

## INVESTIGATION ON THE PRODUCTIVITY OF MILLING Ti6Al4V WITH CRYOGENIC MINIMUM QUANTITY LUBRICATION

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### Abstract

Because of its unique material properties, Ti6Al4V is used for components in the aerospace industry which are subject to high mechanical and thermal loads. Due to that, this material is considered as difficult to cut from a machining point of view. In order to improve productivity in machining Ti6Al4V the use of an effective cooling and lubrication strategy is necessary. This challenge can be managed with the innovative hybrid technology (CMQL) combining liquid carbon dioxide (CO<sub>2</sub>) and minimum quantity lubrication (MQL) being under investigation in this article. At first, investigations on the liquid CO<sub>2</sub> release behaviour and the application of oil by the CMQL were conducted. Secondly, CNC milling experiments were carried out using carbide end mills. The CMQL technique was compared to MQL and flood cooling in respect to tool wear, cutting moment and surface integrity. For the milling operations the cooling parameters of the CMQL as well as the cutting parameters were modified, in order to reduce tool wear or increase productivity. The analysis revealed that the development of an appropriate CO<sub>2</sub> free jet and a continuous application of oil by the CMQL is achievable without changing the state of aggregation of CO<sub>2</sub> from liquid to supercritical. The analysis of the milling experiments indicated that CMQL is more advantageous compared to flood cooling and MQL for higher cutting parameters.

### Keywords:

Carbon dioxide; Cryogenic; CMQL; Ti6Al4V; Milling; Spray test

## 1 INTRODUCTION

The outstanding properties of the titanium alloy Ti6Al4V, such as the high strength-to-weight ratio, the corrosion resistance and the ability to retain these properties even at elevated temperatures, involve disadvantages for the machinability. The high strength of the material leads, combined with the low thermal conductivity, to increased mechanical and thermal loads on the cutting tool. Hence, the tool wear development is augmented. To avoid the heat induced tool wear an efficient cooling strategy is necessary. As the cooling potential of conventional methods like flood cooling or even dry machining are not sufficient for difficult-to-cut materials, new approaches are to be considered. The cryogenic machining with liquid nitrogen (LN<sub>2</sub>) or carbon dioxide (CO<sub>2</sub>) has been examined in recent studies.

## 2 STATE OF THE ART

The penetration of the cutting zone with LN<sub>2</sub> results on the one hand in a reduction of the process temperature and on the other hand in a decrease of friction [Aramcharoen 2014]. The absorption of heat is resulting in an evaporation of LN<sub>2</sub>, whereby a cushion between the tool and chip interface is created which depresses the friction coefficient [Hong 2001]. Such behavior is not observed when using CO<sub>2</sub> as cryogenic. Therefore, a combination of CO<sub>2</sub> with a minimum quantity lubrication is necessary to ensure, besides the cooling, the lubrication of the cutting

process. Different strategies are conceivable for the guidance of the two medias. Cordes used a modified Walter copy milling cutter. The CO<sub>2</sub> and the lubricoolant aerosol are supplied internally via separated channels to the cutting zone. In comparison with dry milling a wear reduction or an increase of productivity was verified [Cordes 2014].

Pereira also utilized a separated supply of CO<sub>2</sub> and MQL. In contrast to pure MQL a prolongation of cutting time was documented. In addition, the internal supply of CO<sub>2</sub> did not cool the workpiece, whereby an increase of workpiece hardness was suppressed [Pereira 2014, Pereira 2015].

Like Cordes, Tapoglou studied the separated, internal CO<sub>2</sub> plus MQL supply by milling experiments with an indexable, five insert end mill. Tool life was extended for a cutting speed of  $v_c = 70$  m/min and  $v_c = 80$  m/min compared to pure MQL. However, at a cutting speed of  $v_c = 100$  m/min the MQL was more advantageous than CO<sub>2</sub> plus MQL [Tapoglou 2017].

