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QUANTIFICATION OF THE COOLING EFFECT OF CRYOGENIC COOLING SUPPLY STRATEGIES THROUGH TEMPERATURE MEASUREMENT WITH FUNCTIONAL TOOL COATINGS FOR TURNING PROCESSES OF POLYPROPYLENE

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Abstract
A current trend towards sustainable machining can be found in the gradual substitution of lubricants by cryogenic media in the form of liquid carbon dioxide. This strategy has been proven to reduce the tool wear and increase productivity and energy efficiency in milling processes of titanium alloys. While various adjustments to the CO_2 supply system such as pre-cooling or pressurization are viable, it remains challenging to adjust the cryogenic cooling capacity to the specific requirements of each process. To do so, an approach to quantify this cooling effect by temperature measurements with functional coatings of the cutting insert during turning processes of polypropylene is proposed in this research. The results show that the influence of the nozzle distance to the cutting tool and the nozzle diameter are reduced by a variation of the CO_2 density. The lowest cutting temperatures are achieved with an increase in pressure levels and hence a drastic increase in CO_2 flow rates. Furthermore, the liquid CO_2 based cutting temperatures are compared to those obtained by cooling with a vortex tube. The utilization of vortex tubes as a cooling strategy shows potential as an alternative for easy-to-cut materials like polypropylene, since the effort for the machine integration as well as operator safety precautions are minimized.

Keywords:
Cryogenic Cooling, temperature measurement, cooling capacity

1 INTRODUCTION

Sustainability as a present topic in today's society is also important in production technology research and practice. In machining processes, sustainability can be increased by extending tool life and by reducing the consumption of cooling lubricants. These two central levers can be impacted if liquid carbon dioxide (LCO_2) will be applied as a medium for cryogenic cooling [Gross 2021]. However, there are only few attempts to determine the optimal amount of LCO_2 and achieve cost and environmental impact reduction. In the following research, this aim is achieved by utilizing a coated turning tool to measure the process temperature in the turning of polypropylene for different LCO_2 supply variations.

2 STATE OF THE ART

The following paragraphs are designated to give an overview of recent publications in the fields of cryogenic cooling, the applications of vortex tubes as well as temperature measurement in the machining sector. The combination of these three aspects generates a deeper insight into the necessary coolant application quantity.

2.1 Cryogenic Cooling

Cryogenic cooling, especially when combined with minimum quantity lubrication (MQL), has been found to be more energy efficient than flood cooling for the milling of titanium alloys according to life cycle assessment principles. Even though there is a high energy expenditure for the compaction and liquefaction of the CO_2, an increased tool life leads to an overall lower energy demand [Gross 2021]. Alternatively, [Stanford 2009] have shown that liquid nitrogen (LN_2) also drastically reduces tool wear for high-speed turning of plain carbon mild steel. The application of LN_2 is thus also considered to be more sustainable in comparison to conventional flood cooling [Stanford 2009]. This reduction in tool wear by the application of LN_2 as a cryogenic medium is confirmed by *Meng et al*. for the turning of grey cast iron and compacted graphite iron. They have further described a reduction in surface roughness and cutting forces by utilizing this alternative cooling strategy [Meng 2024].

While the aforementioned advantages have mostly been found for cooling with LCO_2 as well [Villarazo 2023], there are various aspects that favor the selection of LCO_2 as the cryogenic medium. For instance, it is not possible to combine the cryogenic medium with lubricants in pure internal cooling circuits with LN_2 [Sterle 2021]. Additionally, excessive cooling with LN_2 has been found to reduce the tool life [Outeiro 2015]. Another disadvantage has been observed by *Busch et al:* They have discussed that an insulating gaseous film on surfaces at room temperatures is created upon contact with the LN_2 due to its vaporization which prohibits the coolant to reach the cutting edge. Furthermore, they highlight that an internal integration into the machine is complicated due to the need for insulation of technical components to avoid hazards and a loss of cooling capacity [Busch 2016]. In contrast, LCO_2 can be fed at ambient temperature ($\vartheta = 20$ °C) through uninsulated pipes at a pressure level of $p = 57.29$ bar or higher [Wagner 2013].

This approach has been investigated by *Gupta et al.* Therein, a significant improvement in tool wear – especially adhesion – in comparison to both dry turning of aluminum alloys and the application of MQL due to the better cooling performance of the cryogenic medium has been concluded [Gupta 2023]. Furthermore, the surface integrity for the cryogenic machining of Inconel 718 has been analyzed to show a lower surface roughness as well as a harder and thinner surface layer by *Pušavec et al*. Thus, the final workpiece quality has been considered to be improved by this process [Pušavec 2011]. Recent publications have taken a deeper dive to understand the cooling effect in cryogenic cooling in order to adjust the amount of the cooling medium to each specific process. *Pušavec et al.* have developed a testing station to determine the cooling capabilities of both LCO_2 and LN_2 based on a heated thermocouple [Pušavec 2019]. A similar objective is reached by *Meier et al.* by utilizing a heating resistor and measuring the electrical power that is required in a steady-state between the cooling by the CO_2-stream and the heating of the resistor. Therein, various supply strategies such as pre-cooling and pressurization of the LCO_2 have been discussed [Meier 2024]. As these have only been characterized with a testing station apart from real machining conditions, the present study aims to explore the correlation between the measured cooling capacity and the process temperature directly at the cutting edge.

2.2 Vortex tubes

Vortex Tubes use the principle of energy separation which was first discovered by *Ranque* [Ranque 1933]. These findings have been expanded upon and proposed for cooling applications by *Hilsch* [Hilsch 1946]. Therefore, they are also often called Ranque-Hilsch vortex tubes (RHVT). This technology is mostly applied in refrigeration technology where recent publications focus on the optimization of the temperature difference by varying the swirl generator material or the tube length to diameter ratio [Rattanongphisat 2024]. While there is no clear singular description of the mechanism of energy separation and flow in the literature, *Fig. 1* gives an overview of the simplified principle. The compressed air enters the vortex tube on the left side close to the cold air nozzle and is transformed into a swirl. At the cone valve, a fraction of the air stream exits the pipe system and a smaller, inner swirl is reflected back. Due to a frictional heat exchange between the inner and the outer ring vortex, the internal energy is converted into rotational kinetic energy. Thus, the temperature of the inner ring vortex decreases, while the outer swirl maintains its rotation through the kinetic energy gained by this friction [Jing 2025].

