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The effects of liquid-CO_2 cooling, MQL and cutting parameters on drilling performance

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ABSTRACT

An investigation is made into the effects of liquid carbon dioxide (LCO_2) cooling, minimum-quantity lubrication (MQL) and cutting speed in drilling. Experimental measurements of torque, thrust force and temperature are made over a wide range of process and operating conditions. The resulting empirical models are used to quantify the individual contributions of the controlled parameters on drilling performance, and to facilitate temperature-based process optimization. Of particular interest is the need to carefully adjust the LCO_2 flow rate for any combination of MQL flow rate and cutting speed. The optimization is validated both in simulation and actual drilling tests.

1. Introduction

High-performance drilling with carbide tools normally involves flood cooling, which delivers an emulsion through the tool at high pressure to facilitate heat evacuation and chip removal [1]. Transitioning to fossil-free production requires reduced use and replacement of mineral-oil-based metalworking fluids (MWFs) with more sustainable cooling lubricants. The alternatives must offer optimal cooling and lubrication, something not yet achievable by dry or minimum-quantity lubrication (MQL) substitutions of conventional flood cooling. Nevertheless, the recently developed lubricated liquid carbon dioxide (LCO_2) system using pre-mixed LCO_2 and oil delivered via MQL principle offers a viable solution. Here the lubricant is first injected into the stream of LCO_2, where it dissolves and then atomizes into small oil droplets when exiting the nozzle [2]. In this system, the efficiency of cooling and lubrication depends on the LCO_2 and MQL flow rates [3,4]. This technology solves the problem of excessive temperatures and tool wear [5] in dry drilling. Similarly, it overcomes the limitations of using (pure/straight) liquid nitrogen (LN_2) in cryogenic drilling [6]: the inability to provide lubrication and evacuate chips from the cutting zone. In addition, excessive LN_2 cooling can induce higher mechanical loads and lead to tool fracture or shorter tool-life compared to flood cooling because low temperatures and improper lubrication [7] lead to higher torques and thrust forces. In general, MQL is able to reduce cutting temperatures compared to dry drilling [8], but not to the extent of flood cooling [9].

When investigating temperatures in drilling, researchers typically use FEM simulations [6,7,10-12] or pyrometers along with thermocouples [9], which are inserted into the internal cooling channels of the drill [5] or embedded in the workpiece [8]. Most of these studies are concerned with the influence of cutting parameters on temperature for various cooling-lubrication methods (e.g., dry vs. flood vs. MQL). However, no investigation has yet been made into the combined effects of LCO_2 and MQL at different cutting speeds while simultaneously delivering cooling-lubricant through the tool in a single channel. Therefore, research is needed to understand the joint LCO_2+MQL cooling and lubrication effects to achieve the desired heat removal, friction and chip evacuation from the cutting zone.

This paper discusses an experimental investigation into the effects of cutting speed, LCO_2 and MQL flow rates on torque, thrust force and temperature in drilling of chromium-molybdenum steel. With this approach, the effect of cooling and lubrication can be analyzed individually or in combination. Experimental measurements are modelled empirically and analyzed via the extended Kienzle equation. Finally, the models are used for temperature-based optimization of cooling, lubrication and cutting conditions.

2. Experimental

Drilling tests were performed using a 6-axis robot (KUKA KR150), modified for through-spindle LCO_2+MQL delivery via a single-channel. This application was chosen due to the increasing demand for robot drilling in aerospace industry. Solid carbide drills with AlCrTiN coating and internal cooling channels were used (Sumitomo SDP 0400 U 3 HAK; diameter $D = 4$ mm; lip clearance angle φ = 140°). An HSK-A40 shrink-fit tool-holder was adapted to accommodate the LCO_2+MQL supply channel. The workpiece material was 42CrMo4 steel (quenched and tempered, tensile strength 1000 N/mm^2, hardness 31 HRc) with 10 mm thickness. The experimental setup is shown in Fig. 1.

