provided by micro-oils with the intensive cooling effect of CO2 [7, 8]. Experimentally, Mahata et al. [7] showed that SQL (Small Quantity Lubrication) combined with liquid CO2 improves the grindability of titanium more effectively than dry grinding or the use of CO2 alone. Furthermore, studies on hybrid cryogenic MQL for Ti-6Al-4V machining have highlighted the distinct technological potential of the CO2/MQL direction [16–19].

Based on these considerations, this paper provides a comprehensive review of cooling and lubrication strategies for the internal grinding of Ti-6Al-4V, with a specific focus on the potential of MQL combined with chilled CO2 as a priority solution for further research.

2. LITERATURE REVIEW METHODOLOGY

This review is conducted as a targeted critical review, aimed at analyzing cooling and lubrication strategies relevant to the internal grinding of Ti-6Al-4V, while elucidating the potential of MQL combined with chilled **CO2**. This approach focuses on three primary questions: (i) which mechanisms govern the effectiveness of each cooling method; (ii) how coolant delivery configurations

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influence the confined grinding zone; and (iii) why the chilled CO_2–MQL direction warrants greater attention within the context of Ti-6Al-4V internal grinding [8, 15].

The literature sources were selected from scientific publications related to titanium machining, Ti-6Al-4V grinding, internal grinding, MQL/SQL, cryogenic cooling, Cryo-MQL, and internal or hybrid delivery systems. The primary keywords used include: *Ti-6Al-4V; titanium alloy grinding; internal grinding; cylindrical grinding; MQL; SQL; cryogenic cooling; liquid CO_2; Cryo-MQL; coolant delivery; and surface integrity* [8].

The reviewed literature is categorized into three groups:

The first group comprises fundamental studies on the machinability of titanium and the thermo-frictional characteristics during Ti-6Al-4V grinding [1–5].

The second group includes experimental studies directly related to titanium grinding under MQL/SQL, cryogenic cooling, or CO_2 combined modes [4–7, 11–14].

The third group consists of research on internal cylindrical grinding, internal/hybrid delivery systems, and hybrid CO_2/MQL publications with significant transferability to the Ti-6Al-4V internal grinding problem [8–10, 15–19].

On this basis, the literature was analyzed along three main axes: action mechanisms, delivery configurations, and technological output indicators. This analytical framework allows for the evaluation of each strategy not only by the type of medium but also by its suitability for internal grinding conditions.

3. THERMO-FRICTIONAL FOUNDATIONS OF TI-6AL-4V GRINDING

Ti-6Al-4V is an alloy characterized by low thermal conductivity, a low modulus of elasticity, high strength retention at elevated temperatures, and high chemical reactivity. Consequently, the energy generated during the machining process is difficult to dissipate rapidly from the contact zone [2, 3]. Ezugwu and Wang [2] stated that for titanium, the concentration of heat near the cutting zone is significantly higher than that of steel. Furthermore, the low elastic modulus causes the material to easily spring back, increasing the tendency for rubbing and plowing rather than pure cutting. Therefore, at the material level, Ti-6Al-4V inherently tends toward high contact temperatures, high friction, and unfavorable thermo-mechanical loads during grinding [2].

In grinding, these disadvantages become more pronounced because material removal is performed by numerous abrasive grains at high speeds, while the depth of cut for each individual grain is extremely small. Under these conditions, the proportion of energy consumed by friction, plowing, and plastic deformation can be very high, thereby increasing the specific grinding energy and promoting heat accumulation at the wheel–workpiece interface [4, 5]. Elanchezhian et al. [5] pointed out that the high friction in the grinding zone is the direct cause of increased heat and the subsequent risk of thermal damage when grinding Ti-6Al-4V.

As the temperature in the contact zone rises, the material tends to undergo local softening and plastic flow around the tips of the abrasive grains. This increases the likelihood of material adhesion to the grains, leading to clogging (loading) of the grinding wheel's working surface [2, 5]. Once the wheel is clogged, its cutting capability decreases, and the proportion of rubbing and plowing increases, which in turn causes the temperature to rise further. Therefore, the core challenge in Ti-6Al-4V grinding is the simultaneous control of the grinding zone temperature and the frictional state at the wheel–workpiece interface [4, 5, 7].

From a technological standpoint, these thermo-frictional mechanisms directly govern grinding forces, surface roughness, wheel wear, and surface integrity [4–7]. This also explains why cooling strategies focusing on only a single mechanism often have limitations, while hybrid configurations are increasingly gaining attention [7, 8].

