

Machinability of Ti-6Al-4 V in the milling process using cryogenic cooling and nanofluid MQL

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ABSTRACT

Titanium alloys, valued for their lightweight properties, are increasingly in demand as advanced materials in the aerospace industry. However, they are classified as difficult-to-machine due to their heat resistance and elastic characteristics, necessitating further research. Additionally, conventional lubrication methods present challenges related to the working environment and operator health, underscoring the need for alternative solutions. This study focuses on the milling process of the titanium alloy Ti-6Al-4 V, aiming to optimize the machining environment to enhance key performance metrics such as cutting temperature and surface quality. Experimental results indicate that hybrid nMQL (nanofluid minimum quantity lubrication) combined with cryogenic cooling significantly reduces tool wear. While cryogenic environments tend to produce microcracks, debris, and cutting marks, the nMQL environment is primarily associated with cutting marks and microcracks. Notably, surfaces processed under the combined nMQL + cryogenic environment exhibit greater stability than those produced under other machining conditions. Moreover, when cryogenic cooling is used in conjunction with nanofluid lubrication (nMQL), surface residual stress is reduced by up to 76.6 %, and cutting temperature decreases by as much as 25 % compared to other machining setups. Residual stress measurements, conducted using the hole drilling method with strain gauges, confirmed a significant reduction in surface stress under hybrid lubrication conditions. Additionally, while cutting temperature varies with cutting speed, it was observed to decrease by up to 25.8 % when the hybrid method was applied. The improved performance is attributed to the compressive surface residual stress induced by the elasticity and heat resistance of Ti-6Al-4 V. Consequently, the reduction in residual stress under the cryogenic + nMQL environment enhances tool wear resistance, surface quality, and temperature control, outperforming other machining conditions.

1. Introduction

With carbon regulations becoming a crucial global issue, the transportation sector, including the aviation and automotive industries, is undergoing significant changes. In particular, the aviation industry is actively implementing various measures to reduce carbon emissions. One of the key strategies is to achieve weight reduction by altering the material composition of aircraft, thereby reducing fuel consumption and associated carbon emissions. As a result, there is a growing trend in aircraft structural design to adopt composite materials, titanium alloys, and lithium-aluminum alloys, leading to an increasing demand for these materials [1–3].

Among these, titanium alloys are well known for their excellent high-temperature resistance, lightweight characteristics, superior corrosion

resistance, and biocompatibility [4,5]. These properties make titanium alloys widely applicable in various industries, including aerospace [6]. However, titanium alloys are classified as difficult-to-machine materials due to their low thermal conductivity, high chemical reactivity, and low modulus of elasticity [7]. These characteristics lead to high temperatures, strong adhesion, and issues related to chip formation during machining, making it essential to analyze cutting temperature and forces [8].

Several studies have explored the combined effects of various lubrication and cooling techniques on the machining of titanium alloys. For instance, Park et al. conducted milling experiments under five distinct conditions: wet cooling, nano-MQL, external cryogenic cooling, internal cryogenic cooling, and a combination of nano-MQL with internal cryogenic cooling. They found that the combination of hBN +

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MQL + internal cryogenic cooling achieved the lowest cutting loads and significantly extended tool life [9]. Shokrani et al. examined the cryogenic milling of Ti-6Al-4 V and observed that cryogenic milling reduced surface roughness compared to dry and wet machining. Microscopic evaluations of surfaces machined under wet and dry conditions revealed increased roughness due to thermal softening and chip reattachment, while the cryogenically machined surface exhibited the highest hardness [10].

Nguyen et al. investigated the milling of Ti-6Al-4 V using a hybrid nanofluid composed of Al_2O_3 -MWCNT and confirmed that the addition of nanofluids improved friction conditions, reduced cutting forces and energy consumption, and enhanced surface roughness [11]. Similarly, Jamil and Muhammad compared MQL, LN_2 , and CO_2 environments in titanium milling, concluding that the CO_2 cooling environment provided the most efficient milling performance in terms of cutting forces and energy efficiency. Additionally, a hybrid setup combining nanofluid-based MQL (MWCNT) and cryogenic CO_2 (-56.6°C) was found to reduce surface roughness and cutting forces [12,13]. Another study compared cryogenic CO_2 cooling and hybrid nanofluid-based MQL in Ti-6Al-4 V turning, demonstrating that while hybrid MQL improved surface quality and tool life, cryogenic cooling was more effective in reducing cutting temperature. These findings underscore the trade-offs between lubrication efficiency and thermal control, which are also relevant to milling processes [14].

Similarly, the hybrid process has also been applied to other difficult-to-cut materials, such as nickel-based alloys with low thermal conductivity. Nickel-based alloys possess high-temperature resistance and corrosion resistance, making them valuable in various industrial applications. However, Nickel-based alloys are also categorized as difficult-to-machine materials due to their low thermal conductivity and high hardness, resulting in inconsistent machining outcomes across different environments [15].

Several studies have applied various lubrication and cooling methods to Nickel-based alloys, but no single method has proven to be universally effective under all conditions. For instance, Ghosh et al. investigated the machinability in turning processes under different cutting conditions (cutting speed, nose radius, and feed rate) and reported that cryogenic environments offered superior machinability compared to nMQL environments [16]. Likewise, Chetan et al. reported that while MQL environments helped reduce tool wear, cryogenic conditions still provided the lowest surface quality [17]. Similarly, Jadhav and Mohanty compared MQL and cryogenic cooling for the difficult-to-machine material Nimonic C-263, finding that cryogenic cooling was more effective than MQL in reducing tool wear, lowering cutting costs, and improving the work environment [18]. Kumar et al. applied hybrid nanofluids to the nickel-based superalloy Nimonic 90 and confirmed their effectiveness in reducing cutting force, cutting temperature, surface roughness, and tool wear compared to dry machining [19].

Previous studies have explored various lubrication and cooling techniques for machining difficult-to-cut materials. As shown in Table 1. However, these techniques have not consistently provided reliable results due to variations in machining conditions, processes, and tools.

This inconsistency complicates the identification of an optimal machining environment. Furthermore, comprehensive process analyses involving hybrid lubrication environments are lacking, and limited studies have investigated the effects of different cooling methods on machining characteristics.

To address these challenges, this study aims to enhance the machinability of Ti-6Al-4 V, a material known for its low thermal conductivity and machining difficulty, by proposing a hybrid process design. Specifically, we hypothesize that the integration of lubrication and cooling techniques in a hybrid machining process will contribute to improved machinability by reducing heat generation, tool wear, and residual stress on the machined surface. While previous studies have demonstrated that cryogenic cooling effectively suppresses heat and minimizes tool wear, its high coolant consumption and limited sustainability remain significant drawbacks. To overcome these limitations, we designed and implemented an indirect cooling approach by incorporating internal cooling channels within the cutting tool. As shown in Fig. 1, the conventional cryogenic cooling method in previous studies adopts a direct cooling approach [Fig. 1(a)], where the coolant is sprayed directly onto the tool from the outside. In contrast, in this study, an indirect cooling approach [Fig. 1(b)] was implemented by designing internal cooling channels within the tool to supply the coolant indirectly to the cutting area.