Cutting forces were measured using a Kistler 9273 dynamometer. Temperature was measured using an infrared pyrometer (Optris CTLaser3MHCF2, temperature range 150−1000 °C). The

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pyrometer was aligned with the axis of the drill – measuring temperature (spot diameter 2 mm) at the instant when the drill exited/penetrated through the workpiece material (see Fig. 1, top left). The bottom side of the workpiece surface was painted with black paint (resistant up to 1000 °C, emissivity 0.95). Forces were sampled at 10 kHz (using NI9234 A/D card), while pyrometer-measurements sampling was done at 300 Hz. Signals were processed with LabView/MATLAB. Drilling was done at three different cutting speeds (v_c = 30, 50, 70 m/min) at a constant feed rate of f = 0.1 mm/rev.

The drilling allowance/depth for each cut was 10 mm, which was sufficient for the drill to penetrate through the entire workpiece. Single-channel LCO_2+MQL delivery used the ArcLub One system, equipped with two Coriolis mass-flow controllers. The flow rate was varied (LCO_2: q_{LCO2} = 0, 125, 250 g/min; MQL: q_{MQL} = 0, 50, 100 ml/h). It is important to note that zero LCO_2-flow and non-zero MQL-flow tests utilized only a gaseous CO_2 as a carrier medium at room temperature at a flow rate of 10 g/min. MQL used Rhenus Lub SSB neat oil (viscosity 3.5 mm^2/s at 20 °C). A full factorial design of experiments was employed for test planning, resulting in 27 unique drilling conditions (where v_c, q_{LCO2}, q_{MQL} were all varied at three levels, as given above). Since each test was replicated three times, the total number of experiments was 81.

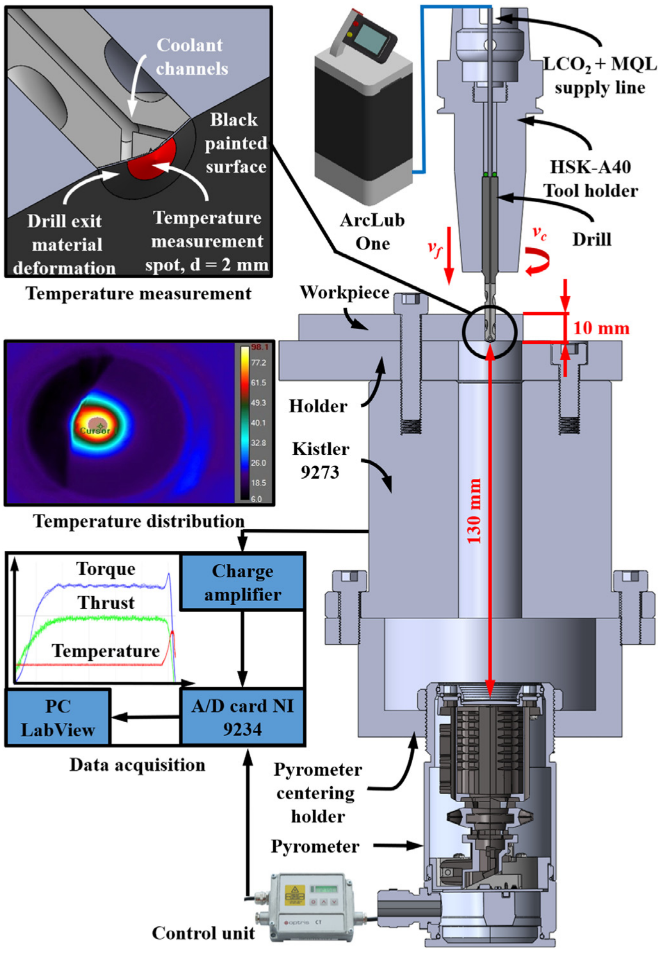

Fig. 1. Illustration of the experimental setup.

The temperature reached a maximum on a conical cap – just before the tip of the drill exits the workpiece. To evaluate how far from the cutting zone the temperature was measured, a typical workpiece cap was analyzed across its thickness (Fig. 2). To determine the thickness of the conical cap, three samples were collected, cut in half (Fig. 2a), and measured using a Keyence VHX-6000 digital microscope (Fig. 2b). The thickness was found to be uniform across all samples, with an average value of 65 ± 10 µm.