Contrary to the above-mentioned authors there exists also the strategy to mix the lubricant and the CO<sub>2</sub> in the supply system. As a result, both media are delivered through one channel to the cutting zone. To prevent a blockage of this channel an adequate solubility or miscibility of the two fluids is necessary. Supekar, Stephenson, Rahim and Mulyana raise the pressure and temperature of the CO<sub>2</sub> above the critical point (critical temperature  $\vartheta_{cr} = 30,98$  °C, critical pressure  $p_{cr} = 73,8$  bar) to pass the CO<sub>2</sub> from liquid to

supercritical state of aggregation [Mulyana 2017, Rahim 2016, Stephenson 2014, Supekar 2013].

According to Stephenson supercritical CO<sub>2</sub> (scCO<sub>2</sub>) is able to transport metalworking lubricants in solution [Stephenson 2014]. In his studies combustor housings consisting of Inconel 750 were machined on a lathe. Thereby, a reduction of wear or an increase of productivity has been shown by the use of scCO<sub>2</sub> combined with soybean oil in comparison to flood cooling [Stephenson 2014].

In micro milling experiments Supekar examined the influence of scCO<sub>2</sub> plus MQL and compared it to dry machining. Burr formation as well as surface quality were improved with scCO<sub>2</sub> cooling [Supekar 2013].

Rahim noticed a decrease of cutting forces and cutting temperature by means of cooling the turning process with a mixture of scCO<sub>2</sub> and synthetic ester instead of pure MQL [Rahim 2016]. Mulyana performed milling experiments with a TiN coated indexable carbide end mill. As reference dry machining and experiments with MQL were conducted. An advantageous impact of scCO<sub>2</sub> plus MQL in respect to cutting forces, cutting temperature and tool life was shown. Furthermore, the positive effect of the CMQL rises as the scCO<sub>2</sub> flow rate and the MQL flow rate increase [Mulyana 2017].

These studies substantiate the beneficial use of scCO<sub>2</sub> plus MQL in machining. But the requirement of passing the CO<sub>2</sub> in the supercritical state of aggregation to transport the added lubricant to the cutting zone is no subject of the examinations. For low oil concentrations, ester-based lubricants have depending on temperature and pressure the potential to be soluble in liquid CO<sub>2</sub>. In general, the solubility increases with an increase of pressure and a decrease of temperature. In scCO<sub>2</sub> neither ester-based oils nor oils based on hydrocarbons are soluble [Fahl 2002]. Hence, the authors ought to focus on the use of liquid CO<sub>2</sub> to reduce the energy consumption of the system and the investment costs.

There exist only few studies which examine the CMQL supply in one channel with liquid CO<sub>2</sub>. In drilling, milling and turning experiments with internal cooling supply and different lubricants such as synthetic ester or organic ester showed a better performance in comparison to a fatty alcohol due to their better solubility properties [Gross 2019, Hanenkamp 2018, Kirsch 2018].

### 3 EXPERIMENTAL SETUP

As shown in Fig. 1 the preliminary and the milling experiments were conducted on a Doosan DNM 500 vertical CNC machining center. The preliminary tests were completed to gain an understanding of the behavior of CO<sub>2</sub> and the CMQL system. The subsequent machining tests were used to verify the results of the preliminary tests.

#### 3.1 Temperature measurement of CO<sub>2</sub> jet

To measure the temperature in the CO<sub>2</sub> free jet the experimental setup shown in Fig. 1 (bottom right) has been used. Smooth jet nozzles (SJN) with different orifice diameters *d* and a plastic tube (PT) were attached consecutively to the end of the CO<sub>2</sub> supply system and clamped horizontally. A thermocouple type K has been fixed vertically. The end of the probe, which is responsible for temperature measurement, has been positioned in the center axis of the CO<sub>2</sub> jet. A metal tube is necessary to stabilize the probe. By an incremental increase of the distance between the nozzle orifice and the probe, distance dependent temperature profiles were recorded. The CO<sub>2</sub>

has been released without lubricant. Test N° 4 has been conducted with a high pressure (HP) supply of CO<sub>2</sub>. Thereby the CO<sub>2</sub> supply pressure has been augmented from *p*<sub>CO<sub>2</sub></sub> = 56 bar to *p*<sub>CO<sub>2</sub></sub> = 71 bar. The experimental design is shown in Tab. 1. Each of the four trials have been performed three times for statistical significance.