4. INTERNAL GRINDING AND COOLING SYSTEM REQUIREMENTS

Internal grinding is a finishing operation employed when high dimensional accuracy, roundness, concentricity, and superior surface quality of a bore are required. Compared to surface or external cylindrical grinding, this process occurs within a confined machining space, making access to the grinding contact zone, chip evacuation, and thermal field control significantly more unfavorable [9, 10].

Another critical characteristic of internal grinding is that the grinding wheels typically have small diameters, the quill (wheel spindle) has a large cantilever length, and the overall stiffness of the technological system is lower. Consequently, this process is more sensitive to vibrations, orbital deviations, and local thermal deformations [9, 10]. Under these conditions, any abnormal increase in grinding forces or contact zone temperature can directly impair the geometric accuracy and surface layer quality of the finished hole.

The most fundamental challenge of internal grinding lies not in the medium itself, but in the ability to deliver the medium precisely into the grinding contact zone. Within the narrow workspace, the momentum of the fluid jet often dissipates before reaching the wheel–workpiece interaction zone; simultaneously, the motion of the wheel, the workpiece, and the air barrier (boundary layer) rotating around the wheel further reduce the penetration efficiency of the medium [5, 8]. Kieraś et al. [10] showed that in internal cylindrical grinding, combining an external cold air stream with a centrifugal MQL flow delivered through internal channels in the wheel mandrel can improve cooling and lubrication conditions at the contact interface. Nadolny et al. [15] also emphasized that the delivery system is a vital component of sustainable and efficient grinding.

Therefore, for the internal grinding of Ti-6Al-4V, an appropriate cooling system must simultaneously ensure penetration into the contact zone, facilitate chip evacuation, reduce wheel loading (clogging), and maintain both heat transfer and boundary

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lubrication [8–10, 15, 16]. This forms the basis for why hybrid configurations—specifically MQL combined with cryogenic media—have become a more compelling research direction for this problem.

5. COOLING AND LUBRICATION STRATEGIES IN TITANIUM AND TI-6AL-4V GRINDING

Cooling and lubrication strategies for the grinding of titanium and Ti-6Al-4V can be analyzed along two primary axes: the action mechanism at the grinding contact zone and the coolant delivery configuration [4–8, 15]. Based on the mechanism, the main approaches include conventional flood grinding, MQL/SQL, cryogenic cooling, and hybrid configurations. Regarding delivery configurations, current systems are typically organized into external, internal, and hybrid delivery modes [8, 15, 16].

5.1. Conventional Flood Grinding

Conventional flood grinding offers the advantage of providing a high flow rate of coolant, which aids in heat transfer and flushing chips away from the grinding contact zone [5, 15]. However, the practical effectiveness of this method depends heavily on the coolant's ability to penetrate the contact zone. Elanchezhian et al. [5] demonstrated that the air boundary layer surrounding the grinding wheel can significantly impede coolant penetration. In internal grinding conditions, this limitation is even more pronounced due to the confined workspace and the fact that the spray direction is constrained by the bore geometry [8–10, 15].

Consequently, conventional flood grinding is often regarded as a baseline benchmark but is not always the most effective solution for restricted contact zones [5, 15].

5.2. MQL/SQL

MQL (Minimum Quantity Lubrication) and SQL (Small Quantity Lubrication) are strategies focused on boundary lubrication, aimed at reducing friction at the wheel–workpiece interface and limiting the clogging (loading) of the wheel's working surface [4, 7]. Sadeghi et al. [4] indicated that MQL is a suitable direction for Ti-6Al-4V grinding. Guo et al. [6] also showed that MQL can reduce grinding forces and specific energy when grinding titanium alloys with SiC wheels. Along the same lines, Mukhopadhyay and Kundu [11, 12] demonstrated that the efficiency of Ti-6Al-4V grinding clearly depends on the delivery method, while Ghorai et al. [13] found that coolant concentration also significantly affects grindability.

However, the advantage of MQL/SQL lies primarily in friction control, whereas its heat dissipation capacity remains limited due to the small volume of fluid used [4, 7]. Therefore, under high thermal loads or in difficult-to-access contact zones, standalone MQL/SQL is often insufficient to simultaneously control both temperature and friction [4, 8].