As shown in Table 2, preliminary experiments demonstrated that the indirect cooling method reduced cryogenic coolant consumption by up to 48 % and by at least 27 % compared to direct cooling. Based on these findings, we hypothesize that a hybrid process combining indirect cooling with nano-MQL (Minimum Quantity Lubrication) will be more effective in optimizing machining performance than relying solely on a single cooling strategy. To validate this hypothesis, we designed a hybrid machining environment integrating indirect cooling and nano-MQL and evaluated its effectiveness in reducing heat generation, improving surface quality, and minimizing tool wear.

Ti-6Al-4 V is widely used in the aerospace industry, where stringent quality requirements must be met. Therefore, beyond improving machinability, the proposed hybrid process design is expected to contribute to enhancing surface integrity and extending tool life, which are critical factors in aerospace applications. By establishing optimal machining conditions, this study aims to support advancements in the manufacturing processes of high-performance aerospace components.

2. Experimental setup and condition

The experimental setup for machining the titanium alloy Ti-6Al-4 V is illustrated in Fig. 2. This setup involves a 5-axis machining center (HTC-1000, HNK) integrated with cryogenic cooling and lubrication functions, specifically designed to optimize the machining process. The process monitoring system consists of a dynamometer (Type 9257B, KISTLER) for measuring cutting forces, a pyrometer (IGA 6/23, Impac) for monitoring the temperature within the machining environment, and a data acquisition unit (Labamp type 5167a, KISTLER). A microscope (VHX-7000, Keyence) was employed to measure tool wear and

Table 1
Effectiveness and application of various cooling and lubricating strategies [20].

Effects of cooling and lubricating strategy	Flood (emulsion/oil)	Dry (compressed air)	MQL (oil)	Cryogenic (LN_2)	Hybrid (LN_2 + MQL)
Cooling	Good	Poor	Marginal	Excellent	Excellent
Lubricating	Excellent	Poor	Excellent	Marginal	Excellent
Chip removal	Good	Good	Marginal	Good	Good
Workpiece cooling	Good	Poor	Poor	Marginal	Marginal
Machine cooling	Good	Poor	Poor	Good	Good
Dust/Particle control	Good	Poor	Marginal	Marginal	Good
Product quality	Good	Poor	Marginal	Excellent	Excellent
Sustainability	Water pollution, microbial infestation, and high cost	Poor surface integrity due to thermal damage	Harmful oil vapor	Initial cost	Initial cost, oil vapor

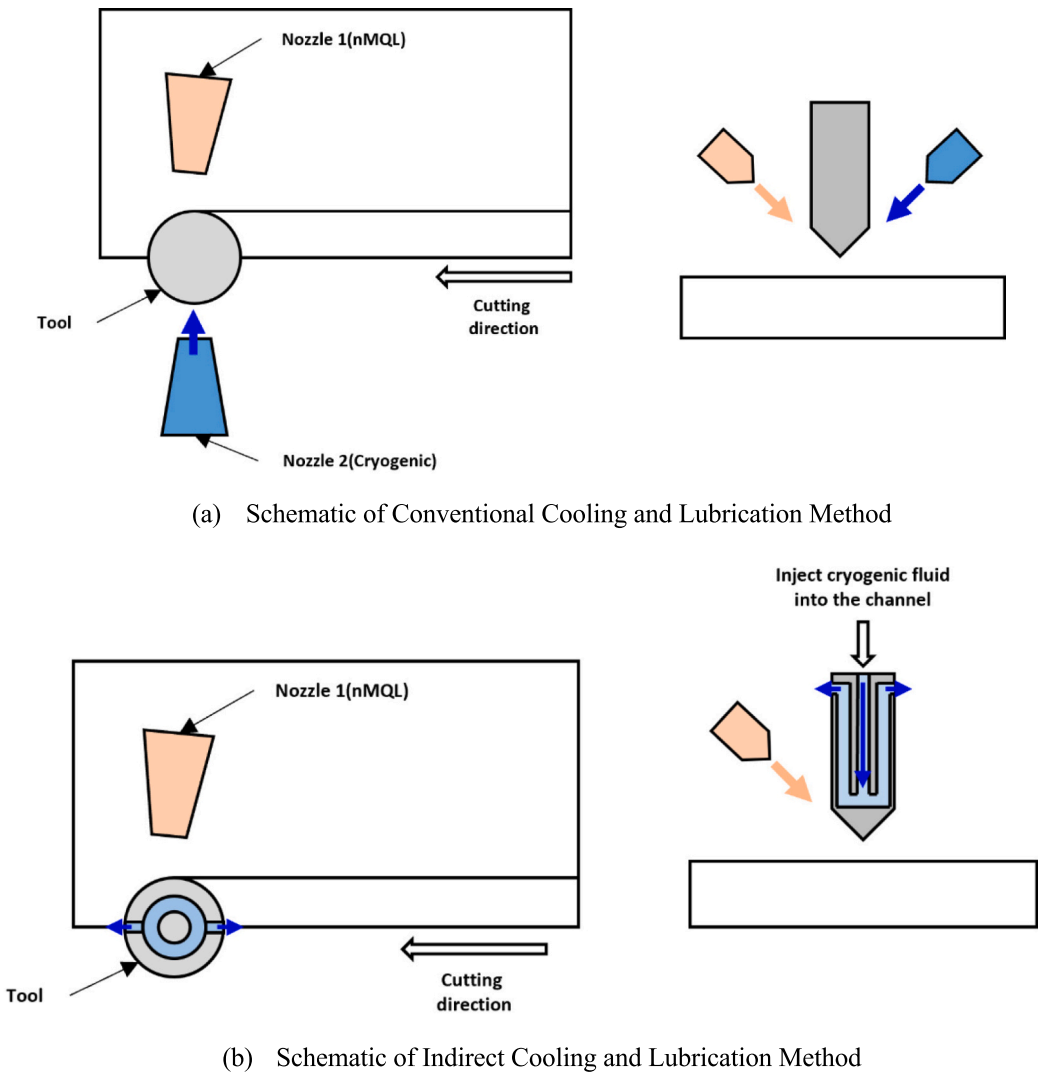


Fig. 1. Comparison of Conventional and Indirect Cooling and Lubrication Methods.

Table 2
Cryogenic Consumption Analysis Based on Cooling Methods.