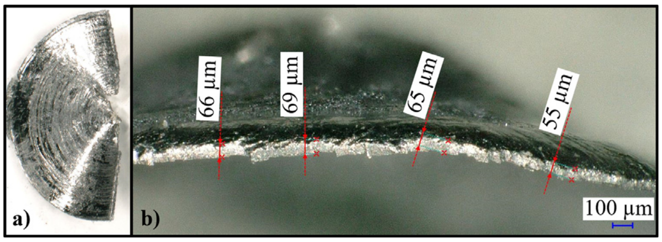

Fig. 2. Conical cap: a) sample cut in half; b) thickness measurements.

3. Results

Drilling performance was evaluated by measuring torque, thrust force and temperature for various combinations of v_c, q_{LCO2} and q_{MQL}. An example is shown in Fig. 3, where average values of torque and thrust are given along with maximum temperature. The largest variation is seen in the torque, which decreases greatly before stabilizing once the lubrication is introduced (Fig. 3c). This trend was observed for all cutting speeds and all LCO_2 flow rates due to a reduction of chip clogging during chip evacuation. Note that straight LCO_2 delivered at 5.7 MPa also assists the chip evacuation. However, the major contributor to torque reduction and stabilization is MQL, which simultaneously lubricates both the cutting zone and the chip-evacuation channels.

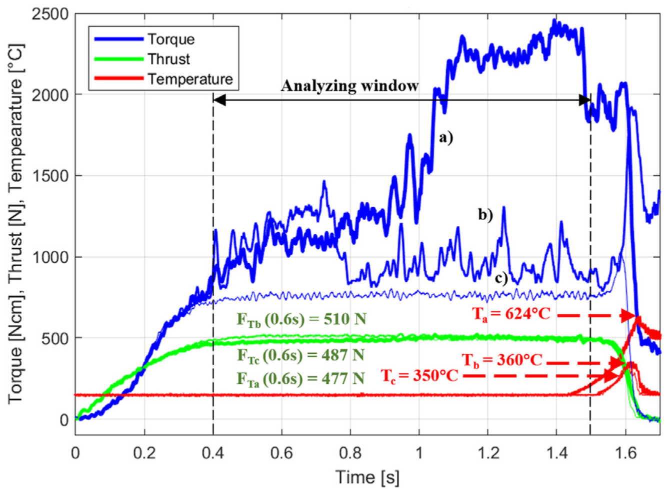

Fig. 3. Drilling performance at v_c = 50 m/min: a) dry; b) q_{LCO2} = 125 g/min and q_{MQL} = 0; c) q_{LCO2} = 125 g/min and q_{MQL} = 100 ml/h.

The effects of LCO_2 and MQL on thrust force are not as pronounced. However, LCO_2 can reduce the drilling temperature (and limit workpiece-material softening), especially at higher flow rates. The measured torque, thrust force, and temperatures were used to develop empirical models, which were then used to analyze and optimize cutting speed and LCO_2 and MQL flow rates. The modeling was non-parametric – based on natural neighbor interpolation and Delaunay triangulation of experimental data [13]. Here, the "nature" of the functional relationship between the response (dependent) and the explanatory (independent) variables is not predetermined (which is in contrast to parametric regression), but are adjusted to capture "hidden" features of the data. The resulting response surfaces for torque, thrust force and temperature are shown in Figs. 4, 5 and 6, respectively.

