Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 141 (2026) 168–172

www.elsevier.com/locate/procedia

10th Conference on High Performance Cutting (CIRP-HPC 2026)

Development and Validation of a Resource-Efficient Tribometer for Cutting Fluid Evaluation

Jan Wolf[a,*], Adrian Fried[a], Nithin Kumar Bandaru[b], Martin Dienwiebel[b,c], Hans-Christian Möhring[a]

[a]*Institute for Machine Tools (IfW), University of Stuttgart, Holzgartenstraße 17, 70174 Stuttgart, Germany*
[b]*Institute for Applied Materials (IAM), Microtribology Center µTC, Karlsruhe Institute of Technology, Straße am Forum 5, 76131 Karlsruhe, Germany*
[c]*Fraunhofer Institute for Mechanics of Materials (IWM), Wöhlerstraße 11, 79108, Freiburg, Germany*

* Corresponding author. Tel.: +4971168583834; *E-mail address:* jan.wolf@ifw.uni-stuttgart.de

Abstract

Guide pads provide radial support of the tool head and thereby enable high dimensional accuracy and low surface roughness of the borehole. Due to their direct contact with the borehole wall, guide pads are exposed to complex tribo-mechanical loads, which can lead to pronounced adhesive wear when machining difficult-to-cut materials such as austenitic steels. To systematically evaluate the influence of different cutting fluids on guide pad wear, a tribometer was upgraded with a closed-loop coolant supply system. This modification enables resource-efficient wear testing under process-relevant normal stresses and sliding velocities. Five cutting fluids were investigated with respect to their time-dependent wear behaviour using optical 3D measurements based on focus variation and a profile-based evaluation method that allows reproducible quantification of wear scar evolution. The results reveal significant differences between the tested fluids: While one cutting fluid exhibited almost no material removal due to the formation of a protective tribofilm that effectively suppressed adhesion, other fluids resulted in material losses, irregular wear craters. The experimentally determined ranking of the cutting fluids aligns with observations from industrial deep hole drilling operations, validating the functionality and suitability of the tribometer. Results have implications for cutting fluid developers, as only 15 liters of liquid are required for evaluation.

© 2026 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/)
Peer-review under responsibility of the scientific committee of the 10th Conference on High Performance Cutting (CIRP-HPC 2026)

Keywords: cutting fluid; wear; tribometer

1. Introduction

Guide pads are central functional elements of deep-hole drilling tools. During the machining process, they provide radial guidance of the tool head within the borehole, thereby contributing significantly to high accuracy as well as low surface roughness. However, due to their direct contact with the borehole wall, guide pads are exposed to high tribological loads. The resulting contact forces arise from a combination of mechanical pressure, relative movement between the tool and workpiece, and thermal effects during chip formation. Especially when drilling difficult-to-machine materials, such as austenitic steels, pronounced adhesion tendencies lead to accelerated wear. To increase tool life and ensure borehole quality, guide pads are therefore specifically optimized with regard to geometry and coating. Further, the optimization of the cutting fluid plays a crucial role in wear behaviour. Gerken et al. [1] therefore reasons that the local lubrication conditions at the guide pad contact represent a key factor for process stability and tool life.

Water-mixable emulsions are predominantly used in industrial deep-hole drilling due to their favourable cooling

2212-8271 © 2026 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/)
Peer-review under responsibility of the scientific committee of the 10th Conference on High Performance Cutting (CIRP-HPC 2026)
10.1016/j.procir.2026.03.089

performance and additivation with extreme-pressure and anti-wear components. However, tribological studies on machining-relevant contacts demonstrate that lubrication under such conditions is typically governed by boundary lubrication rather than full-film hydrodynamic effects. The effectiveness of a cutting fluid is therefore strongly linked to its ability to form protective boundary or tribochemical films under high normal pressures and sliding velocities [2].

This aspect becomes particularly critical when machining austenitic stainless steels, which exhibit pronounced adhesion tendencies and promote accelerated guide pad wear. Experimental investigations on deep-hole drilling of AISI 304 conducted by Felinks et al. [3] confirm that bore quality and wear behavior are strongly dependent on the selected cutting fluid, indicating that lubrication at the guide pad and bore wall interface is decisive for process performance.