Injection Method	Injection Pressure (bar)	Injection Time(sec)	LN2 Tank Weight (kg)	LN2 Consumption per Minute(kg/min)
External Cooling	2	607	10.1	0.99
	4	615	11.5	1.12
	6	600	13.2	1.32
	8	613	15.5	1.51
Internal Cooling	2	615	5.3	0.51
	4	631	8.6	0.81
	6	612	8.9	0.87
	8	619	10.7	1.03

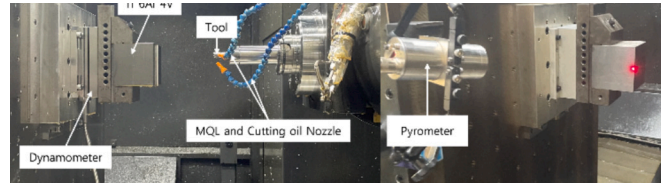


Fig. 2. Experimental setup.

geometry. Additionally, surface characteristics were precisely measured using a laser microscope (VK-X100K, KEYENCE) integrated with the VK Analyzer analysis software.

The mechanical properties of the Ti-6Al-4 V alloy used in the experiments are summarized in Table 3, while the chemical composition is detailed in Table 4, providing crucial background information for this study.

For the machining experiments, the specimen was securely fixed on a dedicated jig, measuring 100 × 100 × 100 mm. The cutting tool developed for cryogenic application was designed with a diameter of 16 mm and four cutting edges. A cooling method was applied via internal channels within the tool to supply cryogenic coolant. The pressure of the cryogenic coolant was selected based on preliminary experiments. The cutting speed was set at two levels, 80 m/min and 120 m/min, according to the tool manufacturer’s recommendations. The detailed cutting conditions are summarized in Table 5.

In this study, different environmental conditions were explored to

Table 3
Mechanical properties of Ti-6Al-4 V.

Properties	Value
Tensile strength	886.4 MPa
Yield strength	844.64 MPa
Elongation	12.29 %

Table 4
Chemical composition of Ti-6Al-4 V.

Elements	Wt.(%)
Ti	89.53
Al	6.09
V	4.05
Zr	0.0016
Fe	0.108
Si	0.016

Table 5
Machining conditions.

Machining parameters	Value
Tool diameter	16 mm
Number of tool flutes	4
Cut length	26 mm
Workpiece size	100 × 100 × 100 mm
Axial depth of cut (A_p)	5 mm
Radial depth of cut (A_e)	1 mm
Feed per tooth (F_z)	0.08 mm/tooth
Cutting velocity (V_c)	80, 120 m/min
Cryogenic injection pressure	2 bar
nMQL injection pressure	4 MPa
Nano particle size	70 nm

improve the machinability of the Ti-6Al-4 V alloy. Considering the inherent difficulties associated with machining this alloy, the experiments were conducted under three distinct environments, as outlined in Table 6. In the nanoparticle MQL (nMQL) environment, hexagonal boron nitride (hBN) particles were selected. According to previous studies, hBN has been shown to improve the micro end-milling characteristics of Ti-6Al-4 V, attributed to its layered structure. This structure promotes a sliding effect that reduces cutting forces and decreases both surface roughness and tool wear [21]. Hence, hBN was specifically chosen for its advantageous properties in the nMQL cutting environment.

3. Results and discussion

This study focuses on analyzing the milling characteristics of Ti-6Al-4 V, with particular emphasis on the following key factors: (1) tool wear, (2) surface integrity, (3) residual stress, and (4) cutting temperature. The experimental results were analyzed in relation to machining conditions, cryogenic cooling, and lubrication, with the research aiming to understand the impact of these critical parameters.

3.1. Tool wear

The cutting tool used in this study was equipped with four flutes, and tool wear was measured at two representative locations per flute, as illustrated in Fig. 3. Each measurement was repeated five times, and the average values and error ranges were calculated to ensure statistical consistency. The overall results are presented in Fig. 4. In the cryogenic cooling condition (Case 1), excessive smoke generation and thermal distortion limited the cutting cycles to 15, and thus, tool wear was evaluated after 15 cuts. For the nanofluid MQL (Case 2) and hybrid cooling condition (Case 3), tool wear was measured after 95 cutting cycles to maintain experimental consistency across all conditions.

Table 6
Cooling and lubrication experimental design.

Case	Lubrication	Cryogenic cooling
1	N/A	LN2
2	nMQL (hBN)	N/A
3	nMQL (hBN)	LN2

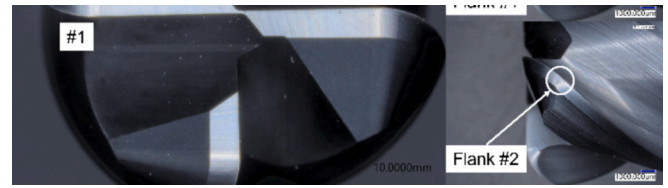


Fig. 3. Tool wear measurement method.

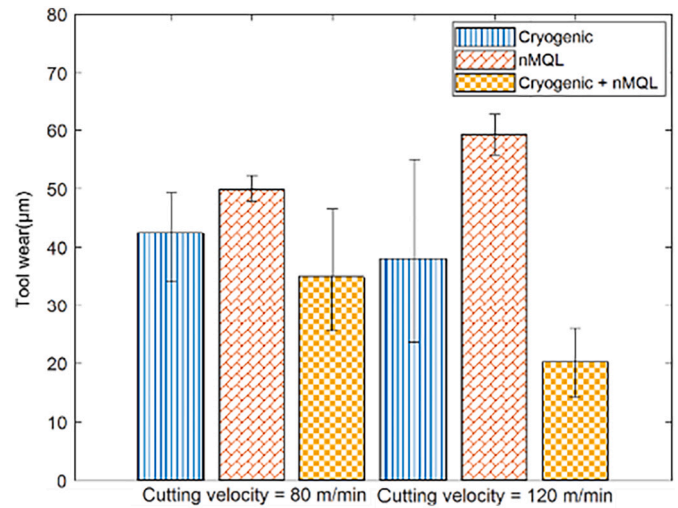
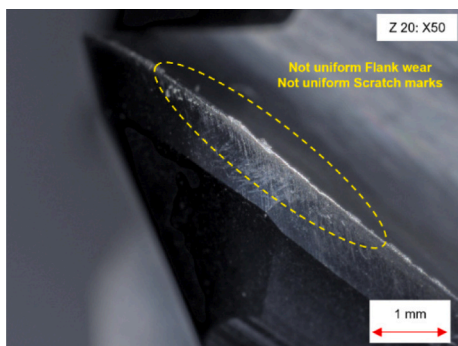


Fig. 4. Tool wear results in the machining environment.

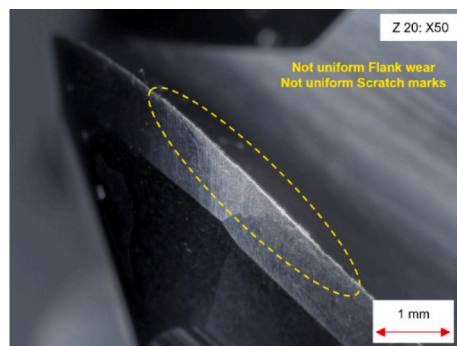
The experimental results demonstrated that the most severe tool wear occurred under the nMQL condition (Case 2), while the hybrid condition (Case 3) resulted in the lowest degree of wear. With increasing cutting speed, tool wear generally intensified under all conditions; however, the hybrid environment consistently exhibited the most stable and minimal wear progression. Representative tool wear morphologies under each condition are provided in Figs. 5(a)–(l). In the cryogenic condition [Figs. 5(a)–(d)], uneven wear and distinct scratch marks were observed on the flank surface, attributed to non-uniform cooling efficiency. Under the nMQL condition [Figs. 5(e)–(h)], chipping was evident at low cutting speeds. In contrast, the hybrid condition [Figs. 5(i)–(l)] displayed uniform wear with relatively smooth surfaces.