A current trend towards applying this working principle to machining processes has been described by [Swain 2022]. For example, the application of a vortex-tube based cooling strategy has led to an improved tool life in comparison to dry milling for carbon-fiber reinforce plastics (CFRP) [Nor Khairusshima 2017]. The reduced process temperature during the milling of CFRPs due to the utilization of vortex tube-based cooling has been found to enable higher cutting speeds and feed rates. Furthermore, the surface damage of the workpiece material has been reduced and the tool life has been increased [Nor Khairusshima 2013]. However, the specific cutting energy in the turning of Inconel 718 has been found to be similar in dry, vortex-tube chilled-air assistance and minimal quantity nanolubricant conditions. *Mahboob Ali et al.* have concluded that the lack of lubrication leads to an inferior performance for hard-to-cut materials [Mahboob Ali 2018]. Hence, investigations have been conducted regarding the combination of RHVT with minimum quantity lubrication for the milling of titanium alloys. *Liu et al.* have shown the promise of combining these strategies for application in further processes [Liu 2023]. In the following investigation, there is no need for lubrication in the turning of polypropylene (PP). Thus, an unmodified vortex tube serves as a suitable, easily integrable alternative to the cryogenic cooling strategies.

2.3 Temperature measurement in the process zone

In order to evaluate the cooling effect of both the various cryogenic cooling strategies such as pre-cooling or pressurization of the LCO_2 as well as the vortex tube, the temperature must be measured as close to the process zone as possible. One approach in recent publications can be found in optical measurement principles. For example, *Han et al.* have explored a near-infrared fiber-optic spectrometer system in which the optical fiber is integrated into the cutting insert [Han 2022]. While the application of infrared cameras offers an alternative solution for the temperature measurement in the process zone*, Moreira et al.* have described extensive preparations to quantify various external influences with the highest influence stemming from alternating emissivities of the metal workpieces [Moreira 2021]. However, the robustness of optical measurement systems regarding their accuracy in

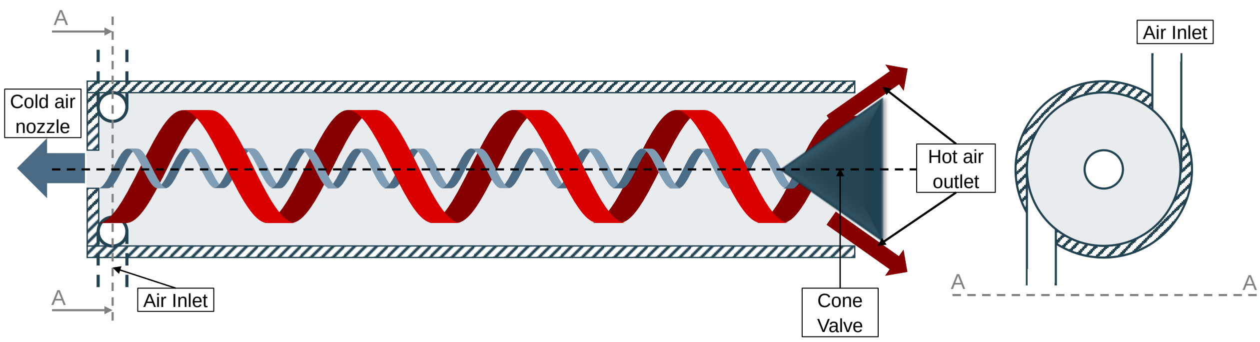

Fig. 1: Schematic functioning principle of a vortex tube according to [Promvonge 2005].

either flood cooling or extensive chip formation conditions has been found to be challenging. In addition, they usually cause higher costs [Bartolomeis 2021, Pereira 2022]. These disadvantages are resolved by *Kus et al.* by the usage of cost-efficient thermocouples which are embedded into the cutting insert. This approach has been utilized to validate the simulated heat distribution within the tool [Kus 2015]. A similar approach is utilized by *Campidelli et al.* for a milling process. Since the tool is rotating, their focus has been on a wireless data transition from the thermocouple sensor in the cutting tool to the data processing unit [Campidelli 2019]. With the aim of avoiding structural weaknesses in the cutting insert and reducing the distance of the measurement sensor to the cutting edge, *Plogmeyer et al.* have designed thin-film conductor tracks that act as a thermocouple on the rake face [Plogmeyer 2024]. Similar approaches have been realized by *Uhlmann et al.* and *Chen et al.*, where the former has created conductor tracks by directed boron-doping of the diamond cutting material and the latter has applied boron-doped diamond layers in a coating process to form a resistance temperature detector [Uhlmann 2021, Chen 2023]. An alternative solution to the measurement with conductor tracks to achieve thermocouple structures on the tool has been discussed by *Bobzin et al.* for CrN/AlN+TiAlN and CrAlN+TiAlN coatings. Although it is technically possible to measure with this conductor material, they concluded that the number of coating processes should be reduced to ensure an economic application [Bobzin 2021]. The temperature measurement utilized for this research is also based on two diamond layers which are deposited in consecutive chemical vapor deposition processes. Therein, the outer diamond layer has been doped with boron to create a semiconductor with p-conductivity and form a thermocouple with the WCCo-Substrate (overall n-conductivity) of the cutting tool [Borchardt 2020].

As demonstrated in the state of the art, there have been many advancements in the machining sector by the application of cryogenic cooling. The evaluation of the cooling capacity of different adjustments to the LCO_2 supply has only been studied to a limited extent in real machining conditions. Furthermore, there have been multiple investigations into monitoring the cutting temperature during the process. While vortex tubes have been applied in machining operations, they are seldom compared to cryogenic cooling. The research gap described in this study thus tackles the quantifiable comparison between these cooling strategies in machining conditions by utilizing a novel coating structure to achieve a robust temperature measurement under these circumstances.

