Wear 588 (2026) 206520

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Performance of top-of-rail products under contaminated conditions with pre-existing cracks: Impacts on traction and surface damage

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ARTICLE INFO

Keywords:
Friction modification
Rolling-contact fatigue
Wear
Low friction
Wheel-rail contact
Iron oxides
Water

ABSTRACT

Top-of-rail (TOR) products are used to optimise friction and reduce wear in the wheel–rail contact. However, their performance is affected by the presence of oxide layers naturally formed on the rail surface and by other environmental contaminants such as water. In this study, two types of TOR products (one friction modifier and one TOR lubricant) were tested under dry and wet conditions on both clean and oxidised specimens. In addition, some specimens were preconditioned to form pre-existing cracks, allowing a comparison between undamaged and damaged surfaces. The investigation focused on traction (CoT), wear rate, and rolling contact fatigue (RCF). The results showed that, with respect to CoT, water influenced the TOR lubricant much more than the friction modifier, as it extended its retentivity and led to extremely low friction levels (CoT down to 0.05). Both products effectively reduced wear and prevented crack initiation. However, when pre-existing cracks were present, the combination of water and the liquid base of TOR products accelerated crack propagation and caused severe spalling. Interestingly, oxidation also contributed to crack growth, as oxide formation inside the crack induced internal pressure that promoted secondary crack propagation.

1. Introduction

In railway operation, top-of-rail (TOR) products are applied to the wheel-rail (W/R) interface to mitigate the adverse effects of friction, such as increased fuel consumption [1], wear, and noise [2–7]. Generally, two types of TOR products are used: solid sticks pressed against the wheel [8] or liquid-based suspensions sprayed onto the railhead. Liquid TOR products can be divided into two main groups based on their base medium. The first group includes friction modifiers, which use water as the base, while the second group includes TOR lubricants, which use an oil or grease base [9]. The difference between these two types lies in their friction modification mechanisms, which result from their drying/non-drying nature. In friction modifiers (FMs), water acts as the transport medium, carrying solid lubricants along the rail. When it evaporates, it leaves behind a dry layer with low shear strength, typically composed of solid lubricants like graphite or molybdenum disulfide, which reduces friction [10]. On the contrary, due to their oil/grease base, TOR lubricants do not dry out. Instead, they form a thin lubricating film on the rail surface, providing boundary or mixed lubrication regimes [11].

Frictional conditions in the W/R contact are often described by the coefficient of traction (CoT), defined as the ratio of the traction force to the normal force. Several studies have assessed the effectiveness of TOR products in reducing wear and noise while maintaining sufficient CoT [12–17]. Recently, the possibility of using TOR products to mitigate rolling contact fatigue (RCF) was investigated. RCF is caused by the traction force, which induces minor plastic deformation that accumulates over time. Once the ductility of the material is exhausted, small cracks form in the deformed subsurface layer. These cracks then grow larger until a chunk of the material is removed from the surface, a process known as spalling [18]. Typically, there is competition between wear and RCF, as cracks are naturally removed due to wear [19,20]. In some cases, when wear rates are very high, RCF may not develop at all.

Some papers have reported the ability of TOR products to prevent crack formation, as they reduce CoT and thus the traction force, which results in a transition from plastic shakedown limit to the elastic region in the shakedown map [21–23]. However, a recent study by Hardwick et al. [24] reported results of tests where cracks already existed in the specimen surface before the TOR product was applied. The results showed that although FMs were effective, water and TOR lubricant

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https://doi.org/10.1016/j.wear.2026.206520
Received 28 July 2025; Received in revised form 3 December 2025; Accepted 3 January 2026

accelerated the growth of pre-existing cracks, causing massive surface delamination and material loss of up to 1740 % compared to dry conditions. Similar findings were also reported by Maya-Johnson et al. [25]. Hardwick et al. [24] identified that the varying effects of different TOR products on RCF and crack growth depend on whether the product is drying or non-drying. In the case of drying products (FMs), water evaporates quickly, leaving only dry particles on the surface. However, for non-drying products (TOR lubricants), the base medium may enter cracks and accelerate their growth due to fluid pressurisation and flank lubrication, as shown by Xavier et al. in their study [26]. The viscosity of the base medium significantly influences this effect, as TOR lubricants with low-viscosity oil have a much more substantial impact on crack growth than those based on high-viscosity grease. In addition, Seo et al. [27] investigated the effect of the liquid quantity. In their experiments, FM was not effective in preventing RCF, and interestingly, the most significant crack growth was observed in so-called "mixed conditions", referring to the situation when FM is almost dried out, so only a negligible amount of fluid is present. Then, the crack growth is enhanced due to the combination of the adverse effects of both dry friction (high CoT) and fluid-driven mechanisms of accelerated RCF.

Based on studies [21–24], applying FMs or high-viscosity TOR lubricants may seem an effective way to deal with wear and RCF, as FMs dry out and grease may struggle to penetrate cracks. However, the study by Seo et al. [27] challenges this, as it showed that RCF may develop under FMs, and the reason for this is the water contained in their composition. It is essential to note that the experiments in most of the studies are typically conducted under clean conditions, free from contaminants. On the actual track, water is often present (e.g. from rain or morning dew), as it is the most common contaminant [28]. Many studies experimentally confirmed the role of water as a lubricant in the W/R contact [29–33]. In addition, various numerical models were developed to describe the influence of specific parameters in water-contaminated contact. These studies have shown that surface roughness has a significant effect on CoT [34,35], together with water temperature [36–38], as it influences viscosity and thus film thickness [36]. Moreover, rolling speed plays a critical role, as at higher speeds, a thicker film forms, causing a transition to fluid film lubrication regime [39,40].

So, in water-contaminated contacts, it seems that TOR products will influence RCF differently than in dry conditions, as water has a significant effect on their performance [41,42]. However, it is not clear to what extent. Moreover, the state of the wheel and rail surfaces will also play a significant role, as they are naturally subject to oxidation. As the surfaces oxidise, the upper layer turns to a layer of iron oxides with lower shear strength than steel [43]. The crack growth, geometry and capillary forces between the crack face and entrapped liquid will differ in the oxidised layer compared to the conditions tested before, as previous studies usually used clean and non-oxidised specimens. The need for research on how iron oxides and water, combined with TOR products, affect wear has been highlighted in a study by Zhu et al. [43].

So, in the present study, the effectiveness of two commercial TOR products on reducing wear, RCF and their ability to maintain intermediate CoT was tested. A drying FM and a high-viscosity TOR lubricant (NLGI 0) were selected to address the problems discussed in this chapter. The novelty lies in the special attention paid to how water contamination and oxide layer will impact the performance of TOR products. Tests were conducted on both oxidised and non-oxidised specimens under dry and wet conditions. Additionally, specimens with and without pre-existing cracks were used to evaluate the ability of these products to prevent crack formation. This study addresses whether TOR products can maintain sufficient CoT and effectively mitigate wear and RCF in contact with oxidised surfaces and water contamination, simulating near-field conditions in a laboratory environment.

2. Material and methods

2.1. Experimental setup

All tests were conducted on a twin-disc machine (MJP-30A, Southwest Jiaotong University) capable of simulating rolling-sliding contact under various conditions. In this setup, the rail disc (mounted on an upper shaft) and wheel disc (mounted on a lower shaft) are driven by separate servo motors, allowing different percentages of slip to be set by varying the speed of both motors, see Fig. 1. The final slip (λ) value in % is a result of the wheel disc running faster than the rail disc and can be

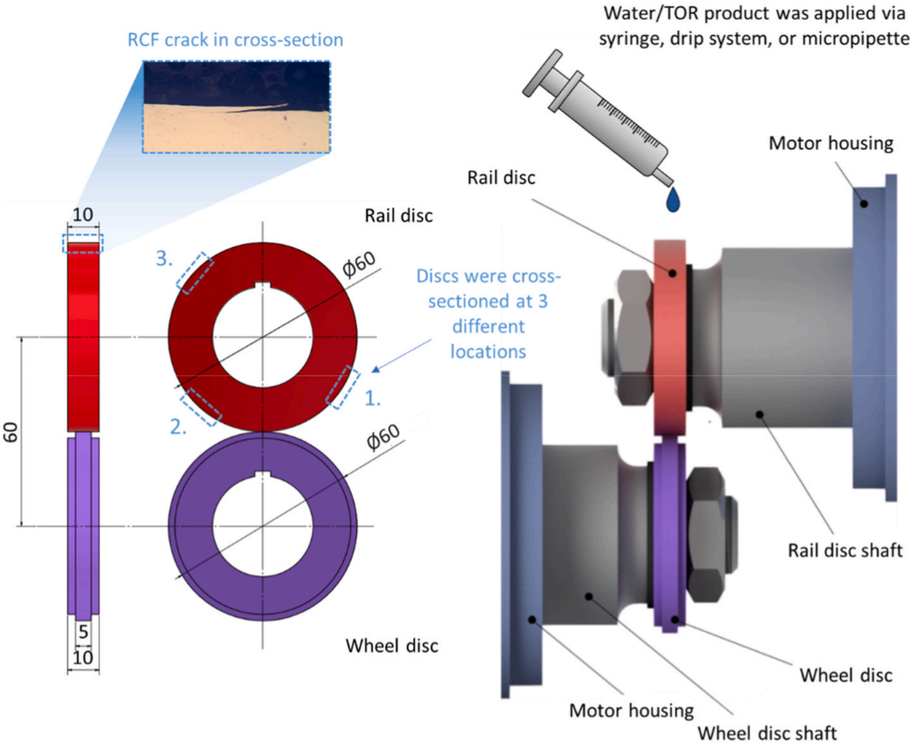

Fig. 1. Specimens dimensions and the MJP-30A twin-disc machine setup.

calculated as follows:

$$\lambda = \frac{w_{wheel} \cdot r_{wheel} - w_{rail} \cdot r_{rail}}{w_{wheel} \cdot r_{wheel}} \cdot 100\% \tag{1}$$

where w_{wheel} and w_{rail} are angular speeds (r/min) of discs and r_{wheel} and r_{rail} are their radii (mm). Both discs were loaded against each other by a hydraulic loading system. The frictional conditions were quantified in terms of CoT, which can be calculated as follows:

$$CoT = \frac{M_{wheel}}{r_{wheel} \cdot F_N} \tag{2}$$

where M_{wheel} is the torque (N · m) measured on the wheel shaft, r_{wheel} is the wheel disc radius (mm) and F_N stands for the normal force measured by the attached load sensor. The control of all test parameters and data acquisition was performed by the desktop computer connected to the machine.