The observed variations in tool wear characteristics are closely associated with the thermal and tribological mechanisms specific to each cooling and lubrication strategy. The nMQL condition (Case 2) provided effective and consistent lubrication at the tool–chip interface, but its limited cooling capability likely resulted in elevated interface temperatures, leading to accelerated tool wear due to thermal softening and adhesive mechanisms. The cryogenic condition (Case 1) effectively suppressed the cutting temperature, yet the absence of lubrication support made the system vulnerable to localized flank wear. In contrast, the hybrid condition (Case 3) leveraged the complementary advantages of both approaches. At higher cutting speeds, elevated interface temperatures facilitated the formation of tribofilms from hBN nanoparticles in the nanofluid, thereby enhancing lubrication stability. Simultaneously, the internal cooling channels embedded in the tool structure efficiently dissipated heat, preserving tool rigidity and suppressing thermal-induced wear, particularly under high-speed conditions.

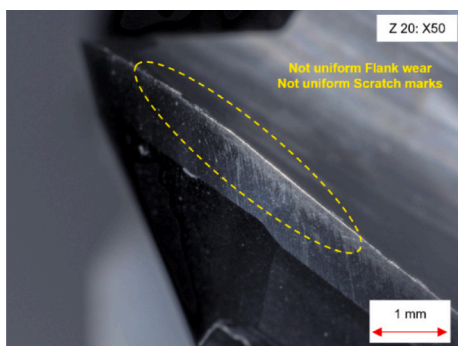
At low cutting speeds (80 m/min), the hybrid condition exhibited relatively higher variability in wear measurements, as represented by wider error bars in Fig. 4. This variation is presumed to result from the insufficient or unstable formation of tribofilms under low interface temperature conditions induced by cryogenic cooling, which may have led to non-uniform lubrication. However, with increasing cutting speed,



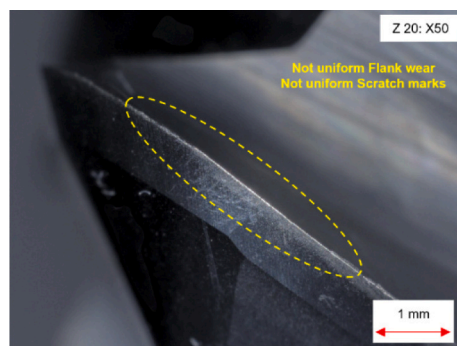
(a) Cutting velocity 80 m/min, Cryogenic, Flank #1 images



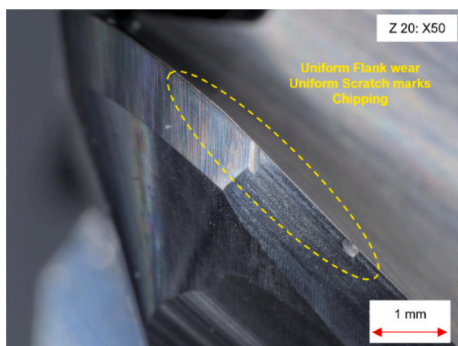
(b) Cutting velocity 80 m/min, Cryogenic, Flank #2 images



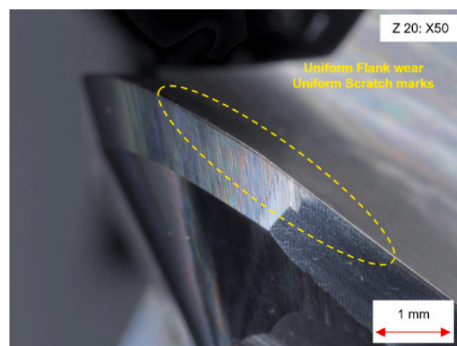
(c) Cutting velocity 120 m/min, Cryogenic, Flank #1 images



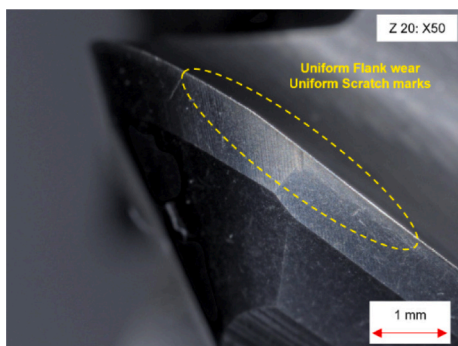
(d) Cutting velocity 120 m/min, Cryogenic, Flank #2 images



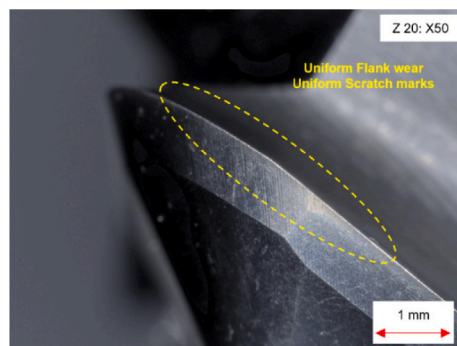
(e) Cutting velocity 80 m/min, nMQL, Flank #1 images



(f) Cutting velocity 80 m/min, nMQL, Flank #2 images

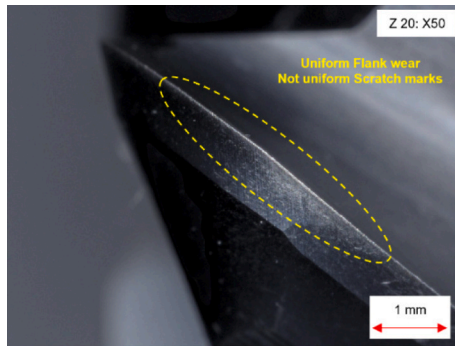


(g) Cutting velocity 120 m/min, nMQL, Flank #1 images

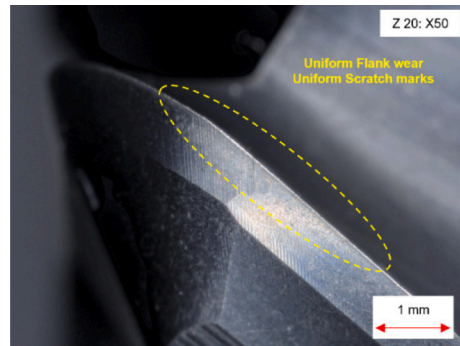


(h) Cutting velocity 120 m/min, nMQL, Flank #2 images

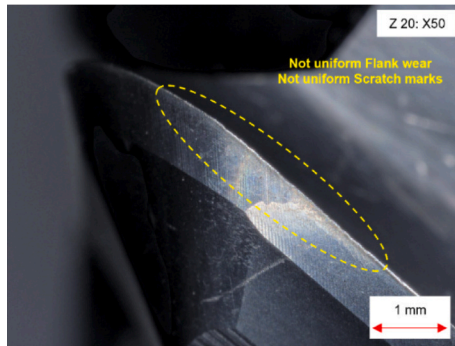
Fig. 5. Tool wear image after machining.