3 EXPERIMENTAL SET UP

The following section will give an overview of the applied equipment and methods in this investigation. The main focus is put on the temperature measurement principle which differs from the ones described in the state of the art.

3.1 Functional coating of the cutting insert

While this novel coating of the cutting insert with the purpose of measuring the process temperature directly at the cutting edge also utilizes boron-doped diamond layers as in *Uhlmann et al.* and *Chen et al*. [Uhlmann 2021, Chen 2023], it does not rely on conductor tracks or a selective doping process. This simplifies the coating process as there is no requirement for precisely machined masks. *Fig. 2* gives a schematic overview of the structure of the indexable insert. The coating structure utilizes the measurement principle of a thermocouple which is explained in the upper half of *Fig. 2*. Therein, two different electrically conductive materials are connected at the measuring point. The thermoelectric voltage created by this material pair is measured at the reference point and added to a known reference temperature (see thermocouple below). The two materials in this application are a boron-doped diamond (BDD) coating and the original cutting insert consisting of WCCo. Those two materials are separated and electrically isolated from another by an undoped diamond coating. The measurement point and the electrical connection to the data acquisition PC are realized by laser structuring which enables a high flexibility regarding the position of the measurement point. A conventional K-type thermocouple monitors the temperature at the reference point to take the heating of the cutting insert during the turning process into account. For this investigation, the measurement point is located on the rake face just behind the cutting corner of the coated carbide tool by Sandvik Coromant of type CNMG 12 04 08-QM H13A. The data acquisition is performed by a PXIe-6341 measurement card by National Instruments and the data is processed using LabVIEW software. [Röckelein 2025]

3.2 Testing conditions

All of the following experiments are conducted on a DMG Mori CLX 350 turning lathe on polypropylene workpieces with a diameter of d_{PP} = 182.5 mm. During the face turning of the material a diameter in the middle of d_{Mid} = 60 mm is not processed. As the objective of these experiments is to evaluate the cutting temperature for different cooling strategies, the cutting parameters are kept constant at a feed speed of F = 0.2 mm/rev, a cutting depth of a_p = 0.25 mm and a cutting speed of v_c = 250 m/min. These

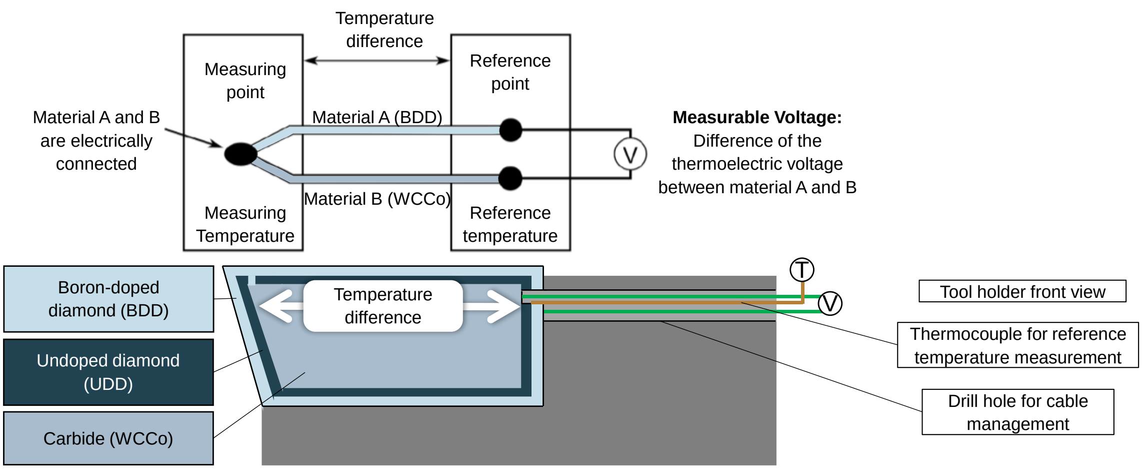

Fig. 2: Schematic depiction of the temperature measurement set up [Röckelein 2025]

parameters have been proven to lead to solid results in dry turning and are therefore applied here. The workpiece material polypropylene is partially crystalline thermoplastic polymer with a density of $\rho = 0.903\ g/cm^3$. This is considered the lowest density for all polymers. Its Young's modulus is described at E = 1450 MPa. Its glass transition temperature is $T_G = -10$ °C, whereas its melting temperature lies at $T_M = 163$ °C [Arnold 2024]. Between those temperatures, the polymer remains in an entropy elastic state [Eyerer 2020]. Polypropylene is usually applied in the production of foils, pump casings, household appliances and pipes [Czichos 2012].

There are two different nozzle diameters of $d_{D1} = 0.2$ mm and $d_{D2} = 0.3$ mm for the cryogenic cooling strategies available which are both used during the experiments. In an unaltered state of the LCO_2 these nozzles lead to flow rates of $\dot{m}_{D1} = 5.1$ kg/h and $\dot{m}_{D2} = 11.4$ kg/h respectively. On the one hand, the LCO_2 density and therefore the flow rate can be increased by pre-cooling. This pre-cooling is performed by a heat exchanger of type CWP100 by Lindr. A stainless steel pipe with an inner diameter of $d_{pipe} = 1.7$ mm is inserted into the cooling basin filled with V = 8 l of water in spirals. The pipe length amounts to $l_{pipe} = 3.20$ m. In previous experiments it has been found that a pre-cooling water temperature below $\vartheta_C = 12$ °C does not significantly improve the flow behavior. On the other hand, these LCO_2 properties can be varied by pressurization. This is achieved with the inert gas dosing device DSD 500 by Maximator GmbH and Linde AG. These possibilities lead to various experiments illustrated in *Tab. 1*. All the LCO_2 based experiments are conducted for both nozzle diameters. Furthermore, the results are compared to a vortex tube assisted machining with a vortex tube from Saratools. Every experiment is performed three times to ensure statistical validation.

