Analysis of Cryogenic Minimum Quantity Lubrication (cMQL) in Micro Deep Hole Drilling of Difficult-to-Cut Materials

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Abstract. In modern manufacturing processes, the environmental impact becomes an increasingly important aspect. The aim of developing new coolant strategies is therefore an approach to increase the efficiency of the machining process while reducing coolant consumption. The priority is to optimize the supply of coolant to the tool-workpiece interface. In case of cryogenic machining, low-temperature liquefied gases are used to cool the tool's cutting edges and to decrease the overall process temperatures. The high cooling rates of this technology can reduce the thermomechanical loads for tools and workpieces especially in machining operations. Since cryogenic medium have no lubricating effect, additional lubrication strategies, e.g. Minimum Quantity Lubrication (MQL), are necessary to enhance the application limits of the cryogenic cooling technology. Nevertheless, in deep hole drilling, using small diameter twist drills, it is impossible to supply internal cryogenic coolant and MQL simultaneously. Therefore, this paper deals with a novel combination of cryogenic Minimum Quantity Lubrication (cMQL) by determining the lubricant's efficiency according to its solubility in liquid CO_2. The strategy leads to a significant increase in performance during deep hole drilling of difficult-to-cut materials and shifts the process limits in terms of tool life and feasible cutting parameters using environmentally friendly MQL techniques.

Keywords: cryogenic MQL · difficult-to-cut materials · small size diameter · twist drill · deep hole drilling · sustainable manufacturing

1 Introduction

Motivated by ecologic and economic demands, cutting processes are increasingly realized without emulsion-based coolant. In mass production, especially in automotive industry applications, it is required to design near dry cutting operations using minimum quantity lubrication. However, in drilling processes it is difficult to realize near dry machining, e.g., in machining of difficult to cut materials such as nickel-based alloy Inconel 718 and stainless steel X90CrMoV18. In such cases, the bottleneck is given by a combination of poor chip evacuation and low cooling rates [1].

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In addition, due to miniaturization trends in many industry sectors, an increasing demand for small-size parts and structures can be found. Hence, reliable manufacturing processes have to be designed to ensure economic value creation. Nevertheless, using small diameter twist drills, internal MQL supply becomes a major problem. Miniaturized cooling channels only enable the transfer of small amounts of coolant. Hence, using internally applied minimum quantity lubrication in demanding dimensions becomes a challenge. Consequently, insufficient lubricant supply could lead to increased tool wear and premature tool failure. Thus, the development of new strategies is necessary to extend process limits of near dry manufacturing processes. One attempt for reliable deep hole drilling processes is realized by high pressure coolant supply. Here a small amount of emulsion based coolant is applied at pressures of $p > 80$ bar. Unfortunately, energy consumption of the required equipment is relatively high, e.g. high pressure pumps [1, 2].

In order to further improve cutting processes, various studies on cryogenic coolants with a focus on process productivity, tool wear and workpiece quality, have been presented in recent decades. These technologies either use liquefied nitrogen (LN_2) or liquefied carbon dioxide (CO_2) to cool the cutting process [3]. The needed equipment defines differentiating factors between these two solutions. Since LN_2 is provided at temperature of $T = -196$ °C of coolant ducts through machine spindle and machine tool need to be insulated. In comparison, CO_2 technique can easily be retrofitted to existing machine tools. For that, the cryogenic coolant can be stored in gas cylinders at a pressure of $p = 57$ bar and at a room temperature ($T = 20$ °C) [2]. Consequently, liquefied CO_2 can be transferred to the point of action without the need for insulation. Expansion of liquefied CO_2 leads to cooling of the gas due to phase transformation and the Joule Thomson effect. To maximize this effect, pressure loss in gas pipes should be reduced to a minimum. Due to the expansion of CO_2, temperature of $T = -79$ °C are achieved [4, 5]. The relaxation of the pressure liquefied gas at the tool tip results in a snow jet containing dry ice crystals and cols CO_2 gas both of which are applied to the point of cutting. Since the lubrication effect of CO_2 is poor, cryogenic cooling can cause high friction at the tool-chip interface and increased tool wear. Thus, cooling techniques providing both cooling and lubrication have to be developed [6], e.g. by adding MQL liquids to the liquefied CO_2. Usually, both liquids are delivered to the chip formation or cutting zone by different pipes and applied individually [7–9]. However, internal supply of both liquids cannot be realized whenever dimensions of tools or tool interfaces with machine spindles do not allow appropriate piping.