The MJP-30A enables testing in various conditions typical for W/R contact. In this study, a Hertz contact pressure of 1.1 GPa (exerted by a normal force of 2500 N) was chosen for all experiments, as it falls within the typical range of contact pressures between the wheel tread and the top of the rail. The mean speed of 1.5 m/s (corresponding to a rotational speed of 500 RPM) was set. To achieve 2 % slip (a value from the effective part of the creep curve near the saturation point), the wheel disc rotates slightly faster and the rail disc slightly slower, resulting in the desired slip value. This study carried out two types of tests: "friction tests" and "wear and RCF tests". The friction tests focus on evaluating the influence on the CoT, whereas in the wear and RCF tests, metallographic samples will be prepared to investigate the effects on surface damage and crack propagation. Further details will be provided later in the paper.

2.2. Tested TOR products, contaminants and specimens

One FM and one TOR lubricant were selected for testing to examine both drying and non-drying types of TOR products. The manufacturers do not provide information about the composition of these products. However, the datasheets for the TOR lubricant indicate that the base is a biodegradable ester oil with a viscosity between 41 and 53 mm^2/s at 40 °C. It also contains an organic thickener and particles of soft metals and their compounds. The NLGI grade for this product is "0". The suitable application quantity for a downscaled twin-disc machine differs from field recommendations. Therefore, preliminary friction tests were conducted to examine the effects of varying application quantities in down-scaled contact. As detailed in the Results chapter, suitable quantities were chosen for each product based on their performance: 20 μl for FM and 10 μl for the TOR lubricant (see Fig. 3).

Water was applied to the contact in two different ways. In the "friction test" (where CoT was recorded as a function of the number of cycles), water was applied using a pipette (error ± 0.04 μl) in the following quantities: 30 μl, 120 μl and 480 μl. In the case of "wear and RCF tests", water was applied continuously from a drip system hung above the testing machine via a needle at the rate of one drop per second. The number of cycles during which water was fed to the contact is specified in Table 3.

In "wear and RCF tests", the influence of an oxide layer was investigated. In these tests, specimens were first run-in for 5000 dry cycles to form pre-existing cracks. After that, the oxidation process was carried out as follows: after the initial run-in, the discs were placed in a chamber preheated at 60 °C for 24 h, during which vapours from a solution of water, ethanol, and magnesium dichloride induced oxidation. Then, the discs were weighed to quantify the amount of oxide, and the tests were carried out. Please note that the mass of the resulting iron oxide includes both the mass of the original metal and the mass of the oxygen that has been added. X-ray diffraction (XRD) analysis showed that the oxide layer was composed primarily of magnetite, hematite, goethite, and akaganeite.

Regarding the specimens, both wheel and rail discs were cut from the actual wheel and rail, respectively. In the case of wheel discs, the material was C-class steel with a hardness of 388 ± 9 $HV_{0.5}$. Rail discs were made of U71Mn steel with a hardness of 290 $HV_{0.5}$. The detailed chemical composition of both materials is given in Table 1. Furthermore, both discs had the same diameter of 60 mm, and the width of the contact path was 5 mm (linear contact), see Fig. 1.

2.3. Test methodology

2.3.1. Friction tests

First, preliminary friction tests were performed without contaminants to select a suitable quantity of FM and TOR lubricant, as the manufacturer's recommendation for field application may not be ideal for the downscaled linear contact in the used apparatus. Both TOR products were applied using an electronic micropipette (error ± 0.04 μl) in the following amounts: 5 μl, 10 μl, 20 μl, and 30 μl for FM, and 5 μl, 10 μl, and 15 μl for TOR lubricant. All details are summarised in Table 2. Furthermore, the chosen quantity was tested three times to check repeatability. A model friction test is depicted in Fig. 2 a). The criterion for selecting the optimal amount was that the products provide intermediate CoT levels (green zone) for a reasonable time and do not cause low CoT (red zone).

The CoT levels were defined as follows: according to the benchmarking methodology for TOR products [44], the intermediate CoT level, where wear is reduced, but CoT is still sufficient for traction/braking, is defined between 1/3 and 2/3 of dry contact CoT. Typical CoT values for dry contact measured on the MJP-30A are between 0.4 and 0.5 [45]. Thus, the intermediate CoT level was defined between 0.15 and 0.3 (1/3 and 2/3 from 0.45 – the middle interval value where CoT stabilises for the dry contact). The value of 0.4, the minimum boundary of the dry contact CoT interval, was considered the threshold at which the product no longer had any significant effect. The test was stopped when this value was reached.

Furthermore, CoT lower than 1/6 of dry contact CoT is considered low [44], leading to a value of approx. 0.075 under these conditions. Moreover, Ishizaka et al. [46] state that a CoT higher than 0.09 is usually required for effective braking. However, they don't specify for which slip % this CoT value is relevant. Thus, this study defined a low CoT level for values lower than 0.1, similar to the previous study [42], to stay conservative on the low CoT definition. Regarding the above-stated intervals for CoT levels, the well-performing TOR product maintains CoT in the 0.15–0.3 interval for as long as possible (marked as "effective retentivity" in Fig. 2 a) and never causes a drop below 0.1. Friction tests are categorised into two groups based on the presence of oxides, see Table 2.

In tests conducted under wet conditions, water was always applied before the TOR products. Preliminary experiments showed that reversing the order led to inconsistent wetting. When the TOR product, particularly the TOR lubricant, was applied first, it spread across the surface and formed a continuous film due to its strong wetting ability. As

Table 1
Chemical composition of specimen materials (wt.%).

Disc	Steel	C	Si	Mn	P	S
Wheel	C-class	0.67–0.77	0.15–1.00	0.60–0.90	0.030	0.005–0.040
Rail	U71Mn	0.65–0.75	0.10–0.50	0.80–1.30	≤0.025	≤0.025

Table 2
The parameters and conditions of friction tests.

	TOR product; quantity (μl)	Water quantity (μl)	Run-in	Test duration	Slip; speed; pressure	Fig. #
No oxides	–	–	–	500 cycles	2 %; 1.5 m/s; 1.1 GPa	3 a)
	–	30, 120, 480	To stable CoT 0.4–0.5	CoT reached 0.4		3 b–d)
	FM; 20[1]	–				3 i)
	TOR lubricant; 10[2]	–				3 l)
	FM; 20	30, 120, 480				3 j)
	TOR lubricant; 10	30, 120, 480				3 m)
With oxides	–	–	–	500 cycles	2 %; 1.5 m/s; 1.1 GPa	3 e)
	–	30, 120, 480	To stable CoT 0.4–0.5[3]	CoT reached 0.4		3 f–h)
	FM; 20	30, 120, 480				3 k)
	TOR lubricant; 10	30, 120, 480				3 n)

[1] The FM was tested in the following quantities: 5 μl, 10 μl, 15 μl and 20 μl, from which 20 μl was chosen for further testing as it provided the optimal results.
[2] The TOR lubricant was tested in the following quantities: 5 μl, 10 μl and 15 μl, from which 10 μl was chosen for further testing as it provided the optimal results.
[3] The run-in was conducted before the creation of the oxide layer.

Table 3
The testing parameters and conditions of wear and RCF tests.

	Labeled as	TOR product; quantity (μl)	The TOR product is applied when	Water	Pre-existing cracks	Test duration (cycles)	Slip; speed; pressure	Fig. #
No oxides With pre-existing cracks	Test 1	–	–	–	No cracks were present at the time of application	5000	2 %; 1.5 m/s; 1.1 GPa	4 a)
	Test 2	–	–	–		25 000		4 b)
	Test 3	FM; 20	CoT = 0.3	–		25 000		4 c)
	Test 4	TOR lubricant; 10	CoT = 0.3	–		25 000		4 d)
	Test 5	–	–	1 drop/s		25 000		4 e)
	Test 6	FM; 20	CoT = 0.3	–	Run-ins were conducted to form pre-existing cracks	20 000 (+5000 cycles dry run-in)		4 f)
	Test 7	TOR lubricant; 10	CoT = 0.3	–				4 g)
	Test 8	–	–	1 drop/s				4 h)
	Test 9	FM; 20	Every 600 cycles[1]	1 drop/s				4 i)
	Test 10	TOR lubricant; 10	Every 2200 cycles[2]	1 drop/s				4 j)
With oxides	Test 11	FM; 20	Every 600 cycles[1]	1 drop/s	Run-ins were conducted to form pre-existing cracks	20 000 (+5000 cycles dry run-in)		9 a)
	Test 12	TOR lubricant; 10	Every 2200 cycles[2]					9 b)
	Test 13	–	–					9 c)

[1] FM was applied once every 600 cycles to match the total amount used in the test without water contamination, see 4 c).
[2] TOR lubricant was applied once every 2200 cycles to match the total amount used in the test without water contamination, see 4 d).

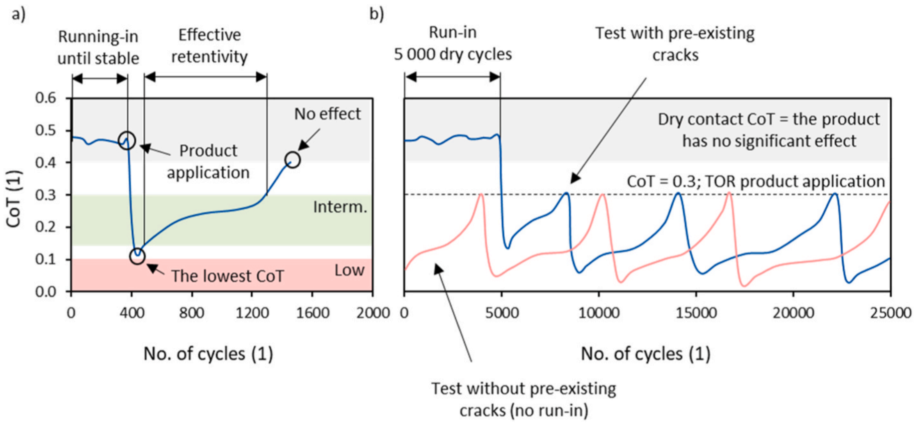

Fig. 2. a) The "optimal" TOR product performance and b) the wear and RCF tests procedure.

a result, the subsequently applied water could not reach the contact because it slid over the lubricant film and ran off the disc surfaces.