Despite this relevance, systematic and resource-efficient laboratory methods for evaluating cutting fluid performance with respect to guide pad wear under process-relevant conditions remain limited.

When studying the wear behaviour under metal cutting conditions, significant challenges arise, as custom laboratory tribometers are not capable of reproducing the normal pressures, velocities and temperatures found in the cutting regime. Therefore, a custom tribometer depicted in Figure 1 was recently proposed by Wolf et al. [4]. Although several designs of these tribometers were presented and compared in the literature review by Schulze et al. [5], they are mostly used to determine friction coefficients between tool coatings and work materials under dry cutting conditions. Only in some cases these tribometers were used with coolant supply, as studied by Rech et al. [6] while even fewer focus on the actual wear behaviour like Rech et al. [7].
When summarizing the state of the art, it is clear that previous studies did not utilize custom tribometers for specifically studying the wear progression of pins or guide pads with application of cooling. Further, it is not known whether these setups enable the quantification of the influence of various cutting fluids on the wear propagation. This study therefore aims to close this gap.

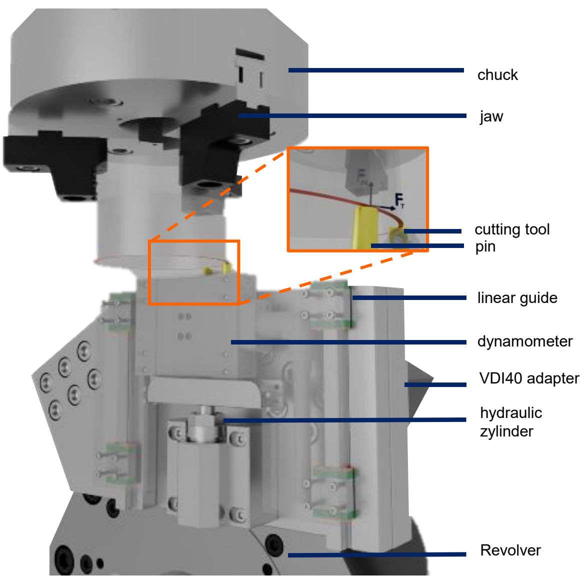

Fig. 1. Utilized tribometer published in Wolf et al. [4].

2. Materials and Methods

The tribometer operates on a pin-on-disk principle to replicate cutting conditions and is mounted directly on a lathe EMAG VLC 250. Forces on the pin are measured using a Kistler 9119AA2 multicomponent dynamometer, which captures both normal and tangential forces up to 4 kN. Normal load is applied via a HAWE 16-8 hydraulic cylinder capable of generating up to 10 kN at 500 bar, powered by a Röhmheld 7.1600 hydraulic unit with a maximum flow of 0.82 l/min. The dynamometer is guided along the z-axis by HIWIN MGN12 linear rails to ensure precise movement. The tribometer in Figure 1 is upgraded to a new version depicted in Figure 2 to support a closed loop coolant supply. The aim of this setup was to allow the evaluation of cutting fluids without the need to equip an entire CNC machine with hundreds of liters of fluid, which would hinder systematic testing due to high costs and excessive waste when assessing multiple fluids. First, the custom VDI40 tool holders were utilized to assemble an aluminium plate for fluid collection. The plate features a drain to direct the fluid back to a reservoir with a pump. The pump supplies the fluid via a blue hose back to the guide pad. Acrylic sheets were employed to collect droplets. An additional adapter mounted on the dynamometer is installed which enables the installation of the actual guide pad holder with a high positional repeatability due to the shoulders of the adapter. This is necessary if the guide has to be removed in between the experiments for wear assessment. O-rings are used to seal threaded connections. In the centre of the aluminium plate, there is an opening through which a tool and the pin holder protrude. To seal this area, this part of the tribometer was completely lined with a film, which was pulled over the edges of the opening and pressed in place by an additional clamping plate. With equation (1) the static hertzian contact pressure σ_H can be calculated given the normal force F_N, the Young's modulus of the disk E_1 and the guide pad E_2, the length of the contact l, radius of the guide pad r and the poisson ratio ν.

