Effects of Lubrication on Wear and Rolling Contact Fatigue Behaviour of Class B Wheel Steels Against R350HT Rail Steels Using a Twin Disc Wear Simulator

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Abstract

Wear and rolling contact fatigue (RCF) are major causes of delays and unavailability of rail systems. The presence of lubricants at the rail and wheel interface influence wear and RCF. Lubricants include naturally occurring types such as water from rain and leaves from trees next to rail lines and materials applied on purpose to help improve adhesion and friction such as friction modifiers, greases and traction gels. The aim of this work was to study the wear behaviour of AAR class B wheel versus R350HT rail materials in the presence of water and oil in comparison with the dry condition. There is currently a lack of knowledge regarding the combination of these materials in a twin-disc simulator, and this work will provide information on their impact on RCF and wear performance for use by the rail industries. It was found that wear was much lower when water or oil was introduced at the wheel-rail interface compared to dry conditions, for all slip ratios. When water was used, the main cause of RCF was found to be fluid crack pressurisation. The RCF cracks were also observed under dry contact.

Keywords: Rolling contact fatigue, wear, friction, plastic deformation, lubrication.

Introduction

The wheel/rail interface is a very complex system, and it is further complicated by the presence of third body materials as they affect the performance of rails and wheels. Third body materials include naturally occurring humidity, precipitation, solids such as sand and leaves from nearby vegetation. Some are applied intentionally such as friction modifiers, greases and traction gels to help with adhesion and friction. Third body materials affect the adhesion of the wheel on the rail influencing the performance of the braking system. Some tend to reduce friction resulting in an increase in braking distance by trains while others such as sand do the opposite. Solid third body materials such as oxides and wear debris are very detrimental to wear resistance of wheel and rail materials as they tend to increase wear and rolling contact fatigue (RCF) in the wheel-rail contact area [1]. Lubrication is applied on the wheel-rail contact to reduce wear, but this tends to affect adhesion and fatigue whereas sand is applied to improve adhesion and fatigue which impacts negatively on the wear resistance of the materials [1, 2]. Therefore, it is important to strike a balance between the two factors by having properly scheduled maintenance procedures to improve performance and safety of railway systems. Leaves have also been found to affect adhesion between the wheel and rail especially during autumn season when leaves are falling from trees and wind carries them around and some end up on the railway line [3]. When leaves fall onto a railway line, a train wheel crushes them into the rail, creating a slippery layer that might be difficult to remove and decreasing the adhesion between the wheel and rail [3, 4]. Wet leaves have more effect on the reduction of adhesion between the rail and wheel than dry leaves [5].

Lubricants such as water and oil have been found to reduce wear rates as well as coefficient of friction at the wheel-rail contact. Water enters the railway system at the wheel-rail contact from different forms such as morning dew, fog and rain resulting in different adhesion levels [6]. Even though water can decrease wear, but it has been discovered to have a negative impact on

RCF because it accelerates cracking through a mechanism called "fluid crack pressurisation". Fluid crack pressurization refers to the process by which water enters into a crack at the contact point between the wheel and rail, generating shear stress at the tip of the crack resulting crack initiation and propagation [1, 7, 8, 9]. Water has also been found to increase the possibility of cracking through corrosion and uptake of hydrogen [10]. Wang et al. [11] and Lewis et al. [1] have found that water accelerates crack growth during wear testing of wheel and rail materials using a twin-disc wear simulator.

This paper intends to study the effects that water and oil lubricants have on RCF and wear performance of AAR class B wheels and R350HT rail steels as well as their effects on fluid crack pressurisation, surface roughness and depth of deformation at different slip ratios. Knowledge regarding the combination of the two materials in the presence of fluids using a twin-disc simulator is not available, hence this study will offer valuable information on their wear performance and behaviour under different contact conditions. The R350HT rail steel has a very fine lamella spacing as previously stated [12], making it more resistant to wear compared to AAR class B wheel steels. This work will provide more information on how both the AAR class B wheels and R350HT rails perform under lubrication contact, the effect of lubrication on propagation of RCF cracks as well as other forms of damage. Lubrication has been found to promote propagation and growth of RCF cracks. RCF defects include head cracks, spalling and shelling. RCF cracks formation mechanisms have been previously described by a study by Makino et al. [13]. Their study also found out that as the slip ratio increased, so did the traction coefficient, while the fatigue strength decreased [13]. The decrease in fatigue strength was due to more formation of branching fatigue cracks with increase with slip ratio causing shelling and spalling to occur which is an indication of catastrophic wear. Previous works [14, 15] have shown that at high slips and contact pressures micro cracks initiate. With the presence of water at the contact, the initiated cracks propagate forming crack branching which may cause severe damage such as shelling compared to dry contact. As wear has a competitive relationship with RCF [15, 16], its presence at the wheel/rail contact is crucial . Higher wear rate can continuously help to remove any layers where cracks may have developed, lowering the possibility of serious damage [16].