A new approach to near dry machining and combining the advantages of CO_2 and MQL has been achieved by generating a single-phase solution from MQL fluids and liquefied CO_2. Thus, liquefied CO_2 is used as transport medium. Owing to the expansion of the CO_2 at the tip of the tools, MQL liquids get atomized and conveyed by the CO_2 flow into the cutting zone. This single-phase cooling and lubricating dissolution does not require special equipment, just one small pipe that easily can be integrated into machine tool. Most importantly, separation by centrifugal forces does not take place. Thus, cMQL can be used in combination with high spindle speeds as required in high speed cutting and machining with small diameter tools.

2 Experimental Setup

In the first place, solubility of MQL fluid in pressure liquefied CO_2 must be tested and optimized accordingly. In addition, cutting tests are required to evaluate the potential of the cMQL. Thus, in order to study effects and performance of cMQL supported metal cutting processes different research areas have to be taken in account. A critical deep hole drilling process using small size twist drills to machine difficult to cut materials has been defined to determine enhanced process limits. Preliminary test were realized with respect to probability of tool breakage due to insufficient lubrication.

2.1 Laboratory Setup to Evaluate Solubility of Different MQL-Fluids

Different MQL fluids were tested with respect to their miscibility with liquefied CO_2. The test rig and additional equipment are depicted in Fig. 1. CO_2 and MQL fluid are filled and mixed in a view cell.

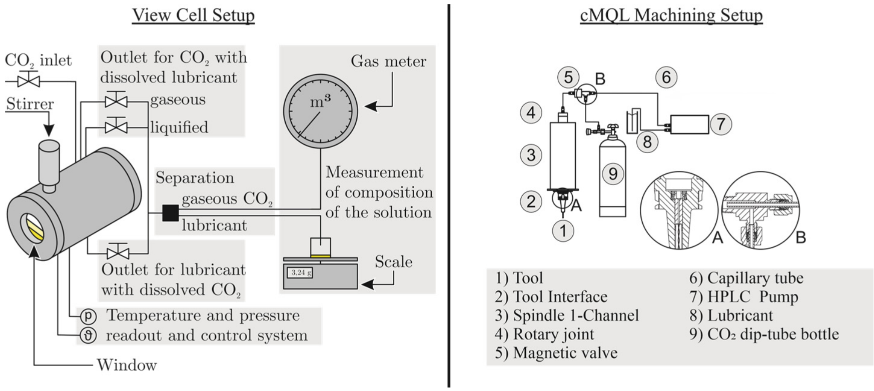

Fig. 1. Left: High pressure view cell; Right: Setup of machining system for cMQL

Pressure as well as temperature of components to be dissolved are controlled and can be adjusted individually. To measure phase equilibrium, samples can be drained off using various outlet valves placed in different positions of the cell. Thus, three different phases of fluids can be observed: CO_2 in lubricant, lubricant in liquefied CO_2 and lubricant in gaseous CO_2. Additionally, the mixing processes and the status of the system can be monitored and documented through an observation window at the front of the view cell. Measuring the phase-equilibrium of mixed fluids took place via a device in which CO_2 and lubricant are separated. In this process, the MQL sample is first deposited in a test tube. Due to the pressure drop, the CO_2 contained in the mixture becomes gaseous and escapes through a gas meter, which measures the contained CO_2 gas volume. Furthermore, the mass of separated lubricant is measured by a micro scale in order to analyze sample composition. At least, residual CO_2 dissolved in separated MQL fluid is eliminated e.g. by heating the sample. The contained CO_2 and lubricant mass can be determined from the volume of escaped CO_2-gas, in the mass of CO_2 dissolved in MQL fluid and the mass of the taken MQL fluid itself. Hence, the exact lubricant and CO_2 composition of the taken sample can be determined. During sampling, it is particularly important to keep pressure in the view cell constant, to avoid disturbance of phase equilibrium. Therefore, a hydraulic piston is used to compensate taken sample volume in the view cell.

As depicted in Fig. 2, a phase diagram can be created, showing the phase equilibrium of CO_2 and MQL fluid depending on temperature and pressure. Most importantly, these test do not only provide information on the maximum soluble amount of lubricant in CO_2 but also on the time needed to generate a saturated solution. These data must be considered, when designing a mechanical system to be integrated in production machine tools.

