TRIBOLOGICAL INVESTIGATION OF THE INTERFACE BETWEEN STEEL PIN AND CFRP TUBE

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ABSTRACT

Carbon fiber reinforced plastics (CFRP) offer great potential for lightweight construction due to their high specific stiffness and strength, especially in electric drive systems with rotating components. However, the substitution of steel by CFRP in highly stressed, tribologically relevant interfaces, such as hollow shank taper interfaces (HSK), is hindered by numerous influencing factors. To systematically investigate these factors, particularly the winding angle and lubrication, the tribological properties of CFRP are analyzed on an application-oriented test rig.

For this purpose, pin-on-tube tests are conducted using CFRP tube samples with three winding angles (±10°, ±45°, ±89°), as well as hardened steel references tested against steel counterfaces are conducted. The samples undergo linear reciprocating motion under a normal force of 450 N over 20,000 cycles. The friction coefficients are determined under dry conditions as well as under flood lubrication with a water-miscible coolant lubricant.

The results show that lubrication with coolant lubricant significantly reduces the dynamic coefficient of friction. The lowest friction coefficients, 0.17, are achieved at a winding angle of ±10°. In lubricated tests, the specific wear was below the measurement resolution. Microscopic images show typical fiber-matrix damage in unlubricated samples, which is significantly less pronounced under lubricated conditions. A comparison with literature values for steel HSK interfaces demonstrates the influence of the pin-on-tube arrangement for reference samples. The investigations show the suitability of CFRP for tribologically stressed interfaces. However, further studies are necessary for transfer to real applications such as HSK.

1 INTRODUCTION

Lightweight construction in various application areas, such as aerospace or electric drive systems with rotating components, aims to increase energy efficiency. The replacement of steel components with lighter materials is particularly important in applications where the drive itself is in motion, such as in machine tools. A low component weight combined with high stiffness, thermal stability, and dynamic damping represents a significant competitive criterion for drive components [1]. With increasing demands on the power density of electric drive systems, conventional materials are reaching their physical limits [2]. A promising solution lies in the use of CFRP. Due to its excellent ratio of strength and stiffness to weight, CFRP offers a high lightweight potential and allows for a significant reduction in component mass. Interfaces to other drive components are still predominantly made of steel, as CFRP interfaces, such as bearing seats or the hollow-shank taper interface, have been scarcely investigated with regard to surface quality, coefficient of friction, and wear behavior.

The HSK interface according to DIN 69893-1 [3] between the machine tool spindle and tool holder is a tribologically highly stressed interface. This interface demands tight tolerances for flatness and concentricity (< 3 µm) to ensure interchangeability, repeatability, secure torque transmission, and high bending stiffness [4]. However, clamping processes and dynamic loads lead to wear mechanisms that reduce the service life of these interfaces. In particular, wear on the taper surface, which primarily serves for alignment, can impair the required high precision in terms of concentricity and repeatability [Bre16]. In material-removing machining of workpieces, coolant lubricant (KSS) is used [5]. The main function of KSS is to dissipate heat and reduce friction. Additionally, during a tool change, KSS is used to clean the taper surfaces of impurities, thereby reducing HSK wear [6]. According to Landmann [7], KSS affects the mechanical properties of CFRP depending on exposure duration, diffusion rate, and type of coolant lubricant. While the carbon fibers themselves are hardly affected by contact with coolants, the matrix undergoes intermolecular interactions, hydrolysis, oxidation, and leaching, which lead to a deterioration of mechanical properties [7].

Compared to conventional metallic materials, CFRP offers considerable advantages. Higher specific stiffness and strength enable higher rotational speeds and accelerations, improving the efficiency of relevant systems. However, replacing steel with CFRP also increases the complexity of tribological influencing factors, especially due to material-dependent parameters such as the type of fiber and matrix materials, fiber content, and fiber orientation. According to Friedrich [8], fiber orientation significantly influences the tribological behavior of fiber-reinforced composites. The lowest friction and wear values occur when fibers are oriented perpendicular to the friction surface (N-orientation), whereas parallel (P) and antiparallel (AP) orientations lead to significantly higher friction and wear rates.

To investigate influencing factors, model tests such as pin-on-plate tribometers have been conducted [9, 10]. However, with increasing abstraction of the tribological system, the transferability of results decreases, making application-oriented investigations necessary [11]. Since the use of CFRP involves a multitude of influencing factors that cannot be isolated in field tests, an application-near test rig is necessary, allowing targeted variation and analysis of individual parameters. The aim of this work is to systematically investigate the influencing factors on the tribologically stressed HSK interface caused by the substitution of steel with CFRP. For this purpose, an application-near tribometer is used to analyze the effects of the degree of abstraction of the test geometry, lubrication, and fiber orientation on friction and wear behavior, thereby providing a basis for the industrial application of CFRP interfaces.

2 EXPERIMENTAL STUDIES

To investigate cost-effectively and individually the high number of influencing factors, the tribological system is abstracted so that model tests are carried out in a pin-on-tube arrangement according to Kilian et al. [12]. In this arrangement, a rounded block rubs against the inside of a tube specimen, which undergoes a linear reciprocating motion. The schematic setup of the arrangement with the functional principle and the measurement technology is shown in the half-section in Figure 1. By using tube specimens, the same manufacturing process as in the application case can be employed, as well as the simulation of the same type of motion and surface pressure. A reduction of the influencing factors compared to the application case is achieved through the cylindrical geometry of the tube specimens, since this test setup avoids an overlap of axial and radial forces, as occurs in the force transmission in an HSK, and additionally allows conclusions to be drawn about other tribologically stressed interfaces such as bearing seats.

