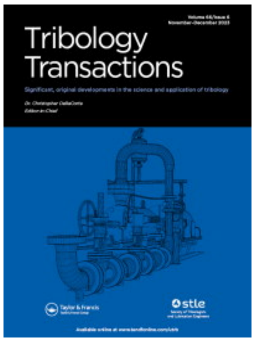

Taylor & Francis
Taylor & Francis Group

Tribology Transactions

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/utrb20

Investigation of the Influence of Triboactive CrAlMoN Coating on the Joint Wear of Grease-Lubricated Roller Chains

Martin Rank, Manuel Oehler, Oliver Koch, Kirsten Bobzin, Christian Kalscheuer & Max P. Möbius

To cite this article: Martin Rank, Manuel Oehler, Oliver Koch, Kirsten Bobzin, Christian Kalscheuer & Max P. Möbius (2023) Investigation of the Influence of Triboactive CrAlMoN Coating on the Joint Wear of Grease-Lubricated Roller Chains, Tribology Transactions, 66:6, 1105-1116, DOI: 10.1080/10402004.2023.2264908

To link to this article: https://doi.org/10.1080/10402004.2023.2264908

Published online: 13 Nov 2023.

TRIBOLOGY TRANSACTIONS
2023, VOL. 66, NO. 6, 1105–1116
https://doi.org/10.1080/10402004.2023.2264908

Investigation of the Influence of Triboactive CrAlMoN Coating on the Joint Wear of Grease-Lubricated Roller Chains

Martin Rank[a], Manuel Oehler[a], Oliver Koch[a], Kirsten Bobzin[b], Christian Kalscheuer[b], and Max P. Möbius[b]

[a]Machine Elements, Gears and Tribology (MEGT), RPTU Kaiserslautern, Kaiserslautern, Germany; [b]Surface Engineering Institute (IOT), RWTH Aachen University, Aachen, Germany

ABSTRACT
Physical vapor deposition (PVD) coatings are vital for enhancing wear resistance. However this technology faces challenges when coating inaccessible surfaces due to its line-of-sight characteristic. A potential remedy is utilizing triboactive CrAlMoN coatings. These form a tribofilm in the contact zone when applied to one contact partner along with a suitable lubricant. This tribofilm can subsequently safeguard inaccessible yet tribologically stressed surfaces. One of the main applications for this method is roller chain drives, whose longevity depends on the joint wear and the resulting chain elongation. Large-scale pin coatings have proven effective in curbing wear and prolonging chain life. However, the inaccessibility of bushes complicates standard PVD coating procedures. Triboactive coatings offer the possibility of forming transfer layers on the bushes, thereby enhancing friction reduction and wear protection. Experimental material studies for chain drives can be cost-intensive due to complexity and numerous components. This article demonstrates that CrAlN and CrAlMoN coatings in combination with greases with the additives phosphorus and sulfur can reduce friction and wear in chain joints. Furthermore, it is shown that a reasonable selection of tribometer testing can significantly reduce costs. Comparing the results of tests on a pin-on-disk tribometer and component tests show that model tests cannot completely replace component tests. But the combination offers an efficient way to optimize test matrices. Triboactive coatings like CrAlMoN hold promise for addressing the challenge of inaccessible surfaces. Reasonable tribometer test selection can help mitigate the costs of experimental studies, making these coatings a more practical solution.

ARTICLE HISTORY
Received 30 June 2023
Accepted 26 September 2023

KEYWORDS
Chain drives; greases; coatings (wear-resistant); coatings (friction-reducing); wear/failure testing devices

Introduction

With greater social and legal requirements for sustainable products, the optimization of efficient systems is becoming increasingly important. Tribological contacts have a significant influence on global CO_2 emissions, comprising about 23% of the world's energy demand. About 20% of this energy is converted into friction, and 3% is used to replace worn components (*1*).

This particularly affects systems such as chain drives. The service life of these systems is determined by wear. Consequently, an increase in wear resistance leads to a longer service life and thus also to more sustainable use. Roller chains are used as timing chains in internal combustion engines (*2*), as drive chains in industrial applications (*3*), in conveyor drives, as well as in agriculture (*4*). Thus, they are used in most production processes as well as in a wide range of transportation applications (*5*). Due to their extensive industrial applications, friction and wear reduction in roller chains play an essential role in reducing CO_2 emissions.

Roller chains consist of outer links in which pins are pressed with outer plates and inner links in which bushes are pressed with inner plates. The rollers are mounted on the bushes and can rotate freely on the bush, as well as roll on the sprockets when the chain moves (Fig. 1).

Wear in roller chains occurs mainly through abrasion in the joints, where a sliding relative movement takes place between the pin and bush, especially when running over sprockets, but also through dynamic processes in the runs (*6*). The wear is formed locally in the area of the contact zone of pin and bush and is determined by the pitch angle τ of the sprockets (Fig. 2).

Because the chain is almost load free in the return strand, wear is induced mainly in the load strand. The sliding distance s of the joint per chain revolution is thus determined by the sum of the pitch angles of the wheels and the pin radius r_P (Eq. [1]).

$$s = r_P \cdot (\tau_1 + \tau_2). \tag{1}$$

The elongation due to wear causes an increase in the pitch P and consequently an increase in the pitch diameter.

CONTACT Martin Rank martin.rank@rptu.de
Review led by G. Barber.

Nomenclature

f_s	Sampling rate (Hz)	T	Temperature (°C)
F	Force (N)	W_V	Wear volume (μm^3)
H	Hardness (HRC)	z	Number of teeth
M	Torque (Nm)	δ_h	Wear height (mm)
n	Rotational speed (1/min)	Δl	Joint elongation (μm)
p	Pitch (mm)	Δl_{max}	Joint elongation limit (μm)
p_{max}	Maximum contact pressure (N/mm^2)	ΔP	Pitch elongation (mm)
P_L	Laser power (mW)	λ	Wavelength (nm)
r_B	Bush inner radius (mm)	μ	Coefficient of friction
r_P	Pin radius (mm)	ν	Kinematic viscosity (mm^2/s)
s	Sliding distance (m)	τ	Pitch angle (rad)
S_k	Core height (µm)		
S_{sk}	Skewness	***Subscripts***	
t	Time (s)	1, 2	Driving, driven
t_c	Cleaning time (s)		
t_E	Exposure time (s)		

This results in transmission errors and impulses on the sprocket teeth and rollers when the chain runs on. The permissible chain extension depends on the application and type of drive. In the case of timing chains of internal combustion engines, the elongation must not exceed 0.8%, because the transmission error will interfere with the operation of the engine (*7*). For drive chains, elongation up to 3% is tolerated according DIN ISO 10823 (*8*). If this is exceeded, the chain may skip and fail abruptly (*9*).

Various ways of influencing the tribological properties of the system to improve system wear have already been investigated. In addition to the choice of material for the individual components, the manufacturing process in particular has a significant influence on the properties and tolerances of the components. Furthermore, the wear resistance of the components can be improved by heat treatment (*10*). Microstructuring of surfaces also makes it possible to improve friction behavior. It was shown that laser structuring caused a significant reduction in the coefficient of friction (CoF) compared to polished components. However, the level of the CoF was not significantly lower than that of the series components. Also no influence on the wear of the components was detected (*11*). The use of cold spray deposition technology to structure a surface with TiO_2 particles also showed reduced friction in initial tribometer tests. The application of TiO_2 particles resulted in a stable excavation of the CoF at a significantly lower level than in the unmodified reference samples. Again, no influence on the wear behavior was observed (*12*). However, improved wear resistance can be achieved by nitriding or chrome nitride coating. Physical vapor deposition (PVD) or chemical vapor deposition processes are mostly used for coating deposition.

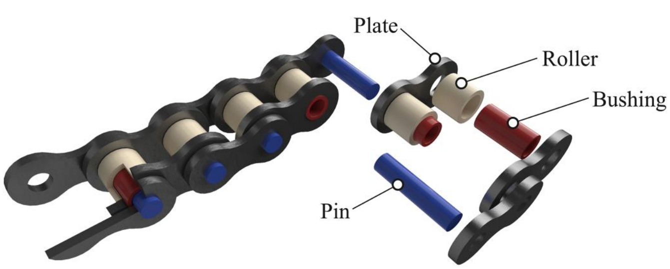

Figure 1. Schematic structure of roller chains.