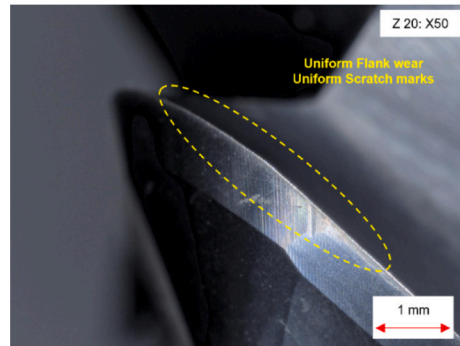
(i) Cutting velocity 80 m/min, Cryogenic + nMQL, Flank #1 images



(j) Cutting velocity 80 m/min, Cryogenic + nMQL, Flank #2 images



(k) Cutting velocity 120 m/min, Cryogenic + nMQL, Flank #1 images



(l) Cutting velocity 120 m/min, Cryogenic + nMQL, Flank #2 images

Fig. 5. (continued).

tribofilm formation became more stable, contributing to consistent lubrication, reduced wear, and lower measurement uncertainty. These findings suggest that the hybrid cooling-lubrication strategy (Case 3) offers the most optimized performance under high-speed machining environments, where both thermal and tribological stresses are more critical.

3.2. Surface integrity

The surface integrity of Ti-6Al-4 V was analyzed under various machining environments, and distinct surface features were identified depending on the applied cooling and lubrication strategies. As shown in Fig. 6, the cryogenic condition (Case 1) resulted in the formation of linear milling marks, spiral tool paths, and micro-cracks. These defects are attributed to abrupt thermal gradients and local thermal stresses generated during machining, which can induce brittle responses in the material's surface layer. Similar surface defects were also observed under the nanofluid MQL condition (Case 2), where insufficient cooling led to thermal accumulation despite effective lubrication. This thermal build-up is considered a contributing factor to the observed micro-cracks and surface irregularities.

In contrast, the hybrid condition (Case 3)—a combination of cryogenic cooling and nanofluid-based MQL—exhibited surface characteristics comparable to the cryogenic condition but with noticeably reduced defect density and improved uniformity. This improvement is attributed to the synergistic interaction of cooling and lubrication, which concurrently mitigates tool-workpiece friction and suppresses excessive heat accumulation at the cutting zone. The resulting stabilization of the thermal-mechanical environment during cutting minimizes the risk of surface softening, deformation, and crack initiation.

Three-dimensional surface morphology analysis further confirmed that the surface generated under the hybrid condition exhibited a more regular height distribution with a narrower range of deviations, as

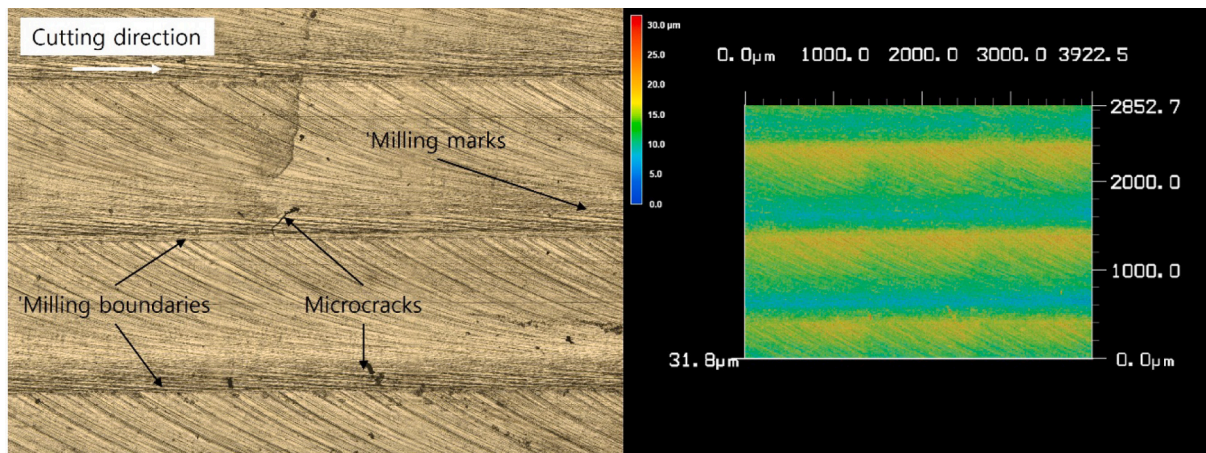
illustrated in Figs. 6(e)–(f). These results suggest a significant reduction in both thermal and mechanical disturbances during machining.

Given that surface quality directly affects residual stress formation, fatigue crack nucleation, and the localization of stress concentrations, the enhanced surface stability achieved under the hybrid condition is expected to contribute substantially to the overall reliability and performance of the machined component.