Tab. 1: Experimental design for temperature measurement of CO<sub>2</sub> jet.

#	Nozzle type	<i>p</i> <sub>CO<sub>2</sub></sub> (bar)	<i>m</i> <sub>CO<sub>2</sub></sub> (kg/h)	distance Δ <i>x</i> (mm)
1	PT <i>d</i> = 0,5 mm	56	5,8	2; 5; 10; 15; 20;
2	SJN <i>d</i> = 0,2 mm	56	4,7	30; 40; 50; 60; 80;
3	SJN <i>d</i> = 0,3 mm	56	8,6	100; 120; 160;
4	SJN <i>d</i> = 0,2 mm	71	8,0	200

PT = plastic tube | SJN = smooth jet nozzle

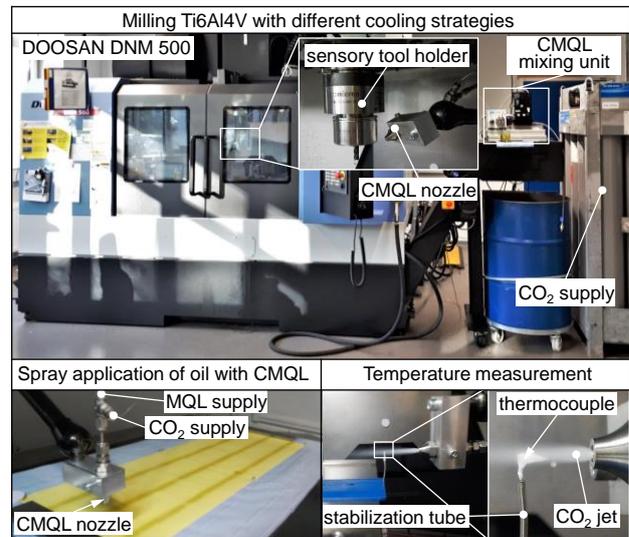


Fig. 1: Experimental Setup for preliminary and milling experiments.

#### 3.2 Application of oil with CMQL

To guarantee the lubrication supply while machining, the application of oil with the CMQL system was verified. As shown in Fig. 1 (bottom left), the CMQL nozzle has been fixed in the milling center in a downward directed position. The lubricant supply has been connected to the CO<sub>2</sub> pipeline. Two sheets blotting paper were attached in a row onto the machine table. The vertical distance between the nozzle orifice and the sheets has been adjusted to Δ*z* = 60 mm.

Tab. 2: Lubricant properties.

Property	Mineral oil	Natural ester
Density (20 °C), ρ (g/cm <sup>3</sup> )	0,81	0,91
Kinematic viscosity (40 °C), ν (mm <sup>2</sup> /s)	22	37
Flash point (°C)	230	>180
Viscosity index	133	N/N

Tab. 2 shows the properties of the used mineral oil. Within the experiments a lubricant flow rate of *V*<sub>oil</sub> = 0,048 l/h has been adjusted and feed rate of the nozzle with *v*<sub>f</sub> = 2000 mm/min.

As reference the test were performed with compressed air instead of CO<sub>2</sub>, which is equivalent to MQL cooling strategy. The conditions for the experiment are shown in Tab. 3.

Tab. 3: Conditions for the application of oil with CMQL.