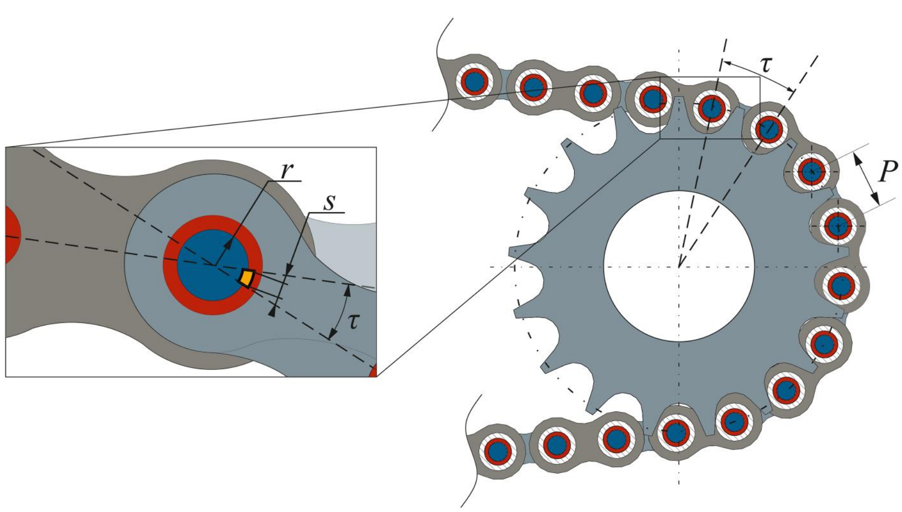

Figure 2. Dependence of sliding distance s in the chain joint of a chain with pitch P on the pitch angle τ and the pin radius r_P.

However, for production reasons, mainly pins are coated (*13*).

In addition to the contact partners, the tribological system is influenced by the lubricant. In the case of chains, oils or greases are generally used as lubricants (*14*). Because the optimization of combustion engines has been a major motivation for the optimization of timing chains in recent years, research has focused on oil-lubricated systems (*15*). One research emphasis is the examination of additives and the optimization of oils (*16*). For example, initial results indicated that triboactive CrAlMoN and CrAlMoCuN coatings can be used to produce transfer layers on chain bushings under oil lubrication, which has a positive effect on friction and wear behavior (*17*). Simple comparative tribometer tests are often used for parameter investigations on chains. But these model tests represent a strong abstraction of the chain link. For realistic investigations, on the other hand, tests on entire chain drives are usually used. Parameter studies on chain drives are often cost-intensive due to the large number of components. Conventional system test rigs are consequently only suitable to a limited extent, especially for investigations of material influences using prototypes. A chain joint tribometer (CJT) was therefore developed at the chair for machine elements, gears, and tribology to investigate individual chain joints (*18*). This allows the test setup to be reduced to a single joint, thus minimizing costs for prototypes and model lubricants. At the same time, load spectra can be mapped that correspond to the real loads on a joint in the chain drive (*19*). The CJT thus occupies a position between highly simplified tribometers and the real system. Test matrices can be planned sensibly by the systematic use of different test rigs. A preselection of coating systems can be made by a pin-on-disk (PoD) tribometer, which can be further analyzed in more complex CJT with a reduced sample size and under realistic operating conditions.

The focus of the investigations carried out was on the chain pins. Mechanical processing or coating of the bushings by means of the PVD process is technically difficult and not economical viable. To improve the tribological properties of the joints, pins with triboactive coatings are used. With a suitable lubricant, these create transfer layers on the bushing (*20*). PoD tribometer tests showed that the use of Mo:S embedded in a CrAlN matrix in tribological systems has a positive influence on the friction and wear behavior (*21*). Tribological transfer coatings can also be detected in lubricated systems through the interaction of CrAlMoN coatings and sulfur-containing lubricants (*22*). A positive influence of a CrAlMoN coating of chain pins and the use of a lubricating grease with sulfur additives on the friction in the chain link has been proven (*23*). PoD experiments showed a high comparability with the friction measured with the CJT. The lowest CoF was measured for the CrAlMoN + S systems in the PoD (Fig. 3) (*23*). Despite its unstable course, the CrAlN + S system showed a lower CoF compared to the uncoated reference, which is in accordance with the CJT results.

In the PoD, the CrAlMoN + S system achieved improved wear resistance compared to systems with uncoated and CrAlN-coated samples. Although the use of a phosphorus additive grease did not improve friction, it led to reduced wear of the coated flat specimen (Fig. 4). Furthermore, indications for the formation of a transferred tribolayer were found (*23*).

It was assumed that the PoD would be a viable tribometer to preselect promising coatings and lubricants for subsequent tests in the chain joint tribometer (*23*). However, wear analysis was not performed on a statistically viable level in previous investigations. Therefore, this article investigates whether the findings obtained on the PoD can also be confirmed in experiments with the CJT. For this purpose, the wear behavior of the various chain joints is investigated in individual joint tests. In addition, whether the grease with phosphorus additive also has a beneficial effect on the friction in contrast to PoD tests will be investigated.

Experimental methods

All tests were performed on roller chain joints of size 10B-1 with a pitch $P = 15.875$ mm (5/8″) according to DIN ISO 606 (*24*). The joints had a pin radius of $r_P = 2.51 \pm 0.005$ mm and a bush inner radius $r_B = 2.54 \pm 0.01$ mm. Two nitrided pin coatings, a CrAlN reference coating and an extended CrAlMoN coating with a composition according to Table 1, were used.

Both coatings were synthesized using an industrial coating unit for PVD. This unit works with magnetron sputtering and has four direct current magnetron sputtering cathodes and two high-power pulse magnetron sputtering

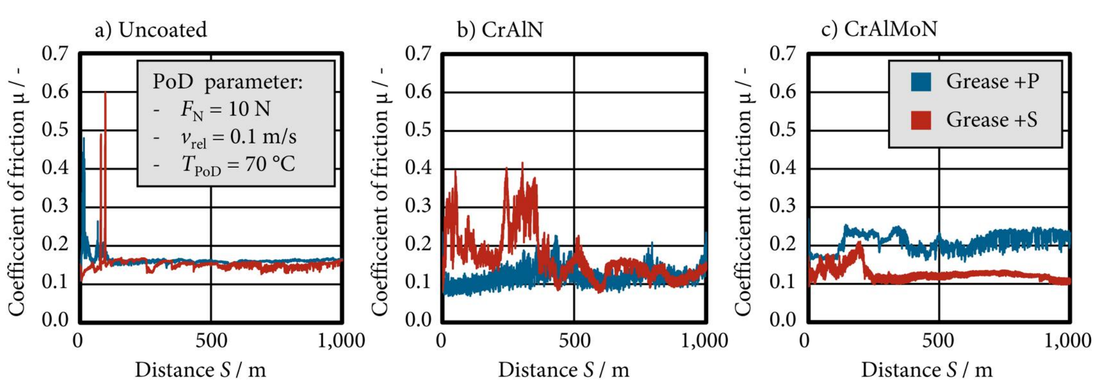

Figure 3. Friction analysis in the PoD (*23*).