2.3.2. Wear and RCF tests

Parameters of wear and RCF tests are summarised in Table 3, with each test labeled as Test 1–13. The fundamental categorisation of the tests is based on the presence/absence of a pre-prepared oxide layer (as was described in Subchapter 2.2). Furthermore, 5000 cycles of dry run-in were conducted in tests 6–13 to create pre-existing cracks, so the ability of TOR products to prevent their formation could be evaluated by comparing tests with and without run-ins. Then, the test started, and depending on the type of the test, the water/TOR product was added

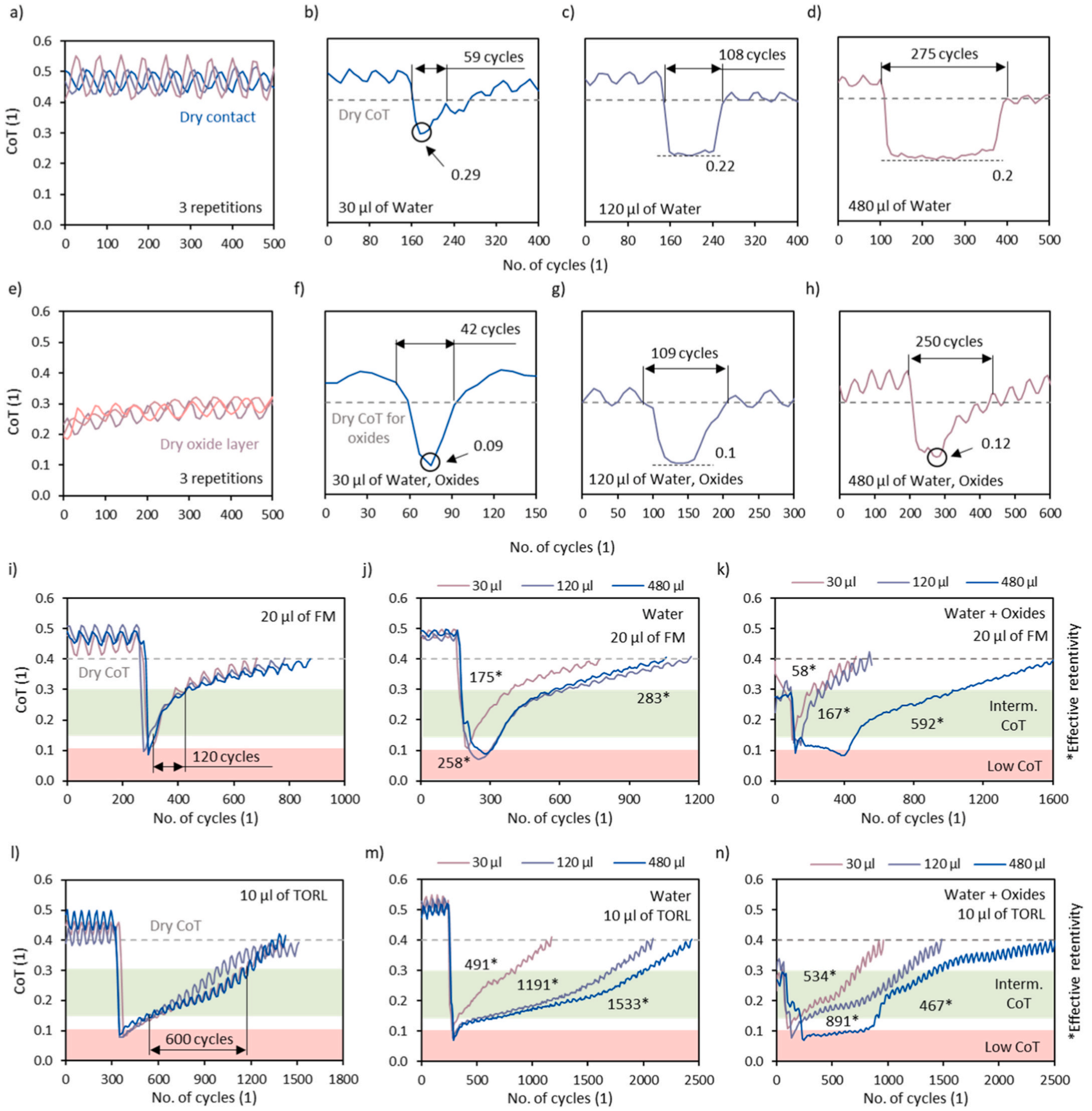

Fig. 3. a) Dry contact CoT, b–d) Different quantities of water on clean discs, e) Dry oxide layer CoT, f–h) Different amounts of water on oxidised discs, i–k) Tests with FM under various conditions, l–n) Tests with TOR lubricant under different conditions.

either from the beginning or after the initial run-in. TOR products were applied each time CoT reached the value of 0.3, an upper boundary of the intermediate traction level, see Fig. 2 b). Contrary to friction tests, water was continuously added from a drip system at a rate of 1 drop/s. All test parameters, applied quantity, etc., are summarised in Tab. 3.

In wear and RCF tests, the discs were weighed before and after testing to determine the total mass loss. The wear rate was calculated as the average mass loss normalised per 1 m sliding distance. After the test, discs were sectioned at three different locations (see Fig. 1), and polished samples were observed via optical (OM) and electron (SEM) microscopes for cracks and other surface damage. Furthermore, energy-dispersive spectroscopy (EDS) was used to analyse whether FM and TOR lubricant can enter the cracks.

In the preliminary phase of the study, several friction tests and selected wear and RCF tests were repeated to check the consistency of the procedure. However, full repetition of all wear and RCF tests was not conducted, as each experiment required destructive sectioning of the discs for metallographic analysis. Given the large number of test conditions investigated, repeating every case would have required preparing a proportionally large number of additional wheel and rail specimens, since each disc could be used for only a single test. The authors acknowledge that for future research, a more narrowly focused study design with a higher number of repetitions would be preferable.

3. Results

3.1. Results of friction tests

The results of tests with water without the TOR product are depicted in Fig. 3b–d). It can be seen that with an increase in water amount, the CoT decreases to lower values and the recovery time to dry values of CoT is prolonged. Next, the same tests with water were repeated on specimens with an oxide layer, see Fig. 3f–h). Compared to tests with clean specimens, CoT has now decreased to lower values. However, it can be attributed to the fact that while the CoT for clean specimens stabilises above 0.4, the corresponding value for specimens with an oxide layer is 0.3, see Fig. 3 a) and e). Therefore, the higher decrease in CoT is probably caused by lower initial values, which is also supported by the fact that the drop duration was similar for both types of tests.

In the next step, TOR products in different quantities were tested to choose the optimal dosage. The following quantities were tested: 5 μl, 10 μl, 20 μl, and 30 μl for FM, and 10 μl, 15 μl, and 20 μl for the TOR lubricant. For the FM, 20 μl was selected, as lower quantities did not provide a sufficient duration of effective retentivity. However, increasing the quantity beyond 20 μl did not bring any benefits. After application, the CoT briefly dropped to 0.08 as the liquid phase flooded the contact, temporarily separating the surfaces with a thin fluid film. Still, after a few cycles, the CoT rose to the desired levels. The duration of effective retentivity was approximately 120 cycles. Please note that the "duration of effective retentivity" refers to the number of cycles for which the value of CoT belonged to the intermediate interval, see Fig. 2 a). This test was repeated three times to check the repeatability, see Fig. 3 i).

Subsequently, the same amount was tested on clean and oxidised specimens under wet conditions, see Fig. 3 j) and k). Water was applied first to wet the surfaces, simulating wet rail conditions. The application of FM followed immediately. On clean specimens, the duration of the initial drop and the effective retentivity of the FM increased with the increase in applied water amounts. The situation was less clear with oxides, as their presence sometimes led to prolonged retentivity and sometimes had the opposite effect. The most significant impact was seen on oxidised specimens when 480 μl of water was applied, resulting in a drop lasting several hundred cycles. However, after the evaporation of water, the product behaved similarly to the case where the FM was applied under dry conditions. In this context, "performed similarly" refers to the stage that typically occurs near the upper boundary of the Intermediate CoT zone. Once most of the water has evaporated, the contact gradually transitions toward dry conditions but still contains residual solid lubricants originating from the FM. Beyond this point, the behaviour corresponds to dry contact with a thin layer of solid lubricants, influencing the friction level. This trend was consistent across most tests, except for those with oxide contamination and the test with 480 μl of water, where the surface may have remained partially wetted and the presence of oxides may have affected the contact mechanics, resulting in longer retentivity of the FM.

The same tests were conducted for the TOR lubricant. Following the same criteria, the quantity of 10 μl was assessed as optimal. TOR lubricants are known to cause over-lubrication when applied in excessive amounts. In the context of this paper, the term over-lubrication refers to a condition in which the CoT falls below the intended range. As TOR products are designed to provide an intermediate level of friction (low enough to reduce wear and noise, yet high enough to maintain effective traction and braking), this condition is undesirable. Although over-lubrication did not occur with any tested quantity, it is expected that in wear and RCF tests, where TOR lubricant is applied repeatedly, TOR lubricant would accumulate over time, preventing CoT recovery if a higher quantity were selected.

Under wet conditions, the lasting effect was significantly prolonged, see Fig. 3 m). The water has a substantially more pronounced impact on the TOR lubricant than on FM. For clean discs, the TOR lubricant follows the same trend as FM, and with an increase in water amount, effective retentivity also increases. This is not the case when oxides are present – while the CoT recovery took longer under 480 μl of water, the effective retentivity was the longest under 120 μl. It seems that the influence of oxide layers on TOR products cannot be generalised as purely increasing or decreasing CoT, as it depends on several factors such as oxide type, hardness and layer thickness. A possible explanation for the irregular behaviour observed in the case where 120 μl of water resulted in the longer effective retentivity than 480 μl is that oxide layers have low shear strength, and they break down in a non-uniform way during rolling–sliding. As a result, local cracking and flaking may disturb or partially remove the TOR lubricant film and change the contact conditions. This may explain why the expected trend of increasing effective retentivity with increasing water amount was not observed and why some CoT curves show unexpected shapes or sudden changes.

3.2. Results of wear and RCF tests: No oxides

First, tests 1 and 2 under dry conditions were conducted: the first for 5000 cycles to check the formation of pre-existing cracks after the run-ins and the second for 25 000 cycles for comparison with tests with water/TOR products. In these tests, the CoT stabilised in the 0.4–0.5 interval after the initial 2500 cycles, see Fig. 4 a) and b).