Tab. 1: Overview of the experimental plan

Experiment	Parameter		
	1	2	3
Nozzle distance a_D (cm)	2	4	6
Nozzle angle β (°)	30	45	60
Pre-cooling temperature ϑ_C (°C)	12	14	16
Pressure level p (bar)		200	
Vortex tube nozzle diameter d_{RHVT} (mm)	6.5	9.5	12.5

4 RESULTS

While the parameters nozzle distance, nozzle angle, pre-cooling temperature and pressure level focus on the optimization of the LCO_2 cooling capacity, the machining with a vortex tube based cooling serves as an easily integrable alternative for the machining of soft to cut materials like polypropylene. It is to be expected that a smaller nozzle distance, a lower pre-cooling temperature and a higher pressure level lead to lower process temperatures. However, the exact influence as well as the behavior for different nozzle angles need to be quantified.

4.1 Nozzle distance

The nozzle distance is set to $a_D = 2$ cm, $a_D = 4$ cm and $a_D = 6$ cm in this experiment. So far, the nozzle has been set up at the $a_D = 2$ cm margin for previous experiments. However, a satisfying cooling effect at larger distances would simplify the integration into the machine. As the pre-cooling has been proven to reduce flow rate fluctuations [Meier 2024], the pre-cooling is set to $\vartheta_C = 12$ °C for this experiment. The nozzle is fixed at an angle of β = 45°.

As illustrated in *Fig. 3*, the temperature at the cutting edge is very low in the beginning of up to T = -100 °C. This can be attributed to a measurement error, as T = -70 °C would be realistic for the evaporation of LCO_2. Furthermore, the fluctuation of the data curves signals a need for improvement. However, for a first estimation of the cooling effect of each strategy, the accuracy of this measurement principle is considered adequate. The reference temperature from the dry turning processes is included with an average temperature of T = 300 °C. At this temperature, the polymer chips start to melt and adhere to the workpiece surface which leads to a deteriorated surface quality. Duet to the tool movement, a share of chips is also moved to the outside of the cylindrical workpiece where it the melted chips stick to the outer surface. This behavior is prevented by the application of LCO_2 cooling.

For the upper half of *Fig. 3* which resembles the process temperature for the smaller nozzle of nozzle diameter $d_{D1} = 0.2$ mm, a rising process temperature with increasing nozzle distance can be detected. The lowest temperature for a nozzle distance of $a_D = 2$ cm is measured at below T = 100 °C. For the larger nozzle diameter in the lower half of the image, there is no clear difference between the temperature measurements. It is concluded that a higher flow rate creates a stronger beam which contains the cooling effect over a longer distance. While the end temperature in this process is comparable to that of the smaller nozzle for $a_D = 2$ cm, this beam behavior simplifies the set up in the machine as such small distances cannot be realized for every process setup.

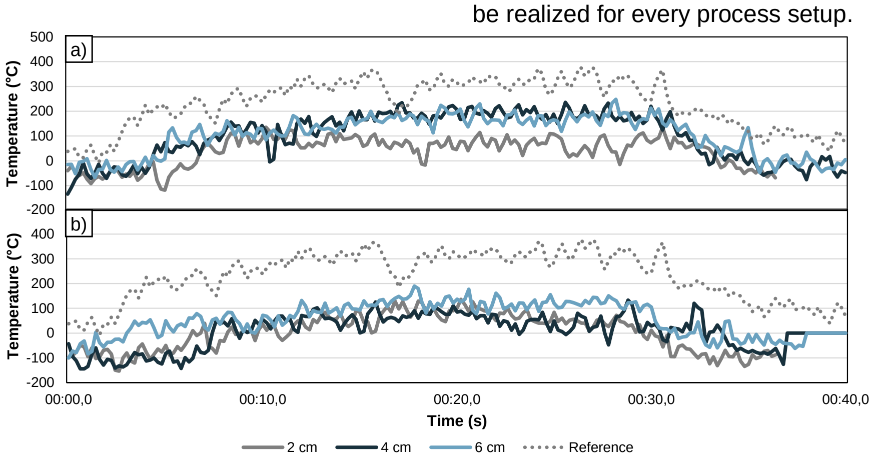

Fig. 3: Process temperature for different nozzle distances with a) nozzle diameter d_{D1} = 0,2 mm and b) d_{D2} = 0,3 mm

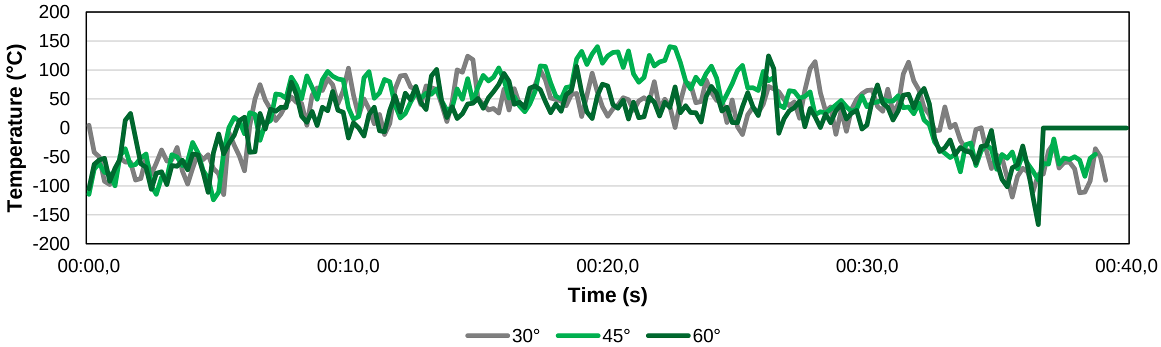

Fig. 4: Influence of the nozzle angle for a nozzle distance of a_D = 4 cm and a nozzle diameter of d_{D2} = 0.3 mm at a pre-cooling temperature of ϑ_C = 12 °C

4.2 Nozzle angle

Another aspect regarding the feasibility of mounting a cryogenic supply system into the machine room can be found in the nozzle angle. Possible effects include a more intensively cooled tool and workpiece surface for smaller nozzle angles but also a tendency to deflect the CO_2 beam. Thus, the process temperature is measured in *Fig. 4* for the nozzle angles β = 30°, β = 45° and β = 60°. A larger variance of nozzle angles is not possible due to other machine elements such as the tool revolver. The LCO_2 is pre-cooled to a temperature of ϑ_C = 14 °C which is also used to reduce density variations and therefore flow rate fluctuations between experiment repetitions. With the objective of enabling a higher variance between the nozzle angles, the nozzle distance is set to a medium a_D = 4 cm with the bigger nozzle diameter of d_{D2} = 0.3 mm.

