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IMPACT OF CRYOGENIC MILLING ON TOOL LIFE AND SURFACE INTEGRITY

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Abstract
The machining of titanium alloys is associated with high temperature levels which result in rapid tool wear and poor surface integrity. To overcome this issue, cooling the cutting zone has emerged as a solution. This study evaluates the impact of different cooling/lubrication techniques on tool life, tool wear, and surface integrity during the milling of Ti-6Al-4V. The results show that using LCO2 and MQL extends tool life by factors of 2.4 and 2.9, respectively, compared to conventional flood cooling. These techniques also improve the surface quality of the machined parts.
Keywords:
Cryogenic Machining, Titanium, Tool Life, Tool wear, Surface integrity

1 INTRODUCTION

Titanium alloys are characterised by exceptional mechanical properties, including high strength, corrosion resistance and a high strength-to-weight ratio even at high temperatures [Arrazola 2009], [Wang 2018]. These alloys are widely used in various sectors such as aerospace, biomedical and automotive [Arab 2019]. However, machining titanium alloys remains challenging due to short tool life, poor surface integrity and low productivity. Their low thermal conductivity limits heat dissipation through the chips or the workpiece. Consequently, the heat generated during machining tends to accumulate at the cutting zone, resulting in elevated temperatures. In addition, their strong chemical reactivity with most cutting tool materials lead to rapid tool wear [Ezugwu 2005], [Hoyne 2015].

Flood cooling is commonly used to lubricate and cool the cutting zone. However, this technique has limited cooling effectiveness, poses environmental risks and can be harmful to operators' health [Krolczyk 2019]. As a result, alternative cooling strategies such as cryogenic assistance using liquid carbon dioxide (LCO2) and minimum quantity lubrication (MQL) have emerged as solutions.

[Sadik 2017] demonstrated that cryogenic cooling with LCO2 significantly extended tool life compared to emulsion when milling Ti-6Al-4V with a carbide insert at cutting speeds of 80 m/min and 100 m/min. Their results showed that LCO2 increased 6 times tool life compared to emulsion. The authors also analysed the wear mechanisms for each cooling condition. With emulsion, tool degradation was primarily due to chipping and material loss, which accelerated wear. In contrast, cryogenic cooling with LCO2 led only to the propagation of cracks perpendicular to the cutting edge.

[Sadik 2016] showed that using LCO2 increased tool life by 200% compared to conventional flood cooling when milling Ti-6Al-4V at a cutting speed of 80 m/min. They noted that increasing the LCO2 flow rate further improved cooling efficiency and extended tool life.

[Jamil 2021] conducted a comparative study assessing the impact of different cooling/lubrication techniques on surface roughness and tool wear during the milling of Ti-6Al-4V. Their results showed that cryogenic cooling with LCO2 reduced surface roughness by 53% compared to dry milling.

[Shokrani 2019] investigated the effect of cooling strategy on surface quality, tool wear mechanisms and tool life. They compared the use of LN2+MQL, LN2 and MQL to conventional flood emulsion. The authors reported that MQL produced the best surface quality among the tested cooling methods.

[Jamil 2020] and [Kummamkandath 2020] showed that the cooling with LCO2 when milling the Ti-6Al-4V generated superior residual stresses compared to emulsion and MQL.

This study investigates the impact of different cooling techniques on tool life, tool wear mechanisms and surface integrity. Milling trials were conducted under three conditions: conventional flood cooling, minimum quantity lubrication (MQL), and liquid carbon dioxide (LCO2). The main objective is to compare the performance of MQL and LCO2 with the conventional emulsion method.

2 EXPERIMENTAL WORK

To study the effect of cooling/lubrication methods on tool life, wear mechanisms and surface integrity during the machining of Ti-6Al-4V alloy, surface milling trials were conducted. These experiments were divided into two main

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series. The first series aimed to assess the impact of the cooling/lubrication method on tool life. A spiral toolpath was used with a gradual entry into the material, as illustrated in Fig.1. This machining strategy was chosen to minimize the impact of shocks during material entry, which could influence wear progression over time.