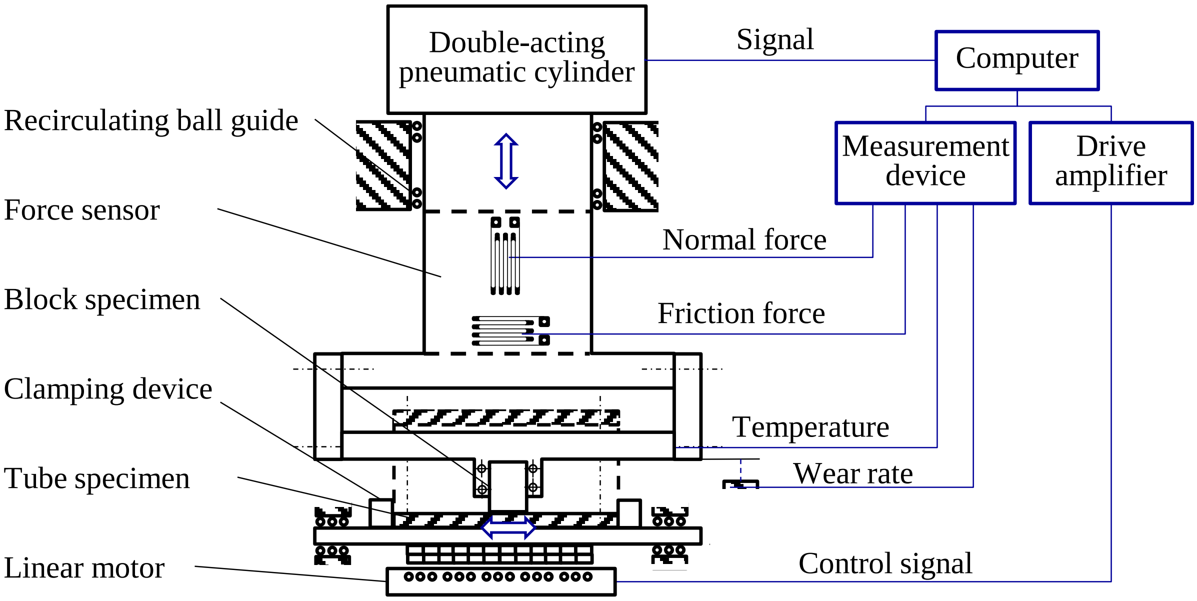

Figure 1: Schematic setup of the model tests in pin-on-tube arrangement in half-section with the functional principle and measurement technology.

2.1 MATERIALS AND SAMPLE PREPARATION

The CFRP samples are manufactured using the filament winding process with T700 carbon fibers (company Toray) and the epoxy winding resin LY556 (company Huntsman). To investigate the influence of the winding angle, three CFRP specimens with balanced winding angles of ±45°, ±89°, and ±10° are wound. Hardened steel specimens (material 16MnCr5) with a Rockwell hardness, scale C of 56±4 HRC serve as reference samples. The specimens are ground to an inner diameter of 52 mm, an outer diameter of 60 mm, and a length of 40 mm. The form and positional tolerances are chosen in accordance with the HSK interface 63 according to [3], whereby, for example, the concentricity and roundness of the tubes are tolerated within 3 µm.

Figure 2: CFRP specimens in the orientations from left to right:
winding angles of ±10°, ±45°, and ±89°.

As the tribological counterbody, rounded steel blocks with the dimensions 10 × 10 × 20 mm are chosen. The steel blocks are made of 16MnCr5 and are case-hardened (56±4 HRC) like the reference specimens. The functional surface, i.e., the rounded area, is ground to a nominal radius of 26 mm with tolerance limits of +0.000 and –0.025 mm to enable area contact between the friction partners. Additionally, a surface form tolerance of 3 µm is maintained. A borehole in the rounded block allows the use of water cooling during the tests.

2.2 EXPERIMENTAL SETUP

The tribological investigations of the influencing factors are carried out using the LRT test rig (Linear-Reciprocating Tribological test bench) in the pin-on-tube arrangement. In this test rig, a linear motor drives a tube specimen while a block, rounded to match the tube specimen, is pressed against it to induce friction. Figure 2 shows the LRT test rig on the left and a close-up of the friction partners in the pin-on-tube arrangement on the right. The block is loaded with a normal force via a double-acting pneumatic cylinder. The tube specimen, exemplarily shown with balanced winding angles of ±45°, undergoes a linear reciprocating motion.

A 3-axis force sensor of the type K3D120 from the manufacturer ME-Meßsysteme GmbH, with a nominal force of 1 kN per axis, continuously measures the normal, lateral, and friction forces above the sample holder of the block. For displacement measurement in the vertical direction, a laser sensor of the type optoNCDT 1220 from the manufacturer MICRO-EPSILON with a measuring range of 0-25 mm is used, while for displacement measurement in the horizontal direction, a laser sensor of the type optoNCDT 1402 with a measuring range of 0-200 mm is employed. Temperature measurement is conducted using two surface thermoelements of type K, which are attached with polyimide adhesive tape to the outer surface of the specimen and placed on the surface of the steel holder close to the steel block.