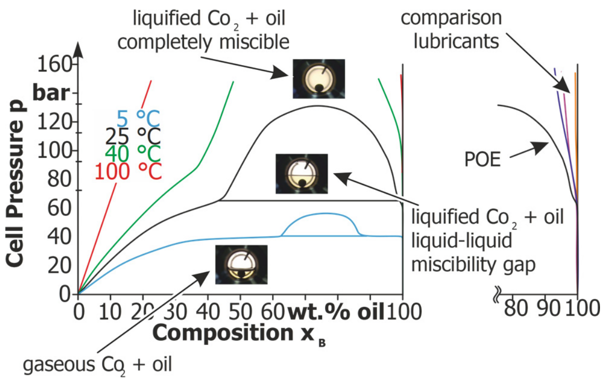

Fig. 2. Phase diagram of a system of polyolester (POE) and CO_2 compared to e.g. mineral oil [based on [10, 11]]

2.2 Machining Setup

As mentioned before, it is beneficial to generate single-phase solution in order to prevent separation of substance during discharge through pipes and machine spindle. On the other hand, MQL fluids not only need to enable the formation of single-phase systems, but also provide lubrication to improve performance of cutting processes. Therefore, a test setup was designed to evaluate the performance of various cMQL compositions in drilling small diameter holes using standard twist drills (Fig. 1). Injection of MQL fluid into CO_2 is controlled by a magnetic valve, which is mounted close to the rotary joint. The lubricant is injected through a second stainless capillary tube in a tee connector, just before the valve. Flow rate and pressure of MQL fluid are controlled by a HPLC-pump (High Performance Liquid Chromatography), which is used to feed the lubricant. The machine tool used enables spindle speeds of up to $n = 30000$ rpm and feed rated up to $v_f = 10$ m/min, thus, HSC and HPC machining processes can be realized.

2.3 Test Planning

This work focuses deep hole drilling in difficult to cut materials using small diameter twist drills. Hence, solid carbide drills with a diameter of $d = 1.4$ mm were used to drill through holes. Workpieces were made out of material 2.4668 (Inconel 718) and 1.4112 (X90CrMoV18) respectively. The tools enable boreholes with a length-to-diameter ratio of l/d = 8, thus, workpiece thickness of $s = 11.2$ mm was selected to fully exploit this ratio. The internal cooling channels of tools have a diameter of $d_{cc} = 0.2$ mm. Thus, low flow rates of CO_2 can be expected and no additional nozzles are required. In general, drilling test were realized under environmental conditions of $T_r = 20$ °C and $pCO_2 = 57$ bar which gives a mass flow of $\dot{m}$ $CO_2 = 2.2$ kg/h. Cutting parameters were set according to tool manufacture's recommendations. Therefore, feed was set to $f = 0.021$ mm. Nevertheless, in drilling 2.4668, cutting speed has to be reduced to $v_c = 25$ m/min whereas 1.4112 can be machined with a cutting speed of $v_c = 60$ m/min. Additionally, pilot holes were used with a depth of $t = 2$ mm. In order to enable a comparison of tool performance when applying cMQL with results achieved with conventional MQL lubrication, appropriate drilling tests were conducted as well. Drilling of nickel-based alloys tends to generate relatively long chips, which tend to jam in deep holes. Therefore, peck drilling was applied to improve chip removal and to minimize risk of premature tool failure. The number of strokes was set to $n = 1$ for cMQL and for eMQL to n = 3 to realize that the cutting edge is sufficiently lubricated. The increased number of machining strokes reduced the thermal load and consequently the tool wear. Evaluation of process and tool performance is based on feed force F_f and drilling torque T_D measured at different intervals and numbers of processes realized. To determine process characteristics the mechanical tool loads were measured at intervals of 25 holes in case of 2.4668 and 50 holes in case of 1.4112 since a higher tool life can be expected in drilling stainless steel compared to nickel based alloys. Furthermore, to evaluate tool wear, chip shape and burr formation a digital microscope was used.

3 Experimental Results

Based on results gained in preliminary tests the solubility of three polyolesters (POE) with different additive compounds have been examined with respect to their capability to develop single-phase systems. The most promising combinations were used to perform cMQL deep hole drilling operations into X90CrMoV18 and Inconel 718.