Tests 3–5 were conducted without any run-ins, so the water/TOR product was applied right from the beginning. Thus, no major cracks were present on the surface at the moment of application. While FM and TOR lubricant were applied each time the CoT reached 0.3 (resulting in 36 and 10 applications for FM and TOR lubricant, respectively), water was applied continuously with a rate of 1 drop/s, see Fig. 4c–e). Each application of the TOR product led to a similar CoT curve. Both TOR products were able to provide values from the intermediate CoT level throughout the test, which was achieved with a total amount over 7 times lower for TOR lubricant than for FM. Water maintained stable CoT values between 0.1 and 0.2, see Fig. 4 e). Although those values are not considered optimal, they are still above the low CoT level.

From the friction perspective, there was no significant difference in the performance of TOR products in tests without (3 and 4) and with pre-existing cracks (6 and 7), see Fig. 4 f) and g). However, when comparing tests with water (5 and 8), there is a clear difference in frictional behaviour, see Fig. 4 e) and h). In the first 5000 cycles of water application, CoT in test 8 had a similar development to that in test 5. But then, CoT gradually rose and became less stable, almost reaching dry contact values at the end of the test. A similar phenomenon, although to a limited extent, was also observed in test 9, where FM was applied together with water, see Fig. 4 i). As it was limited to tests where water and pre-existing cracks were present, it is most likely a result of RCF, which will be discussed later. This behaviour was not observed in test 10 with TOR lubricant and water, see Fig. 4 j). Under wet conditions, neither of the TOR products could maintain intermediate CoT. The combination of water and TOR product caused over-lubrication, and CoT values dropped below 0.1.

For the wear analysis, specimens were weighed before and after each test to evaluate the mass loss of the wheel disc and rail disc separately. The "total system" represents the combined mass loss of both discs. Fig. 5 a) shows mass loss of discs after tests 1–10 (no oxides). The chart is divided into two parts: tests without pre-existing cracks (1–5) and tests where an initial 5000 dry cycles were conducted before the water/TOR application to form pre-existing cracks. Fig. 5 b) is divided into two parts in the same way as Fig. 5 a) and displays information about wear rate, which was calculated as total system mass loss per 1 m of sliding distance. Please note that, in tests with pre-existing cracks, the initial 5000 dry cycles were excluded from the evaluation, so the number represents only the part of the test under lubricated conditions.

Fig. 5 a) shows that under dry conditions, the mass loss of the wheel

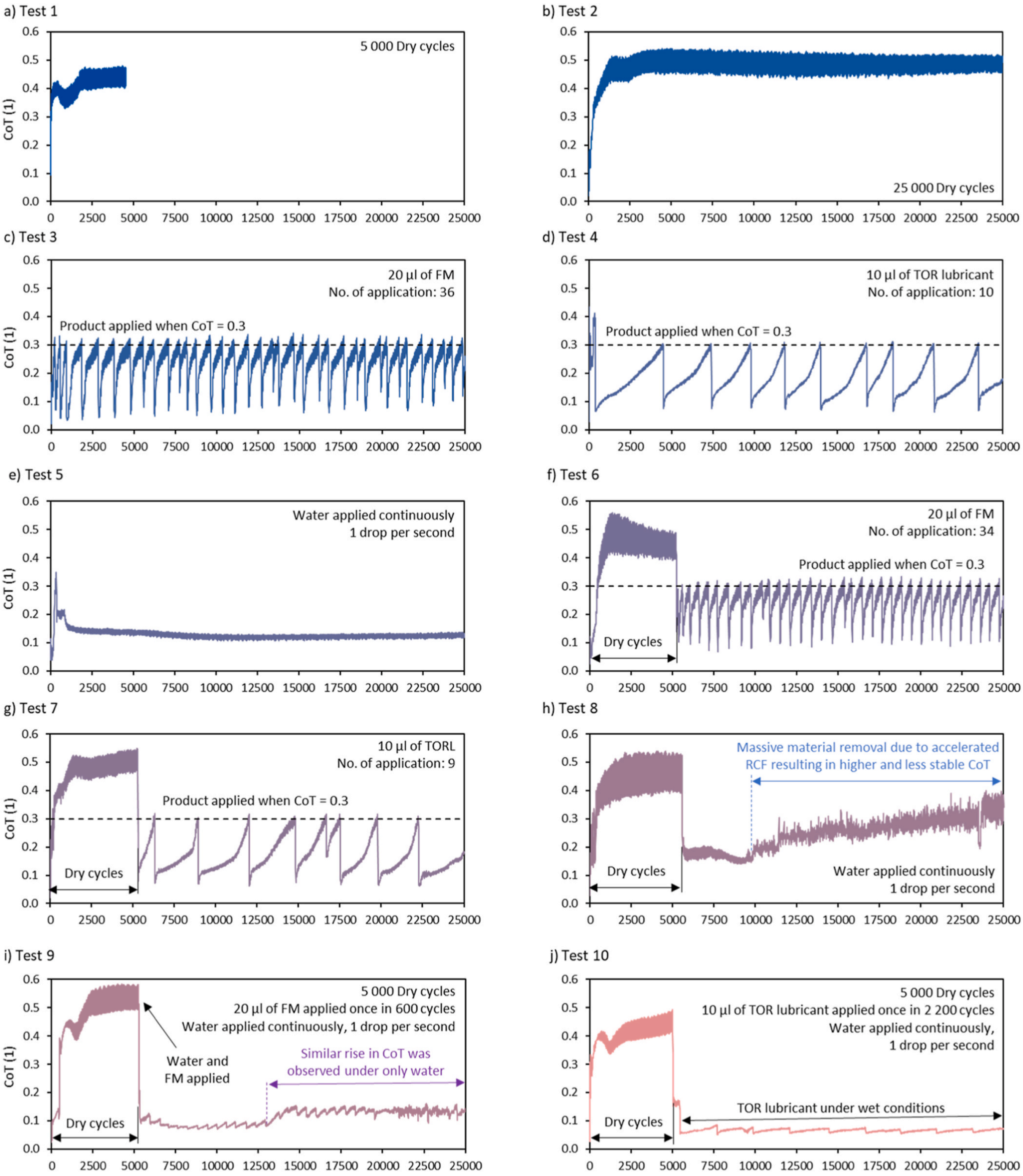

Fig. 4. Friction data for wear and RCF tests: No oxides. Tests 1–5 (a–e) were conducted without run-ins. Tests 6–10 (f–j) are with pre-existing cracks. No oxides.

disc is higher than that of the rail discs (tests 1 and 2), but the opposite was true in the rest of the tests. Both TOR products effectively reduce wear, as the total system mass loss decreased 10 times when using FM and 35 times when using the TOR lubricant. In a direct comparison of both products, the TOR lubricant proved to be more than three times as effective as FM in reducing wear. Water achieved similar wear reduction as TOR lubricant, resulting from maintaining low and stable CoT throughout the test and, thus, lower adhesive wear.

The situation changed significantly in tests with pre-existing cracks. The increase in mass loss was observed in all cases, although it is essential to point out that TOR products, when applied to dry surfaces, still provided wear reduction to some extent. Wear rate, calculated as total system mass loss normalised per 1 m of sliding distance, is a better indicator of changes in wear intensity in tests 6–10, as it excludes wear

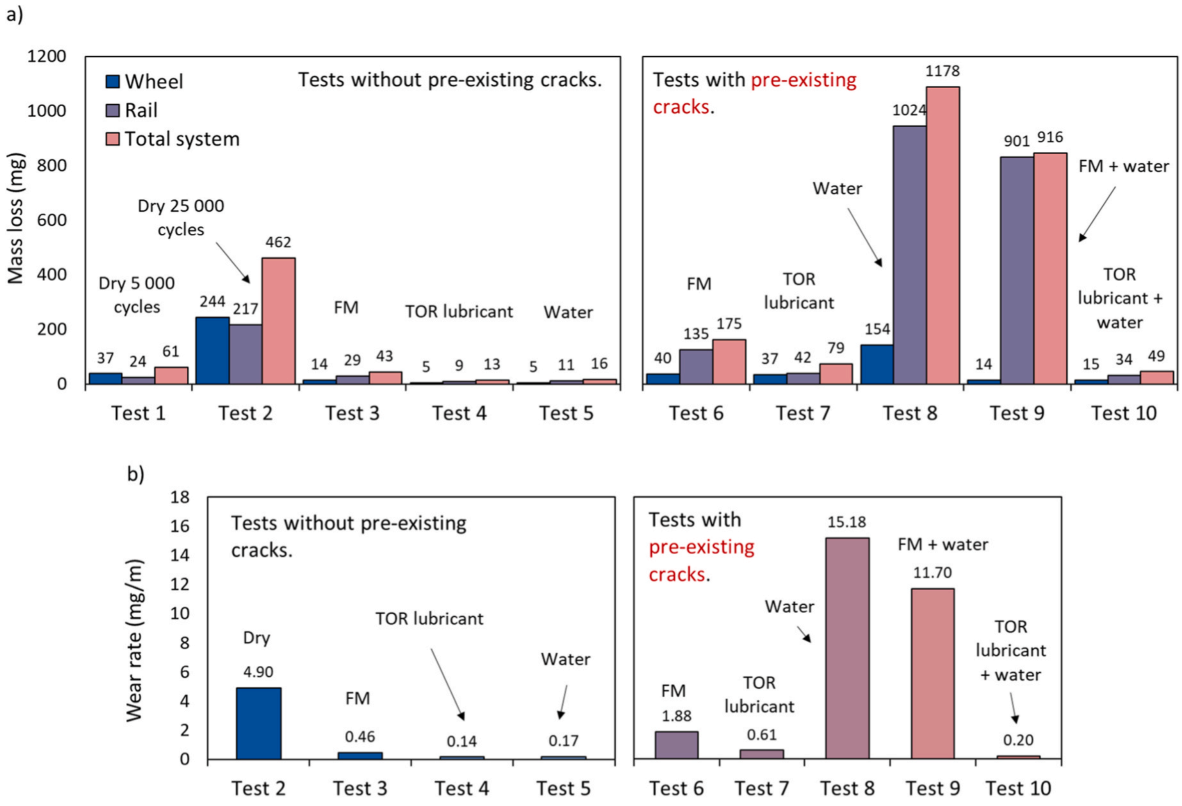

Fig. 5. a) Mass loss of wheel disc, rail disc and total system. Part b) shows the total system wear rate in mg per 1 m of sliding distance (run-ins were excluded from the evaluation). No oxides.

during the first 5000 dry cycles, see Fig. 5 b). The presence of pre-existing cracks and water resulted in an 89 times increase between tests 5 and 8.