Fig. 4 clearly shows that there is no decisive difference between the cutting temperatures for the three investigated nozzle angles. All three angles result in temperatures between T = 50 °C and T = 100 °C. An exact distribution in that range cannot be recognized due to the measurement inaccuracy described before. For a short while at about t = 20 s, the temperature at angle β = 45° is peaking above the T = 100 °C level. This occurs due to a large amount of hot flow chips collecting on top of the rake face and inducing additional heat into the measurement system. Apart from that, it is concluded that the exact nozzle angle in this range does not matter regarding the cooling performance of the cryogenic cooling strategy. In theory, this could differ for smaller or higher angles which could not be discussed in this experimental set up.

4.3 Pre-cooling of the LCO_2

Pre-cooling the LCO_2 achieves the objective to increase the density due to the lower temperature and therefore enabling a higher flow rate. Thus, a larger amount of the liquid cryogenic medium can expand at the nozzle exit and should therefore lead to a higher cooling capacity. The pre-cooling has also been described to reduce fluctuations in the flow rate which would otherwise lead to a pulsation of the beam. However, a pre-cooling temperature of below ϑ_C = 10 °C leads to the formation of dry ice due to the very high density which again might partially block the LCO_2 stream [Meier 2023]. With the aim of finding the maximum cooling capacity resulting from this parameter, the nozzle distance is set to a_D = 2 cm. The nozzle angle has been proven to have no influence and is set to β = 45°.

Regarding the process temperature, two effects can be observed. On the one hand, the larger nozzle diameter does not achieve a lower cutting temperature by pre-cooling the LCO_2. There is also no recognizable trend for lower temperatures in this experiment. One reason might be the low heat generation in the turning of PP so that the maximum required cooling effect is already met with the higher flow rate of the larger nozzle without any pre-cooling. On the other hand, there are visible influences on the cutting temperature for the application of the smaller nozzle diameter of d_{D1} = 0.2 mm which are shown in *Fig. 5*.

The maximum cutting temperature of this set of experiments is found at T_{max} = 200 °C when LCO_2 is not pre-cooled. The lowest temperature T_{min} = 100 °C can in turn be measured with a pre-cooling temperature of ϑ_C = 12 °C. The difference between the individual cooling temperatures cannot be considered significant based on this measurement accuracy. Upon further analysis, the density improvement between these three parameter sets only amounts to 1.8% which leads to almost the same flow rates for each of the three variations. Hence, the cooling capacity and the process temperature only differ slightly from another. However, every pre-cooling temperature achieves a lower process temperature compared to an uncooled state and leads to an improved beam form. Especially when considering to combine the cryogenic cooling strategy with minimum quantity lubrication for other

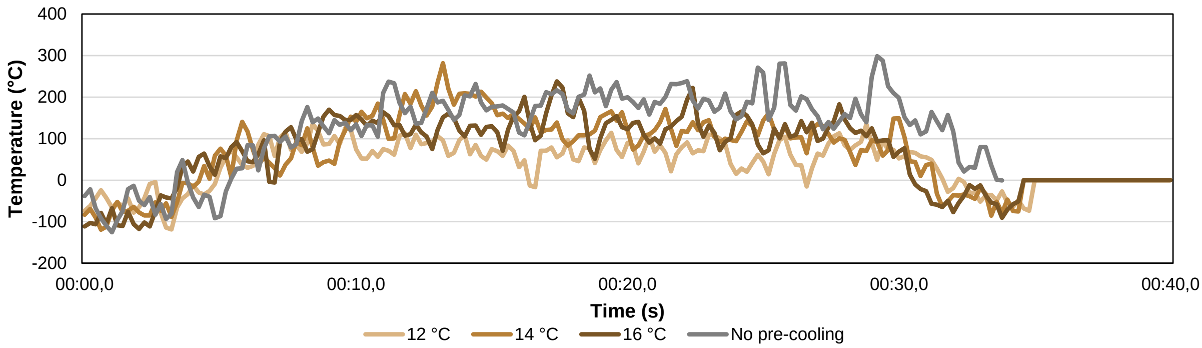

Fig. 5: Influence of the pre-cooling temperature on the cutting temperature for a nozzle diameter of d_{D1} = 0.2 mm, a nozzle distance of a_D = 2 cm and a nozzle angle of β = 45°