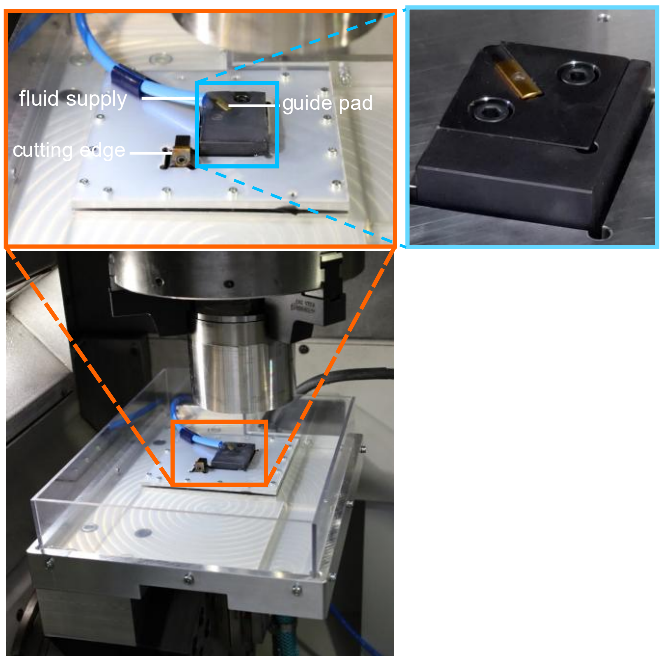

Fig. 2. Upgraded tribometer for closed loop coolant supply.

$$\sigma_H = \sqrt{\frac{2F_N E_1 E_2}{2\pi r l (E_1+E_2)(1\text{-}\upsilon^2)}} \qquad (1)$$

Tubes with diameter 114.3 mm were used as the workpiece. The radius of the guide pads is 6.45 mm. The normal force is chosen as 300 N to reach a normal stress of 1 GPa, which is typical in the cutting regime. The cutting speed is set to 50 m/min, representing industrially relevant machining conditions. Tribometer tests were interrupted in time increments of one minute with a total experimental time of four minutes. To evaluate the guide pad conditions, the confocal microscope Alicona G5 was used. Therefore a time discrete wear development could be captured. The Alicona measurements were evaluated with the following workflow: Based on the 3D dataset, a cross-sectional line was defined across the wear region, from which the software automatically extracted the corresponding two-dimensional height profile. The resulting profile was then exported for further analysis, enabling quantitative assessment of surface geometry and potential wear characteristics. After extracting the x- and y-coordinates of the averaged profile into a text file, the data were analyzed in a Python program. Two intervals corresponding to regions without observable wear were then selected to serve as the basis for a circle approximation. Using these intervals, a circular fit was applied to reconstruct the unworn profile, providing an approximated representation of the original, unaltered surface geometry. Furthermore, the highest point of the fitted circle was selected as a reference, enabling the consistent superposition of subsequent measurements of the same guide pads. The methodology is shown in Figure 3. In total five emulsion cutting fluids, each with a concentration of 10 %, designed for deep hole drilling were tested. For confidentiality reasons, the manufacturer and product name are not disclosed and the cutting fluids are renamed instead as fluid one to five. When ordering the cutting fluids wear behaviour based on prior deep-hole drilling operations, the manufacturer expects the cutting fluid one perform the best up to five, which is supposed to be the least favourable.