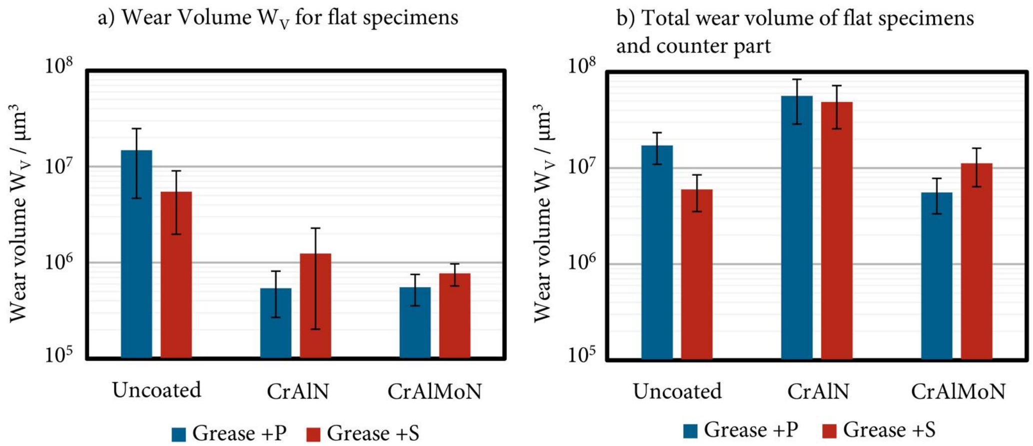

Figure 4. Wear analysis after PoD tests.

Table 1. Chemical metallic composition of the pin coatings and top layer thickness.

Coating	Cr (at%)	Al (at%)	Mo (at%)	Coating thickness (μm)
CrAlN	59	41	–	1.92±0.1
CrAlMoN	17	13	70	1.79±0.04

Table 2. Properties of the two greases.

Configuration	NLGI class (25)	Additives	Viscosity (cSt)
Model grease +S	0	AO + 6600 ppm S	<1000
Model grease +P	1	AO + 350 ppm P	<1000

cathodes. More detailed information of the coating process and coating properties can be found in our previous study (*23*).

Tests were also carried out with the original chain joint without modified pins. The serial pins were made of 58CrV4, quenched and tempered to a hardness of $H = (50\pm1.5)$ HRC. The bushings used were made of wound C15 steel and in case-hardened condition.

Two different variants of the same model grease were used for the test. The model grease consists of an ultra-high-viscosity mineral base oil of $\nu_{40} = 13,600$ mm^2/s and $\nu_{100} = 406$ mm^2/s as well an inorganic thickener and with antioxidants (AO) added. One variant contained a sulfur additive (S) and the second contained a phosphorus additive (P; Table 2). Due to the high amount of sulfur, NLGI classes (*25*) differed slightly. Both wear and friction tests were performed on three specimens for each combination of coating and grease. To ensure comparability, the coatings and lubricants were identical to those used in previous studies.

Chain joint tribometer

The CJT is a single joint test rig that can be used to perform friction and wear tests on individual chain joints of bush and roller chains. The test specimens are thus serial components, whereby individual contacts such as the pin–bush contact or the bush–roller contact can be examined in detail. In addition, various lubricants, such as oils or greases, can be used. Temperatures of the test specimens can also be adjusted. The CJT represents a bridge from model tests like PoD to conventional system test rigs, on which entire drives are investigated. By examining individual joints, new possibilities are offered in the analysis of contacts.

Conventional wear measurements are performed on entire chains. A standardized test load is applied to the chain and the chain length is determined (*24*). This is related to the initial length of the chain when new, and the relative chain elongation is determined. For a measurement, chains are usually disassembled and conditioned to a defined test temperature. Therefore, wear measurements are usually very complex (*6*). By looking at a single and stationary joint, the CJT offers the possibility to measure wear in real time (Fig. 5). This means that test cycles do not have to be interrupted for a measurement and measurement errors due to assembly processes can be avoided. In addition, a detailed temporal resolution of the joint elongation is possible, whereas only discrete points during the test cycle can usually be recorded when measuring complete chains. There is also a very high level of agreement between the two measurement methods (*26*).

Another advantage of the CJT is that the accessibility of a locally stationary joint allows direct friction measurement, which is difficult with a revolving chain joint and can usually only be determined using secondary metrics such as system efficiencies. With the CJT, any load spectra can be set. Thus, the kinematics of the chain drive can be resolved and idealized collectives can be investigated in addition to the systemically conditioned load collectives. This allows friction measurements to be compared and is therefore ideal for the direct comparison of different test parameters (*27*).

Friction tests on the 10B-1 joints were carried out with the three coating systems and two different greases. Three specimens were tested for each joint variant. The joints were loaded with constant normal loads between $F = 200$ and $1,000$ N and at three different constant contact speeds of $v_{rel} = 0.27$, 0.55, and 0.83 mm/s. The friction was measured over 30 angular cycles with a total of 150,000 measuring points at a sampling rate of $f_s = 4$ kHz per individual test. For comparison with the PoD test, the testing temperature for the CJT friction test was also set to $T = 70^\circ$C. Tests were performed on the specimen in both as-new state and after running in under identical conditions (*27*). Thus, 90 (30

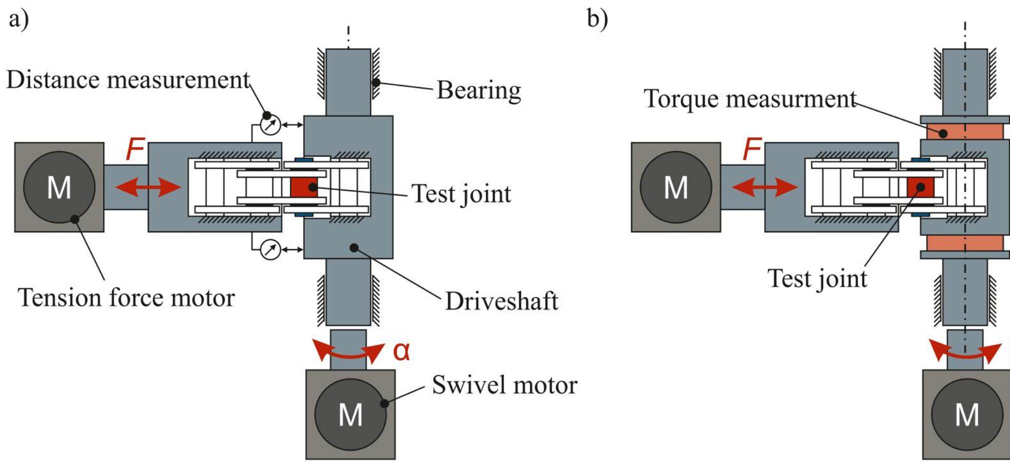

Figure 5. Schematic of CJT in configuration for analysis of (a) wear and (b) friction of chain components.

Table 3. Load parameters for different tests and resulting joint contact pressures in as-new and run-in state calculated with the procedure described by Simo Kamga et al. (29).

Configuration	Maximum tensile force (N) F_{max}	Maximum contact pressure (as-new) (N/mm^2) $p_{max,\,new}$	Maximum contact pressure (run-in) (N/mm^2) $p_{max,\,run-in}$
Friction$_1$	200	21.0	11.0
Friction$_2$	400	42.0	22.0
Friction$_3$	600	62.5	33.5
Friction$_4$	800	85.0	41.0
Friction$_5$	1,000	115.0	50.5
Wear	1,100	135.3	60.7

per speed) individual tests were carried out for each joint variant, for a total of 540 (180) individual tests. Wear analyses were carried out on the basis of a real-life load spectrum that was simulated using multi-body simulation (*28*) of a drive with a number of teeth of $z_1 = 17$ and $z_2 = 45$, operated at a constant driving speed of $n_1 = 1,000\ \text{min}^1$ and a constant braking torque of $M_2 = 125$ Nm. The collective was thus at the upper end of the permissible load of the chain according to DIN ISO 10823 (*8*). The sliding distance in the joint corresponded to a pitch angle $\tau_{sum} = 29.2\ ^\circ$ of the chain and a pin radius $r_P = 2.51$ mm. The sliding distance was therefore $s = 1.27$ mm per joint revolution, with one revolution requiring approximately $t = 0.42$ s. The resulting joint pressures were calculated with the procedure described by Simo Kamga et al. (*29*) and are presented in Table 3. In addition, three joints per variant were examined in the wear tests. Thus, a total of 18 individual tests were carried out.