3.1. Torque

Measured torque values ranged from 0.68 Nm to 1.55 Nm. The maximum torque occurred in dry drilling at v_c = 50 m/min, where excessive chip clogging was observed. An increase in cutting speed from 30 to 50 m/min resulted in an average torque increase from 1.2 to 1.55 Nm. However, the torque subsequently dropped to 1 Nm at the highest cutting speed (v_c = 70 m/min). This is likely related to unpredicted chip clogging (because friction coefficient decreases at higher speeds) and material softening at elevated temperatures. All surges in torque occurred under dry conditions – without lubrication and poor chip evacuation. Straight LCO_2 (q_{MQL} = 0) rectified the situation somewhat by adding pressure (5.7 MPa) to the process to aid chip evacuation. This resulted in decreased torque values to 0.85–0.95 Nm (q_{LCO2} = 125 g/min). Nevertheless, a further increase in LCO_2 flow rate (q_{LCO2} = 250 g/min) proved not beneficial. Here, the torque values rose again to 1.0–1.1 Nm, as excessive cooling hindered material softening. It should also be noted that MQL had an effect even at the highest LCO_2 flow, resulting in lowering the torque from 0.9 to 1.0 Nm to 0.7 Nm at the cutting speed of 50 m/min. This clearly demonstrates the need to optimize the LCO_2 flow rate. The addition of MQL to the LCO_2 flow completely eliminated chip clogging. In this case, the torque values were reduced to 0.68–0.79 Nm (with q_{MQL} = 50 ml/h being sufficient to achieve such reduction). Increasing the q_{MQL} to 100 ml/h did not bring tangible benefits in terms of torque reduction. Again, this illustrates the need to optimize q_{MQL} in parallel to q_{LCO2}.

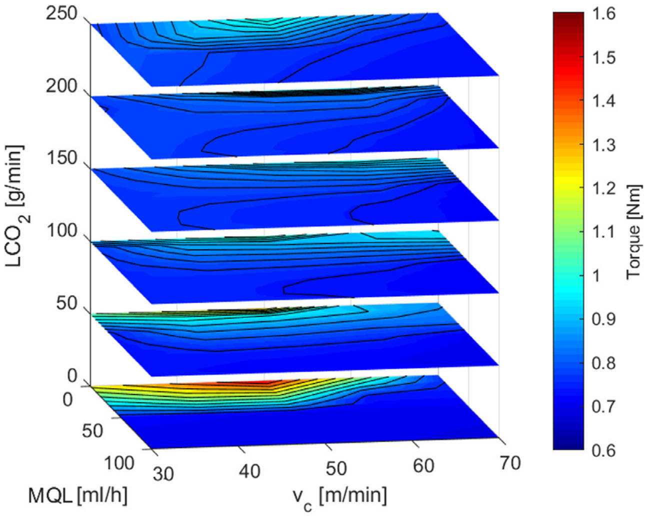

Fig. 4. Torque vs. v_c, q_{LCO2} and q_{MQL}.

To quantitively evaluate the influence of v_c, LCO_2 and MQL, the extended Kienzle equations for F_c and F_f have been constructed:

$$F_i = k_{c1,1} b h^{(1-m_c)} e^{v_c \cdot a_{i0}} e^{LCO_2 \cdot a_{i1}} e^{MQL \cdot a_{i2}}; \ i = c, f \quad (1)$$

where $b = \frac{D}{2 \cdot \sin\varphi/2}$ and $h = \frac{f}{2} \cdot \sin\varphi/2$. The experimentally obtained values were: specific cutting force $k_{c1,1}$ = 1823 N/mm^2 and coefficient m_c = 0.25. The remaining factors were as follows: a_{c0} = 0.003; a_{c1} = −0.0004 and a_{c2} = −0.003, indicating the effects of cutting speed, LCO_2 and MQL. Here, MQL has the biggest effect on torque, shown by the larger base values compared to the cutting speed along with the sign (negative). This confirms the observed behavior, where MQL significantly improves chip evacuation. In addition, more lubricant added to the LCO_2 flow lowers the torque.

3.2. Thrust force

The measured thrust forces ranged from 441 to 522 N (variation of ± 10% from mean value). The highest thrust force was observed at maximum the cooling rate of q_{LCO2} = 250 g/min, i.e., at the lowest temperatures, which limit material softening. Both MQL and cutting speed had little effect on thrust force, although higher temperatures at higher speeds lead to a slight decrease in the force. Chip clogging could also potentially add to the thrust force via friction between chips and the drilled hole wall. The factor analysis was based on extended Kienzle's model of the thrust force F_f. The experimentally determined specific feed force was $k_{f1,1}$ = 2259 N/mm^2, with coefficient m_f = 0.25. The fitted factors were the following: a_{f0} = −0.0005, a_{f1} = 0.0032 and a_{f2} = −0.0005. This confirmed that LCO_2 had the greatest influence on thrust force – as higher thrust forces can be expected with increasing flow rate. Increased cooling is usually beneficial for tool life. However, excessive cooling can also result in higher mechanical loads on the tool, which can have a detrimental effect.