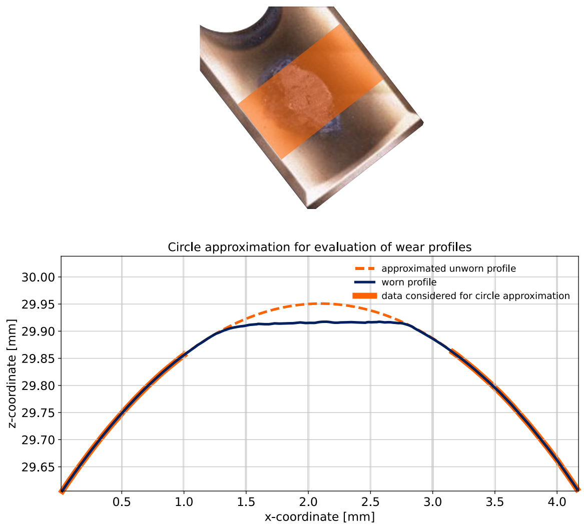

Fig. 3. Selected worn region of the guide pad (top) and extracted wear profile (bottom).

3. Results

The results of the wear experiments with five selected cutting fluids are depicted in Figure 4 for an interval of 60 s. The adhesive tendency of V2A on the guide pads was observed to varying degrees. While no adhesive wear was detected for cutting fluid 1, the other applied cutting fluids, particularly cutting fluid 5, offered reduced protection against adhesion. Considering the height of the contact zone, which corresponds to the wear mark width, the fluids can be ranked in ascending order from cutting fluid 1 to cutting fluid 5. However, it was noted that regions with material adhesion change over the duration of use, with localized detachment of adhered material occurring. Since all guide pads were measured three-dimensionally prior to the wear tests, a direct comparison between unworn and worn guide pads in the z-direction allows the creation of a difference mask, as illustrated in Figure 5, where the final wear marks after 240 s are compared with the unworn guide pads for each studied cutting fluid.

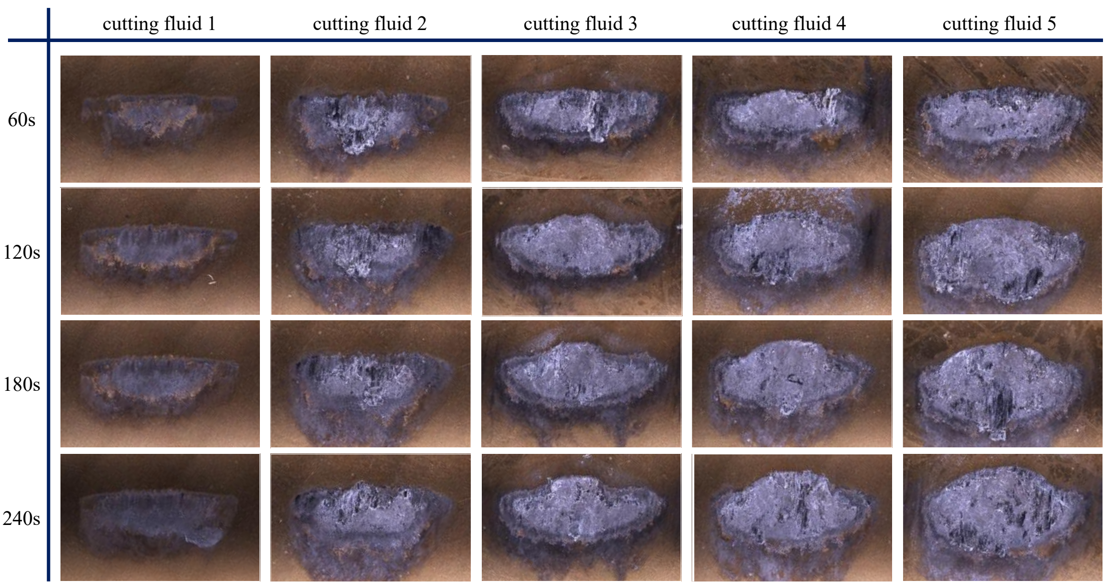

Fig 4: Wear behaviour of guide pads depending on cutting fluid.