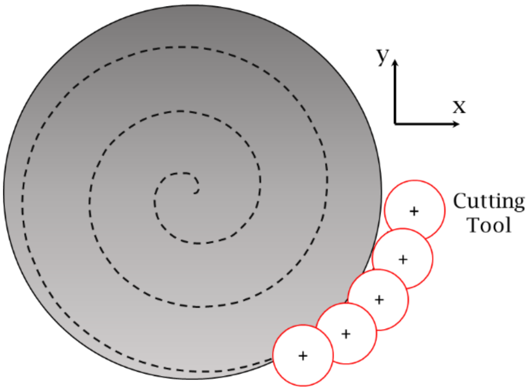

Fig. 1: Spiral toolpath

The tests were conducted until the maximum flank wear (VB_{max}) reached 0,3mm according to the ISO 8688-1 standard. Maximum flank wear was measured regularly using a binocular microscope. For each test with different cooling techniques, a new insert was used to eliminate any influence of prior wear.

The second series of experiments aimed to identify the effect of lubrication techniques on surface integrity. The machining strategy was modified from a spiral toolpath to straight line passe as shown in Fig.2. A new insert was used for each test to ensure that the results reflected only the impact of the lubrication method.

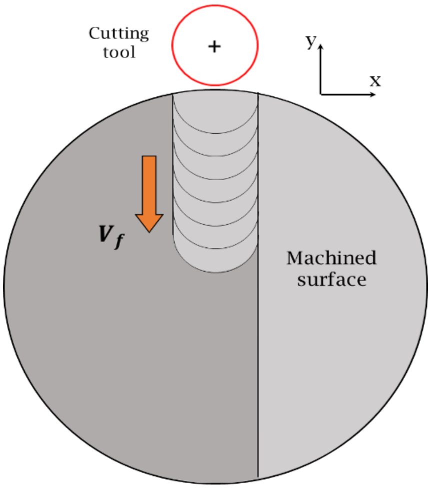

Fig. 2: Straight line passes

The cutting parameters were kept constant for all the face milling experiments as detailed in Tab 1. A single tooth milling was used in all the trials.

Tab 1: Cutting parameters

Parameter	Value
Cutting speed: Vc ($m.min^{-1}$)	150
Feed per teeth: fz ($mm.rev^{-1}$)	0.15
Number of teeth: Z	1
Radial depth of cut: ae (mm)	12.5
Axial depth of cut: ap (mm)	1

2.1 Machined material

The workpiece material used in this study was a Ti-6Al-4V bar with a diameter of 90 mm and a length of 150mm, supplied by TIMET. The material is a biphasic (α + β) alloy with a duplex microstructure, consisting of alpha (α) grains with a hexagonal close-packed (hcp) structure, surrounded by beta (β) grains with a body-centered cubic (bcc) structure as shown in Fig 3. The mechanical properties of this alloy are outlined in Tab 2.

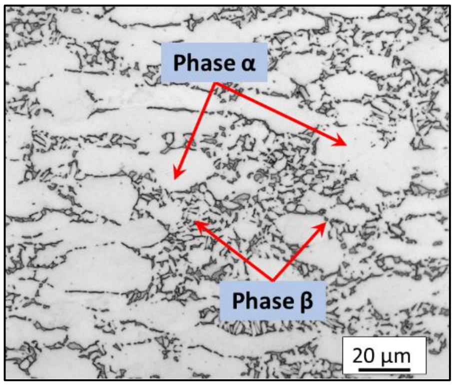

Fig. 3: Microstructure of Ti-6Al-4V

Tab 2: Mechanical properties of Ti-6Al-4V (TIMET)

Rm (MPa)	Rp 0.2 %(MPa)	A %	Hardness (HRC)
937	873	21.5	33

2.2 Machines and cutting tool

In this study, the cutting trials were conducted on a 3-axis DIAM 1270 vertical center. The cutting tool has a diameter of 25 mm and is referenced as ARP5PR2503SA25M, manufactured by MITSUBISHI MATERIALS. It has internal cooling channels with outlets designed to accommodate M4 coolant nozzles, allowing the delivery of different lubrication fluids to the cutting zone (Fig. 4). The inserts used for machining the Ti-6Al-4V alloy are identified as RPHT1040M0E4-M. These inserts are made of a tungsten carbide substrate protected by a multilayer coating (Al, Ti, N).