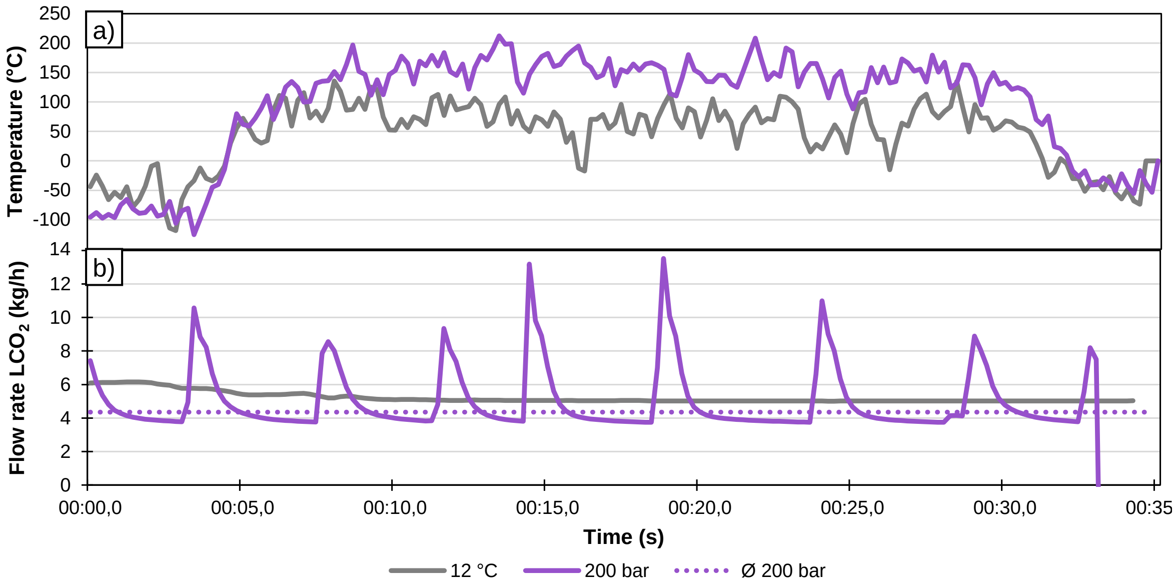

Fig. 6: Influence of the pressurization for a nozzle diameter of $d_{D!}$ = 0.2 mm on a) the cutting temperature and b) the flow rate

processes, a pre-cooling of the LCO_2 is recommended in order to ensure controlled lubrication of the tool. On the one hand, the more uniform beam enables a stable direction of the small oil droplets to the tool. On the other hand, the lack of pulsation leads to a continuous cooling and lubrication without reaching short-term critical temperatures.

4.4 Pressurization of the LCO_2

Another alternative to increase the density and the flow rate instead of pre-cooling is pressurization. In this experiment, the pressure of the LCO_2 is increased to p = 200 bar for a maximum cooling effect. This is the highest pressure level possible with the inert gas dosing device DSD 500 by Maximator GmbH and Linde AG. Therein, a single compressor piston is applied. The results are compared to the so far maximum cooling capacity with a pre-cooling temperature of ϑ_C = 12 °C. The nozzle distance and angle are kept constant at a_D = 2 cm and β = 45° respectively. For the smaller nozzle of diameter d_{D1} = 0.2 mm the cutting temperature in the pressurized state exceeds that of the pre-cooled condition in *Fig. 6*. While the pressurized supply strategy leads to maximum temperatures of T = 150-200 °C, the pre-cooled temperatures are measured at T = 100 °C as seen before. This is caused by the flow rate behavior in this set up. The bottom half of *Fig. 6* shows the peaks in flow rate after every single stroke of the inert gas dosing station. Since the amplitude of those peaks is limited by the nozzle diameter which acts as a bottleneck and the frequency of the strokes is quite low, the average flow rate in the pressurized state is beneath that of the pre-cooled condition.

This bottle neck is removed in the application of the larger nozzle diameter of d_{D2} = 0.3 mm. This leads to an increase in flow rate from an average of $\dot{m}_{0.2}$ = 4.35 kg/h to $\dot{m}_{0.3}$ = 17.7 kg/h with the assistance of a pressurization to p = 200 bar. In this case, the pressurized flow rate is higher than the one with pre-cooling at a temperature of ϑ_C = 12 °C. This fact leads to a new overall minimum processing temperature of below T = 50 °C which is depicted in *Fig. 7*.

4.5 Vortex tube

An alternative to this high consumption of the cryogenic medium and the need for employee safety precautions due to the evacuation of CO_2 from the machine room by air filter systems is found in the application of vortex tubes. In this set up, the vortex tube is supplied using the standard compressed air supply at p = 9 bar. There are further three nozzles available with a diameter of d_{RHVT} = 6.5 mm, d_{RHVT} = 9.5 mm and d_{RHVT} = 12.5 mm. For smaller nozzles, the cold air swirl inside the vortex tube gets smaller which leads to a more extensive heat exchange and thus lower temperatures after the air exits the nozzle. Initial experiments have also shown that the lowest nozzle diameter for vortex tubes is also least influenced by increasing nozzle distances to the tool. Therefore, the smallest nozzle diameter of d_{RHVT} = 6.5 mm is chosen for

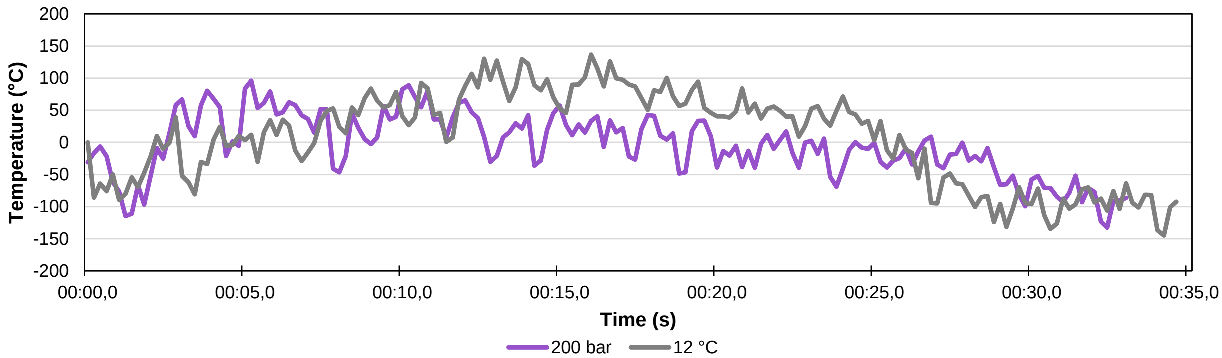

Fig. 7: Influence of increase pressure at p = 200 bar for a nozzle diameter of d_{D2} = 0.3 mm in comparison with a pre-cooling temperature of ϑ_C = 12 °C