Analysis

To analyze the wear volumes on the disks and pins after PoD tests, a confocal laser scanning microscope was used. The specific method for wear volume measurement was described in detail in Bobzin et al. (*23*) For analysis of the joint components after the wear tests, shape measurements were performed on the contact partners in addition to the in-line measurement of the CJT. This allowed the individual wear components of the pins and bushings to be assessed (*30*). An industrial roundness tester was used for this purpose. Determining component wear allows conclusions to be drawn about the extent to which the coatings on the pins have been worn and the influence of the coatings and lubricant on the wear behavior of the bushings. Furthermore, these tests were used to validate the CJT measurements.

In addition, the topology of the surfaces and their changes due to wear were studied in more detail. For this purpose, optical analyses were carried out with a confocal microscope, and an evaluation of the surface parameters was performed using a commercial software (*31*).

Tribochemical analysis was performed by Raman spectroscopy after tribological tests with the PoD and CJT respectively. These analyses were performed to investigate the influence of different coatings and grease lubricants on the formation of a wear- and friction-reducing tribofilm and transfer film. All investigations were performed with an industrial Raman spectroscope with a laser wavelength of $\lambda = 532$ nm, an 1, 800 l/mm grating, and a laser power of $P_L = 2.6$ mW. For Raman mappings, an exposure time of $t_E = 3$ s was used. A representative spectrum was selected for visualization. Prior to Raman analysis, all samples were cleaned in cyclohexane for approximately $t_c = 30$ s.

Results and discussion

In a previous work, in PoD tests of the CrAlMoN coating with the sulfur-added grease, Bobzin et al. showed that a reduction in friction of up to 50% was achieved compared to an uncoated system (*23*). Rank et al. confirmed the transfer of this result to the CJT (*27*). Furthermore, PoD tests showed an improvement in wear resistance using a CrAlMoN coating in combination with greases with sulfur and phosphorus additives. The findings obtained were compared with studies on the chain joint and are analyzed in more detail in the following.

Friction tests

The use of the grease with phosphorus as an additive has a strong influence on the friction behavior of all coating variants of the chain joint (Fig. 6). In the series of tests with grease + S (model grease with Sulfur additive), the system with the CrAlMoN pin coating had significantly lower friction values. The system with the grease + P (model grease with Phosphorus additive) had an identical magnitude of CoF as the uncoated system. However, the CrAlN system showed a very low CoF and reached a comparable level as the CrAlMoN + S system. Additionally, the observation that higher normal forces within the experimental limits lead to a reduction in friction in the chain joint was confirmed. One explanation for this phenomenon could be the higher contact ratio due to deformations of the asperities (*32*). However, the CoFs of the three systems were of a similar order of magnitude. This may be an indication of tribochemical reactions between the CrAlMoN coating and sulfur, whereas phosphorus had no influence on the friction. This finding agrees with previous research (*23*).

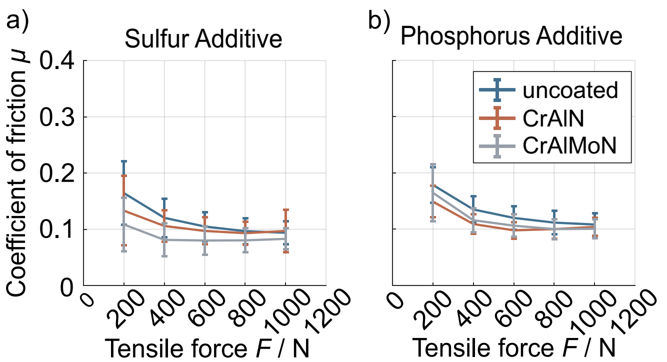

Figure 6. CJT investigation of the CoF of 10B-1 joints with different pin coatings with varied normal forces and grease with additives (a) sulfur and (b) phosphorus in as-new state at a sliding velocity v of 0.83 mm/s.

An increase in contact speed led to a slight decrease in friction. This effect was independent of the coating and the tensile force (Fig. 7). A comparable observation was made for the grease with sulfur as an additive (*27*).

The investigations also showed that the systems reacted strongly to the running-in process. Wear tests, which are considered in more detail below, showed complete running-in after 20 h at the described load. The samples for friction tests were therefore conditioned over 24 h with the same load collective as the wear tests. Whereas the uncoated systems showed only a relatively small increase in friction, the coated systems showed a significant increase in friction, which reached a factor of up to 3 with grease + P compared to the initial condition (Fig. 8).

The strong increase in friction between the as-new state and after running in din not correspond to the comparatively constant friction values from the PoD tests (*23*). One

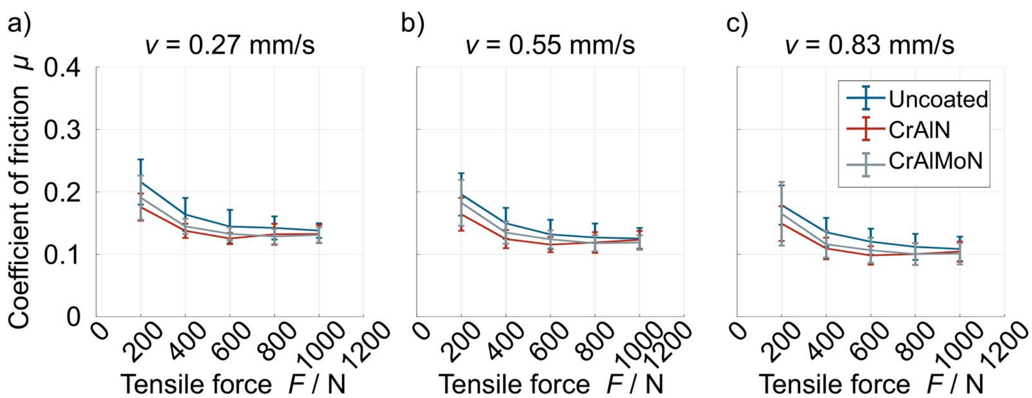

Figure 7. CJT investigation of the CoF of 10B-1 joints with different pin coatings with varied normal forces and grease with phosphorus additive in as-new state at a sliding velocities of (a) $v = 0.27$ mm/s, (b) $v = 0.55$ mm/s, and (c) $v = 0.83$ mm/s.

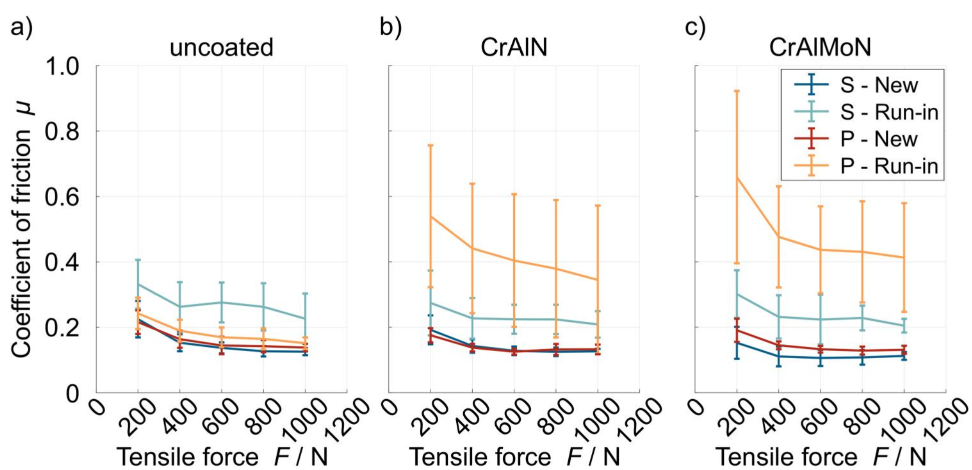

Figure 8. Comparison of CJT-measured CoF of run-in and as-new specimens versus tensile force; grease lubricated with sulfur and phosphorus additives for the systems with (a) an uncoated pin, (b) a pin with CrAlN coating, and (c) a pin with CrAlMoN coating at a sliding velocity v of 0.83 mm/s.

possible cause would be the entrapment of wear particles in the chain joint. The component contact at the PoD was open. This allowed particles to be conveyed out of the system. In the chain joint, on the other hand, the tribological system was closed off by the bushings and the link plates of the outer links. There was therefore minimal material exchange with the environment, and wear particles were not conveyed out of the contact. The coated pins also had a significantly higher hardness than the uncoated ones (*23*). Accordingly, the wear particles removed from the pins should also have had a greater hardness and thus have a greater influence on the system. Further experiments must be conducted for a deeper understanding.