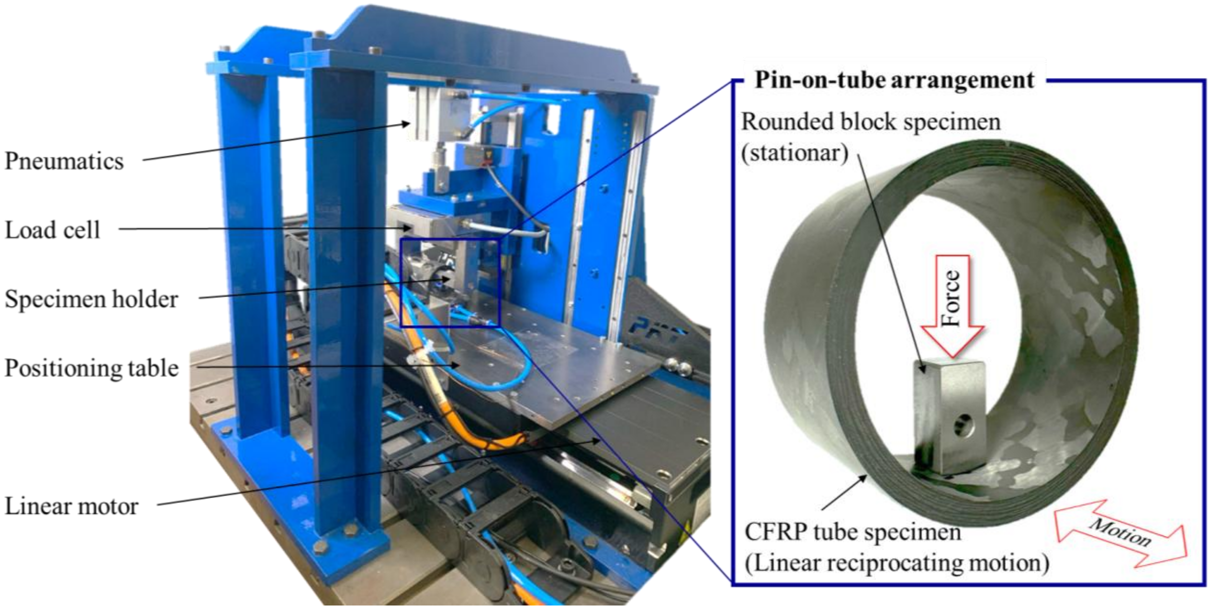

Figure 3: LRT test rig with a close-up of the pin-on-tube arrangement.

The test procedure is divided into four steps, which are followed for each test (see Figure 4). To ensure a plane-parallel contact between the triboelements, the steel block is ground with 800-grit sandpaper before the test (a). During this process, 300 grinding cycles are performed under a normal force of 50 N under dry conditions. The specimen is then cleaned with isopropanol, and the surface roughness is determined using the roughness measuring instrument MarSurf UD 120 from the manufacturer Mahr. The CFRP specimens are conditioned over a period of eight hours at a temperature of 50 °C to remove any absorbed moisture from the material and to avoid potential measurement distortions. The weight determination is carried out using the laboratory precision balance Sartorius Basic BA110S from the manufacturer Sartorius. Subsequently, the specimens are reinstalled in the LRT test rig.

Depending on whether testing is to be performed with or without lubricant, coolant lubricant is added to a bath (b). For this purpose, a water-miscible, mineral oil-based coolant concentrate from the manufacturer unitech Kühlschmierstoffe GmbH with the trade name HOSMAC-S 3630 is used. To use a solution that is as critical as possible for carbon fiber-reinforced plastics, the maximum possible coolant concentration is chosen during mixing, corresponding to an eight percent solution. For each test, 50 ml of coolant is added so that the contact area between the CFRP specimen and the steel stamp is completely surrounded by coolant, thus achieving flood lubrication.