2.3 Cooling/lubrication strategies

In order to investigate the impact of cryogenic machining on the tool life and the surface integrity of the machined workpiece, three machining environments were tested:

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- Flood emulsion cooling was applied using an external nozzle with a diameter of 5 mm. The sprayed fluid is of a mixture of 5% cutting oil (ECOCOOL CS+) and 95% water, delivered at a flow rate of 12 $L.min^{-1}$ and a pressure of 5 bar.

- Minimum Quantity Lubrication (MQL): This technique uses a small volume of cutting oil (Aerosol Master Lubricant C-TI-1) at a flow rate of 25 $mL.h^{-1}$ and a pressure of 2.4 bar. The oil is mixed with compressed air and delivered directly into the cutting zone through the tool's internal channels at a pressure of 2.6 bar. The MQL is applied using a micro-lubrication system developed by KNOLL.

- Cryogenic machining with Liquid Carbon Dioxide (LCO2). The jet delivered through the tool at a flow rate of 9.5 $Kg.h^{-1}$ and a pressure of 60 bar, as illustrated in Fig. 4.

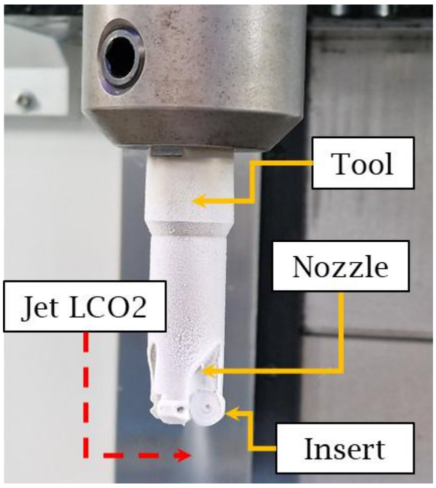

Fig. 4: Cooling technique with LCO2

3 RESULTS AND DISCUSSION

Flood cooling with water-based coolant is the most common method used in the industry for cooling and lubrication during machining processes. The performance of LCO2 and MQL will be compared to this method.

3.1 Tool life

The results of tool life trials are presented in Fig. 5. In conventional lubrication, the tool wear criterion was reached after 14.25 minutes. Indeed, conventional flood cooling is the least effective cooling method among the three investigated conditions. This inefficiency can be attributed to the non-optimized geometric position of the nozzle, which prevents the cutting fluid from effectively reaching the chip/tool/workpiece interfaces.

As for the MQL, the flank wear (VB_{max}) reached 0.3 mm after approximately 34.6 minutes. It is clear that this strategy improved significantly the tool life, achieving a 2.4-fold improvement over flood cooling. In fact, this performance can be attributed to the lubricating effect of the sprayed oil on the flank and rake faces, forming a protective film [Krolczyk 2019]. This film reduces friction at the contact interfaces. Furthermore, the oil mist sprayed under pressure can penetrate deeply into the workpiece/tool/chip interfaces, reducing friction and temperature in the cutting zone. This effect led to an increase in tool life [Jamil 2021].

In the case of cryogenic machining with liquid carbon dioxide (LCO2), a significant improvement in tool life was achieved. Tool wear exceeded the wear limit after 41.5 minutes. As a result, cryogenic cooling with LCO2 extended tool life by a factor of 2.9 compared to conventional flood cooling. This performance may have been attributed to the cooling effect of LCO2, which effectively removed the heat generated in the cutting zone.

The flank wear evolution showed a steady and slow progression, except during the last minutes of machining. The tool wear curve can be divided into three different stages. Initially, VBmax started with a peak of 0.05 mm. This was followed by a steady plateau and slow growth until 32.5 minutes of machining. Finally, in the third stage, wear increased rapidly, reaching 0.34 mm at 42.5 minutes.