Wear tests

Despite the massive change in friction after running in of the joints, some systems showed significantly improved wear resistance. In particular, the CrAlN + P and CrAlMoN + S systems showed barely any wear at the start of loading and thus no discernible running-in wear (Fig. 9). Only after a sliding distance of $s = 450$ m was there an increase in the wear gradient. The CrAlMoN + P system also exhibited a small joint elongation, although a clear running-in was observed in the first 250 m. After that, the elongation was almost constant and only increased slightly after a total of 600 m. The uncoated systems and the CrAlN + S samples also showed running-in within the first 250 m. After that, linear wear with a significantly higher gradient occurred.

These observations were also confirmed by the shape measurement of the pins and bushings. The lowest wear was recorded for the CrAlN + P and CrAlMoN + S systems (Fig. 10). In addition, it was clear that the joint elongation was significantly influenced by the pin wear. Only in the two systems mentioned above was a symmetrical distribution of wear between the pin and bushing discernible. It was also evident that the wear protection of the tribological system depended on the combination of grease and coating. The low level of dressing in the CrAlMoN + S system was indicative of a reaction between Mo and S, resulting in wear protection and a friction reduction.

The greatest wear was observed in the uncoated system + P, were, a total wear height of up to 200 μm was achieved. Assuming that a maximum permissible joint elongation of 3%, which is defined in DIN ISO 10823 as the parameter determining the lifetime of chain joints, is distributed symmetrical over both pins of a link, the wear limit for a joint is 238 μm according to Eq. [2].

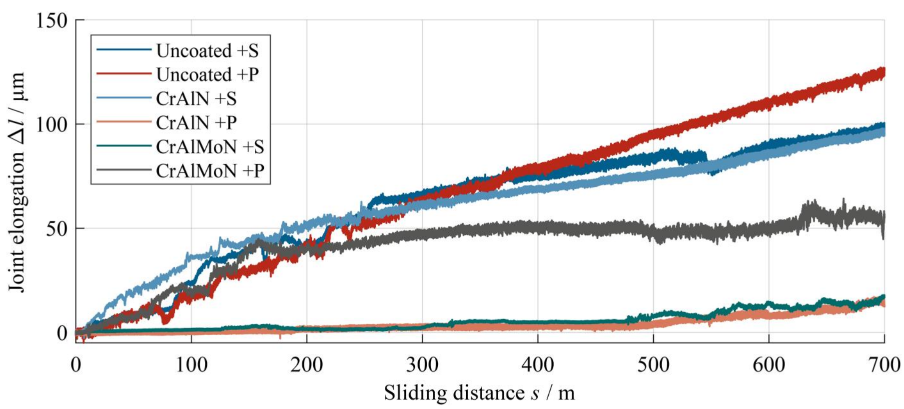

Figure 9. Joint elongation Δl over sliding distance s for different exemplary specimens.

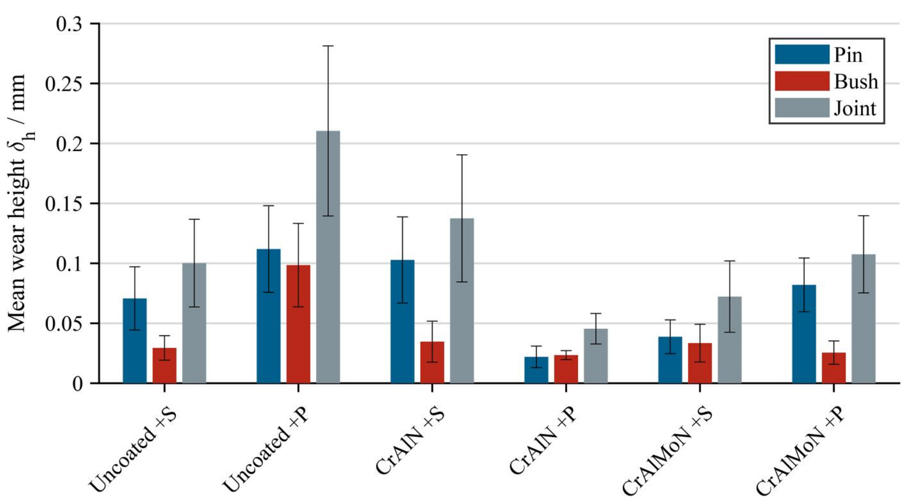

Figure 10. Average wear height δ_h of the pin, bush, and joint (sum) for the different tribosystems determined by tactile shape measurement.

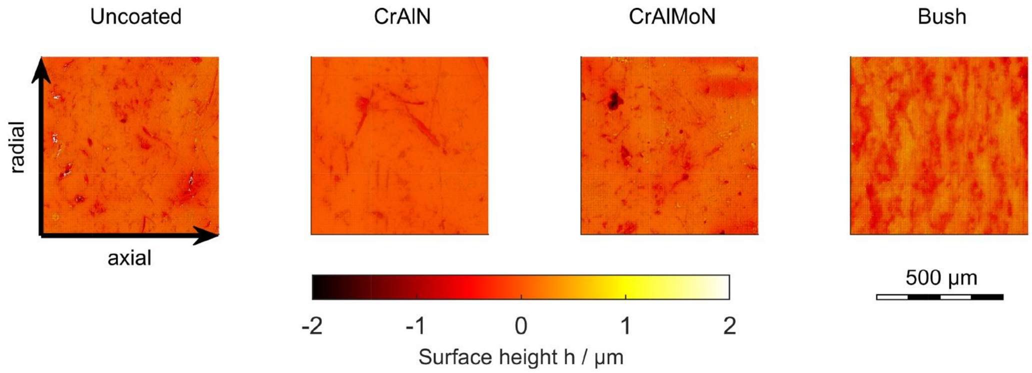

Figure 11. Exemplary surface structure of the new specimen.

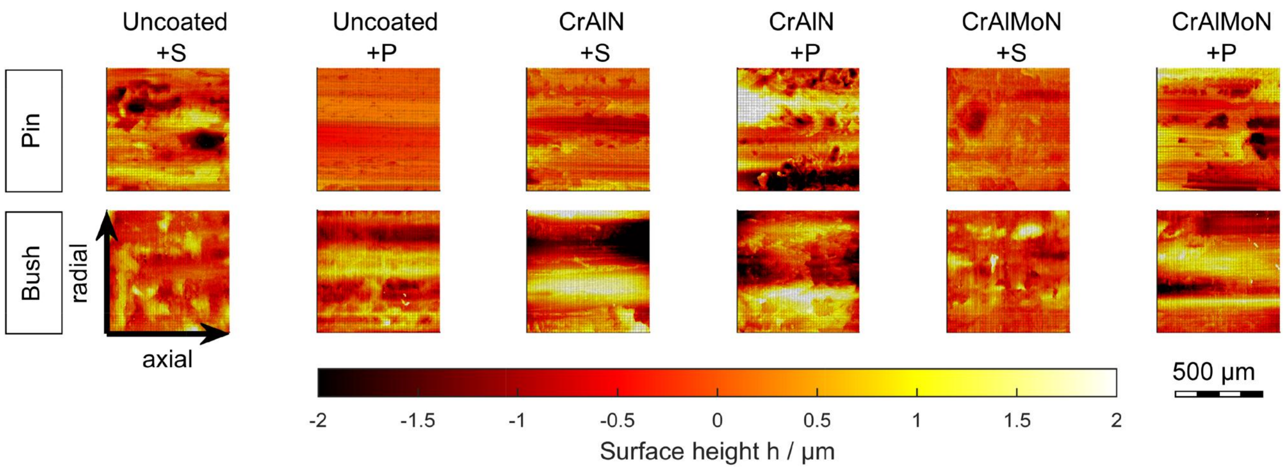

Figure 12. Exemplary surface structure of the worn specimen.

$$\Delta l_{\max} = \frac{\Delta P}{2} = \frac{3\ \% \cdot 15.875\ \text{mm}}{2} = 0.238\ \text{mm}. \quad (2)$$

Consequently, the joint with the highest wear already just reached the wear limit. However, all systems showed a wear height of the pins of more than 2 μm. This is an indication of at least local penetration of the coating and could be an explanation for the increase in wear of the (Cr,Al)N +P and CrAlMoN +S systems after 450 m sliding distance. Also, the gradient of joint wear appeared to converge for all tests after a sliding distance of 650 m. This behavior also indicates incipient failure of the pin coatings.