Furthermore, the wear rate in test 8 was three times higher than in dry tests without lubrication (test 2). An increased wear rate was also observed in test 9, where FM was applied together with water. Although it was lower than in test 8, it remained more than six times higher than when FM was used alone (test 6) and more than twice the wear rate under dry conditions. On the contrary, the effect of water was less pronounced in test 10, where TOR lubricant was used, suggesting that wet conditions influence TOR products differently depending on their base medium type.

After mass loss/wear rate evaluation, surfaces were observed under an optical microscope, see Fig. 6. OM analysis showed signs of minor spalling in tests 3 and 4 but no visible cracks, meaning that both TOR products were more or less effective in preventing crack initiation. However, surfaces in tests with pre-existing cracks exhibited severe spalling and extensive cracking, with the most pronounced damage observed in tests 8, 9, and 10, where water was present.

As the wear and RCF were more severe for the rail discs (see Fig. 5), and the wheel discs often showed no noticeable cracks, the following crack analysis will focus only on the rail discs, which are of greater interest. After 5000 and 25 000 dry cycles, the surfaces showed signs of adhesive wear and minor spalling (see Fig. 6, tests 1 and 2). The black areas represent material peeled off the original surface and then adhered to a different location. As shown in Fig. 7), the median length and depth of cracks were similar in these tests, suggesting that 5000 cycles of running-in are sufficient to create pre-existing cracks. Fig. 8 a) shows that cracks run parallel to the surface, entering at an average angle of around 10°.

The cracks observed in tests 4 and 5, where water and TOR lubricant were used, were very short and shallow and ran under an average angle of around 12°. Only a few turned towards the bulk under a steep 25–50° angle. In contrast, the cracks in test 3 with FM ran under a much smaller angle of 6° and were similar in size to those observed under dry conditions.

Regarding tests with TOR products and pre-existing cracks (Fig. 8b and c), the final length and depth of cracks were somewhat similar to tests without pre-existing cracks. However, there was a substantial difference when TOR products were applied in wet conditions (Fig. 8e–h), as the length of the cracks in test 10 was, on average, almost 58 times longer than in test 4, and their depth increased 94 times. There was an even more significant change in the case of water alone, where cracks in test 8 were, on average, more than 200 times longer and more than 150 times deeper than in test 5. Numerous cracks were found running above one another, causing extensive material peeling. These cracks entered the surface at a shallow angle at first, similar to earlier tests, but then turned towards the bulk and propagated at a much steeper angle, reaching depths of nearly 600 μm, see Fig. 8 d).

Fig. 8 presents SEM images of typical cracks observed in cross-sections from tests 6–10. In tests where water was present (8–10), the cracks propagated deep into the bulk material, exhibiting branching and coalescence. In contrast, in tests 6 and 7, the cracks remained shallow. So, water was able to enter cracks and played a crucial role in crack propagation. In addition, an EDS analysis was conducted to confirm whether TOR products can also enter cracks. As a result, EDS detected carbon particles inside the cracks (see Fig. 8 b) and f). The only possible carbon source was the FM, which usually contains graphite or carboxymethyl cellulose (although authors do not know the exact composition of used TOR products, EDS analysis confirmed carbon as one of the constituents of FM). It is important to note that although the steel used for the discs also contains a trace amount of carbon, it was likely too low to form the thick black coating observed on the crack faces.

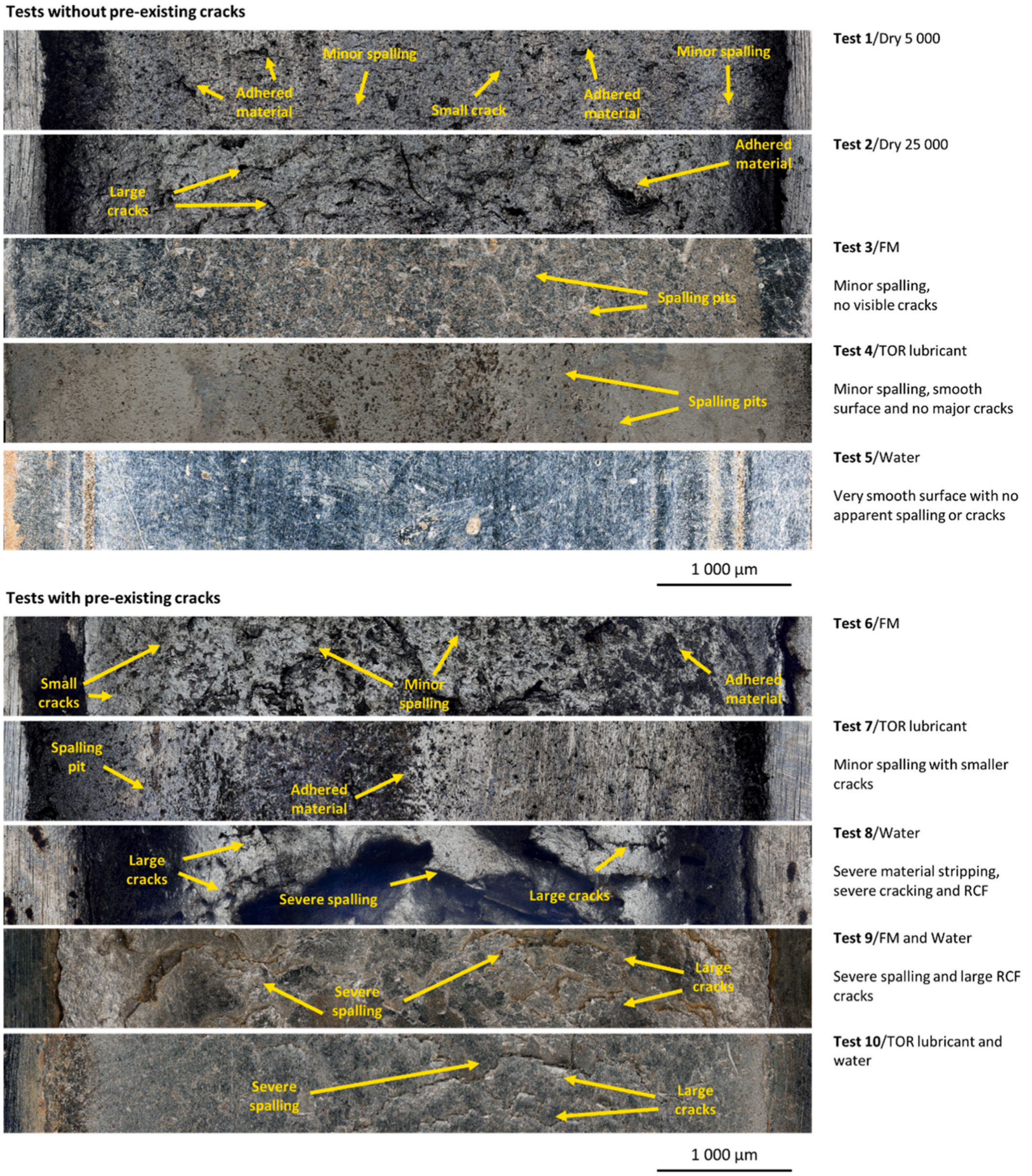

Fig. 6. OM pictures of the surface after testing (rail disc). No oxides.

3.3. *Results of wear and RCF tests: with oxides*

In tests 11–13, specimens were first run-in for 5000 cycles to create pre-existing cracks. After that, both discs were put in a climate chamber for 24 h to form an oxide layer. Then, the test was conducted the same way as in tests 8–10. Regarding friction, CoT measured in tests where TOR products were applied on oxidised specimens stayed in the same range as in tests where clean specimens were used (9 and 10). For FM, this range was between 0.1 and 0.15, see Fig. 9 a). For TOR lubricant, CoT values were slightly lower, as they stayed below 0.1 for most of the test, see Fig. 9 b). However, a difference was observed in tests with water, as the CoT now remained stable around 0.2, unlike in test 8, where CoT gradually increased to values approaching dry contact friction (see Fig. 4 h). This behaviour resembled test 5 (Fig. 4 e), where

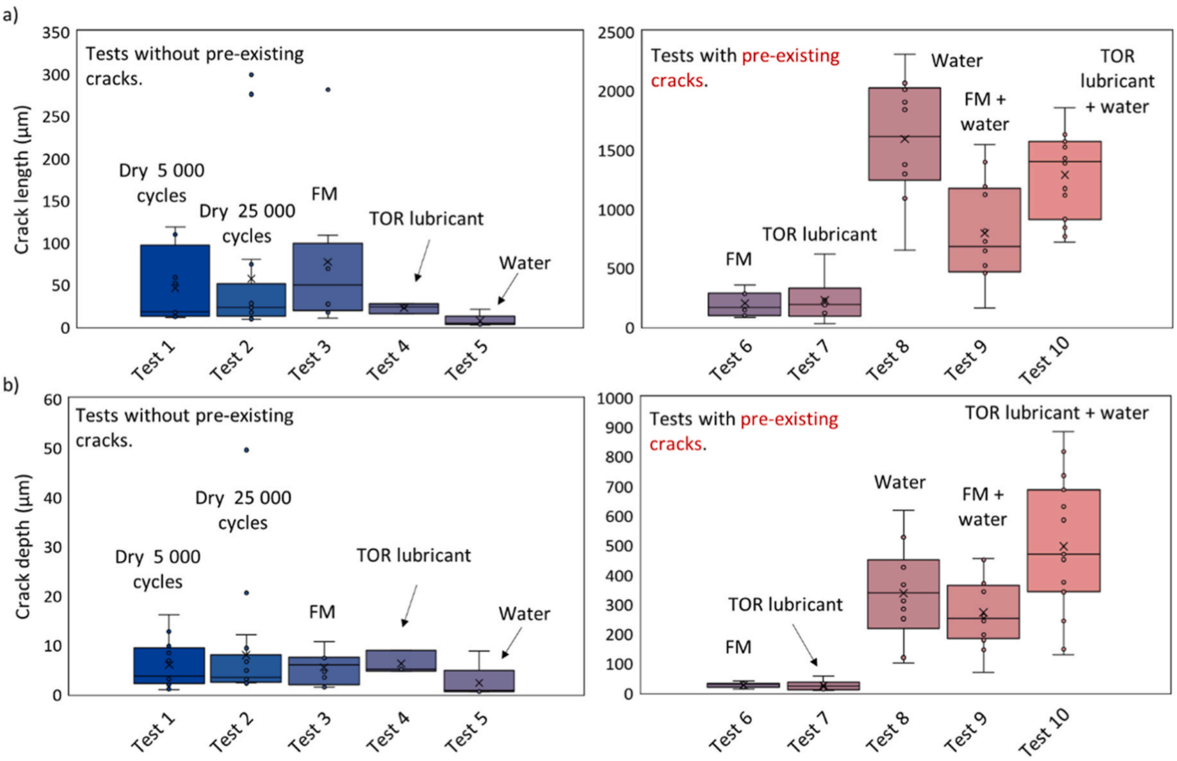

Fig. 7. RCF crack parameters: a) length and b) depth. Tests without and with pre-existing cracks are displayed in separate figures. No oxides.