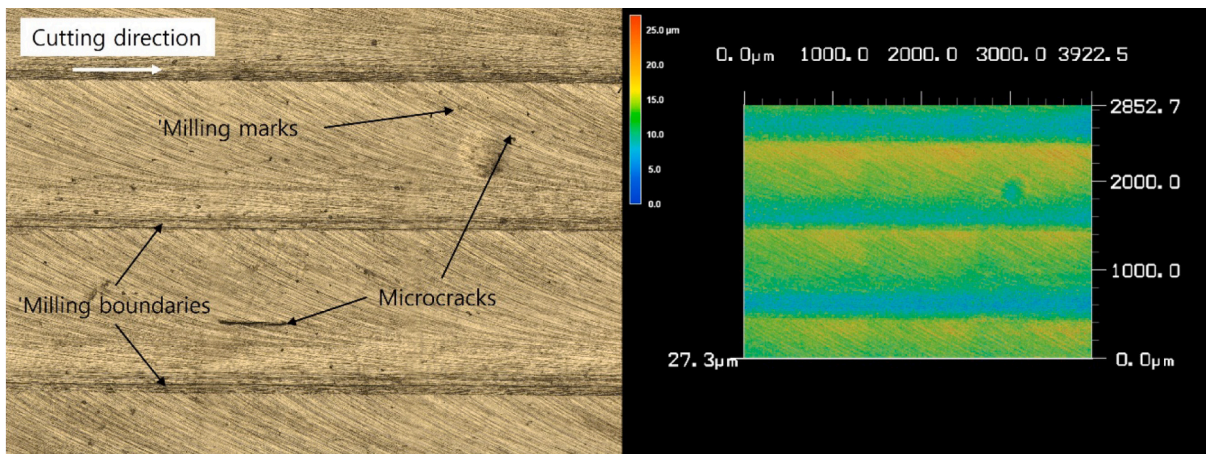
3.3. Residual stress

In the milling process of Ti-6Al-4 V, surface residual stress must be considered due to its impact on crack initiation and fatigue failure [22]. Irfan Ullah and colleagues extensively investigated residual stresses in the titanium milling process. They differentiated tensile and compressive residual stresses based on the presence of a white layer on the machined surface and observed that increased surface hardness leads to higher compressive residual stress [23]. Chen, L. et al. confirmed that with increased spindle speed and tool wear, cutting temperature rises, resulting in higher tensile residual stress. Conversely, increased feed rates and negative rake angles increase cutting forces, leading to higher compressive residual stress [24]. Dahlman, P. et al. performed a turning process on AISI 5210 material and found that increased compressive residual stress correlates with a rise in passive force [25]. Li, G. et al. demonstrated that the generation of tensile and compressive residual stress varies according to cutting temperature [26]. Additionally, Chen et al. investigated the effects of cutting edge radius and cooling/lubrication conditions (Dry, MQL, LN₂, and Hybrid LN₂ + MQL) on residual stress formation in orthogonal machining. Their findings indicated that a larger cutting edge radius led to higher compressive residual stress, while hybrid cooling (LN₂ + MQL) contributed to surface stress stabilization [27].

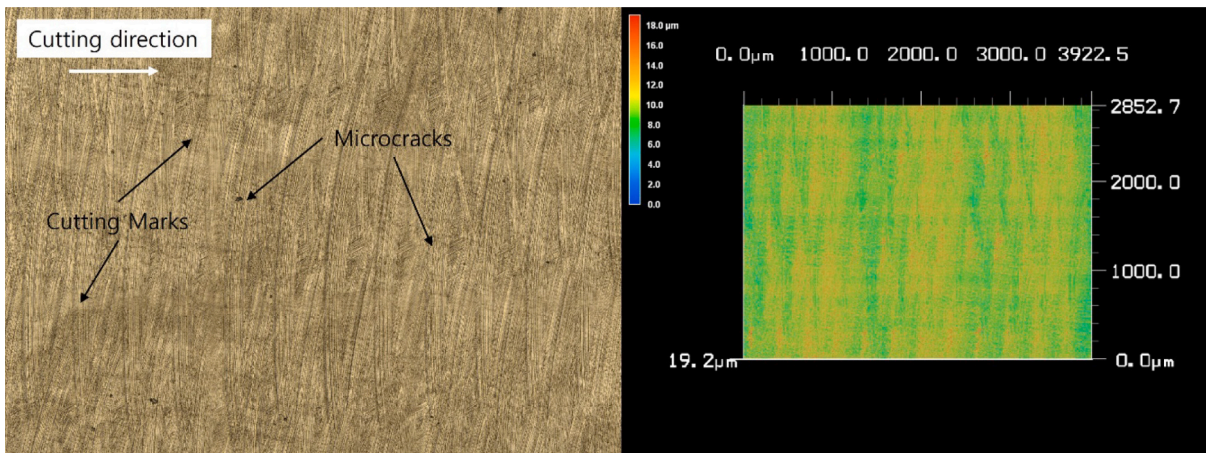
Although this study focused on orthogonal machining, its findings are also relevant to milling processes. In milling, the periodic variation



(a) Cutting velocity 80 m/min, cryogenic conditions surface images



(b) Cutting velocity 120 m/min, Cryogenic conditions surface images



(c) Cutting velocity 80 m/min, Nanofluid conditions surface image

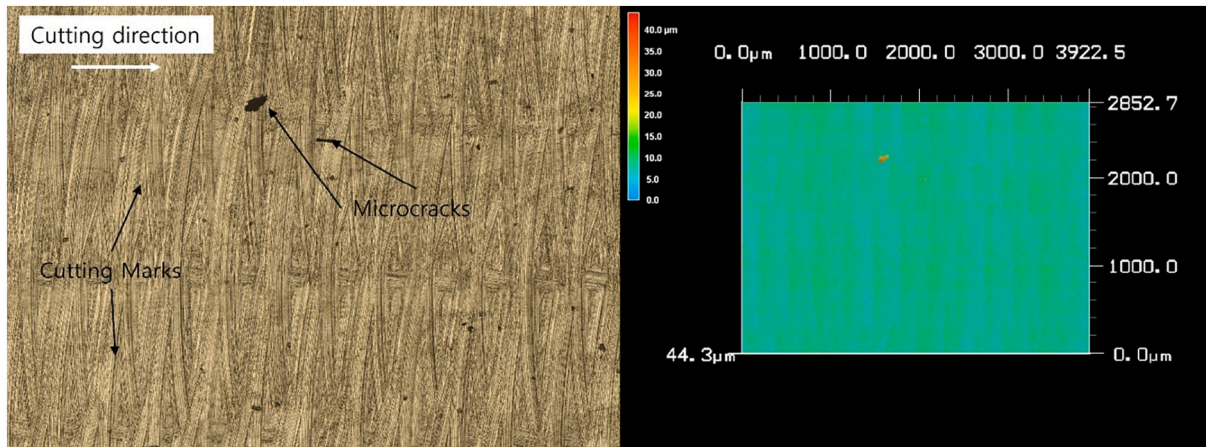
Fig. 6. Surface measurement result after machining.

in cutting forces due to tool rotation can result in a more complex residual stress distribution compared to orthogonal machining. This underscores the need for further research on residual stress formation in milling under hybrid cooling and lubrication conditions.

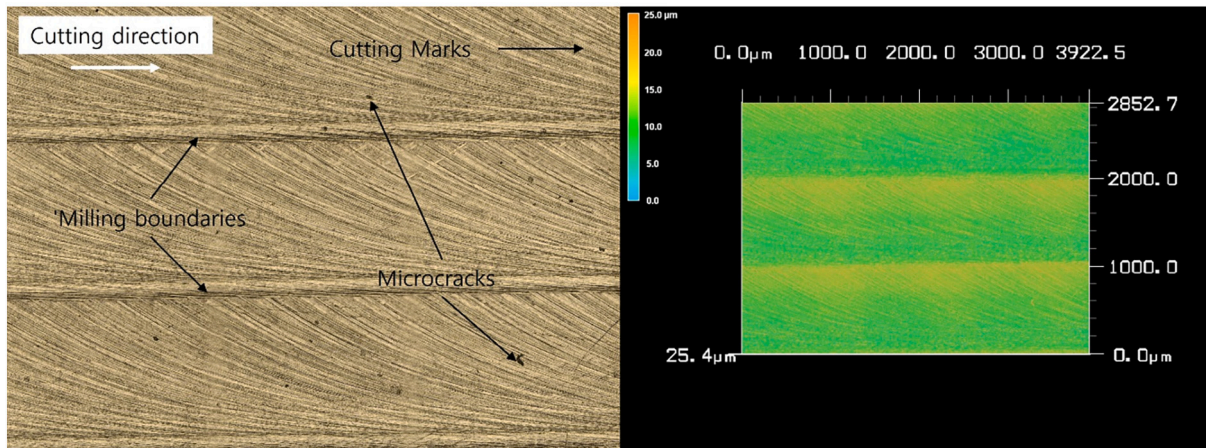
Experiments to measure surface residual stress under varying machining environments were conducted using the hole drilling method, employing strain gauges directly attached to the target material. This method is particularly effective for metal materials and offers a