The surface topography of the worn specimens also indicated that the wear limit was reached in all test runs. Both the new pins and even the bushings had very even and homogeneous surfaces (Fig. 11).

All pins except the uncoated +P and CrAlMoN +S show spalling throughout the contact zone (Fig. 12). Severe surface changes were also observed on the bushings. No scoring occurred in the circumferential direction, the direction of the sliding movement. It can be deduced that microploughing did not occur in the contact.

The blanks of the coated specimens were identical to the uncoated specimen. Due to the coatings, the core heights S_k and skewness S_{sk} decreased slightly. However, all surfaces were roughened by wear. S_k of both the pins and the bushes increased sharply (Table 4). The uncoated pin +S was again an exception. Although the corresponding joints showed a large elongation, the pins had a similar core height as the as-new specimens. The bushes behaved differently. The smallest increase in core height was observed in both the uncoated configurations and CrAlMoN +S. The uncoated pins had a less hard surface. Thus, a low wear of the bushes is plausible. The slight change in the CrAlMoN +S bush was remarkable. Whereas the other coatings provoked severe bushing wear, in this variant tribochemical reactions could lead to a transfer layer and thus protection of the bushing.

Table 4. Core height S_k and skewness S_{sk} of the new and worn chain components in the different configurations.

	S_k (μm)		S_{sk}	
Configuration	Pin	Bush	Pin	Bush
Uncoated new	1.161±0.149	1.260±0.120	−1.644±0.4972	4.081±1.181
CrAlN new	0.544±0.105	–	−2.546±0.9121	–
CrAlMoN new	0.584±0.128	–	−1.829±1.7672	–
Uncoated +S	3.087±1.068	2.395±0.733	0.076±0.573	1.095±0.251
Uncoated +P	1.154±0.336	2.653±1.461	−0.345±0.911	−0.173±0.266
CrAlN +S	3.598±0.425	6.130±4.398	−0.300±0.443	0.593±0.754
CrAlN +P	4.060±1.228	3.425±1.781	−0.185±0.516	0.659±0.665
CrAlMoN +S	3.447±0.763	2.280±0.498	−0.314±0.359	0.558±0.563
CrAlMoN +P	5.088±0.591	3.489±0.393	−0.176±0.283	1.438±1.433

The skewness S_{sk} of the pin surface, which was still clearly negative in the new state, became neutral for all samples. The bushings initially exhibited a strong positive skewness. A decrease toward zero was be observed.

The tribological conditions in the initial state were very favorable. The asperity heights were small and a high real contact area was assumed. In addition, the bushings had valleys, which provided lubricant reservoirs. Wear resulted in symmetrically distributed peaks and valleys at greater core height. The real contact area consequently decreased. However, the wear was so great that no correlation of the surface parameters with the joint elongation was observed.

However, the wear behavior observed in the PoD could not be clearly confirmed. The wear of the flat specimen tended to show good agreement with the wear of the pins in the chain joint (Fig. 4). In both cases, the greatest component wear occurred with the uncoated specimen +P, whereas the CrAlN +P and CrAlMoN +S systems in particular exhibited significantly lower wear. However, the total wear of both tests differed. The lowest wear was observed for the system of the uncoated pin +S, whereas the highest was observed for the CrAlN systems. This suggests a greatly increased wear of the counterparts in the PoD compared to the chain bushes. In contrast to the PoD, the wear in the chain joint was largely determined by the wear of the pins in the tests under consideration. Only the CrAlN +P system exhibited significantly increased bushing wear. The chain joint was a closed system. In addition, the kinematic conditions were different from those of the PoD. On the PoD, a plane contact was loaded with high initial Hertzian pressures of $p_H = 1,420$ MPa (*23*). In the chain joint, on the other hand, there was a conformal line contact in which the pressures were less than $p_{max} = 150$ MPa. The lower pressures had a positive effect on wear of the bushes and resulted in lower total wear.

Tribofilm analysis

After the wear tests in the CJT, tribofilm analyses were performed on chain pins and bushings using Raman spectroscopy. The results for all samples of the grease +S-lubricated systems are displayed in Fig. 13. All Raman spectra showed the same tribofilm composition of iron oxides, indicating that all coatings failed due to wear. These findings agree with the previous results regarding wear analysis in the chain joint. Even the CrAlMoN system under grease +S lubrication showed clear signs of failure.

Next to CrAlMoN with grease +S, the CrAlN system with grease +P showed promising results in previous wear analysis. In Fig. 14, the tribofilm analysis via Raman spectroscopy for all systems with grease +P lubrication is presented. Peaks of iron oxide were found on the bushes of the CrAlN system. However, these were much less significant than in the other samples. On the chain pin in CrAlN +P system, there are no signs of iron oxides. This indicates that this system did not fail until the end of the wear test. However, there were also no traces of other tribofilm components like FeS_2, ZnO, or a-C that were found in previous studies. These findings support the results from previous wear analysis; that is, that the CrAlN coating in combination with the grease +P showed the best wear behavior in the chain joint. The uncoated system and the CrAlMoN system

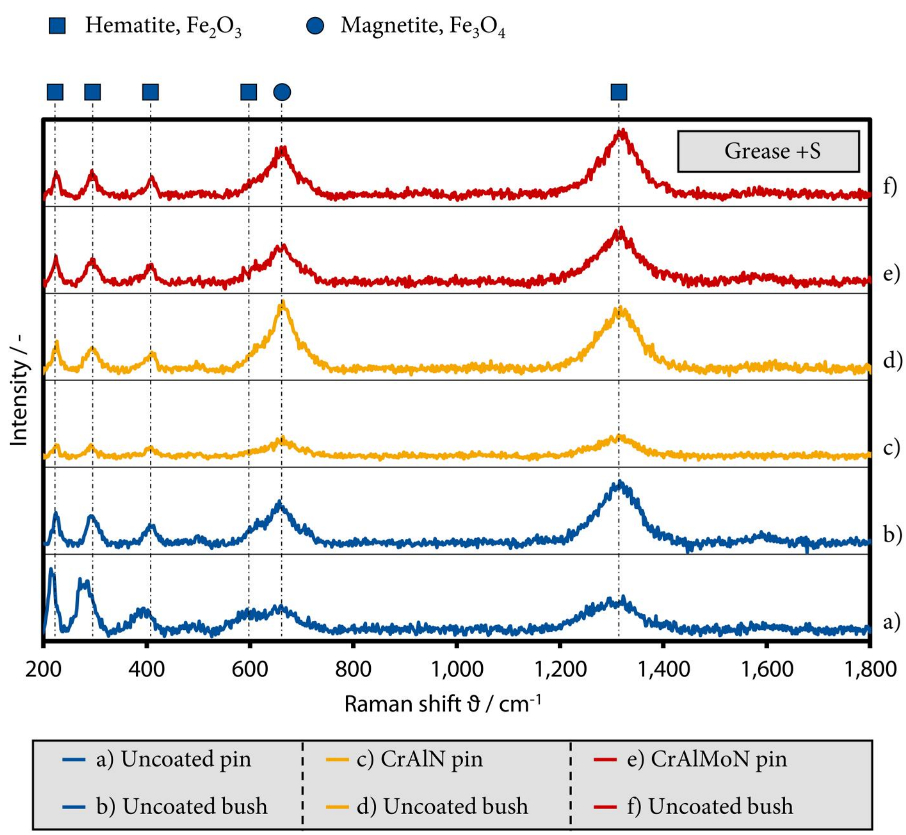

Figure 13. Raman spectroscopy analysis of the tribofilm of the worn chain specimen with grease +S lubrication.