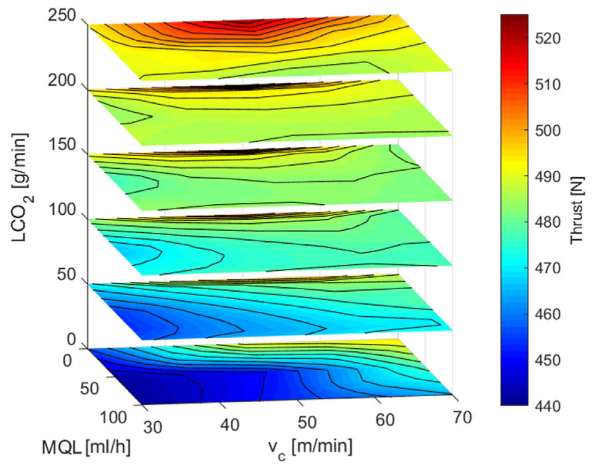

Fig. 5. Thrust force vs. v_c, q_{LCO2} and q_{MQL}.

3.3. Temperature

Observed temperatures were between 179 °C (v_c = 30 m/min; q_{LCO2} = 250 g/min; q_{MQL} = 100 ml/h) and 624 °C (v_c = 50 m/min; dry). Such a wide operating window (± 55% variation from mean) clearly points out the need for optimization. As expected, dry drilling yields the highest temperatures and LCO_2 the lowest. For example, straight LCO_2 can reduce the temperature to 224 °C (at v_c = 30 m/min, a 62% drop) and to 345 °C (at v_c = 70 m/min, a 42% drop). This temperature decrease affects the thrust force, whereas its effect on torque is limited. On the other hand, MQL is able to reduce the temperature by 150 °C at v_c = 30 m/min (24% decrease), and by 70 °C at the highest cutting speed (13% decrease). This is in line with [9], which reports 20–25% temperature reduction when using MQL compared to dry drilling. Note also that MQL's temperature-reduction potential is the highest at a lower LCO_2 flow rate (up to 100 g/min).

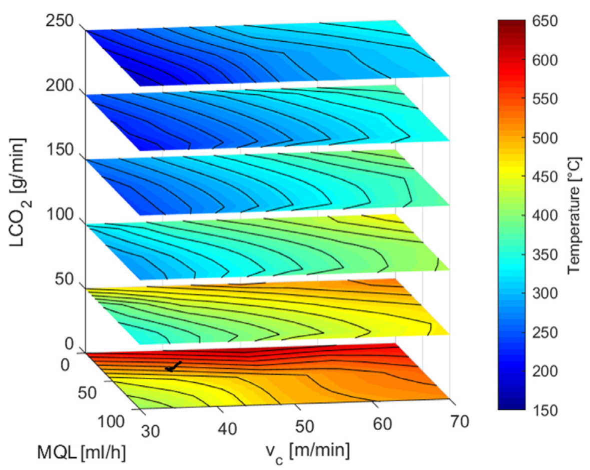

Fig. 6. Temperature vs. v_c, q_{LCO2} and q_{MQL}.