Experimental condition	Description
Machining parameter	$v_f = 2000$ mm/min $\Delta z = 60$ mm
Lubricant parameter	$V_{oil} = 0,048$ l/h
Cooling strategy	MQL; CMQL; HP-CMQL
MQL parameter	SJN $d = 0,2$ mm; $\dot{m}_{CO_2} = 0,0$ kg/h
CMQL parameter	SJN $d = 0,2$ mm; $\dot{m}_{CO_2} = 4,7$ kg/h SJN $d = 0,3$ mm; $\dot{m}_{CO_2} = 8,6$ kg/h PT $d = 0,5$ mm; $\dot{m}_{CO_2} = 5,8$ kg/h
HP-CMQL parameter	SJN $d = 0,2$ mm; $\dot{m}_{CO_2} = 8,0$ kg/h

### 3.3 Milling of Ti6Al4V

A four-edged carbide end mill from Kennametal with a TiAlN coating and a diameter of 6 mm has been used for each milling experiment. These were performed in shoulder climb milling strategy. Roll-In-Entry has been used for each entry of the tool in the workpiece to minimize chipping of the tool edges. The workpiece blocks consisting of the titanium alloy Ti6Al4V were delivered in one batch with a dimension of 200 x 50 x 128 mm<sup>3</sup>.

For the MQL, CMQL and HP-CMQL experiments a natural ester, shown in Tab. 2, has been used and mixed with liquid CO<sub>2</sub> in case of MQL or HP-CMQL cooling strategy. For HP-CMQL the gas dosing station DSD 500 from Linde AG has been integrated in the CO<sub>2</sub> supply system. As a reference a flood cooling process with a 7 % emulsion has been performed.

Tab. 4: Milling conditions.

Experimental condition	Description
Machining parameter	$v_c = 70; 130$ m/min $f_z = 0,04$ mm $a_p = 2$ mm $a_e = 2$ mm
Lubricant conditions	Natural ester $V_{oil} = 0,06$ l/h
Cooling strategy	MQL; CMQL; HP-CMQL; Flood
MQL parameter	SJN $d = 0,2$ mm; $p_{air} = 6,3$ bar
CMQL parameter	SJN $d = 0,2$ mm; $\dot{m}_{CO_2} = 4,7$ kg/h SJN $d = 0,3$ mm; $\dot{m}_{CO_2} = 8,6$ kg/h PT $d = 0,5$ mm; $\dot{m}_{CO_2} = 5,8$ kg/h
HP-CMQL parameter	SJN $d = 0,2$ mm; $\dot{m}_{CO_2} = 8,0$ kg/h
Flood parameter	$6 \times$ SJN $d = 6,0$ mm

All tests have been done with external cooling supply. The SJN has been positioned in 40 mm to the tool with a 25° angle against the horizontal and a 38° angle against the feed direction. If the PT was in use the distance to the tool is reduced to 8 mm. The bending moment causes by the cutting force has been measured with the sensory tool holder SPIKE from promicron during machining.

The flank wear of the cutting edges has been examined with a digital microscope. As tool life criteria a maximum flank wear of  $VB_{max} = 0,2$  mm or a maximum cutting distance of  $l_{max} = 45$  m has been determined. For statistical significance each trial has been performed three times.

Cutting conditions and cooling strategies of the milling experiments are shown in Tab. 4.

## 4 RESULTS OF PRELIMINARY EXPERIMENTS

### 4.1 Temperature measurement of CO<sub>2</sub> jet

In the top of Fig. 2 (a) the CO<sub>2</sub> free jet is shown schematically. After the release of the liquid CO<sub>2</sub> through the SJN a rapid isenthalpic expansion follows. The jet expands until it reaches the effective diameter  $d_e$  after the effective length  $l_e$ . At this point the pressure  $p$  has fallen to ambient pressure  $p_0$  and 31 % to 34 % of the CO<sub>2</sub> has changed to the solid state [Pursell 2012]. From now on the core jet constricts while the outer part of the jet expands slowly due to interactions with the surrounding air [Pursell 2012].