3.1 Solubility of Lubricants

Three different POE were tested and their solubility in CO_2 was evaluated using the pressure cell shown in Fig. 1. Objective of this study was to find out whether dissolution is depending on mixing respectively processing time. Therefore, tests were carried out at room temperature of $T_r = 20$ °C and a pressure of $pCO_2 = 57$ bar. The dissolution strategy was realized in order to observe short time characteristics, near to the conditions within the machine tool. Thus, stirring was done for $t = 5$ s only, stand still time under pressure was set to $t = 60$ s. These strategy was applied to determine in a first step, the thermodynamic equilibrium solubility. In the second step, it was investigated how this equilibrium can be reached at short contact times. These results are important to know since the mechanical set-up for real machining applications allows only short contact times and it is essential to know whether a single phase or two phases are present at the tip of the tool. The most important results of the solubility test (POE 1 to POE 3) are given in Table 1. For statistical reasons three samples (s.1 to s.3) were taken to determine the amount of MQL fluid dissolved.

Table 1. Measured solubility of lubricants in liquefied CO_2 after t = 65 s

T	POE 1	POE 2	POE 3
	65 s	65 s	65 s
s.1	5.2%	3.6%	0.1%
s.2	2.4%	6.0%	1.8%
s.3	2.8%	4.9%	0.0%
$\bar{x}$	3.5%	3.6%	0.6%

As it can be seen, the average value of solubility of POE 1 and POE 2 is almost constant and relatively high, whereas POE 3 is less soluble. However, it has to be considered, that the deviation of the data gained by three samples is quite high. Consequently, additional and intensive research work has to be done in order to improve reliability of these data. Nevertheless, it can be expected that performance of cutting processes applying either POE 1 or POE 2 will be better compared to processes using POE 3. In Fig. 3, effects and characteristics of dissolution processes are shown after a short stirring and relaxation time of the fluids.

Arrows indicate the different levels of fluids within the cell. The lower part of the cell is filled with MQL fluid or a single-phase solution of MQL fluid and CO_2 after stirring respectively. In the middle of the view cell, there is liquid CO_2 or a solution of liquid CO_2 and MQL fluid respectively, were samples are taken from. Obviously, since the volume of MQL fluid is higher after stirring, CO_2 is dissolved into POE 1 and POE 2 leading to a swelling of the liquid phases. This is especially important regarding machining processes, since there will be almost no specific relaxation time because of

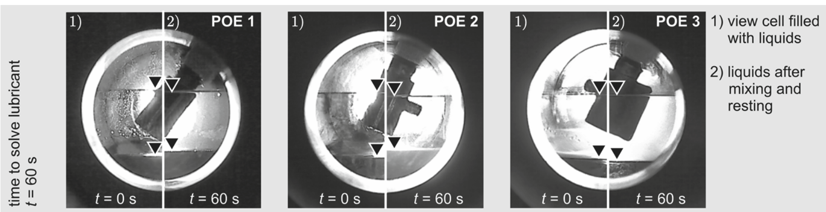

Fig. 3. Observed phase behavior of tested lubricants with liquefied CO_2

the limited length of the pipes providing the fluid through the machine spindle to the tip of tool. Thus, POE 3 probably will not be a suitable for cMQL.

3.2 Cutting Tests

In order to assess potentials of cMQL, deep hole drilling was realized in workpieces made of nickel-based alloy 2.4668 (Inconel 718) and in stainless steel 1.4112 (X90CrMoV18). For the tool life travel path tests, the standard cutting parameters were used (see Chap. 2.3). Furthermore, machining tests were done with different MQL systems. Beside internal cMQL, external (eMQL, $\dot{V}$ = 75 ml/h) as well as an internal double channel MQL system (iMQL, $\dot{V}$ = 75 ml/h) were applied. For internal cMQL the oil flow rate was set to $\dot{V}_{Oil}$ = 6 ml/h, which corresponds to a concentration of $\bar{x}_B = 0.5\%$ of lubricant in the applied coolant mass flow. In order to further investigate potential of cMQL-technique, flow rate of MQL fluid was set to $\dot{V}_{Oil}$ = 30 ml/h ($\bar{x}_B = 1.5\%$) in a second test. The tool life travel path defined the performance of the different configurations. A summary of the results is given in Table 2. It can be seen that external eMQL is not suitable for deep hole drilling in the materials given.