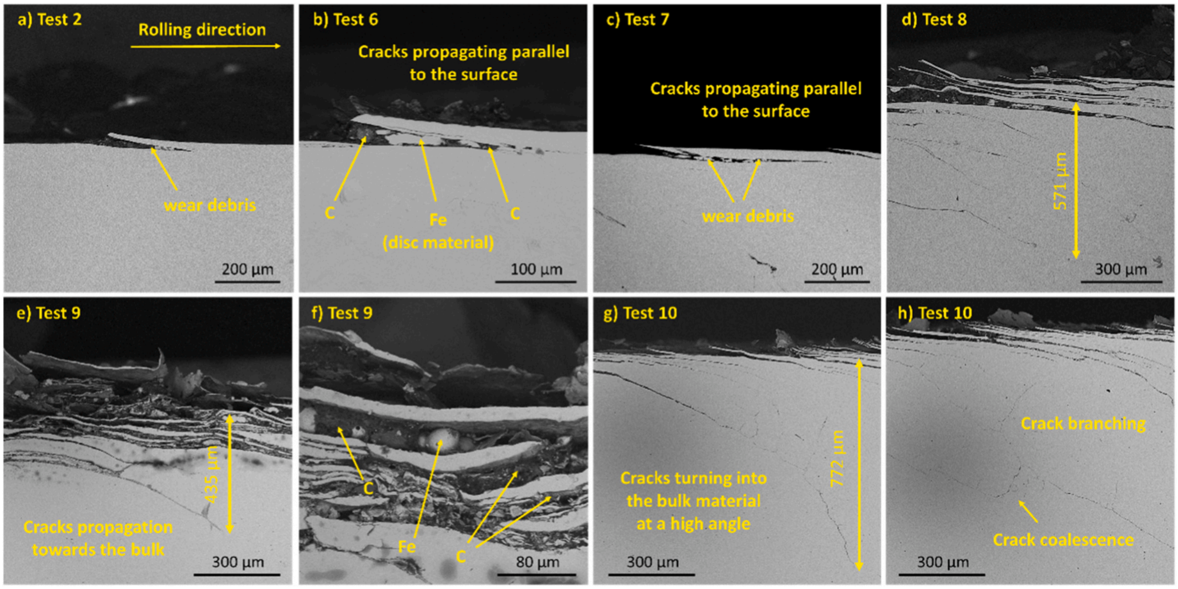

Fig. 8. SEM pictures of cracks: a) Dry 25 000 cycles, b) FM (with pre-existing cracks), c) TOR lubricant (with pre-existing cracks), d) Water (with pre-existing cracks), e) and f) FM in wet conditions (with pre-existing cracks), g) and h) TOR lubricant in wet conditions (with pre-existing cracks). No oxides.

water was used, but no pre-existing cracks were present. This suggests that, from a frictional perspective, an oxide layer suppresses the influence of pre-existing cracks, allowing water to affect CoT like in conditions without cracks.

Specimens were weighed before and after the test to evaluate the mass loss and wear rate. However, it is essential to note that it was impossible to distinguish between the mass loss of the oxides and the bulk steel. As the oxide layer has lower shear strength than steel and is easily worn, the mass loss and wear rate calculated for specimens with oxides could not be meaningfully compared to the wear rate of the specimens in the previous tests without oxides. Nevertheless, the results showed that in the case of the TOR lubricant under wet conditions, the mass loss and wear rate were higher for oxidised specimens than for those without oxide layers (see Fig. 10, test 12), which can be explained by the fact that oxide layers are easily worn due to their low shear strength. However, in tests with water alone and those with water together with FM, the opposite was true (see Fig. 10, tests 11 and 13), as the mass loss and wear rate of specimens with an oxide layer were lower than in tests without oxides. The reason for this was that the exceptionally high mass loss observed for the unoxidised discs was mainly a

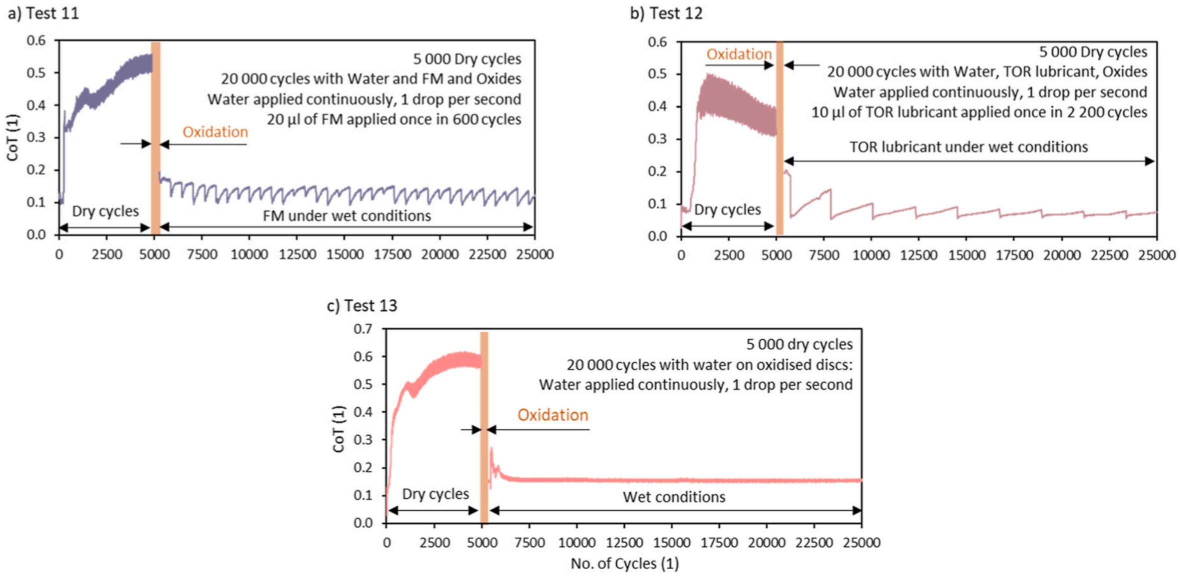

Fig. 9. Friction data for wear and RCF tests: With oxides. All tests were conducted on specimens with pre-existing cracks. a) FM and water, b) TOR lubricant and water, c) water.

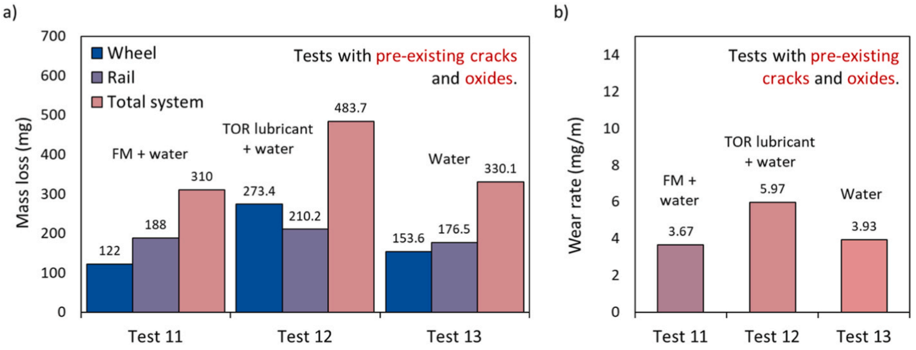

Fig. 10. a) Mass loss of wheel disc, rail disc and total system. Part b) shows the total system wear rate in milligrams per 1 m of sliding distance (run-ins were excluded from the evaluation). Specimens with an oxide layer.

result of severe RCF damage. In contrast, in the tests with oxidised surfaces, water could not enter the cracks, and the mass loss was therefore primarily due to wear. Unlike FM, the TOR lubricant was more effective in preventing mass loss due to the RCF. This is discussed in

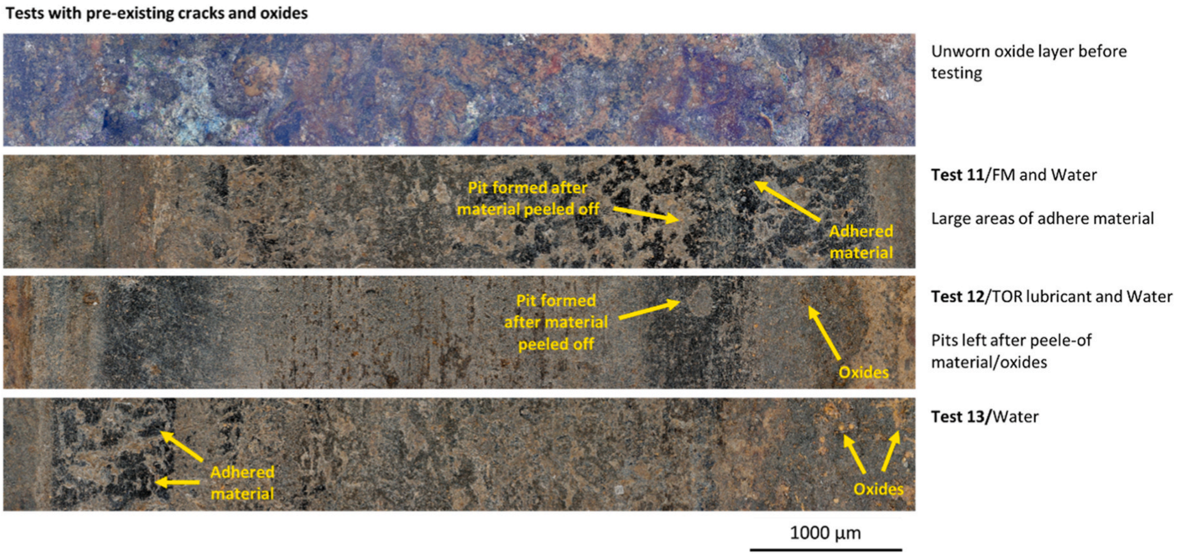

Fig. 11. OM pictures of the surface after testing (rail disc). No oxides.

more detail later in the text in the Discussion section.