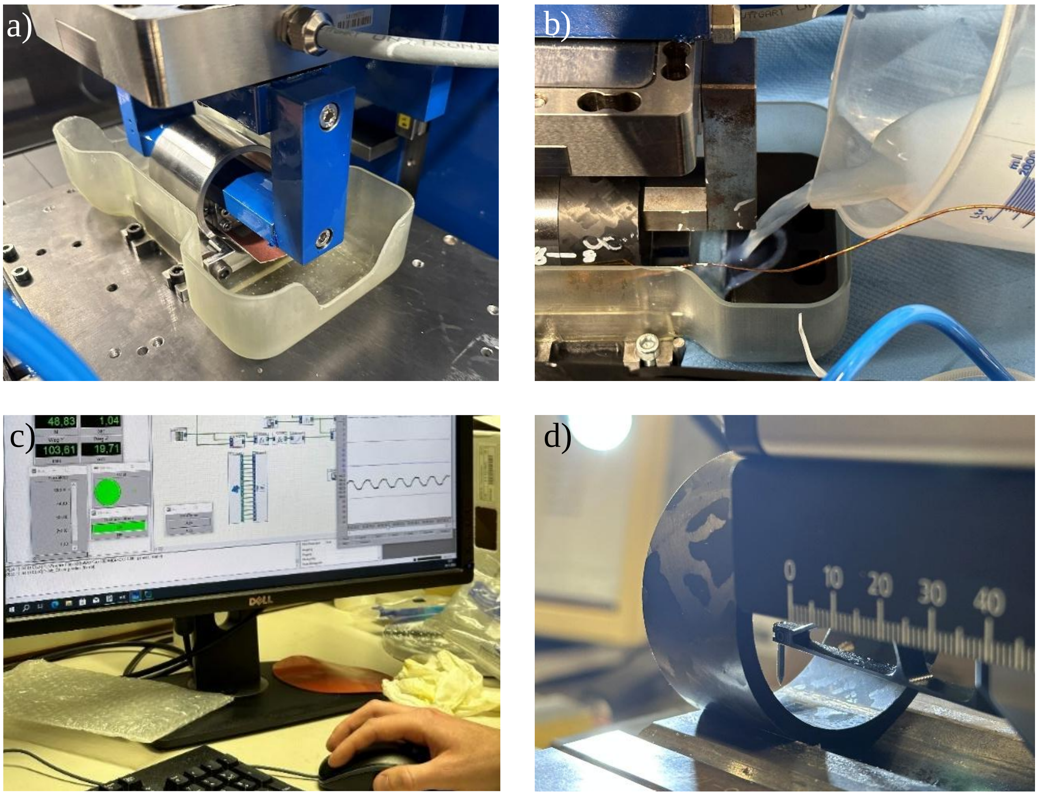

Figure 4: Steps in tribological testing: a) Running-in, b) test evaluation, c) test execution d) test evaluation.

For the tribological investigations, 20,000 cycles with a stroke length of 2 mm are conducted per test (c). The stroke length corresponds to the typical insertion path when inserting a tool holder into an HSK chuck of size 63 [13]. At a 4-axis machining center (Heller MC 12), the speed during the clamping and ejection process was determined to be 2 mm/s. Tests examining the influence of sliding speed on the coefficient of friction have shown that the effect of the sliding speed between 2 mm/s and 36 mm/s lies within the scatter of the coefficient of friction at identical sliding speeds. To reduce the test duration, a sliding speed of 6 mm/s is therefore selected, resulting in an average test duration of 6.4 hours. The test parameters are listed in Table 1.

Test parameters	Values and Properties
Sliding velocity	6 mm/s
Normal force	450 N
Surface pressure	5.4 MPa
Cycles	20000
Stroke	2 mm
Total test distance	80 m
Test temperature	21±4°
Humidity	40±5° RH
Medium	dry, coolant lubricant

Table 1: Test parameters for tribological tests

2.3 DETERMINATION OF THE COEFFICIENTS OF FRICTION AND THE SPECIFIC WEAR RATES

The recording of the forces is carried out continuously at a sampling frequency of 100 Hz over the entire test duration. The coefficient of friction is calculated from the normal force and the friction force. To determine the dynamic coefficient of friction, 20% of the friction coefficient of the half-cycle is used for the calculation. The midpoint of the half-cycle is determined via the zero crossings of the displacement. Starting from the midpoint, 10% before and after the midpoint of the cycle are used for the calculation of the dynamic coefficient of friction, as the friction force is constant in this region [14]. Subsequently, the mean values over the cycles from 10,000 to 20,000 are computed.

For the characterization of wear, the specific wear rate is determined based on the wear volume, the normal force, and the wear distance [15]. The wear volume is calculated as the product of the worn area and the linear wear amount. For the calculation, a worn area of 101 to 104 mm² is used. The linear wear amount is determined based on a contour measurement of the worn surface of the specimen. For this purpose, a perthometer from the manufacturer Mahr, type MarSurf UD 120, is used, where the surface of the specimen is scanned with a diamond tip and the contour of the worn area is traced. The measurement is then evaluated in MATLAB®.

3 RESULTS AND DISCUSSION

In the following section, the results obtained from the tribological investigations are presented and discussed. First, the influence of the KSS on the coefficient of friction is shown. Subsequently, the effect of fiber orientation in tribological tests with lubricant is examined. Finally, the coefficients of friction of the reference specimen are compared with a corresponding value from the literature.

3.1 LUBRICATION

To investigate the influence of the intermediate medium, six tests were conducted with CFRP tube specimens having a winding angle of 45° and steel counter bodies. The averaged dynamic coefficient of friction and the corresponding standard deviation for three tests each with and without lubrication are shown in Figure 5. The average coefficient of friction in the tests without lubrication is 0.31, and in the tests with KSS lubrication, it is 0.18. Lubrication of the contact area leads to a significant reduction in the dynamic coefficient of friction.

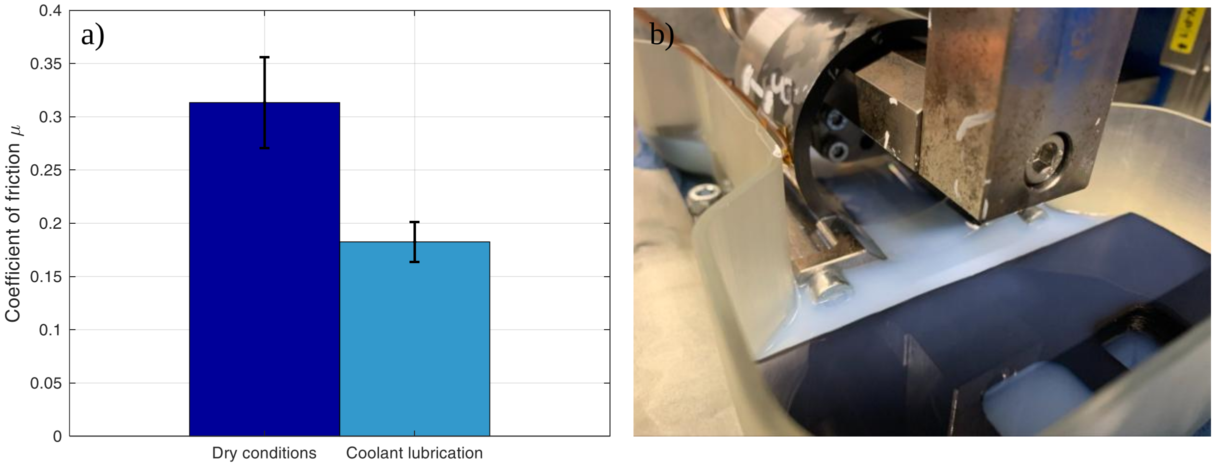

Figure 5: Tests on the influence of KSS on CFRP tube specimens with a winding angle of 45° against steel counter bodies, a) Comparison between the coefficients of friction with and without lubrication, b) mounted CFRP specimen.