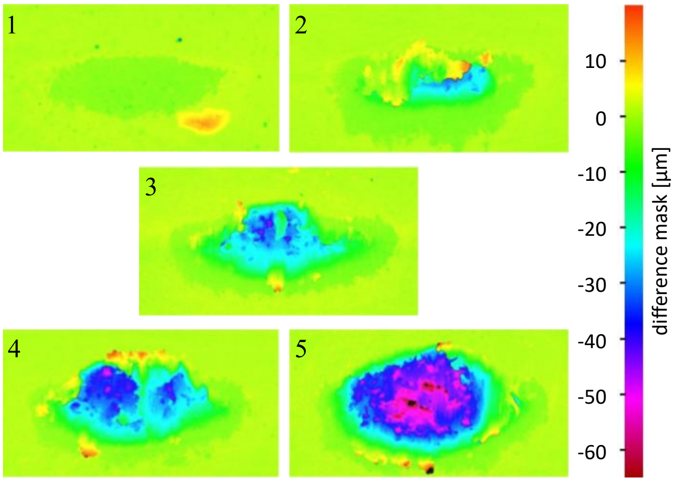

Fig. 5: Height difference mask for the selected cutting fluids 1 to 5 after 240s.

The comparative analysis of the surface profiles highlights the significant influence of the applied cutting fluids on wear behavior. While some fluids resulted in pronounced wear craters with depths of up to 60 µm, others exhibited only moderate wear in the range of 30 µm. Notably, the test with cutting fluid 5 showed the greatest material loss, forming a large and deep wear crater. Even the results with moderate material loss (top right, center, bottom left) reveal irregular wear patterns, which appear to result less from abrasive removal and more from localized material breakouts and adhesive interactions. In contrast, the experiment with cutting fluid 1 (top left) exhibited different behaviour. No significant wear craters were formed and only a slight material build up was observed outside the actual contact area. Noticeably, this cutting fluid was the only one which resulted in a protective tribofilm on top of the guide pad as depicted in Figure 6. The tribofilm protected the guide pad's surface from interaction with V2A, preventing, micro-welding between the pin and disk and thus suppressed the formation of adhesive material breakouts. The comparison clearly demonstrates that the formation of a tribofilm provides the most effective protection against extensive material loss and drastically reduces wear depth compared to the other cutting fluids. With the evaluation methodology presented in chapter 2, the average wear profiles of the guide pads were determined and are shown in Figure 7.

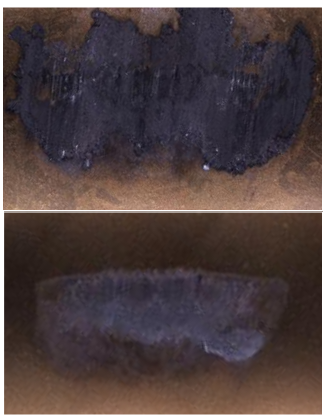

Fig. 6: Resulting profile measurements for cutting fluid one (top) to cutting fluid five (bottom) dependent on time.