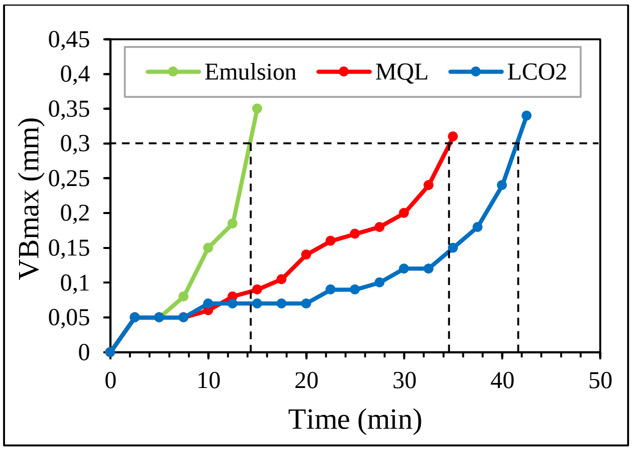

Fig. 5: Tool life

3.2 Tool wear

Fig. 6 presents the SEM images and EDS analysis of the rake face after 15 minutes of machining under emulsion. The microscopic images reveal severe chipping on the rake face, along with a built-up edge (BUE) adhered to the cutting edge. Furthermore, high-magnification analysis detected cracks on the cutting tool, likely resulting from uneven cooling in the cutting zone [Dudzinski 2004]. The

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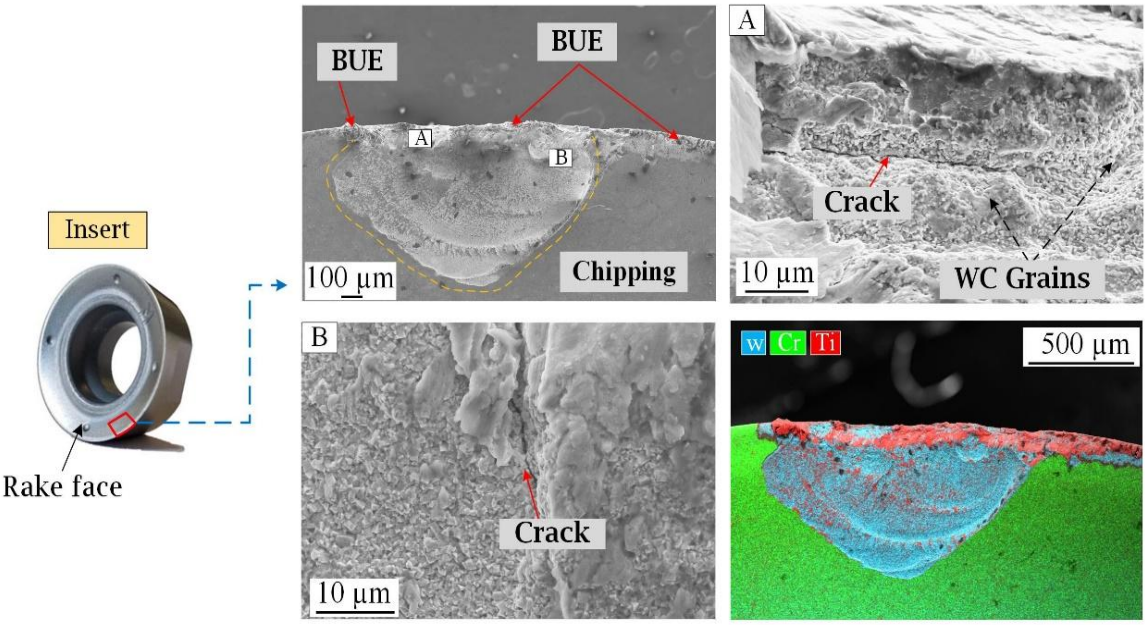