In the tribological tests with KSS lubrication, no specific wear rate could be determined, as the contour changes are below the measurement resolution of the contour measurement. To visualize the wear mechanisms, the surface of the CFRP tube specimen with 45° orientation was examined using a digital microscope, the Keyence VHX-500F. Figure 6 shows a 500-fold magnification of the contact surfaces before the test (a), after the test without lubrication (b), and after the test with KSS lubrication (c) and (d). The bright elongated areas are the carbon fibers, surrounded by the darker matrix areas. After the tribological tests, fiber abrasion, breakage, and wear particles are visible both in the tests without lubrication (a) and with lubrication (b). In the test without lubrication (a), fiber-matrix debonding and matrix failure due to shear are significantly more pronounced compared to the tests with lubrication (b). These failure mechanisms were also identified by Friedrich et al. [15] in unidirectional fiber composite materials without lubrication at 0° orientation. In Figures 6 c) and d) show abrasive wear in the form of grooves along the sliding direction. Furthermore, the images demonstrate that the fibers do not run parallel to the sliding surface but pass through the crossover zone into or out of the viewing plane, resulting in fiber ends in the contact zone. Such a crossover zone is visible in Figure 6 c) after the test with KSS lubrication. Due to the winding process and the subsequent grinding process, fibers on the surface are cut, causing a local change in fiber orientation between the two winding directions. This is visible in Figure 3 by the differently bright areas on the CFRP tube with 45° orientation, which is attributable to varying light reflections due to the changing fiber layers. In Figure 6 c), it can also be seen that the fibers from the right side run under the fibers from the left side, and ´that there is no contact between the fibres and the friction partner in the transition area. The change in fiber orientation and the resulting transition zones may be reasons for the fluctuations in the dynamic coefficient of friction and the wear rate.

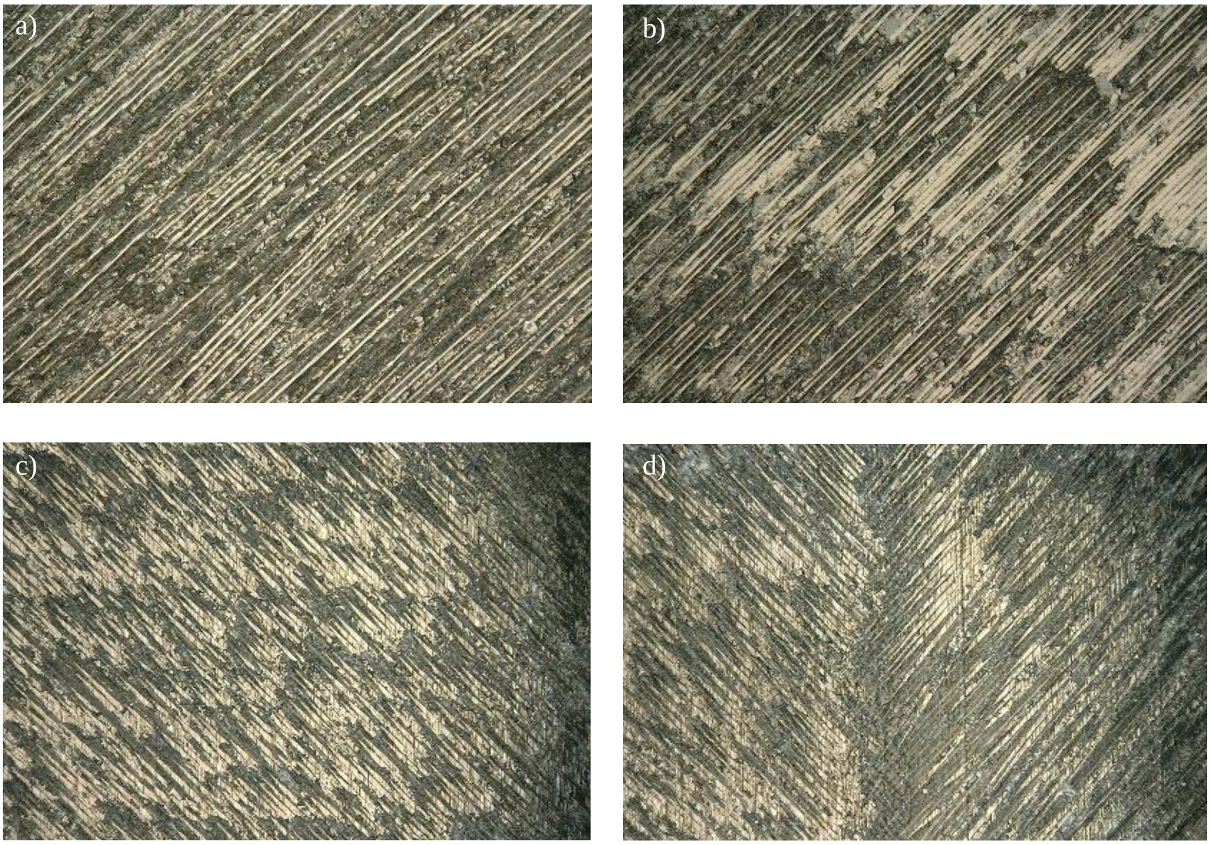

Figure 6: Microscopic images at 500x magnification of the inner surface of the CFRP tube specimen with 45° orientation and sliding direction upwards, a) before the test, b) after the test without lubrication, c) and d) after the test with lubrication.