Table 2. Tool life for different MQL systems ($\dot{V}_{Oil,\ cMQL}$ = 6 ml/h; $\dot{V}_{Oil,\ iMQL/eMQL}$ = 75 ml/h)

	cMQL			iMQL	eMQL
	POE 1	POE 2	POE 3	POE	POE
2.4668	1.72 m	1.29 m	1.11 m	<0.1 m	<0.1 m
1.4112	18.4 m	6.05 m	15.18 m	13.3 m	<0.1 m

In case of drilling X90CrMoV18 (1.4112), tool life significantly is enhanced by iMQL compared to eMQL technology. On the other hand, depending in the POE compound there are different effects, positive and negative, onto tool life when applying cMQL as compared to iMQL. Based on the findings on solubility as well as the tool life studies, the following investigations regarding cMQL were carried out using POE 1. As shown in Fig. 4 wear of cutting edges and formation of build-up edges significantly depend on the volume of MQL fluid applied in cMQL as well as in iMQL technology. As it can be seen, exceptional wear marks can be reached easily. It should be mentioned, that cutting tests were stopped once 2000 holes were drilled. Thus, when using cMQL with POE 1, the end of tool life was not reached yet despite of relatively high tool wear. The comparison of tool wear at length of feed l_f = 13.3 m shows, that influence of cooling with less amount of MQL fluid on tool wear is low compared to built-up edge. Nevertheless, by supplying a high volume of lubricant, not only wear rate can be lowered but also an improved process reliability can be achieved since short-shaped chips can be removed easily from high depth. This also relates to burr formation, which did not take significant effect even after 2000 drilled holes. That confirms, that a combination of an efficient cooling and lubrication has to be applied to improve drilling process, like it is in cMQL.

Changing the workpiece material to Inconel 718 (2.4468), thermomechanical load onto tools is much higher. Thus, in drilling nickel-based alloys, the effect on performance and tool life is massive when cMQL technology is realized (Table 2).

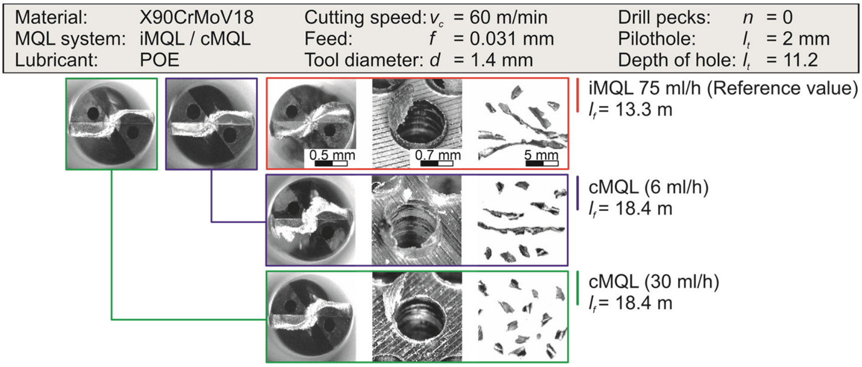

Fig. 4. Comparison of tool wear and burr formation in drilling X90CrMoV18

As compared to conventional MQL, cooling of cutting processes seems to be the key factor, especially when considering the challenging dimensions of the tool. When drilling with eMQL tool failure in most cases occurred, once 5 to 10 processes had been realized. Furthermore, chip formation was affected significantly by coolant technology chosen. Thus, drilling with eMQL generates long threaded chips, which tend to jam in chip flutes and cause tool failure (see Fig. 5 right side). Whereas the high cooling capacity of cMQL ensures formation of discontinuous chips. In addition, process capability and technological process parameters can be increased since discontinuous chips are formed. Hence, cutting speed was increased to 125% ($v_c = 31.25$ m/min) compared to manufacturer's recommendations (red graph). Accordingly, cutting Inconel 718 and applying cMQL productivity of processes can be increased by about 17% (cycle time). A detailed evaluation of process signals measured clearly indicates that in case of drilling Inconel 718, feed force (F_f) and drilling torque (T_D) are significantly smaller when cMQL is used. In addition, force and torque almost stay at the same level during depth of bore.