The unworn oxide layer can be seen in Fig. 11, with its thickness and cross-section visible in SEM images in Fig. 12a–d). SEM images show that the oxides uniformly covered the surface in a layer with thicknesses varying in the order of micrometres. After the tests, OM observation of the surface did not reveal any major signs of RCF. The oxide layer was visibly worn, and several pits were found, most likely due to peeled-off oxides or bulk material (see Fig. 11). The pre-existing cracks are visible in cross-section images in Fig. 12a–d). After testing, crack measurements revealed that their parameters were comparable to those in tests under dry conditions, despite expectations that water or the combination of water and TOR product would enhance crack growth like in previous cases, see Fig. 13 a) and b). A possible explanation for why discs with oxides did not experience severe RCF, as in the case with clean specimens, will be discussed next in the Discussion section.

4. Discussion

4.1. Tests without oxides

In this study, the authors used the interval application of TOR products. Although smart application units that control lubricant applications based on real-time friction data have recently been implemented, interval application remains the dominant method. In this approach, TOR products are applied after a certain number of vehicle passes or a fixed time interval, regardless of weather conditions. Thus, over-lubrication due to lubricant accumulation or contamination is more likely, as was the case in this study. As suggested in the study by Seo et al. [27], potentially interesting phenomena may be observed if the water/TOR product application is less frequent and starvation occurs, requiring application not in fixed intervals but instead depending more on actual CoT data. The author used interval application to examine the worst-case scenario from the point of view of traction/adhesion problems that may occur on the track. From the perspective of future research, the authors will focus on what happens when contact starves, and CoT reaches higher values, approaching dry contact, as it may reveal interesting phenomena. While this aspect is undoubtedly relevant, addressing it in the present study would go beyond its intended scope, making it a natural subject for future investigation.

Problems with over-lubrication did not occur after a single water application in any of the friction tests. However, the situation changed when water was continuously applied in wear and RCF tests. Although water also affected FM somewhat, the results with TOR lubricant were more interesting, see Fig. 4 j). CoT reached the lowest values in this test, staying between 0.05 and 0.07, as the water stopped its recovery. This indicates that TOR lubricants may cause over-lubrication even in recommended dosages when used under wet conditions. A possible explanation may be based on studies describing water–oil/grease interactions, which explain that combining water and grease may lead to a better lubrication effect [47–49]. At first, due to the higher wetting ability of oil, the lubricating film is predominantly formed by the oil phase, even when water is present in larger quantities [49,50]. This allows the film to maintain low shear stress within the contact and consequently a low CoT. When starvation occurs, water now takes a larger part in the lubrication process, and CoT rises [51]. Subsequently, a larger portion of the load is carried by direct asperity and particle contacts, leading to an increase in CoT [42]. Several studies suggest that some thickeners can absorb water, which may lower grease viscosity and enhance contact replenishment and thus delay starvation [52–54]. Furthermore, the manufacturer lists an organic thickener, and the formulation appears consistent with a polyurea-based system commonly used in the industry. Polyurea greases, particularly those based on biodegradable esters, can emulsify water up to several per cent and, under intense mixing, absorb as much as 70–80 % of water without losing structural integrity. This remarkable water uptake likely accounts for the prolonged period of low traction coefficient ("over-lubricated" state) observed during continuous wetting in the TOR lubricant tests.

However, a more detailed understanding of the water absorption behaviour would require additional testing, which was beyond the scope of this study. Such testing could include the construction of a water uptake curve using standardised methods such as ASTM D4049 (spray test) or ASTM D7342 (Karl-Fischer titration) to track moisture content over time. Polyurea/ester-based greases absorb up to approximately 5–10 wt % of water under mild exposure and considerably more under blending conditions. A previous study [42] examined water interactions with TOR lubricant in more detail using a ball-on-disc tribometer. It confirmed that the two phases do mix, leading to a temporary drop in CoT. Since the same product was tested here, these conclusions are also applicable to this work. Since the present study focuses mainly on wear and RCF, readers are referred to that paper for a more detailed discussion of the friction behaviour.

Now, the effect of pre-existing cracks will be discussed. FM reduced

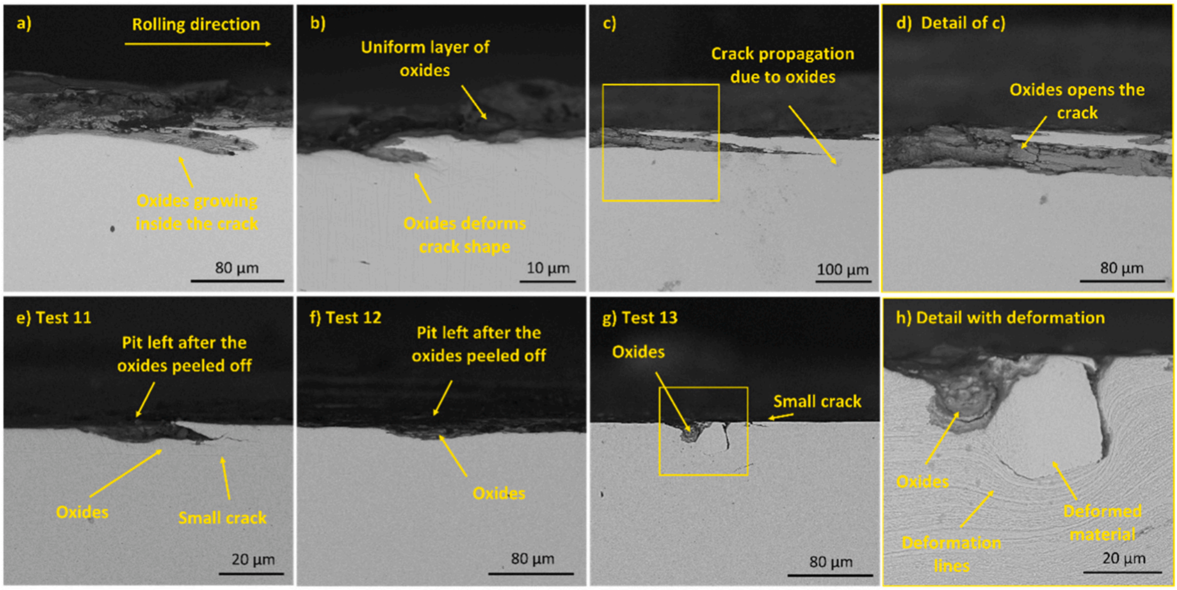

Fig. 12. SEM pictures: a–d) intact oxide layer before testing, e) after test with FM and water, f) TOR lubricant and water, g) water, h) detail on deformed material. Tests with oxides and pre-existing cracks.

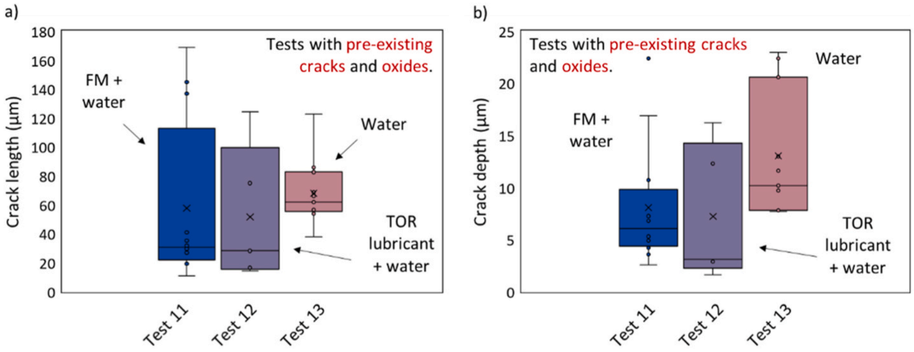

Fig. 13. Crack a) length and b) depth. Tests with oxides and pre-existing cracks.

the wear rate in tests without pre-existing cracks by a factor of 10 (test 3), while the TOR lubricant achieved a 35-fold reduction (test 4). Meanwhile, water in test 5 led to a 29 times reduction compared to dry conditions, see Fig. 5 b). FM achieved worse wear reduction than the TOR lubricant as it repeatedly dried out, causing an increase in CoT and, consequently, higher adhesive wear. In contrast, water maintained a stable and low CoT. Although the TOR lubricant also periodically reached a CoT of 0.3 like FM, it exhibited a longer-lasting effect than FM, providing a lower CoT for an extended period. Overall, it can be said that both TOR products were effective in reducing wear, and no significant signs of RCF were found, but TOR lubricant was more effective.

In tests with pre-existing cracks, all aspects of RCF increased substantially. A crack length and depth comparison with previous tests showed that a liquid base of both TOR products accelerated crack growth (see Fig. 7 a). However, water on its own had an even more significant effect on RCF, as under these conditions, the crack depth and length were an order of magnitude higher than under TOR products. In reality, cracks are always present in the rail surface. Thus, applying TOR products may severely impact rail service life, which may not be apparent from testing in laboratory conditions if new specimens without cracks are used for testing. Thus, more interest should be placed on testing specimens with pre-existing cracks and surface damage. These findings follow the study by Hardwick et al. [24], where a similar change in RCF behaviour was observed when pre-existing cracks were present, but for different material pairs and TOR products than used in this study.

The behaviour of TOR products under wet conditions from the perspective of RCF has not been studied yet. Tests 9 and 10 showed that crack lengths were up to five times longer under FM in wet conditions than in tests where FM was applied in dry conditions, and in some cases, cracks propagated up to ten times deeper beneath the surface. The combination of water and TOR lubricant accelerated crack growth even further, reaching depths of up to 900 µm (see Fig. 7 b), the deepest from all tests. Those cracks and signs of spalling were visible to the naked eye (Fig. 6), showing that TOR products affect RCF differently in wet than dry conditions. In the tests with FM, it is more likely that the exceptionally high mass loss resulted from the presence of water rather than from the FM itself. Unlike TOR lubricant, FM could not prevent it, as it is soluble in water, and thus, the mass loss was similar to water-only conditions. Instead of drying out, the base medium of FM remains liquid and, together with water, enters cracks, accelerating their growth due to crack face lubrication and hydropressurization mechanisms [55].