3.2 FIBER ORIENTATION

The influence of the fiber angle on the dynamic coefficient of friction, surface quality, and specific wear rate is investigated on the CFRP specimens with different fiber angles and steel counter bodies under lubrication with KSS. In the tests, a winding angle of 0° means that the fibers are aligned parallel to the sliding direction. For the CFRP specimens with balanced winding angles of ±10°, ±45°, and ±89°, the dynamic coefficient of friction is determined. The dynamic coefficient of friction is lowest at a winding angle of ±10°, with a value of 0.17. At winding angles of ±45° and ±89°, the coefficient of friction is around 0.18. A similar influence of the fiber angle was observed by Sharma et al. [16] in tribological investigations of unidirectional carbon fibers with a polyetherimide matrix in a pin-on-disc (horizontal) configuration without lubrication. At an orientation of 0°, i.e., with the UD CFRP fibers aligned parallel to the sliding direction, the lowest coefficients of friction were found compared to 45° and 90°. Weidmann [17] confirmed this influence of the fiber angle for the orientations 0° and 90°, antiparallel to the sliding direction, in linear reciprocating pin-on-plate tests.

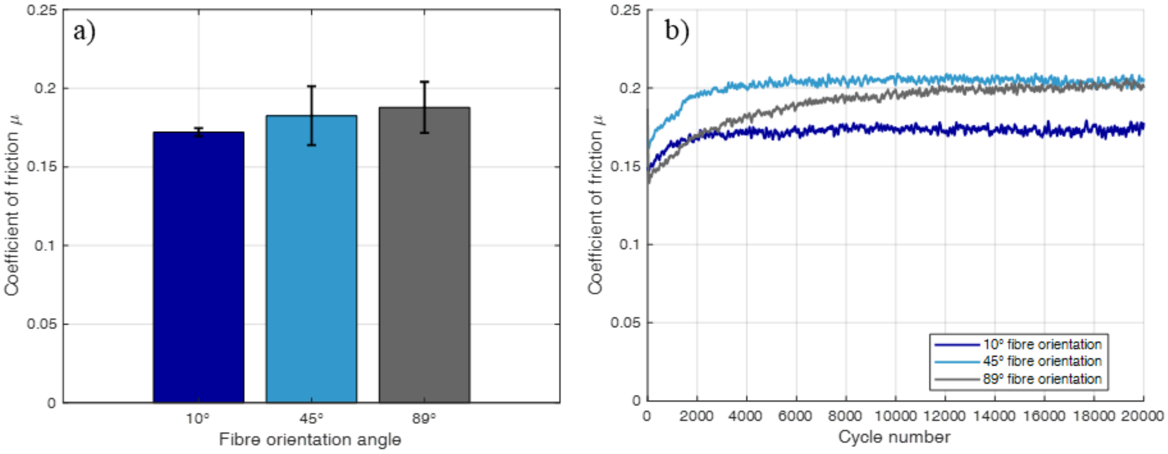

Figure 7: Coefficients of friction over fiber orientation (a), coefficients of friction over the number of cycles for different fibre orientations (b).

The influence of the tribological tests with lubrication by KSS on the surface roughness of the CFRP specimens is listed in Table 2. The surface roughness values are measured in the sliding direction, axial to the tube specimen, using the perthometer MarSurf UD 120 and averaged over three measurements. Subsequently, the roughness values are averaged across three tests, and the corresponding standard deviation is calculated. The specimen with a ±89° winding angle exhibits the highest surface roughness before the test. The surface roughness values of the specimens with ±10° and ±45° are lower. Since the same grinding parameters were used during the manufacture of the specimens, this difference is presumably due to the measurement direction of the perthometer relative to the fiber orientation and the fiber orientation itself. In grinding tests, Brouschkin et al. [18] assumed a influence of measurement direction on roughness depth as well as the influence of fiber orientation on surface quality. The tribological tests lead to a reduction in both the arithmetic mean roughness (Ra) and the average maximum profile height (Rz) values. The Ra values are reduced by 0.1 to 0.3 µm before and after the tests. A decline in Rz values is also observed for all specimens. The greatest reduction in Rz occurs in the specimen with ±89° orientation, where the Rz value decreases from 13.3 µm to 10.4 µm.

Fiber orientation	Surface roughness before test		Surface roughness after test	
[°]	Ra in µm	Rz in µm	Ra in µm	Rz in µm
10	0.7 ± 0.1	7.0 ± 1.6	0.6 ± 0.1	6.5 ± 0.9
45	1.0 ± 0.2	8.7 ± 0.5	0.7 ± 0.1	6.7 ± 2.0
89	1.0 ± 0.2	13.3 ± 2.9	0.9 ± 0.1	10.4 ± 0.5

Table 2: Surface roughness of CFRP specimens before and after tribological tests with KSS lubrication, based on Ra and Rz. Values are presented as mean ± standard deviation.