Materials and experimental methods

Test specimens

AAR class B wheel and R350HT rail steels were used for this study. The wheel discs were cut along the wheel rim whereas the rail discs were cut from the rail head closer to the surface. The wheel and rail materials in the as-received condition, had hardness values of 350 ± 8 HV10 and 385 ± 9 HV 10 respectively obtained experimentally using Struers Duramin-40 machine under a load of 10 kgf. The ASTM E 140 – 07 [17] standard was used for conversion of the Vickers hardness of wheel and rail steels to Brinell hardness. The hardness conformed to their respective standards being the AAR M-107/M-208 [18] for wheels and BS EN 13674-1:2011 [19] for rails. The chemical composition (Table 1) was analysed by spark emission spectrometry which also conformed to their respective standards. To obtain the as-received optical micrographs (Figure 1), the specimens were ground and polished to 3 µm surface finish and etched using 3% Nital etchant.

Table 1: Wheel and rail steels' chemical compositions (mass%).

	AAR class B wheel	R350HT rail
Element	Chemical Composition (wt%)	
C	0.660	0.830
Mn	0.800	1.150
S	0.008	0.020
P	0.017	0.014
Si	0.338	0.365
Cr	0.148	0.194
Ni	0.114	0.058
Fe	Balance	Balance

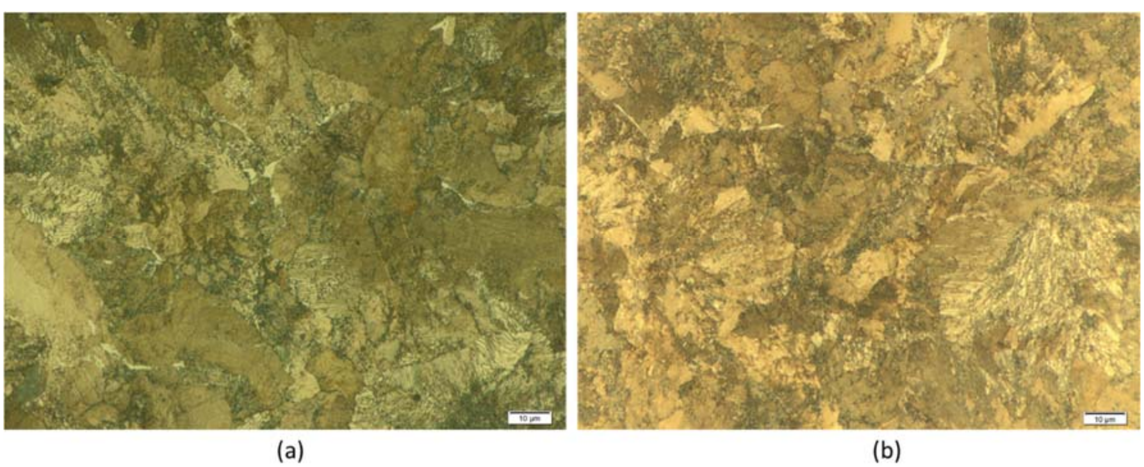

Figure 1: As-received optical micrographs of (a) AAR class B wheel and (b) R350HT rail showing pearlitic microstructures.

The wheel and rail materials were machined into 50 mm diameter and 10 mm thick discs, Figure 2b. Both the wheel and rail materials were sectioned according to recommendations from literature [2, 14, 15] to ensure less variation in hardness across the discs.