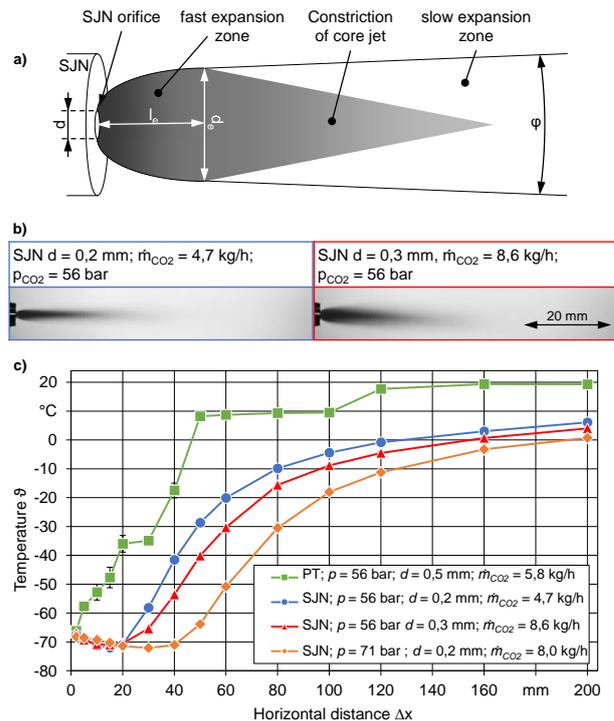


Fig. 2: a) Schematic illustration, b) pictures and c) temperature curves of CO<sub>2</sub> jets.

In the middle of Fig. 2 (b) two pictures of CO<sub>2</sub> jets are illustrated. An enlargement of the SJN orifice from  $d = 2$  mm (left) to  $d = 3$  mm (right) results in an increase of the CO<sub>2</sub> flow rate  $\dot{m}_{CO_2}$  as well as an increase of the effective diameter  $d_e$ , the effective length  $l_e$  and the overall length of the jet.

As shown by the temperature curves in Fig. 2 (c) the increase in the CO<sub>2</sub> flow  $\dot{m}_{CO_2}$  rate due to the bigger SJN orifice does not result in a lower temperature but in an extension of the area with low temperatures. The supply of CO<sub>2</sub> under HP does not affect the minimum temperature  $\vartheta_{min}$  reached but also extends the area of low temperatures. Because of the HP, the flow speed of the liquid CO<sub>2</sub> at the SJN orifice is increased and the temperature profile is shifted to the right. In a distance of 40 mm to the SJN orifice, which equals the distance in the milling experiments, the HP-CO<sub>2</sub> supply reaches the lowest temperature with  $\vartheta = -71,7$  °C. At room temperature, the CO<sub>2</sub> in the bottle has a pressure of about  $p = 57,3$  bar which causes the liquid CO<sub>2</sub> to flow through the pipes to the nozzle.

If the gas dosing station is set to a CO<sub>2</sub> mass flow  $\dot{m}_{CO_2} = 8,0$  kg/h and the SJN  $d_D = 0,2$  mm is selected, the

pressure in the line system increases to  $p = 80$  bar. Due to the Joule-Thomson effect, the pressure increase causes additional cooling in the free jet [Supekar 2012]. In addition, the flow velocity of the CO<sub>2</sub> increases at the nozzle outlet, since a higher mass flow is transported through the same outlet. The higher velocity of the flow causes a shift of the temperature curve to the right.

By using the PT, an agglomeration of ice at the PT orifice is observed. This results in a deflection of the CO<sub>2</sub> jet whereby the temperature probe is not in the center axis of the jet. The consequence is a higher, unsteady temperature profile.

#### 4.2 Application of oil with CMQL

Fig. 3 shows the oil traces applied by the different cooling strategies. By MQL a continuous line of the mineral oil was put on the blotting papers. However, a lot of splashes are detected next to the oil trace. This suggests, that the oil is not focused by the compressed air.