significant advantage by enabling direct measurement without separate specimens. The procedure adhered to ASTM E837 standards, ensuring standardized and reliable results. The measurement system comprised a milling device (RS-200, VMM), specially designed strain gauges (FRS-2-11-1LJB, TML), and a data acquisition system (P3, VMM), precisely capturing stress data [28]. The experimental setup is illustrated in Fig. 7, providing a detailed overview of the configuration.

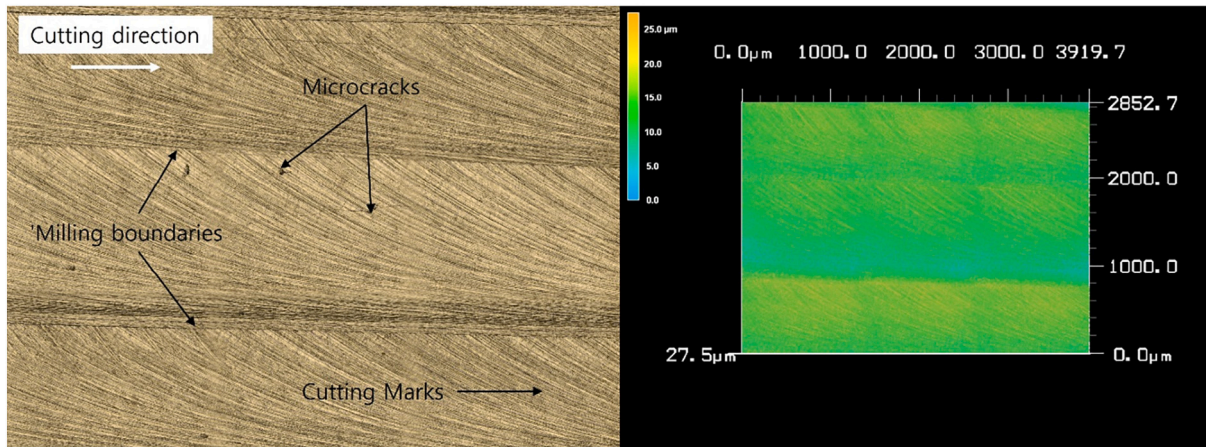
The measurement results indicated that, at a cutting speed of 80 m/



(d) Cutting velocity 120 m/min, Nanofluid condition surface image



(e) Cutting velocity 80 m/min, Hybrid condition surface images



(f) Cutting velocity 120 m/min, Hybrid condition surface images

Fig. 6. (continued).

min, the residual stress was measured as -54 MPa in the cryogenic cooling condition (Case 1), -94 MPa in the nanofluid MQL condition (Case 2), and -22 MPa in the combined nanofluid MQL and cryogenic cooling condition (Case 3). At a cutting speed of 120 m/min, the residual stress was measured as -23 MPa in the cryogenic cooling condition (Case 1), -43 MPa in the nanofluid MQL condition (Case 2), and -11 MPa in the combined nanofluid MQL and cryogenic cooling condition (Case 3). These results confirm that the combination of nanofluid MQL and cryogenic cooling (Case 3) reduced surface residual stress by up to

76.6% compared to other conditions, as shown in Fig. 8.

In conventional machining, thermal expansion occurs due to high temperatures, and uneven contraction during the cooling process can generate tensile residual stress. In contrast, cryogenic + nMQL machining mitigates thermal expansion and contraction by maintaining extremely low temperatures during cutting, promoting the formation of compressive residual stress on the cutting surface. Additionally, cryogenic environments increase the material's hardness, reducing plastic deformation during cutting. By suppressing deformation on the

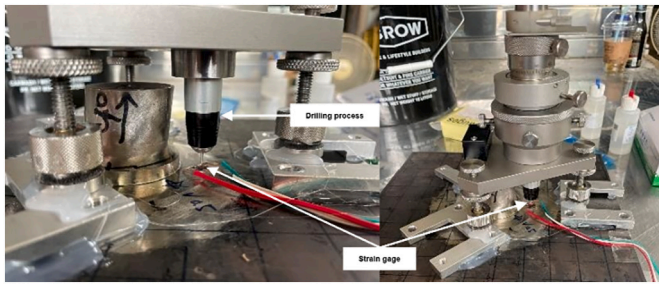


Fig. 7. Evaluating residual stress using hole drilling method.

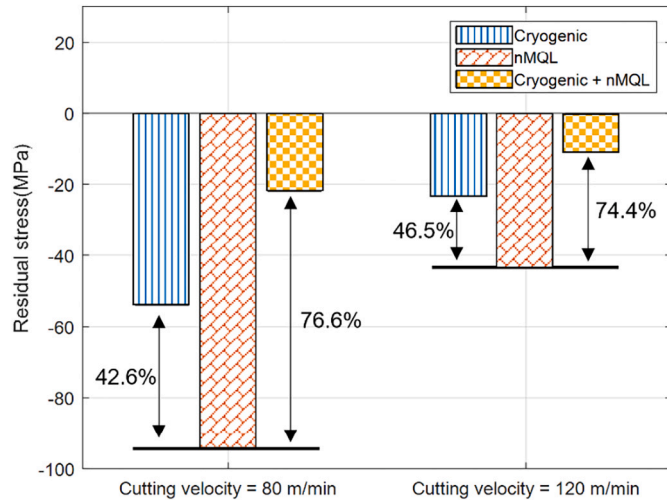


Fig. 8. Residual stress measurement result.

processed surface, elastic restoring forces develop within the material, leading to the formation of compressive residual stress in the surface layer. Furthermore, cryogenic + nMQL machining minimizes friction between the tool and workpiece, ensuring more uniform stress distribution. This reduces the likelihood of tensile residual stress while promoting favorable conditions for compressive residual stress formation.