5.3. Cryogenic Cooling and Hybrid Configurations

Cryogenic cooling has gained significant attention in titanium grinding due to its superior heat absorption capacity and its ability to lower the contact zone temperature [5, 8]. Elanchezhian et al. [5] showed that when grinding Ti-6Al-4V with electroplated CBN wheels under liquid nitrogen (**LN2**) conditions, tangential grinding forces decreased by 8–27%, normal grinding forces by 3–12%, surface roughness by up to 38%, and contact zone temperatures by 55% compared to conventional flood grinding. An et al. [14] also showed that a cryogenic pneumatic mist jet can improve thermal conditions in titanium alloy grinding.

Nevertheless, standalone cryogenic cooling primarily addresses the heat transfer problem, while the boundary lubrication effect at the wheel–workpiece interface remains limited [5, 8]. Thus, if friction and wheel clogging remain high, enhancing cooling alone may not yield optimal results.

The hierarchical classification of cooling and lubrication strategies in Ti-6Al-4V grinding (Figure 1) illustrates the shift from standalone to hybrid configurations. Each strategy is described according to a common comparative standard, including the dominant mechanism, key strengths, and primary limitations (a synthesis developed by the author based on [4–19]).

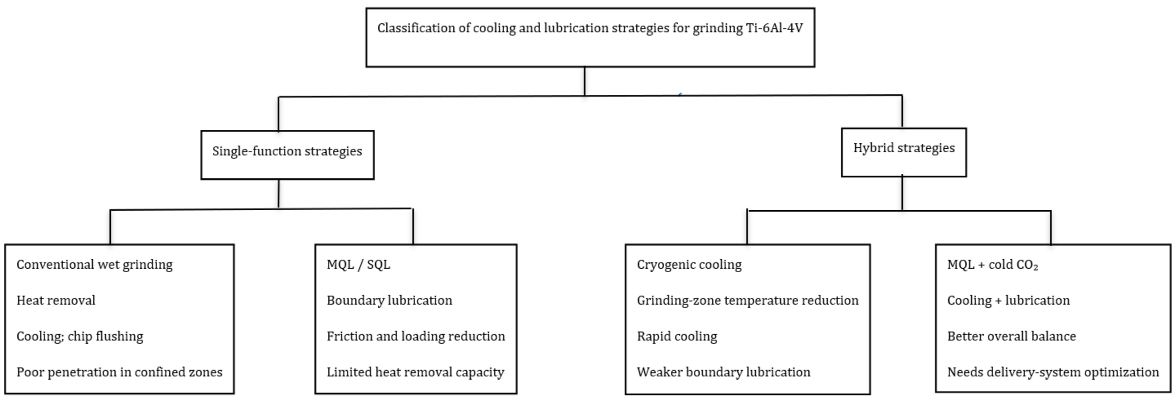

Fig1: Classification of cooling and lubrication strategies for grinding Ti-6Al-4V

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6. POTENTIAL OF THE MQL COMBINED WITH CHILLED CO2 STRATEGY

The integration of MQL with chilled **CO2** warrants significant attention due to its capability to simultaneously address the two governing mechanisms of the Ti-6Al-4V grinding process: boundary lubrication and heat transfer at the contact zone [7, 8]. Mahata et al. [7] demonstrated that when combining SQL (Small Quantity Lubrication) with liquid CO2, the efficiency of titanium grinding was higher than both dry grinding and the standalone use of CO2. These results suggest that CO2 performs more effectively when paired with a small amount of lubricant, rather than acting solely as a cooling agent.

Iruj et al. [8] synthesized that Cryo-MQL systems generally achieve a superior balance between cooling and lubrication compared to standalone configurations. For Ti-6Al-4V machining, Shokrani et al. [17], Ha et al. [18], and Khosravi et al. [19] have all shown that CO2/MQL or hybrid cryogenic MQL configurations can markedly improve machining conditions and technological efficiency. Although direct evidence specifically for the *internal grinding* of Ti-6Al-4V remains limited, the experimental foundation for the CO2+MQL direction is robust enough to consider it a high-priority research path.

In the context of internal grinding, the advantage of the chilled CO2–MQL approach lies not only in the medium itself but also in the flexibility of the coolant delivery system. Iruj et al. [8] indicated that CO2 can be delivered via external, internal, or hybrid modes when combined with MQL. Bergs et al. [16] also proved the feasibility of establishing an **LCO2**+MQL system in an internal delivery configuration for Ti-6Al-4V machining. This is particularly vital for internal grinding, where process efficiency depends heavily on the ability to deliver the medium in close proximity to the contact zone [8, 16].

Currently, there is insufficient evidence to claim that chilled CO2–MQL is the *sole* optimal method for all Ti-6Al-4V internal grinding conditions. However, considering both the thermo-frictional mechanisms and the delivery configurations, this stands out as a prominent direction for prioritized in-depth research [7, 8, 16–19].