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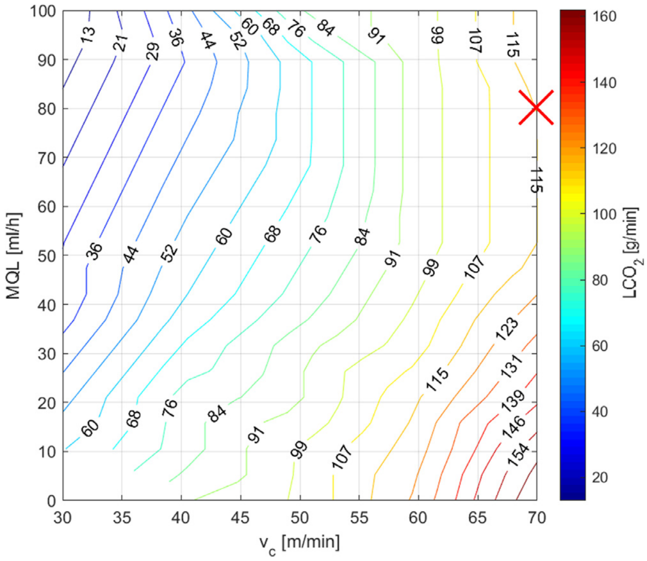

Fig. 7. Drilling conditions to achieve a temperature of $T_m = 400\,°C$ at a distance of 65 µm from the cutting edge (red cross shows the optimum). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Temperature based optimization and validation

Thermo-mechanical tool properties determine the temperature threshold, beyond which rapid tool wear occurs. For AlCrTiN coating, the wear rate starts to increase beyond 700 °C [14].

Therefore, the threshold was set to a critical tool temperature of $T_c = 700\,°C$. The actual temperature on the cutting tool was estimated using the measured temperatures in orthogonal cutting of 42CrMo4 steel [15,16], where the tool temperature reached $600\,°C \pm 44\,°C$, while the temperature $65\,°C \pm 10$ µm below the cutting edge (corresponding to this case study) reached 300 °C ± 94 °C. The difference between the measured temperature on the drill's conical cap and the cutting edge is thus estimated to be around 300 °C, which is taken into account when correlating measured, threshold and optimum temperatures. Based on T_c, the maximum allowable measured temperature on the drill's conical cap (to prevent a rapid degradation of the coating) is expected to be around $T_m = 400\,°C$.

The process cooling and lubrication conditions to reach the tool's optimal performance are shown in Fig. 7, where the isolines point out the necessary flow of LCO_2 for a given cutting speed and MQL flow to obtain the desired temperature T_m. Here the goal is to decrease the LCO_2 consumption (and costs) − not to a minimum, but to the level that is required by the process. The optimal cutting speed to achieve targeted productivity in this application is $v_c = 70$ m/min., which necessitates the use of $q_{MQL} = 80$ ml/h to omit clogging of chips during their evacuation. Based on these two constraints, the optimal LCO_2 flow rate equals $q_{LCO2} = 115$ g/min.

Finally, the validation of optimized drilling conditions was carried out, resulting in the following measured values: average torque 0.718 Nm and thrust force 471 N, at a temperature of 374 °C. These measurements show good agreement with simulated/predicted torque and thrust force (Eq. (1)), i.e., 0.772 Nm and 472 N, respectively.

4. Conclusions

An investigation was made into LCO_2- and MQL-assisted drilling of 42CrMo4 steel. Torque, thrust forces and temperatures were measured. Cooling, lubrication and cutting conditions were analyzed and optimized. The specific findings are as follows:

- LCO_2 cooling improves chip evacuation by means of pressure. This only partially reduces high torque peaks due to chip clogging. However, it provides poor lubrication.
- MQL has a significant influence on reducing and stabilizing torque as it reduces the friction between chips, the drill flutes/hole walls and at the cutting edge. A flow rate of 50 ml/h proved sufficient, while higher flow rates provide little additional benefit.
- Thrust force depends on temperature and clearly correlates with the LCO_2 flow rate. MQL and cutting speed have less of an influence. In the absence of cooling, a reduction in thrust force is due to material softening at higher cutting speeds.
- The highest temperature of 624 °C occurred under dry conditions. MQL proves more efficient at lower cutting speeds. LCO_2 has the highest cooling capacity, keeping temperatures below 350 °C for all tested cutting speeds. LCO_2 + MQL combination gives the lowest temperatures.
- Temperature-based process optimization is proved feasible. Reaching the optimal performance requires optimizing the LCO_2 flow rate for a given cutting speed and MQL condition.

Declaration of Competing Interest

None

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