EDS detected carbon particles inside the cracks for FM but not for the TOR lubricant. However, the influence of oil-based products has been previously investigated in several studies, which have concluded that these products are capable of penetrating cracks and influencing RCF, despite their relatively high viscosity [5,24]. Since water influences grease and enhances replenishment, as stated in Refs. [52–54], it may make it even easier for bleed oil from a TOR lubricant to get into cracks under wet conditions, which EDS would not have detected. In that case, crack faces would be well-lubricated (as CoT decreases as low as 0.05). Thus, internal friction would be very low, allowing cracks to propagate easily. Usually, if the friction between the crack faces is lower than 0.2, cyclic shear crack growth may occur [56]. The CoT was considerably below this value. In addition, any trapped liquid (TOR lubricant, its bleed oil or water) becomes pressurised by load and causes a phenomenon similar to the oil wedge effect [57]. As evident from test 10, the combination of TOR lubricant and water accelerated crack growth the most, as cracks penetrated the deepest into the bulk. This was likely because the TOR lubricant was more effective in reducing wear than the FM. As mentioned earlier, a competitive mechanism exists between wear and RCF, where an increase in wear can shorten or even eliminate cracks [19,20]. In this case, the lower wear rate achieved with the TOR lubricant allowed the cracks to grow deeper compared to the tests where the wear rate was higher.

4.2. *The effect of oxides*

In this study, the authors used a modified approach proposed by Sone [58], which was also adopted in several other studies [59–62]. The adopted procedure involved exposing the specimens to vapours of water, ethanol and magnesium dichloride at 60 °C. As a result, the entire surface was covered with a thick and uniform oxide layer, consisting of magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite (α-FeOOH) and akaganeite (β-FeOOH), see Fig. 14 a) and b). Godfrey [63] provided an overview of fifteen iron oxides and their rust forms and summarised their key characteristics. In rail-tribology, laboratory studies typically focus on hematite and magnetite [64], which are arguably the most frequently tested oxides. In addition, Kempka et al. [65] conducted XRD analysis on railhead swabs collected on the track and identified that goethite and akaganeite were always present when drivers reported problems with traction. Thus, the oxide layer formed in this study was representative of actual track conditions.

Studies often report that hematite and some other oxides increase friction [63]. However, this was not observed in any of the friction tests, where it caused a reduction in CoT under dry conditions from 0.4 to 0.3, see Fig. 3 e). On the contrary, Kempka et al. [65] linked the presence of goethite and akaganeite to low-adhesion problems, and Beagley [66] showed that when mixed with water, even hematite can cause low friction, likely because its particles are strong enough to carry the load but have low shear strength, allowing them to act as an effective lubricant. This was further confirmed in another study by Lu et al. [67]. Thus, while hematite may increase friction under dry conditions, its interaction with moisture in the ambient air, together with the presence of goethite and akaganeite, may explain why lower CoT values were measured on the oxidised specimens. This behaviour is consistent with the fact that oxide layers generally exhibit relatively low shear strength, which reduces the available traction.

The effect of iron oxides on friction has been well examined in many studies [59–62], but their impact on wear and RCF is still unclear [43]. It

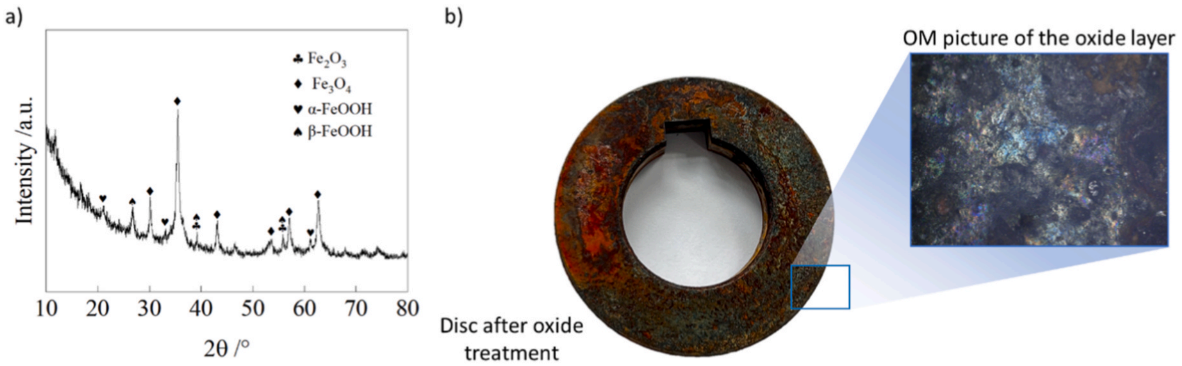

Fig. 14. a) The results of XRD analysis and b) a picture of a disc after oxide treatment.

is true that due to its low shear strength, oxide layers are also easily worn. Yet, the total mass loss in tests involving water was usually higher with unoxidised discs compared to those with oxides. The explanation for that is that while oxides increase wear, they also suppress RCF. The exceptionally high mass loss in tests with water and water together with FM was due to massive delamination and spalling caused by RCF, which was not the case for oxidised specimens.

In Fig. 12, SEM images of cross-sections show that the oxide layer was several microns thick. More importantly, it was observed that the crack faces were also oxidised. As the oxides grow bigger, they fill the insides of cracks and separate their faces. At some point, the oxides start to press against internal surfaces, causing localised stress at the crack tip, potentially initiating further propagation [68]. This process occurs during oxidation, so the crack growth is accelerated even before any testing is conducted. This is supported by the fact that some cracks found after the oxide treatment were significantly larger than those typically created during the run-in, with the oxide being the likely cause. However, at this stage, this hypothesis is based on a simple observation only and will be subject to further research. Once the oxides fill the cracks, they prevent fluids from entering. This means that water or TOR products cannot go inside, and mechanisms such as face lubrication or hydropressurisation cannot occur. As a result, cracks did not grow further during testing, even though liquid was on the surface.

Oxides have low shear strength, so the top layer was quickly worn, meaning cracks could not grow and were also worn. This can be seen in Fig. 12, where images a–d) show the surface and cracks before the test, and e–h) show the surface after the test. After testing, the surface was very smooth, with only small pits in areas where oxides or cracks were previously present before being worn off. An interesting phenomenon is observed in Fig. 12 h), where a crack with an unusual shape was detected. The corrosive solution was sprayed on the crossectioned surface to highlight the deformation lines around this crack (see the detail in Fig. 12 h). Deformation lines are visible on one side of the crack but absent on the other. A possible explanation is that this is not an RCF crack but rather a piece of material initially located on the left side in an upward position. A hole formed next to it due to oxidic wear, and this material was deformed by traction forces and indented into the hole left by the worn oxides. Similar behaviour was also observed in Ref. [69].

The effect of oxides can be summarised as follows. Oxides enhance crack propagation even before the start of the test by exerting pressure on internal faces. However, they also block any liquid from entering, preventing the usual mechanisms responsible for further crack growth. As the top layer is easily worn due to its low shear strength, the result is smooth surfaces without any apparent cracks, see Fig. 12e–h). Thus, RCF is less likely to occur on oxidised surfaces.

5. Conclusion

This study investigated whether TOR products can effectively reduce wear and prevent rolling contact fatigue (RCF) while maintaining an intermediate coefficient of traction (CoT) in the presence of contaminants typically found on the railhead. All tests were conducted on a twin-disc machine, using conditions representative of wheel-rail (W/R) contact. Two types of TOR products were selected: a water-based friction modifier (FM) and a grease-based TOR lubricant, allowing for a comparison between drying and non-drying compositions. Specimens were cut from authentic materials, and some of them were run-in to create pre-existing surface cracks. Given its significant impact on traction and braking, water was chosen as the primary contaminant. Additionally, some discs underwent an oxidation treatment to form an oxide layer on the surface, enabling an examination of the influence of third-body layers on RCF and wear.

From the perspective of CoT, the results can be summarised as follows. Water influenced both TOR products differently. In the case of FM, water delayed the evaporation of the base medium, prolonging friction-modifying effects. For the TOR lubricant, the impact on retentivity was even more substantial. Over-lubrication was observed in tests with repeated applications, primarily due to the product accumulation over time and as a result of the thickener absorbing water. This led to conditions of extremely low friction, with CoT values dropping as low as 0.05 – a value considered insufficient for safe railway vehicle operation. The oxide layer decreased CoT in dry and wet conditions, but the effect was negligible in the presence of the TOR product.

Adhesive wear was the dominant wear mechanism observed under dry conditions. Both TOR products effectively reduced wear rate, with the TOR lubricant proving the most efficient. The FM was less effective, likely due to its tendency to dry quickly. Both products effectively prevent crack formation and reduce mass loss. However, in tests where cracks were formed before the application of products, severe RCF was observed as the liquid component of products accelerated crack propagation due to crack face lubrication and hydropressurisation. RCF damage intensified when TOR products were contaminated by water. The combined effect of FM and water resulted in significant mass loss, whereas TOR lubricant, though not experiencing as high mass loss, exhibited deeper crack penetration. These deeper cracks posed a risk of substantial spalling if allowed to merge, which would possibly happen if the test duration was prolonged.

An interesting phenomenon was found in tests with oxidised specimens. It was observed that the crack faces also oxidise. As the oxides grow, they fill the crack interior, creating pressure and initiating crack propagation. This effect resembled hydropressurisation but occurred under dry conditions without any external load. Furthermore, water or liquid components of TOR products could not enter cracks due to oxides suppressing the usual mechanisms of liquid-driven crack propagation. And, as the oxidised surface is easily worn due to the low shear strength of oxides, the cracks were quickly removed, leaving a smooth surface after testing with no signs of RCF.

CRediT authorship contribution statement

Simon Skurka: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Radovan Galas:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jiaxin Li:** Methodology, Investigation. **Honghao Wang:** Writing – review & editing, Investigation. **Milan Omasta:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Haohao Ding:** Writing – review & editing. **Wenjian Wang:** Writing – review & editing, Project administration, Data curation, Conceptualization. **Ivan Krupka:** Writing – review & editing, Data curation. **Martin Hartl:** Supervision, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT and Grammarly in order to improve the clarity and correctness of the English language in this manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This publication was supported by the project "Mechanical Engineering of Biological and Bio-inspired Systems", funded as project No. CZ.02.01.01/00/22_008/0004634 by Programme Johannes Amos Comenius, call Excellent Research, administrated by Ministry of Education, Youth and Sports of the Czech Republic. The work was also supported by the National Natural Science Foundation of China (No. 52320105007).

Data availability

The data supporting the findings of this study have been deposited in the Zenodo repository (https://doi.org/10.5281/zenodo.15744531), and the preprint of this manuscript has been archived at https://doi.org/10.5281/zenodo.15910051.

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