3.4. Cutting temperature

In this study, the cutting temperature was quantitatively measured using a non-contact infrared pyrometer (IGA 6/23, Impac). The emissivity of the titanium alloy was calibrated to 0.9 based on thermocouple measurements. The maximum temperature was recorded as the tool

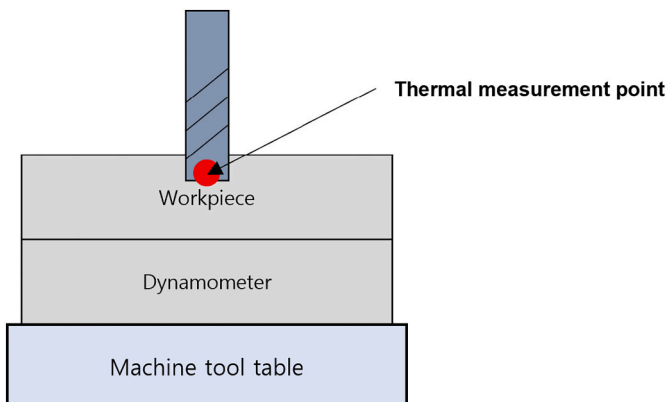


Fig. 9. Machining heat measurement method.

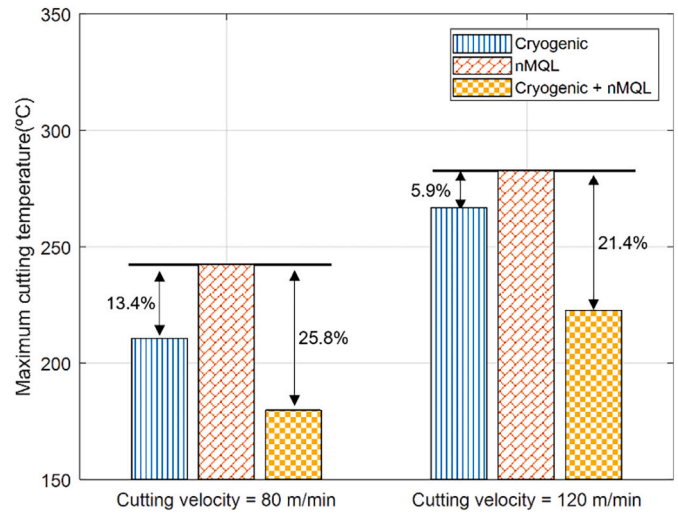


Fig. 10. Machining temperature measurement results.

passed the measurement point, as illustrated in Fig. 9, and the experimental results are presented in Fig. 10.

At a cutting speed of 80 m/min, the cryogenic environment exhibited a 13.4 % reduction in maximum cutting temperature compared to the nMQL condition, while the hybrid condition (cryogenic + nMQL) showed a 25.8 % reduction. Similarly, at a cutting speed of 120 m/min, the cryogenic environment reduced the temperature by 5.9 %, and the hybrid condition achieved a 21.4 % reduction relative to nMQL.

This reduction in cutting temperature can be quantitatively interpreted using Newton's law of cooling, $q = hA\Delta T$, where h is the convective heat transfer coefficient, A is the heat transfer area, and ΔT is the temperature difference across the interface. According to prior studies, the heat transfer coefficient under cryogenic cooling using LN₂ is reported to range from 2.3×10^4 to 4.6×10^4 W/m² • K, K primarily due to the forced convection effect of high-velocity LN₂ jet impingement [1]. In contrast, nMQL is fundamentally based on boundary lubrication and partial evaporation, with significantly lower cooling capability, and the estimated heat transfer coefficient is in the range of 3.5×10^4 to 5.0×10^4 W/m² • K [2].

For the hybrid condition, which combines the two mechanisms, a boundary-based estimation suggests an effective heat transfer coefficient in the range of approximately 3.5×10^4 to 5.0×10^4 W/m² • K. This value reflects the synergistic effect of enhanced heat dissipation and friction reduction, providing a scientific basis for the superior cooling performance observed under the hybrid condition. It is important to note that nMQL primarily reduces temperature through lubrication rather than active cooling, by forming a boundary lubrication layer at the tool-chip interface [2]. Cryogenic cooling, on the other hand, removes heat directly and effectively through physical cooling. The hybrid strategy combines both mechanisms, allowing for efficient heat removal and reduced thermal load during cutting.

Interestingly, the lowest cutting temperature was observed in the hybrid condition, despite its heat transfer coefficient potentially being lower than that of cryogenic cooling. This suggests that cutting temperature is not solely governed by the heat transfer coefficient, but rather by the combined effects of thermal generation, frictional characteristics, and cooling pathways. In the hybrid system, the reduction in heat generation due to effective lubrication, coupled with sufficient convective cooling, results in minimal heat accumulation and the lowest observed cutting temperature. This highlights the importance of considering both heat removal capacity and thermal generation control in optimizing the thermal performance of machining processes.

4. Conclusion

This study quantitatively evaluated the effectiveness of a hybrid cooling strategy that combines cryogenic cooling and nanofluid-based minimum quantity lubrication (nMQL) in improving the machinability of Ti-6Al-4 V during milling. The experimental results confirmed that the hybrid approach significantly reduces cutting temperature, which in turn enhances tool life, surface quality, and residual stress distribution. The key findings are summarized as follows:

1. **Tool Wear:** The hybrid condition yielded the most significant reduction in tool wear, particularly under high-speed machining. However, at lower cutting speeds (80 m/min), greater measurement uncertainty was observed, likely due to unstable tribofilm formation caused by insufficient interface temperatures under excessive cooling.
2. **Surface Integrity:** The hybrid environment exhibited the most stable surface formation, with reduced plastic deformation and enhanced uniformity, owing to the balanced interaction of cooling and lubrication at the cutting interface.
3. **Residual Stress:** The hybrid condition achieved up to a 76.6 % reduction in surface residual stress. This result is attributed to the suppression of thermal expansion and mechanical deformation, which promotes compressive residual stress through enhanced heat dissipation and friction reduction.
4. **Cutting Temperature:** The cutting temperature was reduced by up to 25.8 % under the hybrid condition, a result not solely explained by the heat transfer coefficient but also by the combined effects of reduced heat generation and efficient cooling.

Collectively, these results demonstrate that the hybrid strategy overcomes the limitations of single-mode cooling or lubrication by leveraging the strengths of both mechanisms. While measurement variability at lower cutting speeds suggests a transitional regime due to insufficient tribofilm formation, the hybrid method proves particularly effective under high-speed conditions. The synergistic effects of stable tribofilm formation from hBN nanoparticles and rapid heat removal via cryogenic jets contribute to improved tool wear resistance, surface quality, and residual stress stabilization.

These findings suggest that the hybrid cooling approach is especially suitable for high-speed machining applications, such as those in the aerospace industry, where the reliability and performance of machined components are critical. Furthermore, controlling thermal accumulation and residual stress is essential in machining high-performance materials like Ti-6Al-4 V, and the proposed hybrid method offers practical advantages for enhancing process efficiency and component integrity.

CRedit authorship contribution statement

Song Hyeon Ju: Writing – original draft. **Tae-Gon Kim:** Methodology. **Seok-Woo Lee:** Conceptualization. **Hae-Jin Choi:** Conceptualization. **Jungsoo Nam:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jungsoo Nam reports financial support was provided by Korea Institute of Industrial Technology (KITECH) and Korea Government(MOTIE). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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