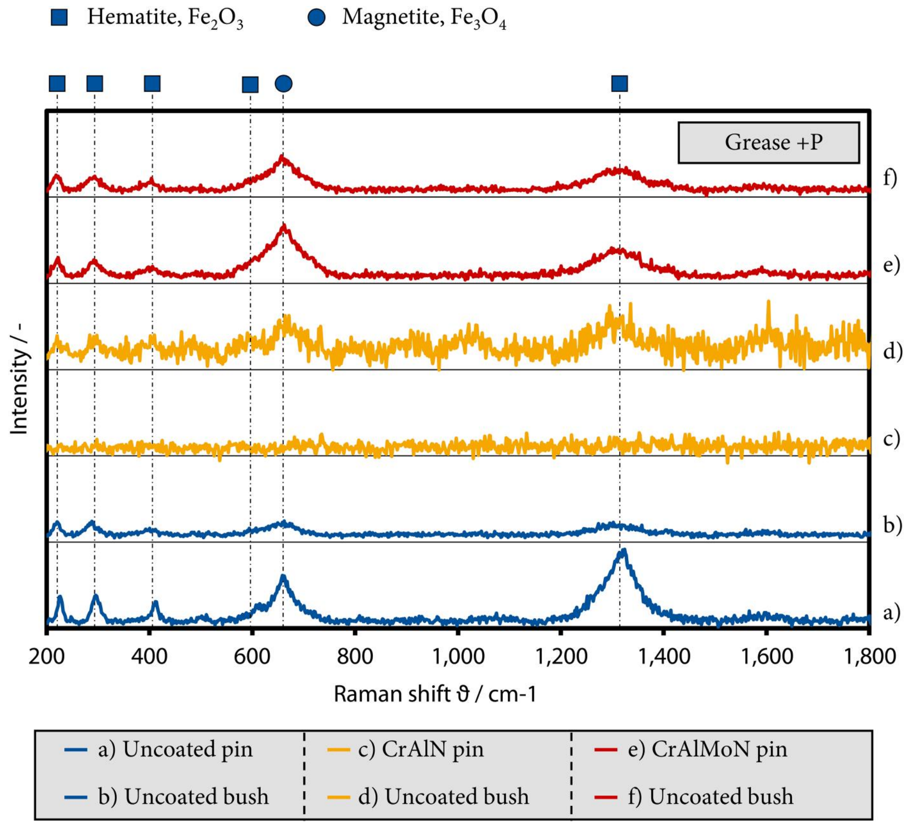

Figure 14. Raman spectroscopy analysis of the tribofilm analysis of the worn chain specimen with grease +P lubrication.

both showed signs of failure due to the high amount of iron oxides found in the tribofilm, which is in line with our previous results.

Though the wear behavior of the two tribometer setups was comparable, an increasing friction after running in was observed in the chain joint, which was not detected in the PoD. In the PoD, the disk and pin were in open contact. An exchange of grease from the environment and thus also a removal of contaminants was thus possible. In the chain joint, the contact was closed by the outer plates, which inhibited the exchange of lubricant. In addition, the contact pressures in the PoD were significantly higher than those in the chain joint. With the PoD, this is set once via the contact pressure of the pin and decreases due to increasing wear. In the CJT, on the other hand, the chain tensile forces are controlled continuously. The kinematics of the two tests are also differed. In the PoD, a continuous sliding movement was performed around a fixed axis. In the chain joint, an alternating pivoting motion with short friction paths occurred. Thus, the contact was loaded locally.

Conclusions

In this work, friction and wear in the chain joint or on simple test specimens were measured on two different test benches. It was shown that model tests on the PoD can be used for preselection of coating systems for chain components, whereby the effort compared to component tests can be significantly reduced. The same trends in friction and wear can be seen on both test benches. However, not all properties of the real system can be reproduced with the PoD. The friction in the run-in chain joint behaves differently than that in the PoD. The findings illustrate that a full substitution of the component test with real components by the PoD is not possible. Further investigation is needed to gain a deeper understanding of the contact in the chain joint. To understand the changes in friction in the run-in joint and to identify influences due to particles or changes in the lubricant, tests could be performed with relubricated systems. To achieve greater agreement between the tests on the chain joint and model tribometer, a different test setup, in which more comparable contact pressures can be set, could be investigated. Despite the slightly different results between PoD and CJT, the best wear and friction properties were observed for the chain joints with CrAlMoN coating system and grease with added sulfur and for the CrAlN system and grease with added phosphorus. Compared with the uncoated systems, a friction reduction of up to approximately 30% was achieved. Wear-related joint elongation was also reduced by up to 50%. It is remarkable that with these two systems, almost no elongation occurs up to a sliding distance of 450 m, whereas other systems already reach the wear limit.

The presence of zinc(-oxide) in the tribofilm was not found on the chain joint components after wear tests with Raman spectroscopy. However, this Raman analysis supported the fact that the CrAlN coating in combination with the grease +P showed the best wear behavior because no iron oxides were found.

The wear tests showed very large wear of all chain joints, although the load spectrum was selected in accordance with the real applications. In addition, circumstantial evidence of pin coating failure was found, which precludes detection of transfer coatings. One possible cause for the high wear could be the use of low additive model greases. Tests with reduced load and a shorter testing time could therefore be useful to investigate the transfer layer formation in more detail. Considering an entire chain drive would be appropriate to achieve a transfer between the CJT and the real system. Chains with the CrAlMoN coating system and the sulfur-added grease could be constructed, with tests performed in terms of the efficiency of the drive and the wear behavior of the chain.

Acknowledgements

The authors thank Wippermann junior GmbH, Hagen, Germany, for providing chain components, and FUCHS Lubricants Germany GmbH, Mannheim, Germany, for providing prototype lubricants for the tests conducted.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was funded by the German Research Foundation, Deutsche Forschungsgemeinschaft (DFG), within the project "Analysis of Transfer Layer Formation in Initially Lubricated, Coated Drive Chains" (SA 898/31-1 and BO 1979/81-1).

ORCID

Martin Rank http://orcid.org/0000-0002-9366-4142
Manuel Oehler http://orcid.org/0000-0001-8251-0896
Oliver Koch http://orcid.org/0000-0001-5967-0242
Kirsten Bobzin http://orcid.org/0000-0003-3797-8347
Christian Kalscheuer http://orcid.org/0000-0002-1606-5090
Max P. Möbius http://orcid.org/0000-0002-2982-8720

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

(1) Holmberg, K., Kivikytö-Reponen, P., Härkisaari, P., Valtonen, K., and Erdemir, A. (2017), "Global Energy Consumption Due to Friction and Wear in the Mining Industry," *Tribology International*, **115**, pp 116–139. doi:10.1016/j.triboint.2017.05.010

(2) Pfalzgraf, J. H. (2011), *Experimentelle Reibleisuntgsuntersuchungen an Kettentrieben im Verbrennungsmotor*, PhD thesis, TU München: München, Germany.

(3) Freidrich, F. (2006), *Beitrag zur Entwicklung von neuen Traglaschenketten in der Fördertechnik*, PhD thesis, TU Chemnitz: Chemnitz, Germany.

(4) Kemper, S. (2015), "Halmgutbergung," *Jahrbuch Agrartechnik 2014*, **26**(2014), pp 156–170. doi:10.24355/dbbs.084-201210110913-94

(5) Jagtap, M. D., Gaikwad, B. D., and Pawar, P. M. (2014), "Study of Roller Conveyor Chain Strip under Tensile Loading," *International Journal of Modern Engineering Research*, **4**, pp 2249–6645.