7. INTEGRATED DISCUSSION

The synthesized results indicate that no single cooling strategy is absolutely superior under all conditions for the grinding of titanium and Ti-6Al-4V. Conventional flood grinding excels at providing high flow rates and supporting heat transfer, but its practical effectiveness is hindered by the limited penetration of the fluid into the grinding contact zone [5, 15]. MQL/SQL proves effective primarily through boundary lubrication and friction reduction, yet its heat dissipation capacity remains restricted [4, 7]. Conversely, cryogenic cooling offers a clear advantage in lowering contact zone temperatures, but its boundary lubrication effect is often insufficient when used in isolation [5, 8]. Consequently, hybrid systems possess a stronger theoretical and practical foundation as they simultaneously address both thermal and frictional aspects [7, 8].

Among the strategies reviewed, the integration of MQL with chilled **CO2** stands out due to its ability to concurrently reduce friction and enhance heat transfer [7, 8]. Mahata et al. [7] demonstrated that SQL combined with liquid CO2 yields better performance than dry grinding or the standalone use of CO2. Iruj et al. [8] also highlighted the high flexibility of CO2 within external, internal, and hybrid delivery configurations. Results obtained from Ti-6Al-4V milling by Shokrani et al. [17], Ha et al. [18], and Khosravi et al. [19] further reinforce the argument that CO2/MQL is a technological direction with a robust experimental foundation. However, there is currently insufficient evidence to definitively label this as the *sole* optimal method for all Ti-6Al-4V internal grinding scenarios. At this stage, it is more rational to view chilled **CO2**–MQL as a scientifically sound direction that warrants high-priority, in-depth research [7, 8, 16–19].

The qualitative matrix (Table 1) compares cooling strategies in Ti-6Al-4V grinding based on four criteria: heat transfer, boundary lubrication, penetration into narrow contact zones, and suitability for Ti-6Al-4V internal grinding. These qualitative levels were established based on a synthesis of experimental and review results from [4–19]. In this matrix, the advantage of the MQL + chilled **CO2** system is derived from its capacity to simultaneously combine cooling effects, lubrication, and versatile coolant delivery configurations [7, 8, 16–19].

Table 1. Qualitative comparison of cooling strategies in grinding Ti-6Al-4V

Strategy	Heat transfer	Boundary lubrication	Penetration into confined grinding zone	Potential suitability for internal grinding of Ti-6Al-4V	References
Conventional wet grinding	Moderate	Moderate	Low	Low–Moderate	[5], [8], [15]
MQL/SQL	Low–Moderate	High	Moderate	Moderate	[4], [6], [7], [11]–[13]
Cryogenic cooling	High	Low	Moderate	Moderate	[5], [7], [8], [14]
MQL + cold CO_2	High	High	High	High	[7], [8], [16]–[19]

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CONCLUSION

This review demonstrates that cooling efficiency during the grinding of Ti-6Al-4V is simultaneously governed by the material's adverse thermal properties, high friction in the grinding contact zone, and the tendency for wheel loading (clogging). These factors directly impact grinding forces, surface roughness, wheel wear, and surface integrity [2–5]. When transitioning to internal grinding, these disadvantages become more severe due to the confined machining zone, which reduces the effectiveness of coolant delivery and chip evacuation [8–10, 15].

The synthesized results also indicate that no single cooling strategy is optimal under all conditions. Conventional flood grinding offers advantages in terms of flow rate but is limited by its ability to penetrate narrow grinding zones [5, 8, 15]. MQL/SQL is more effective for boundary lubrication but remains limited in heat dissipation [4, 6, 7, 11–13]. Cryogenic cooling significantly improves the thermal field but lacks sufficient lubrication performance when used in isolation [5, 7, 8, 14]. Consequently, hybrid systems possess a more suitable foundation as they simultaneously address both thermal and frictional challenges [7, 8].

Among the strategies reviewed, MQL combined with chilled CO2 is a particularly noteworthy direction for the internal grinding of Ti-6Al-4V, as it integrates boundary lubrication, heat transfer, and flexibility in coolant delivery configurations [7, 8, 16–19]. However, there is currently a lack of direct studies on Ti-6Al-4V internal grinding to confirm the effectiveness of this approach under specific conditions. Therefore, future research should focus on optimizing the coolant delivery system and simultaneously evaluating grinding temperature, forces, roughness, wheel wear, and the geometric accuracy of the bore [8–10, 15–19].

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