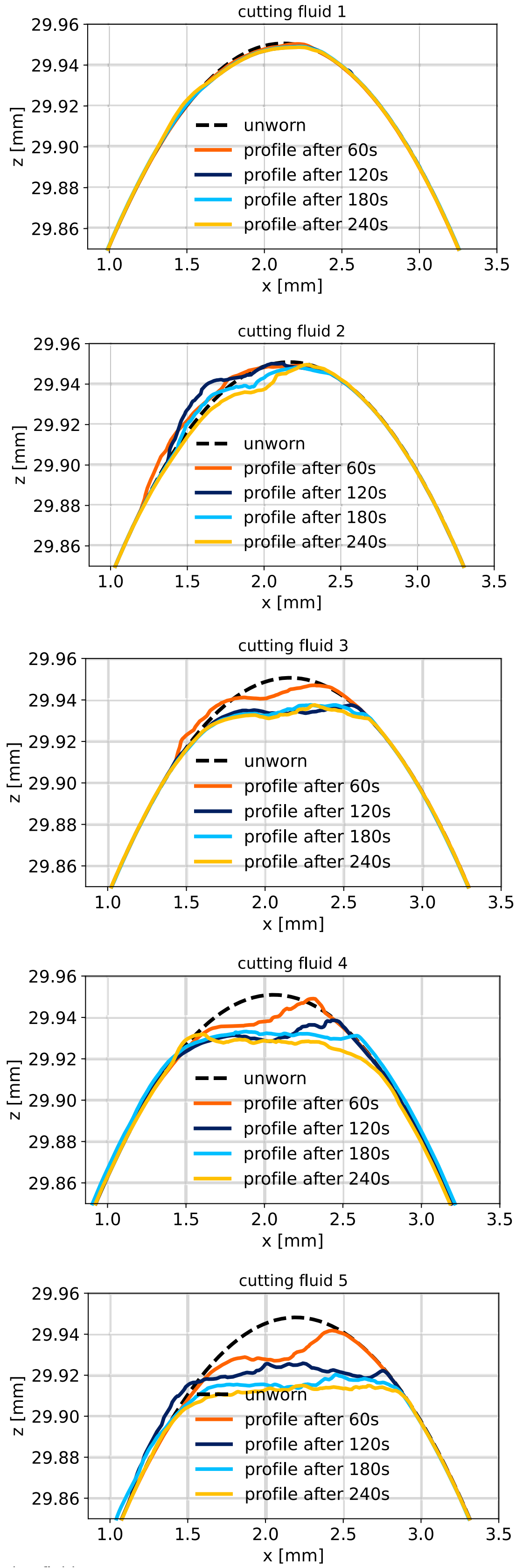

Fig. 7: Resulting profile measurements for cutting fluid one (top) to cutting fluid five (bottom) dependent on time.

An examination of Figure 7 also reveals a pronounced influence of the individual cutting fluids on wear progression. For cutting fluids 3 to 5, measurable material removal in the central region of the profile is already evident after 60 s. As the test duration increases, the profile continues to flatten, while beyond approximately 180 s, hardly any further changes occur. In contrast, cutting fluid 1 shows almost no change in profile shape, while cutting fluid 2 performs as expected by the developer, ranking second-best. This figure complements the observations from Figure 5, as it provides insight into wear progression over the duration of use and eliminates the time discrete wear state inherent in the wear characteristics observed at the 240 s mark.

It is commonly known, that the coefficient of friction (COF) in tribometer tests is strongly linked to the wear progression. Therefore, time series of the friction coefficient are captured to quantify the process conditions at the interface between guide pads and the workpiece. The results are shown in Figure 8, where the top plot shows an exemplary collected times series for cutting fluid 1, whereas the bottom plot depicts the difference of recorded COF depending on the cutting fluid with a sliding window spanning 1s for smoothing. During the tests, cutting fluid 5 exhibited the highest and most unstable friction levels. This shows a general trend in which higher friction corresponds to increased material loss. At the beginning of each test, the friction coefficient decreased noticeably, reflecting a short run-in phase in which surface asperities are smoothed and a more stable contact or lubricating film is established. Several fluids showed pronounced friction spikes later in the test. These spikes can occur when adhesive material builds up and is suddenly removed, which is consistent with the higher wear observed.