Wear testing and simulation

The wear test machine (Figure 2a) was developed in-house, and the details have been described elsewhere [12]. A constant load of 1.8 kN was applied throughout the test for 62 000 rolling cycles measured using a 10 kN compressive load cell. The 1.8 kN normal load corresponds to a maximum contact pressure of 740 MPa according to Hertz theory [20, 21]. Literature [22] has demonstrated that the wheel/rail interface experiences pressure from 500 to 1500 MPa especially between the rail head and the wheel tread. A review study by Rocha et al. [23] has shown that twin-disc rigs have an operating contact pressure ranging from 300 to 1500 MPa. The torque and contact load were measured and recorded during the test. The torque measurements were converted to friction coefficient (μ) values using equation 1. Three contact conditions were used being dry, water (tap water) and oil (SAE 40 railroad engine oil) with water and oil being drip-fed at the contact using a RS PRO diaphragm positive displacement pump at constant rate of 25 mL/min. The wheel material was the driving disc (faster one) while the rail material was the braking disc (slower one) across all slip ratios. The wheel disc speed was changed as per the required slip ratio while the rail disc speed remained constant at 340 rpm. Slip ratios of 2%, 5%, 10% and 20% were used for each of the three contact conditions. The slip ratio was obtained using equation 2.

$$\mu = \frac{T}{FR_r} \qquad 1$$

$$slip\ ratio = \left(\frac{V_w.R_w - V_r.R_r}{V_w.R_w + V_r.R_r}\right) \times 200\% \qquad 2$$

Where T is torque (Nm), F is the contact load (N), V_w and V_r are the rotational speed of the wheel and rail discs (rpm), and R_w and R_r are the rolling radius of the wheel and rail discs respectively [12]. For this study the radius of the wheel and rail disc are equal (R_w=R_r). The oil and water were applied before applying the load to make sure that the whole test was done under lubrication. Before and after testing, the wheel and rail specimens were washed in an ultrasonic bath of ethanol to get rid of contaminants and weighed to obtain the mass loss. A Mitutoyo Surftest (SJ-210) surface roughness tester was utilized to measure the surface roughness on both the worn wheel and rail discs. The equipment measures and calculates the arithmetic mean of roughness value (R_a) in accordance with ISO 4287:1997 standard. The surface roughness was measured along the transverse direction of the worn discs. The discs were sectioned, mounted and polished to 1 µm surface finish and etched with 3% Nital to observe the depth of plastic deformation using the optical microscope and the sub-surface damage using scanning electron microscopy.

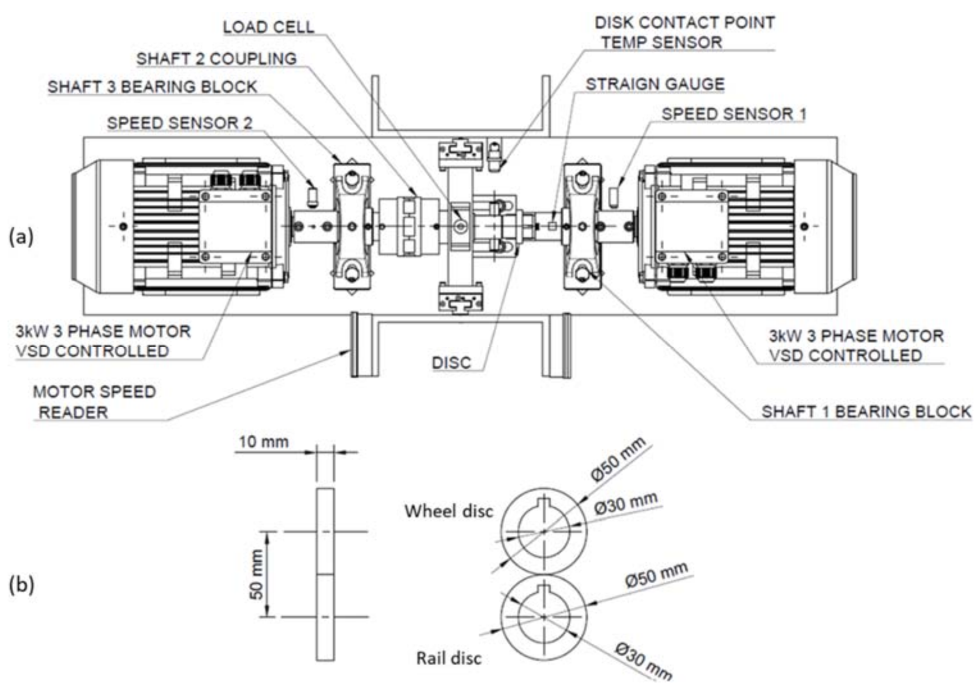

Figure 2: (a) Schematic diagrams showing the University of Pretoria Vertical Twin-Disc Rig (VTDR) and its components and (b) wheel and rail discs.