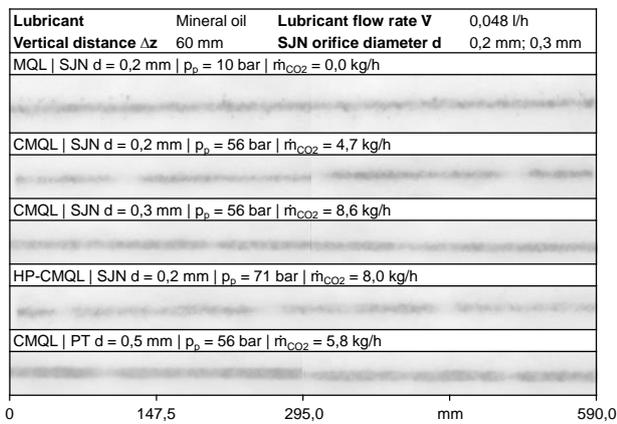


Fig. 3: Application of oil with different cooling strategies.

In comparison, no splashes are registered by using CMQL. It is to be expected that the CO<sub>2</sub> is focusing the oil droplets by an increase of the flow speed. By a further increase of the CO<sub>2</sub> supply pressure to  $p_{CO_2} = 71$  bar by HP-CMQL the focusing of the oil is further improved.

In order to check the oil rate, the oil quantities were determined by weighing the oil reservoir with a precision balance for all tests. The oil losses to the surrounding air are low for HP-CMQL. But for the SJN  $d = 0,2$  mm in CMQL and in HP-CMQL gaps in the oil traces have been observed. These emerge due to the oil pump. When the piston reached the upper dead center of the crank mechanism the oil flow was interrupted because of the high counter-pressure exerted by the CO<sub>2</sub>. By using the PT for CMQL a continuous line without splashes has been applied. Mixing CO<sub>2</sub> with oil reduces the agglomeration of ice at the PT orifice.

Nevertheless, the results show a nearly continuous moistening of oil on the surface. Depending on the outlet geometry and the supply pressure the atomization for pressure higher than 56 bar lead to thinner but wider lubrication films.

### 5 RESULTS OF MILLING EXPERIMENTS

The results of the machining investigations of various cooling strategies with variation of the cutting speed are illustrated in Fig. 4. The wear tests of the tools can be seen in part a). The diagrams shown in part b) and c) correspond to the colour code of the corresponding picture frames.

Tool	Carbide Endmill $\varnothing 6$ mm	Depth of cut $a_p$	2 mm
Coating	TiAlN	Width of cut $a_e$	2 mm
Lubricant	Emulsion 7 %   Natural ester	Cutting speed $v_c$	70; 130 m/min
Lubricant flow rate $\dot{V}$	0,06 l/h	Feed $f_z$	0,04 mm
Material	Ti6Al4V	Length of cut	45 m