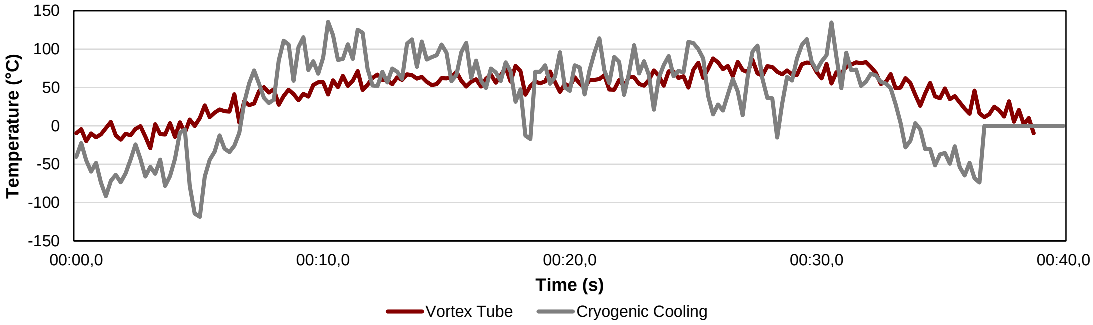

Fig. 8: Comparison of the cutting temperature between a vortex tube application and cryogenic cooling

the comparison with the cryogenic cooling strategy. As the energy and LCO_2 consumption in relation to the cooling effect is most efficient for the pre-cooling strategy [Meier 2024], this supply method is chosen as a representative for the cryogenic cooling strategies. The nozzle diameter for this strategy is set to $d_{D1} = 0.2$ mm and the pre-cooling temperature to $\vartheta_C = 12$ °C. For both variations the nozzle distance amounts to $a_D = 2$ cm. The comparison is depicted in *Fig. 8*.

Firstly, the temperature appears to be more stable for a cooling with the vortex tube. However, this is most likely attributed to a larger disturbing factor of the CO_2 stream on the measurement system and is thus not considered process related. Secondly, the average process temperatures are at a similar level of $T = 60$ °C. This showcases the potential for further applications of vortex tubes in machining operations. The low initial investment costs and lack of air extraction systems make vortex tubes especially attractive for small and medium enterprises. However, this might behave differently for materials that generate a higher heat during the process. Furthermore, the previous results have shown, that cryogenic processes can lead to lower temperatures through alterations in the supply system.

5 SUMMARY

In this study, the cooling effect of both various cryogenic cooling strategies with LCO_2 and an application of a vortex tube are quantified using a structured coating on a cutting insert which acts as a thermocouple. While the measurement accuracy and fluctuation show a need for improvement, multiple conclusions regarding the setup of the cryogenic supply system can be drawn for the use of two nozzle diameters:

1. For the machining of polypropylene, the same cutting temperature can be reached with both nozzle diameters at a close nozzle distance. As the larger nozzle diameter leads to almost double the flow rate, this can be an economic aspect in the application. For larger distances, the cutting temperature is lower with the larger nozzle diameter because of the more stable CO_2 stream. This can simplify the set up in the machine room as small nozzle distances cannot be realized for every process.
2. In a range from $\beta = 30°$ to $\beta = 60°$, the nozzle angle does not have a significant influence on the cutting temperature. This also enables a more flexible machine setup. The results might differ for smaller or larger angles which could not be investigated in this study.
3. A pre-conditioning by cooling of the LCO_2 increases its density and flow rate and thus decreases the cutting temperature in comparison to an untreated LCO_2 supply. However, a pre-cooling temperature below $\vartheta_C = 16$ °C does not significantly reduce the cutting temperature.
4. Alternatively, the LCO_2 can be pressurized to achieve higher flow rates and a higher cooling capacity. Due to the compressing process in this study, the smaller nozzle acts as a bottle neck which actually reduces the flow rate instead. For the larger nozzle, higher flow rates are created which lead to an absolute minimum cutting temperature of below $T = 50$ °C. However, this comes at the cost of a high CO_2 consumption.
5. A possible substitution for the LCO_2 is the application of vortex tubes. While the cutting temperature in the pressurized condition could not be met, the results are comparable to those in the pre-cooled condition. Therefore, the application of vortex tubes presents a suitable alternative for the machining of soft to cut materials such as polypropylene.

For upcoming investigations, the temperature measurement point is moved by laser structuring of the layers to gain insights into the temperature distribution and reduce the effect of burr formation. It remains to be seen if the cooling capacities can be transferred similarly when other materials are machined. Additionally, further optimization of the measurement system is required regarding its robustness for the machining of harder materials and the resulting thermoelectric voltage.

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7 REFERENCES

[Arnold 2024] Arnold, B. and Kern, K. Werkstofftechnik für das Wirtschaftsingenieurwesen. Berlin-Heidelberg, Springer-Verlag GmbH, 2024.

[Bartolomeis 2021] Bartolomeis, A. et al. Future research directions in the machining of Inconel 718. Journal of Materials Processing Technology, Vol. 297, 2021.

[Bobzin 2021] Bobzin, K. et al. Smart PVD hard coatings with temperature sensor function. Surface and Coatings Technology, Vol 423, 2021.

[Borchardt 2020] Borchardt R. et al. World's first Thermoelectric Generator Made of Tailored Carbon Allotropes. Advanced Engineering Materials, Vol. 22, 2020.

[Busch 2016] Busch, K. et al. Investigation of Cooling and Lubrication Strategies for Machining High-temperature Alloys. Procedia CIRP, Vol. 41, 2016, pp. 835-840.

[Campidelli 2019] Campidelli, A. F. V. et al. Development of a wireless system for milling temperature monitoring.

International Journal of Advanced Manufacturing Technology, Vol. 104, 2019, pp. 1551-1560.

[Chen 2023] Chen, Y.-L. et al. Self-sensing of cutting temperature in single point diamond turning by a boron-doped diamond tool. CIRP Annals, Vol 72, 2023, pp. 81-84.

[Czichos 2012] Czichos, H. and Hennecke, M. Hütte – Das Ingenieurwissen ; mit 340 Tabellen. Berlin Heidelberg, Springer Viewg, 2012.

[Eyerer 2020] Eyerer, P. and Schüle, H. Polymer Engineering. Berlin-Heidelberg, Springer-Verlag GmbH, 2020.

[Gross 2021] Gross D. and Hanenkamp, N. Energy Efficiency Assessment of Cryogenic Minimum Quantity Lubrication Cooling for Milling Operations. Procedia CIRP, Vol. 98, 2021, pp. 523-528.