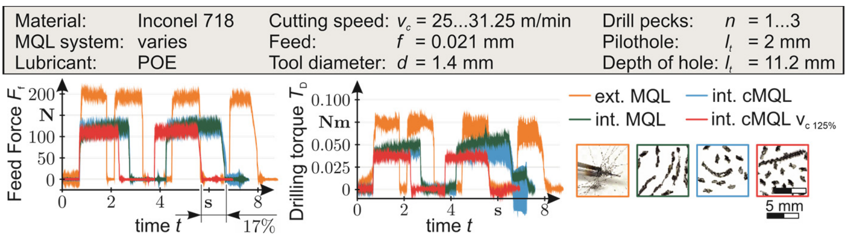

Fig. 5. Measured process force signals and collected chips during drilling Inconel 718

Figure 6 shows the results of drilling tests using a higher concentration of lubricant in the solution (blue) and a cutting speed of $v_c = 31.25$ m/min. As it was shown in drilling X90CrMoV18, a combination of high cooling and lubrication capacity increases tool life significantly. The most important criterion in this process seems to be stability of cutting edges, since breakouts occur in two out of three tools. Differences in the feed force at the beginning of the process can be attributed to the slight deviation of the tool shape. These deviations are within the manufacturer's tolerance. The cause of breakout in tool 1 can easily be found in the jammed cooling channel (Fig. 6 red drill). In case of tool 2, breakout appears after approximately 500 drilled holes. Despite this breakout, however, tool 2 was able to drill a total of 2000 holes. As expected, feed force (F_f) and drilling torque (T_D) were significantly higher after this tool failure occurred. In drilling test of tool 3, 2000 holes were drilled without any process disturbance. Thus, this test clearly shows the potential of cMQL technique. Comparing the chip shape at different feed travel path reflects the high process reliability, since no change can be recognized during the whole tool life. Furthermore, nearly no burr formation can be identified despite the high length of feed. Finally, the uniform wear of tool along the cutting edge, which was achieved with every tool during these tests, should be mentioned.

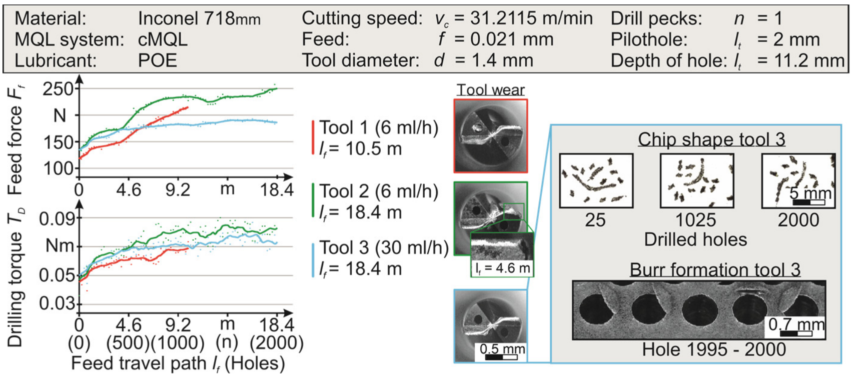

Fig. 6. Measured process force signals, tool wear, burr formation and collected chips during drilling Inconel 718 with cMQL application

4 Conclusion

Machining difficult to cut materials and applying MQL for cooling and lubrication purposes is a challenging process, owing to the fact that the technological window is quite narrow. Depending on workpiece material and machining task, e.g. deep hole drilling of Inconel 718, tool life is poor and reliable process design is almost impossible. To further improve MQL technique, liquefied cryogenic gas (CO_2) was used. Most importantly, MQL fluids, which form single-phase systems, were identified. This feature is prerequisite to enable internal supply of MQL to the tool tip. In doing so, process limits can be significantly increased. The performance of this technology was demonstrated in deep hole drilling of Inconel 718 and X90CrMoV18. In Addition, outstanding tool life can be achieved, if cMQL parameters are optimized with respect to amount MQL dissolved in CO_2 and conveyed to the chip formation zone. Thus, potential of the presented cMQL application is huge, since increased productivity, tool life and bore hole quality could be demonstrated. To further determine process limits and to use full potential of cMQL technique, additional investigations are required. In future investigations the focus will be set on interdependency between lubricant respectively MQL fluid and liquefied CO_2. Furthermore, relationship between process and machining technology must be investigated to gain fundamental process knowledge. Thus, e.g. solubility of different lubricants and their capability as lubricant in machining difficult to cut materials using cMQL will be considered as well. Therefore, drilling Inconel 718 with small diameter twist drills will be investigated by observing tool chip interface in varying cMQL conditions to analyze influence of CO_2 parameters, e.g. influence of pressure p_{CO2} and temperature T_{CO2}, on tool wear (e.g. width of wear mark), borehole quality (e.g. surface roughness, straightness deviations) and chip formation.

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