Results and discussion

Effects of lubrication on coefficient of friction and wear rate

Water and oil reduced the coefficient of friction significantly compared to dry contact as seen in Figure 3a and Figure 3b at 10% and 20% slip ratios respectively. This effect is as a result of the low traction due to the presence of water and oil molecules which provided some form of lubrication. Oil caused more reduction in coefficient of friction than water as it is more viscous than water. The results agree with literature [24, 25, 26, 27, 28] as dry contact leads to high coefficient of friction which is bad for wear but good for adhesion at the wheel/rail interface. At lower slip ratios of 2, 5 and 10% oil did not reach the steady state at the end of the test (62 000 cycles) while at 20% slip ratio, the steady state was reached. This could be attributed to the wear debris being embedded into the contacting surface, affecting the coefficient of friction at lower slip ratio whereas at 20% slip ratio, the higher slip was able to prevent that embedment. However, both dry and water contacts reached the steady state across all slip ratios. Oil and water had lower coefficient of friction values, which resulted in lower wear rates (cumulative mass loss) as may be seen in Figure 4b, compared to dry contact. However, low coefficient of friction leads to poor adhesion at the contact. Poor adhesion is a cause of concern as it may affect performance and safety of the train causing longer braking distance which can result in platform overruns and collisions between trains. Introducing oil and water at the contact reduced wear by an order of magnitude compared to dry contact. This resulted in low cumulative mass losses under water and oil contacts, Figure 4b. For all the three contact conditions (dry, water and oil) cumulative mass loss was found to increase with slip ratio with the highest increase being under dry contact. Therefore, lubrication either due to water or oil significantly reduced wear and the trend is in agreement with previous studies [24, 25].

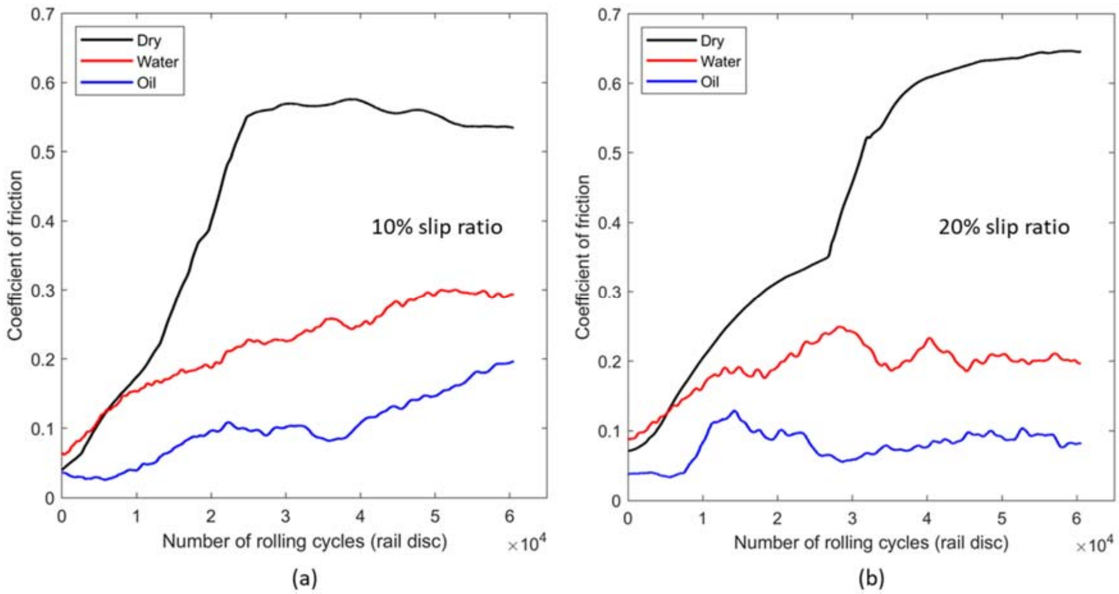

Figure 3: (a) Coefficient of friction versus number of rolling cycles at (a) 10% slip ratio; (b) 20% slip ratio under dry, water and oil contact conditions.