4.1 INFLUENCE OF THE PIN-ON-TUBE ARRANGEMENT

To ensure the transferability of the results obtained from the pin-on-tube arrangement to the application case, it is important to determine the influence of the arrangement. In addition to the CFRP tube specimens, tests were conducted with hardened steel tube specimens to reduce the abstraction between the application case and the specimens. Figure 8 compares the coefficients of friction in the pin-on-tube arrangement for CFRP and steel specimens under KSS lubrication with literature values for HSK interfaces according to Müller [19] and VDMA 34181 [4].

To visualize the comparison, the respective arrangements are shown above the coefficients of friction in the pin-on-tube arrangement and above the simplified HSK interface. The average coefficient of friction for the CFRP tube specimen with 10° orientation against the steel block is 0.17. For the steel tube specimen, the average coefficient of friction is 0.12 ± 0.02.

Müller [19] reports coefficients of friction between 0.12 and 0.4 for HSK interfaces based on field tests. According to VDMA 34181 [4], a coefficient of friction of 0.15 is typically used for the calculation of HSK interfaces. The guideline further states that lower values can be expected when using KSS or oil-based lubrication [4]. These literature values are shown on the right side of the figure, beneath the simplified HSK interface.

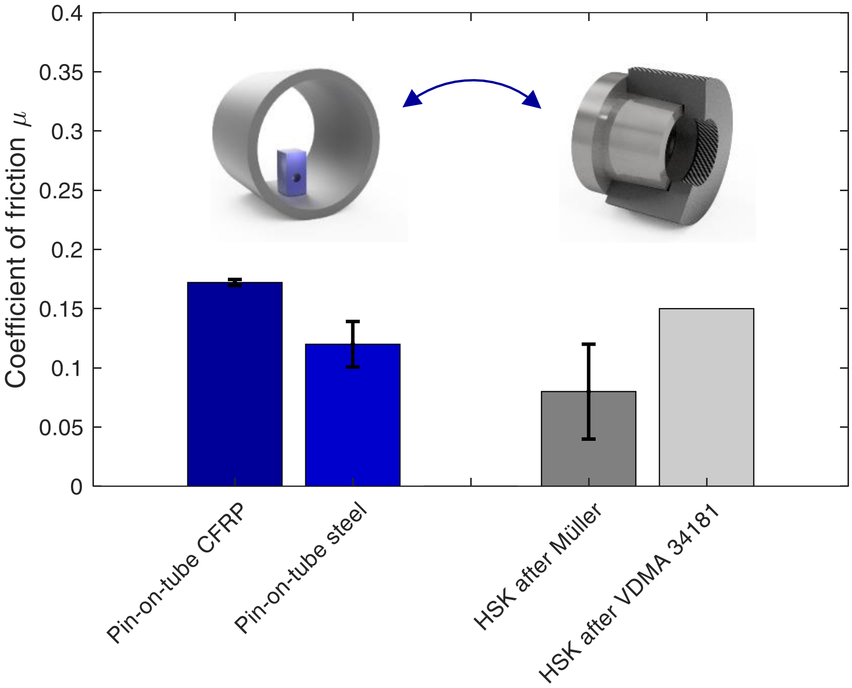

Figure 8: Coefficient of friction in the pin-on-tube arrangement for CFRP tube specimens with 10° orientation and for steel specimens against steel counter bodies compared to HSK interfaces according to Müller [19] and VDMA 34181 [4].

The closest match in boundary conditions, particularly regarding the material and the use of lubrication, is found between the steel pin-on-tube arrangement and the HSK interface described by Müller [19]. The average coefficient of friction obtained from the steel pin-on-tube tests lies at the upper end of the range reported in the literature. Since visible wear marks were observed in the pin-on-tube tests and Becher et al. [20] state that wear in HSK interfaces leads to increased friction, a transferability of the pin-on-tube results to real HSK interfaces can be assumed.

Furthermore, the observed differences in the coefficients of friction are likely attributable to variations in contact pressure and intermediate media arising from the specific test setups. These deviations must be considered to ensure a reliable transfer of the findings to the application context.

The coefficient of friction is particularly important for the HSK interface, as the frictional force opposes the insertion and ejection of the tool holder. Assuming a degree of transferability, the tests using the CFRP tube specimen suggest that, when applied to an HSK interface with a CFRP spindle, higher frictional forces during tool clamping can be expected. These increased friction forces can be compensated by increasing the clamping force, thereby enabling the use of CFRP in such applications.

Wear in the pin-on-tube tests could not be quantified, as it remained below the measurement resolution for both CFRP and steel tube specimens. To enable a reliable assessment of wear, additional tests with a higher number of cycles should be conducted. Nevertheless, the lack of detectable wear suggests that the chosen setup is appropriate for transferability considerations. Moreover, it indicates that CFRP performs comparably to steel and does not show any disadvantages under the tested conditions. Accordingly, the test results suggest that CFRP can be used in tribologically loaded interfaces. However, further investigations using the pin-on-tube arrangement should be conducted to improve the transferability of the findings to practical applications.

5 CONCLUSIONS AND OUTLOOK

The results of this study demonstrate that CFRP is fundamentally suitable as a material for tribologically stressed interfaces. The conducted pin-on-tube tests reveal that the dynamic coefficient of friction is influenced both by the fiber orientation and by lubrication with KSS. Particularly low friction was achieved with CFRP specimens featuring a winding angle of ±10° tested against a steel counterbody, resulting in a coefficient of friction of 0.17. Under lubricated conditions, no measurable wear was detected, enabling the use of CFRP under these operating conditions. However, further tests with higher cycle numbers should be conducted to determine the specific wear rate. Microscopic analyses of the wear surfaces show that tribological loading leads to typical fiber-matrix damages such as fiber abrasion, fiber fracture, and the formation of wear particles, which are more pronounced in unlubricated specimens than in lubricated ones.