(6) Sappok, D. (2016), *Experimentelle und simulative Methoden zur Untersuchung der Verschleißvorgänge im Kettengelenk von Antriebs- und Steuerketten*, PhD thesis, Technische Universität Kaiserslautern: Kaiserslautern, Germany.

(7) Polat, O., Ebrinc, A. A., Ozen, C. and Akca, S. (2009), "Timing Chain Wear Assessment with Different Type of Oils," Paper presented at the *SAE World Congress & Exhibition*, Detroit, April 20–23, 2009, Society of Automotive Engineers (SAE): Warrendale, PA, pp. 2009-01-0198. doi:10.4271/2009-01-0198

(8) German Institute for Standardization. (2006), *Guidelines for the Selection of Roller Chain Drives. ISO 10823*, German Institute for Standardization: Berlin, Germany.

(9) Deters, L. and Mücke, W. (2018), *Zugmittelgetriebe*, Springer: Berlin, Germany. doi:10.1007/978-3-642-39503-1_7

(10) Bauer, P. (2013), *Kettensteuertriebe. Stand der Technik, Anwendungen, Entwicklung und Herstellung*, SZ Scala GmbH: München, Germany.

(11) Rosenkranz, A., Krupp, F., Reinert, L., Mücklich, F., and Sauer, B. (2017), "Tribological Performance of Laser-Patterned Chain Links—Influence of Pattern Geometry and Periodicity," *Wear*, **370–371**, pp 51–58. doi:10.1016/j.wear.2016.11.006

(12) Buhl, S., Schmidt, K., Sappok, D., Merz, R., Godard, C., Kerscher, E., Kopnarski, M., Sauer, B., Antonyuk, S., and Ripperger, S. (2015), "Surface Structuring of Case Hardened Chain Pins by Cold-Sprayed Microparticles to Modify Friction and Wear Properties," *Particuology*, **21**, pp 32–40. doi: 10.1016/j.partic.2014.10.001

(13) Becker, A. (2020), *Entwicklung einer Prüfmethodik für Verschleißuntersuchungen an Kettengelenken von Antriebs- und Steuerketten*, PhD thesis, TU Kaiserslautern: Kaiserslautern, Germany.

(14) Zhang, A., Wang, J., Han, Y., Zhang, J., and Liu, Y. (2022), "Effect of Pin Generatrix on the Elastohydrodynamic Lubrication Performance of Pin–Bush Pair in Industrial Roller Chains," *Proceedings of the Institution of Mechanical Engineers - Part J: Journal of Engineering Tribology*, **236**(8), pp 1545–1553. doi:10.1177/13506501211065954

(15) Krupp, F. (2019), *Untersuchungen zur Reibleistungsreduzierung in Steuerkettentrieben*, PhD thesis, Technische Universität Kaiserslautern: Kaiserslautern, Germany.

(16) Coenen, W. (1984), *Einfluss der Schmierung auf das Verschleißverhalten von Rollenketten*, PhD thesis, RWTH Aachen: Aachen, Germany.

(17) Bobzin, K., Brögelmann, T., Kalscheuer, C., Kühnert, B., and Baumann, M. (2019), "Triboaktive (Cr,Al,Mo)N- und (Cr,Al,Mo,Cu)N-Beschichtungen für Steuerkettenanwendungen," Paper presented at *Tagungsband zur Tribologie Fachtagung der Gesellschaft für Tribologie e.V. (GfT)*, Göttingen, Septmeber 23–25, 2019, Gesellschaft für Tribologie e.V.: Aachen, Germany.

(18) Meffert, D., Oehler, M., and Sauer, B. (2021), "Precise Friction Measurement in Drive Chains Using a Chain Joint Tribometer," *Tribology Online*, **16**(3), pp 151–158. doi:10.2474/trol.16.151

(19) Becker, A., Meffert, D., and Sauer, B. (2019), "Friction and Wear Investigations on Single Chain Joints," *Forschung im Ingenieurwesen*, **83**(1), pp 53–63. doi:10.1007/s10010-019-00297-x

(20) Bobzin, K., Kalscheuer, C., and Thiex, M. (2021), "Understanding the Tribological Behavior of Graded (Cr,Al)N + Mo:S in Fluid-Free Friction Regime," *Tribology Letters*, **69**(4), pp 162. doi:10.1007/s11249-021-01536-5

(21) Bobzin, K., Kalscheuer, C., Thiex, M., Stahl, K., Lohner, T., Maier, E., and Yilmaz, M. (2022), "Adaptive (Cr,Al)N + Mo:Sg Coating for Highly-Stressed Contacts under Dry Rolling-Sliding Conditions," *Tribology International*, **174**, pp 107761. doi:10.1016/j.triboint.2022.107761

(22) Bobzin, K., Brögelmann, T., Kalscheuer, C., Stahl, K., Lohner, T., and Yilmaz, M. (2019), "(Cr,Al)N and (Cr,Al,Mo)N Hard Coatings for Tribological Applications under Minimum

Quantity Lubrication," *Tribology International*, **140**, pp 105817b. doi:10.1016/j.triboint.2019.06.010

(23) Bobzin, K., Kalscheuer, C., Möbius, M. P., Rank, M., Oehler, M., and Koch, O. (2023), "Triboactive Coatings for Wear and Friction Reduction in Chain Drives," *Tribology International*, **185**, pp 108562. doi:10.1016/j.triboint.2023.108562

(24) German Institute for Standardization. (2018), *Short-Pitch Transmission Precision Roller and Bush Chains, Attachments and Associated Chain Sprockets. ISO 606*, German Institute for Standardization: Berlin, Germany.

(25) German Institute for Standardization. (1981), *Lubricants; Consistency Classification of Lubricating Greases; NLGI Grades. 51818*, German Institute for Standardization: Berlin, Germany.

(26) Becker, A., and Sauer, B. (2019), "Verschleiß- und Reibungsuntersuchungen am Bolzen-Hülsen-Kontakt von Steuerketten mit einem Einzelgelenkprüfstand," *Tribologie und Schmierungstechnik*, **66**(3), pp 48–55. doi:10.30419/TuS-2019-0018

(27) Rank, M., Meffert, D., Oehler, M., and Koch, O. (2022), "Einfluss von Beschichtungen zur triboaktiven Transferschichtbildung auf die Reibung in Kettengelenken," *Tribologie und Schmierungstechnik*, **69**(5–6), pp 5–12. doi:10.24053/TuS-2022-0039

(28) Becker, A., Krupp, F., and Sauer, B. (2017), "Systematische Verschleißuntersuchungen an Kettenkomponenten." Paper presented at *Tagungsband zur Tribologie Fachtagung der Gesellschaft für Tribologie e.V. (GfT)*, Göttingen, September 24–26, 2017, Gesellschaft für Tribologie e.V.: Aachen, Germany.

(29) Simo Kamga, L., Meffert, D., Magyar, B., Oehler, M., and Sauer, B. (2022), "Simulative Investigation of the Influence of Surface Texturing on the Elastohydrodynamic Lubrication in Chain Joints," *Tribology International*, **171**, pp 107564. doi: 10.1016/j.triboint.2022.107564

(30) Sappok, D., and Sauer, B. (2015), "Wear Measurement on Chain Joint Components Using a Roundness Instrument,: *Periodica Polytechnica Mechanical Engineering*, **59**(2), pp 51–59. doi:10.3311/PPme.7780

(31) Sappok, D., Merz, R., Sauer, B., and Kopnarski, M. (2015), "Surface Analysis of Chain Joint Components after Tribological Load and Usage of Antiwear Additives," *Conference Papers in Science,* Karlsruhe, Germany, May 6–8, 2014, Dienwiebel, M. (Ed.), Hindawi Publishing Corporation: London, United Kingdom, pp 407048. doi:10.1155/2015/407048

(32) Hossain, M. M., Minkwitz, R., Charoensirisomboon, P., and Sue, H.-J. (2014), "Quantitative Modeling of Scratch-Induced Deformation in Amorphous Polymers," *Polymer*, **55**(23), pp 6152–6166. doi:10.1016/j.polymer.2014.09.045