[Gupta 2023] Gupta, M. K. et al. Potential use of cryogenic cooling for improving the tribological and tool wear characteristics. Tribology International 183, 2023.

[Han 2022] Han, J. et al. Cutting temperature measurement in turning using fiber-optic multi-spectral radiation thermometry and its application in tool wear status recognition. Measurement, Vol. 198, 2022.

[Hilsch 1946] Hilsch, R. Die Expansion von Gasen im Zentrifugalfeld als Kälteprozeß. Zeitschrift für Naturforschung A, Vol. 4, 1946, pp. 208-214.

[Jing 2025] Jing, D. et al. A review of refrigerant-based vortex tube separation characteristics: Devices, thermodynamic cycles and system experiments. Energy, Vol. 320, 2025.

[Kus 2015] Kus, A. et al. Thermocouple and infrared sensor-based measurement of temperature distribution in metal cutting. Sensors, Vol. 15, 2015, pp. 1274-1291.

[Liu 2023] Liu, F. et al. A novel cold air electrostatic minimum quantity lubrication (CAEMQL) technique for the machining of titanium alloys Ti-6Al-4 V. International Journal of Advanced Manufacturing Technology, Vol. 126, 2023, pp. 3437-3452.

[Mahboob Ali 2018] Mahboob Ali, M. A. et al. Specific cutting energy of Inconel 718 under dry, chilled-air and minimal quantity lubricants. Procedia CIRP, Vol. 77, 2018, pp. 429-432.

[Meier 2023] Meier, T. et al. Influence of Carbon Dioxide Temperature on Sprayability and Solubility in Cryogenic Minimum Quantity Lubrication with Bio-Based Lubricants. Manufacturing Driving Circular Economy. GCSM 2022, 2023, pp. 202-210.

[Meier 2024] Meier, T. et al. Investigation of the effects of CO2 pre-cooling on the cooling capacity for cryogenic cooling in machining operations. CIRP Journal of Manufacturing Science and Technology, Vol. 55, 2024, pp. 88-97.

[Meng 2024] Meng, F. et al. A novel approach of composite turning for compacted graphite iron using minimum quantity lubrication and liquid nitrogen jetting by a developed setup. Journal of Manufacturing Processes, Vol. 117, 2024, pp. 278-288.

[Moreira 2021] Moreira, M. d. O. et al. Temperature monitoring of milling processes using a directional-spectral thermal radiation heat transfer formulation and thermography. International Journal of Heat and Mass Transfer, Vol. 171, 2021.

[Nor Khairusshima 2013] Nor Khairusshima, M. K. et al. Effect of chilled air on tool wear and workpiece quality during milling of carbon fibre-reinforce plastic. Wear, Vol. 302, 2013, pp. 1113-1123.

[Outeiro 2015] Outeiro, J. C. et al. Thermo-mechanical effects in drilling using metal working fluids and cryogenic cooling and their impact in tool performance. Production Engineering, Vol. 9, 2015, pp. 551-562.

[Pereira 2022] Pereira, G. et al. Cutting temperature measurement and prediction in machining processes: comprehensive review and future perspectives. International Journal of Advanced Manufacturing Technology, Vol. 120, 2022, pp. 2849-2878.

[Plogmeyer 2024] Plogmeyer, M. et al. Tool-integrated thin-film sensor systems for measurement of cutting forces and temperatures during machining. Production Engineering, Vol. 18, 2024, pp. 207-217.

[Promvonge 2005] Promvonge, P. and Eiamsa-ard, S. Investigation on the Vortex Thermal Separation in a Vortex Tube Refrigerator. ScienceAsia, Vol. 31, 2005, pp. 215-223.

[Pušavec 2011] Pušavec, F. et al. Surface integrity in cryogenic machining of nickel based alloy-Inconel 718. Journal of Materials Processing Technology, Vol. 211, 2011, pp. 773-783.

[Pušavec 2019] Pušavec, F. et al. Cooling capability of liquid nitrogen and carbon dioxide in cryogenic milling. CIRP Annals, Vol. 68, 2019, pp. 73-76.

[Ranque 1933] Ranque G. J. Experiences sur la détente giratoire avec productions simultanees d'un echappement d'air chaud d'un echappement d'air froid. J. Phys. Rad. Ser., 1933, pp. 112-115.

[Rattanongphisat 2024] Rattanongphisat, W. and Jansawang, S. An experimental investigation on the effects of the vortex tube material, swirl generator material and the tube length to diameter ratio on vortex tube performance. International Journal of Refrigeration, Vol. 165, 2024, pp. 122-132.

[Röckelein 2025] Röckelein, A. et al. Temperature Measurement with Indexable Inserts via Functional Coating in Turning Processes. Procedia CIRP, Vol. 134, 2025, pp. 247-252.

[Stanford 2009] Stanford, M. et al. Investigation into the use of gaseous and liquid nitrogen as a cutting fluid when turning BS 970-80A15 (En32b) plain carbon steel using WC-Co uncoated tooling. Journal of Materials Processing Technology, Vol. 209, 2009, pp. 961-972.

[Sterle 2021] Sterle, L. et al. The effects of liquid-CO2 cooling, MQL and cutting parameters on drilling performance. CIRP Annals, Vol. 70, 2021, pp. 79-82.

[Swain 2022] Swain, S. et al. A short review on cooling process using compressed cold air by vortex tube in machining. Materials Today: Proceedings, Vol. 64, 2022, pp. 382-389.

[Uhlmann 2021] Uhlmann, E. et al. Boron-doped monocrystalline diamond as cutting tool for temperature measurement in the cutting zone. Procedia CIRP, Vol. 101, 2021, pp. 258-261.

[Villarazo 2023] Villarazo, N. et al. The Effects of Lubricooling Ecosustainable Techniques on Tool Wear in Carbon Steel Milling. Materials, Vol. 16, 2023.

[Wagner 2013] Wagner, W. et al. VDI-Wärmeatlas. Springer Vieweg, Berlin-Heidelberg, 2013. 978-3-642-19981-3