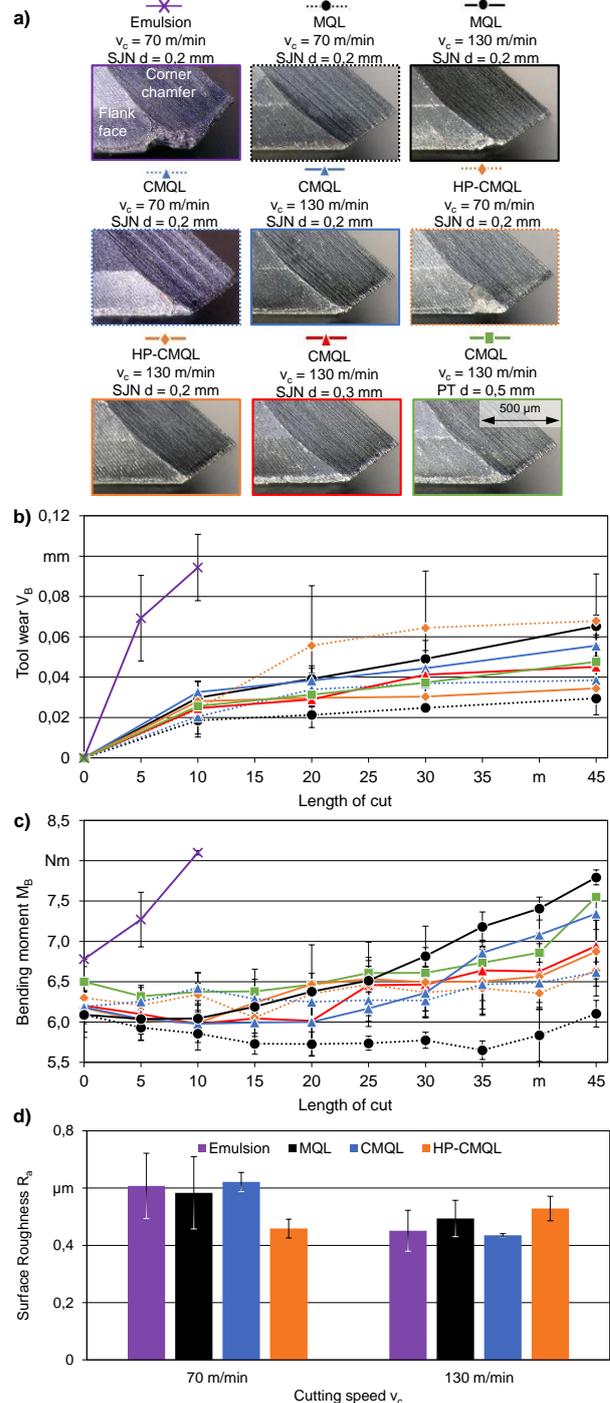


Fig. 4: a) Pictures of the cutting edges and progression of tool wear b) bending moment and d) surface roughness under various cooling conditions and cutting speeds.

The investigations were first carried out with the cutting parameters recommended for the tools of  $v_c = 70$  m/min and a feed rate of  $f_z = 0,04$  mm. This shows that the choice of the cooling lubricant strategy has a significant influence on the machining result. In the case of flood cooling, a clear wear in the form of chipping can be seen after a tool life of 10 m. The reasons for this are the insufficient lubricating effect and the low coolant pressure. This prevents the medium from penetrating far enough to the cutting zone and developing its wear reducing effect. The rapidly progressing

wear can also be proven by the tool wear diagram and the bending moment curve.

The investigations with alternative cooling lubricant strategies show that at a cutting speed of  $v_c = 70$  m/min the MQL is superior to the other strategies. On the one hand, this can be attributed to the cutting temperature. The moderate cutting speed enables the operation in an optimum temperature range for the tool. The cutting conditions selected for this test correspond to the tool manufacturer's specifications.

On the other hand, the use of the oil optimized for this application is an essential component to reduce wear. This oil has already been selected from various oils for the machining of titanium in previous tool life tests [Gross 2019].

With cryogenic minimum quantity lubrication, an increase in wear occurs at  $v_c = 70$  m/min in contrast to MQL, which is nevertheless below the flood cooling level. This can also be attributed to the prevailing temperature, which may have led to a hardening of the material [Krämer 2014]. An influence of the coolant pressure cannot be discerned.

An increase in the cutting speed to  $v_c = 130$  m/min leads to a friction-related temperature increase in the chip zone. This temperature leads to an increased adhesion tendency of the titanium alloy and chipping on the cutting edge during machining under MQL.

When considering the cryogenic cooled cutting edges at the increased cutting speed, a reduction of wear compared to the lower cutting speed is noticeable. The higher cutting speed leads to the optimum temperature for the use of CO<sub>2</sub>, which can be reduced by the CO<sub>2</sub> in such a way that the cutting conditions assume similar conditions as with machining with MQL at  $v_c = 70$  m/min. The wear for  $v_c = 130$  m/min after a tool life of 45 m with the exception of the HP-CMQL strategy is at a similar level for all cryogenic methods. The HP-CMQL strategy has been able to determine the lowest wear under the given cutting conditions. The higher CO<sub>2</sub> pressure allows a deeper penetration of the oil into the cutting zone compared to the bottle pressure and thus a more effective friction reduction.