Fig. 6: SEM images / EDS: Rake Face after 15 minutes of machining with emulsion

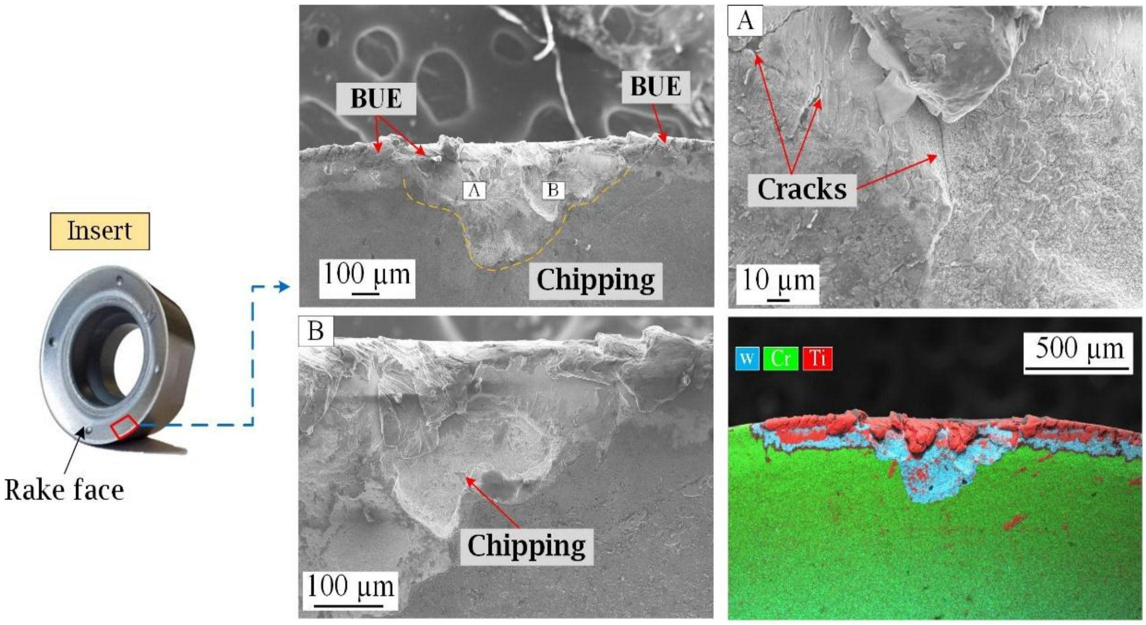

Fig. 7: SEM images / EDS: Rake Face after 35 minutes of machining with MQL

chipping observed on the tool surface may be attributed to the synergistic interaction between BUE formation and crack propagation. This degradation of the cutting edge may explain the short tool life and accelerated wear. Material loss on the rake face likely compromised the tool's structural integrity, further intensifying wear.

Fig. 7 illustrates the rake face of the worn tool after 35 minutes of machining under minimum quantity lubrication (MQL). On the rake face, clear chipping and adhered material are evident. Chipping appears as small, irregular fractures along the cutting edge and contact areas. This phenomenon appears to result from the cyclic mechanical and thermal loads during milling, which lead to brittle fracture of the tool material. In addition, a built-up edge (BUE) has been formed on the cutting edge due to the deposition of workpiece material. The BUE primarily consists of titanium, which adheres to the tool surface under the combined effects of high contact pressure and elevated temperatures. Its instability can cause sudden detachment, resulting in a material loss from the tool. The cyclic formation and removal of the BUE can accelerate tool wear, leading to inconsistent machining performance and rapid tool failure. Microscopic examination reveals crack propagation beneath the adhered titanium layers. As the cracks progress, they compromise the integrity of the

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cutting edge, promoting the chances of further material loss and catastrophic failure.

Fig.8 presents the rake face after machining under liquid carbon dioxide (LCO2) for 42.5 minutes. The images clearly show the formation of a built-up edge (BUE) and micro-chips of titanium adhered to the cutting edge. This phenomenon is confirmed by the chemical composition analysis (EDS).

after milling tests. Residual stresses and surface topography were analysed in three distinct areas along the machined surface, as illustrated in Fig. 9.