The influence of the pin-on-tube arrangement on the coefficient of friction was investigated for both CFRP and steel tube specimens and compared with literature values. The coefficient of friction measured for the steel reference specimens lies within the range of published values for HSK interfaces, indicating a reasonable degree of transferability of the findings.

The insights gained allow for further cost-effective studies on more wear-resistant polymer materials or with thermally conductive fillers. For transferability to real applications such as HSK interfaces, further investigations are necessary, for example regarding the influence of stroke and surface pressure on friction behavior and wear. To confirm the applicability of CFRP in highly stressed tribological interfaces, tribological investigations with real component geometries should be conducted.

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REFERENCES

[1] M. Weck, *Werkzeugmaschinen 2*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006.

[2] L. Kroll, P. Blau, M. Wabner, U. Frieß, J. Eulitz and M. Klärner, "Leichtbaukomponenten für energieeffiziente Werkzeugmaschinen" in *Energieeffiziente Produkt- und Prozessinnovationen in der Produktionstechnik*, 2010.

[3] German Institute for Standardization, *DIN 69893-1, Kegel-Hohlschäfte mit Plananlage - Teil 1: Kegel-Hohlschäfte Form A und Form C; Maße und Ausführung: = Hollow taper shanks with flange contact surface - Part 1: Hollow taper shanks type A and type C; Dimensions and design*. Berlin: Beuth Verlag GmbH, 2011.

[4] *VDMA 34181:2005-07*, VDMA, Berlin, 2005.

[5] *DIN 51385:2013-12, Schmierstoffe_- Bearbeitungsmedien für die Umformung und Zerspanung von Werkstoffen_- Begriffe*, German Institute for Standardization, Berlin, 2013.

[6] H. Victor, M. Müller and R. Opferkuch, Hg., *Zerspantechnik*. Berlin: Springer, 1985.

[7] A. Landmann, "Zur Gestaltung von Maschinenkomponenten aus Faser-Kunststoff-Verbund-Halbzeugen" Dissertation, Shaker Verlag, 2017.

[8] K. Friedrich, *Friction and Wear of Polymer Composites*. Oxford: Elsevier Science, 1986.

[9] A. Rudnytskyj, R. Larsson and C. Gachot, "A Closer Look at the Contact Conditions of a Block-on-Flat Wear Experiment", *Lubricants*, Jg. 10, Nr. 7, S. 131, 2022, doi: 10.3390/lubricants10070131.

[10] M. Rodiouchkina, J. Lind, L. Pelcastre, K. Berglund, Å. K. Rudolphi and J. Hardell, "Tribological behaviour and transfer layer development of self-lubricating polymer composite bearing materials under long duration dry sliding against stainless steel", *Wear*, 484-485, S. 204027, 2021, doi: 10.1016/j.wear.2021.204027.

[11] H. Czichos and M. Woydt, "Tribological Testing and Presentation of Data" in *Friction, Lubrication, and Wear Technology*, G. E. Totten, Hg., ASM International, 2017, S. 16–32, doi: 10.31399/asm.hb.v18.a0006402.

[12] L. Kilian *et al.*, "Hochpräzise Funktionsflächen an CFK-Bauteilen", *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Jg. 119, 7-8, S. 553–557, 2024, doi: 10.1515/zwf-2024-1094.

[13] C. Brecher and M. Weck, *Werkzeugmaschinen Fertigungssysteme 1: Maschinenarten und Anwendungsbereiche*, 9. Aufl. Berlin, Heidelberg: Springer Berlin Heidelberg, 2018. [Online]. Verfügbar unter: http://nbn-resolving.org/urn:nbn:de:bsz:31-epflicht-1599188

[14] *Guide for Measuring and Reporting Friction Coefficients*, G02 Committee, West Conshohocken, PA.

[15] K. Friedrich, R. Reinicke and Z. Zhang, "Wear of polymer composites", *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, Jg. 216, Nr. 6, S. 415–426, 2002, doi: 10.1243/135065002762355334.

[16] M. Sharma, I. M. Rao and J. Bijwe, "Influence of orientation of long fibers in carbon fiber–polyetherimide composites on mechanical and tribological properties", *Wear*, Jg. 267, 5-8, S. 839–845, 2009, doi: 10.1016/j.wear.2009.01.015.

[17] S. Weidmann, *Zur Gestaltung von Gleitlinearführungen und Gewindetrieben aus Faser-Kunststoff-Verbunden Tribologie, Auslegung, Fertigung und Prüfung Susanne Weidmann*, 1. Aufl. Aachen: Shaker Verlag, 2018.

[18] A. Brouschkin, N. Otto, C. Möller and J. Hendrik Dege, "Oberflächenqualität beim Schleifen von CFK", *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Jg. 119, 7-8, S. 558–562, 2024, doi: 10.1515/zwf-2024-1108.

[19] F. Müller, "Methoden zur Charakterisierung von Werkzeugschnittstellen unter statischer Last" Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen; Apprimus Verlag.

[20] Brecher, Christian; Fey, Marcel; Kneer, Florian (2016): Verschleiß an Werkzeughaltern mit Plananlage beim Spannen. In: Werkstatt und Betrieb 149 (12), S. 30–33.