When using CMQL with the SJN  $d = 0,3$  mm or the PT the flank wear was reduced in comparison to CMQL with the SJN  $d = 0,2$  mm. The SJN  $d = 0,3$  mm enabled this by an increase of the CO<sub>2</sub> flow rate  $\dot{m}_{CO_2}$  and thereby a reduction of thermal load. On the contrary, the PT decreased the thermal load by a more effective cooling with a shorter distance between the PT orifice and the tool. Thus, CO<sub>2</sub> was used more economically. The progressions of the measured moments of the different cooling strategies shown in Fig. 4 (c) equal the corresponding wear progressions. With the growth of wear, the tools sharpness decreased, whereby the mechanical load onto the tool and thus the moment increased.

The surface roughness in Fig. 4 (d) is at the same level for all cooling lubricant strategies within the different cutting speeds. The good surface of HP-CMQL can be traced back to the higher pressure of the carrier medium, which leads to a finer oil film distribution and better sliding properties. The better surfaces at higher cutting speeds are due to the resulting higher temperatures and the resulting softening of the material.

Productivity can be increased by adjusting the cutting speed. The productivity of machining can be represented by the material removal rate  $Q$  shown in Eq. 1.

$$Q = A \cdot v_f = a_p \cdot a_e \cdot f_z \cdot z \cdot \frac{v_c}{\pi \cdot d} \quad (1)$$

The material removal rate is calculated as the product of the chip cross section  $A$  and the feed rate  $v_f$ . By raising the cutting speed  $v_c$  from 70 m/min to 130 m/min, productivity can be increased by 85 % from 2,38 cm<sup>3</sup>/min to 4,41 cm<sup>3</sup>/min.

It should be mentioned that there are currently no commercially available tools adapted for cryogenic cooling. A specific optimization of the tools under given cutting conditions can also contribute to the increase in productivity and must therefore be examined more in detail.

Finally, it should be noted that the greatest challenge in establishing cryogenic minimum quantity lubrication is the identification of the optimum process window for the respective cutting tool and workpiece material pairing.

## 6 CONCLUSION

The results of the preliminary tests and the milling experiments with Ti6Al4V are summarized below:

- The minimum temperature  $\vartheta_{min}$  reached in the CO<sub>2</sub> free jet is not effected by the CO<sub>2</sub> flow rate  $\dot{m}_{CO_2}$  and the CO<sub>2</sub> supply pressure  $p_{CO_2}$ .
- The length of the area with low temperatures in the CO<sub>2</sub> free jet grows with the CO<sub>2</sub> flow rate  $\dot{m}_{CO_2}$  and the CO<sub>2</sub> supply pressure  $p_{CO_2}$ .
- The small nozzle diameter allows the flow velocity to be increased and the point of lowest temperature to be positioned further from the outlet. This can be used for a more flexible nozzle arrangement around the spindle head.
- By mixing mineral oil with liquid CO<sub>2</sub> a continuous application of the oil is possible. It can be assumed that the oil is carried away as droplets in the liquid CO<sub>2</sub> flow.
- By raising the CO<sub>2</sub> supply pressure  $p_{CO_2}$ , the losses of the MQL oil to the surrounding air are reduced. It can be assumed that a raised CO<sub>2</sub> supply pressure  $p_{CO_2}$  is followed by a higher flow speed of the liquid CO<sub>2</sub> and the oil droplets at the nozzle orifice whereby the free jet is less deflected. Thus, the majority of the MQL oil is directed towards the cutting zone.
- By mixing oil to the liquid CO<sub>2</sub> the agglomeration of ice particles at the PT orifice is suppressed.
- In the milling experiments with a cutting speed of  $v_c = 70$  m/min MQL was more advantageous than CMQL or HP-CMQL, which led to chipping of the cutting edges.
- HP-CMQL has the lowest tool wear followed by CMQL and MQL for milling with a cutting speed of  $v_c = 130$  m/min.
- By using CMQL the tool wear is further reduced by an intensified cooling. This was realized by an increase of the CO<sub>2</sub> flow rate  $\dot{m}_{CO_2}$  or a decrease of the distance between nozzle orifice and tool.
- CMQL and HP-CMQL are able to increase productivity up to 86 % in contrast to MQL and Emulsion cooling.

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