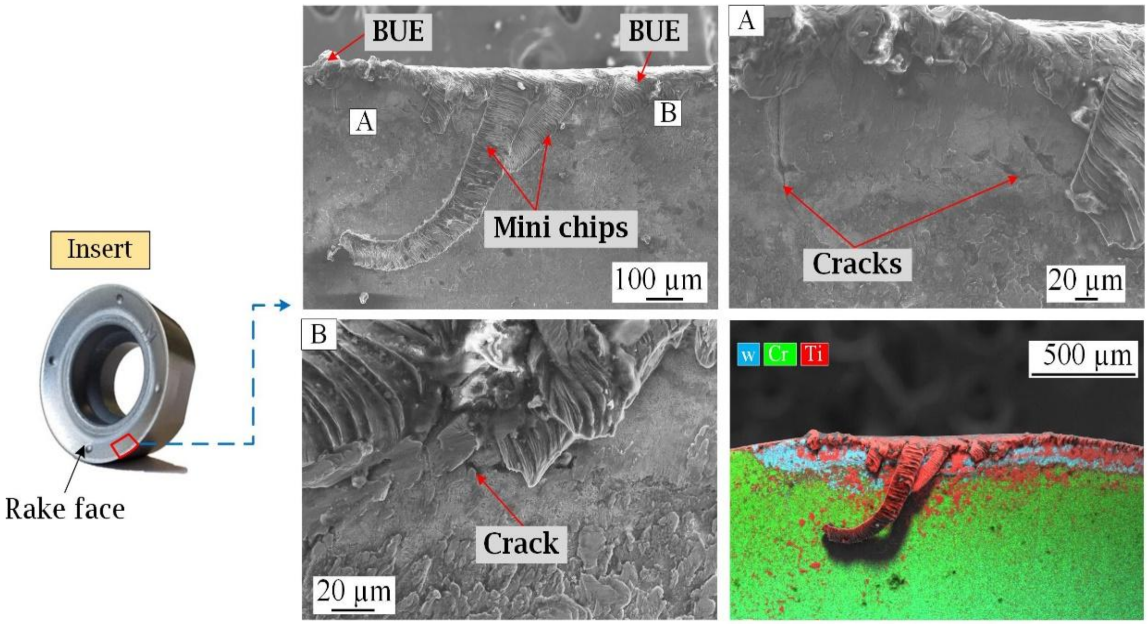

Fig. 8: SEM images / EDS: Rake face after 42.5 minutes of machining with LCO2

Microscopic examination at high magnification reveals cracks propagating perpendicular to the cutting edge on the worn tool, as shown in Fig. 7A–B. A similar phenomenon was reported by [Sadik 2017] during the surfacing of Ti-6Al-4V with LCO2. According to the authors, crack propagation on tool surfaces is caused by cyclic mechanical loads and thermal shocks generated by the intermittent entry and exit of the workpiece material during machining.

Notably, no chipping was detected during cryogenic machining with LCO2. This absence of chipping suggests that the cryogenic environment effectively limits the thermal loads responsible for brittle fracture of the tool material and degradation of the cutting edge. This result can explain the improved performance of LCO2 cooling, which extended tool life by 191% compared to emulsion. The cooling effect of LCO2 reduced the temperature in the cutting zone, thereby limiting the thermal loads that promote adhesion wear and BUE formation. Overall, the use of LCO2 appears to reduce degradation and wear mechanisms such as adhesion and chipping, which would otherwise compromise the integrity of the cutting edge.

3.3 Surface integrity

The analysis of surface integrity focuses on the impact of the cooling method on residual stresses and surface quality

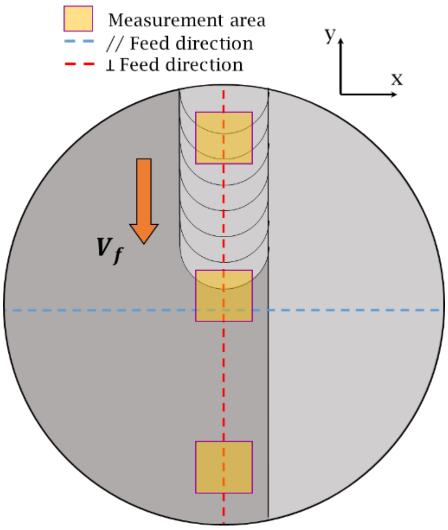

Fig. 9 : Analysis points

- **Residual stresses**

Fig. 10 presents the residual stresses analysed on the machined surfaces under different cooling conditions, using X-ray diffraction. The stresses were evaluated in two directions: parallel to the cutting tool movement and

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perpendicular to the direction of tool advancement as shown in Fig.9.

The results clearly show that the residual stresses remain compressive regardless of the machining environment. In this case, the choice of cooling method (emulsion, MQL or LCO2) does not influence the residual stresses generated after machining. It was expected that LCO2 cooling, known for its ability to significantly reduce temperatures in the cutting zone, would affect the residual stresses as reported in the literature. However, the findings suggest that despite its cooling capability, LCO2 does not lead to any notable change in the residual stress.