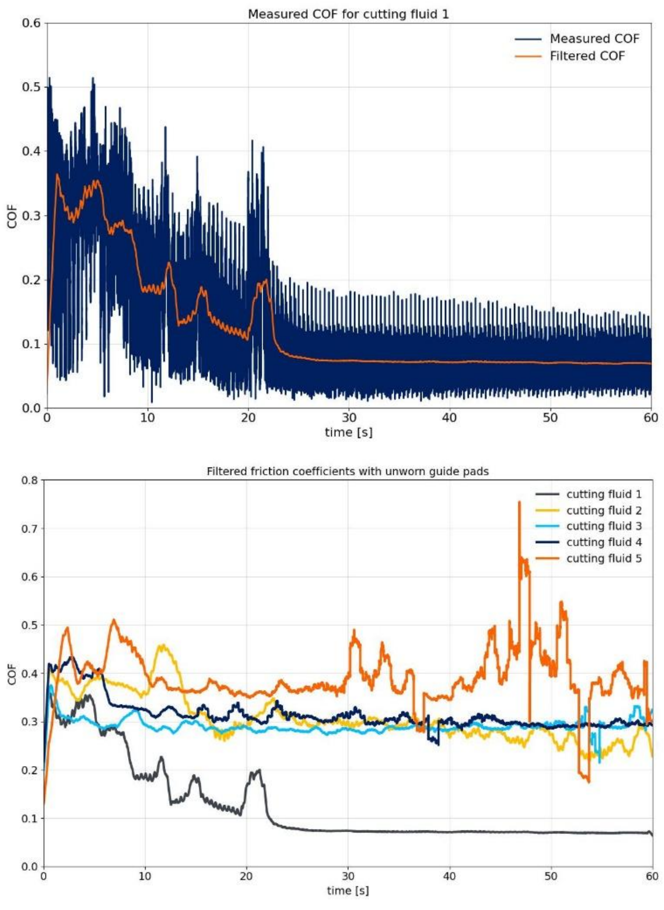

Fig. 8: Exemplary measured and resulting filtered COF for cutting fluid 1 (top) and comparison of filtered COF for cutting fluid 1 to 5 (bottom).

4. Conclusion

The wear state of guide pad is critical for deep-hole drilling, as they ensure precise tool guidance. To study the influence of cutting fluids on wear behaviour, this work introduced a tribometer with a closed loop coolant supply that accurately replicates the normal pressures and cutting velocities found in the cutting domain. Tribometer experiments run with different cutting fluids show that wear behaviour is strongly influenced by the type of cutting fluid. When sorting the cutting fluids by their effect on the wear progression on guide pads, we could replicate the same order as determined in actual deep hole drilling operations conducted by the cutting fluid supplier. Surface analysis revealed that wear occurs primarily through a combination of adhesive wear and fracture, rather than purely abrasive mechanisms. One cutting fluid, significantly reduced wear by forming a tribofilm, demonstrating the importance of fluid selection in prolonging tool life. It was observed that a lower coefficient of friction tends to lead to less guide pad wear. The study confirms the functionality of the tribometer. The results are particularly of interest for cutting fluid developers, as only 15 litres of fluid are required for assessment. Despite these results, the present study has limitations regarding the mechanistic explanation of tribofilm formation and the identification of responsible fluid additives. Surface chemical characterization, is therefore planned as future work to further leverage the methodology for cutting fluid assessment.

Acknowledgements

The work has been supported by the German Research Foundation (DFG) within the research priority program SPP 2402 with project number 521378544.

References

[1] Gerken JF, Canini D, Biermann D, Eberhard P. Analysis of the cooling lubricant flow in the area of cutting edges and guide pads during ejector deep hole drilling. Procedia CIRP 2023; 117:408–413.

[2] Pape F, Poll G, Ellersiek L, Denkena B, Liu H. Tribological Effects of Metalworking Fluids in Cutting Processes. lubricants 2023; 11:224. 10.3390/lubricants11050224.

[3] Felinks N, Rinschede T, Biermann D, Stangier D, Tillmann W, Fuß M, Abrahams H. Investigation into deep hole drilling of austenitic steel with advanced tool solutions. The International Journal of Advanced Manufacturing Technology 2022; 118:1087–1100. 10.1007/s00170-021-07989-1.

[4] Wolf J, Bandaru NK, Dienwiebel M, Möhring H-C. A novel grey-box based friction model for a wide range of machining conditions. Wear 2025; 580-581:206295. 10.1016/j.wear.2025.206295.

[5] Schulze V, Bleicher F, Courbon C, Gerstenmeyer M, Meier L, Philipp J, Rech J, Schneider J, Segebade E, Steininger A, Wegener K. Determination of constitutive friction laws appropriate for simulation of cutting processes. CIRP Journal of Manufacturing Science and Technology 2022; 38:139–158. 10.1016/j.cirpj.2022.04.008.

[6] Rech J, Claudin C, D'Eramo E. Identification of a friction model-Application to the context of dry cutting of an AISI 1045 annealed steel with a TiN-coated carbide tool. Tribology International 2009; 42:738–744. 10.1016/j.triboint.2008.10.007.

[7] Rech J, Giovenco A, Cabanettes F. Toward a new tribological approach to predict cutting tool wear. CIRP Annals 2018;:65–68. 10.1016/j.cirp.2018.03.014.