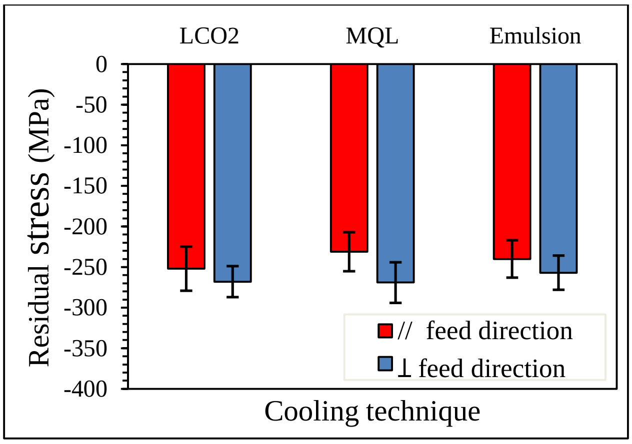

Fig. 10: Residual stresses

- **Surface topography**

Fig. 11 illustrates the surface topography of the machined surfaces, along with the mean surface roughness values for each cooling technique. Surface characteristics were analysed using an optical profilometer (GP-Contour). The results show that both Minimum Quantity Lubrication (MQL) and Liquid Carbon Dioxide (LCO2) significantly improve surface quality, reducing surface roughness (Sa) by 42% compared to emulsion. Specifically, Sa decreases from 0.40 µm under emulsion cooling to 0.23 µm with either MQL or LCO2, highlighting the effectiveness of these methods in enhancing surface finish.

4 CONCLUSION

This study identifies the effects of MQL and LCO2 cooling on the machinability of Ti-6Al-4V during the surfacing operation. The milling experiments conducted at Vc=150 $m.min^{-1}$, ap=1 mm, ae=12.5mm and $f_z = 0.15 mm/tooth/rev$ in different cooling/lubrication conditions lead to:

- Lubricating the cutting zone with MQL extends tool life by 142% compared to flood emulsion.
- The use of LCO2 improves tool life by 191% compared to conventional cooling.
- Cooling/lubrication with LCO2 and MQL enhances surface quality and reduces mean surface roughness by 43%.
- The cooling method has no significant impact on residual stress.

Overall, the use of MQL and LCO2 improves the machinability of titanium alloys compared to emulsion by extending tool life and reducing surface roughness.

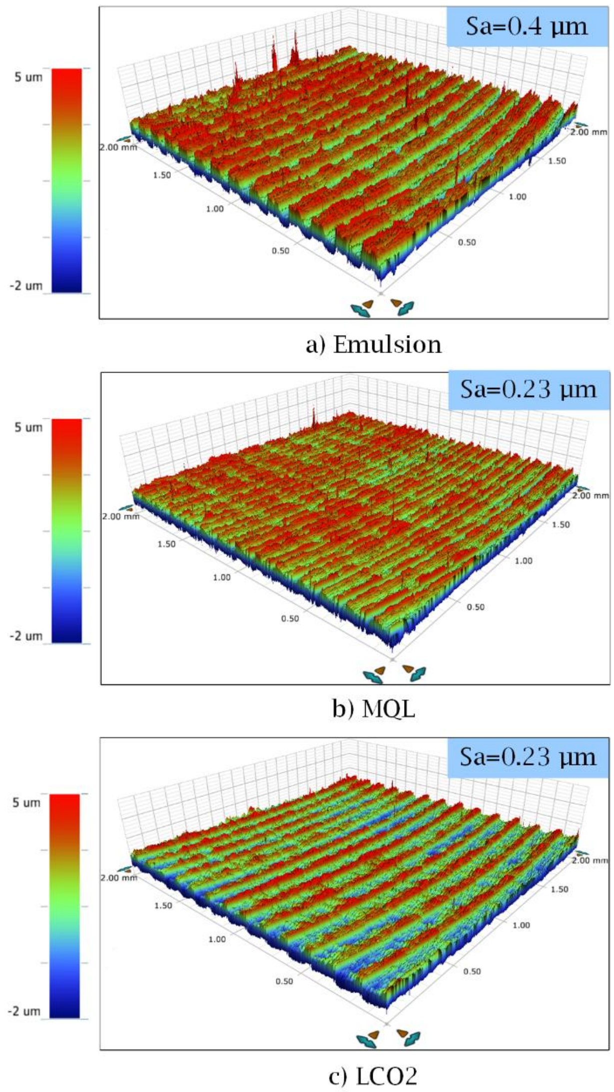

Fig. 11: Surface topography

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