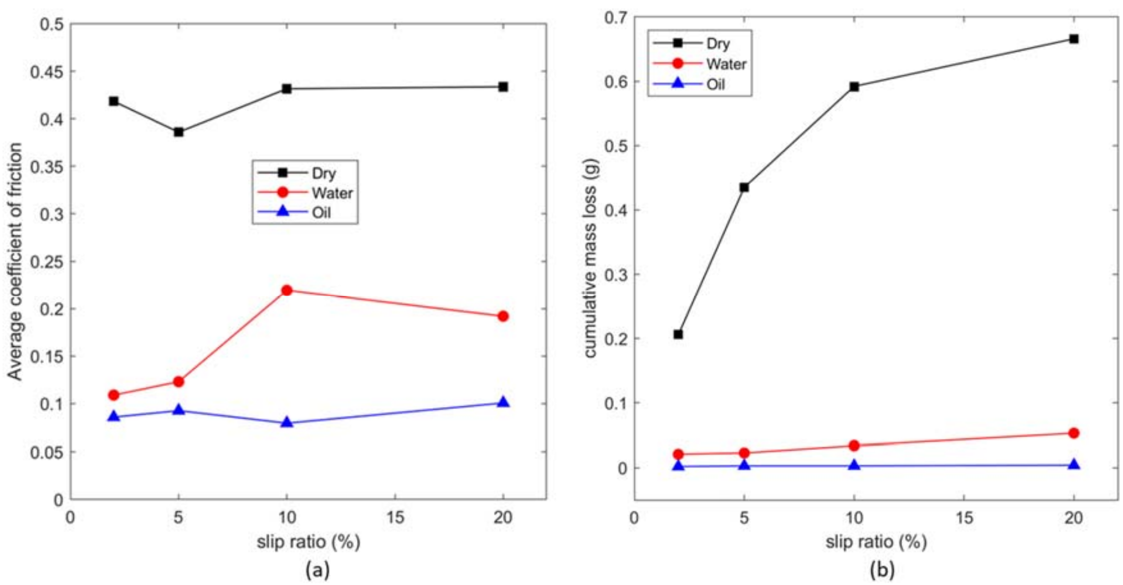

Figure 4: (a) Average coefficient of friction versus slip ratio; (b) Cumulative mass loss (wheel + rail) versus slip ratio under dry, water and oil contact conditions.

Effects of lubrication on surface morphologies and roughness

There was no evidence of surface damage by fatigue, delamination, or material loss by spalling when testing under both water and oil compared to dry testing where surface fatigue and cracking, delamination and material loss by spalling were observed on wheel and rail specimens, Figure 5 and Figure 6. When lubrication was used, wear was mainly by abrasion as evident from abrasive wear marks and smoother surface which are an indication of mild wear whereas under dry contact material loss by spalling and delamination is an indication of severe and catastrophic wear. Previous works [29, 30, 31] have indicated that the presence of abrasive wear marks is an indication of mild wear. Figure 6a and Figure 6b provides good evidence of RCF due to the presence of parallel surface cracks which is an indication of fatigue under dry contact. Pitting was observed when water was used at 2% slip ratio on the wheel specimens and 20% slip ratio on the rail specimens. Pitting is an indication of surface corrosion due to the presence of water molecules. Water increases the likelihood of corrosion and uptake of hydrogen, which may cause more cracking and in the process reducing the fatigue life of wheel and rail steels as previously observed by Cookson et al. [10] and Wang et al. [11]. These negative consequences of water were also observed in the current study, as will be discussed later.

Lubrication by water and oil reduced surface roughness on both wheel and rail steels. Surface roughness was measured using the surface roughness value (R_a), Figure 7. Oil had lower R_a values across all slip ratios compared to both dry and water contacts with dry having the highest values. Oil has high viscosity making it easier for oil particles to accumulate and induce the elastohydrodynamic lubrication (EHL) at the wheel/rail contact. This causes oil to form a thicker film increasing its load carrying capacity by making it more viscous. Therefore, causing less surface damage or roughness compared to water. The wheel exhibited higher roughness values compared to the rail specimen under the same contact conditions especially under dry and water contact.

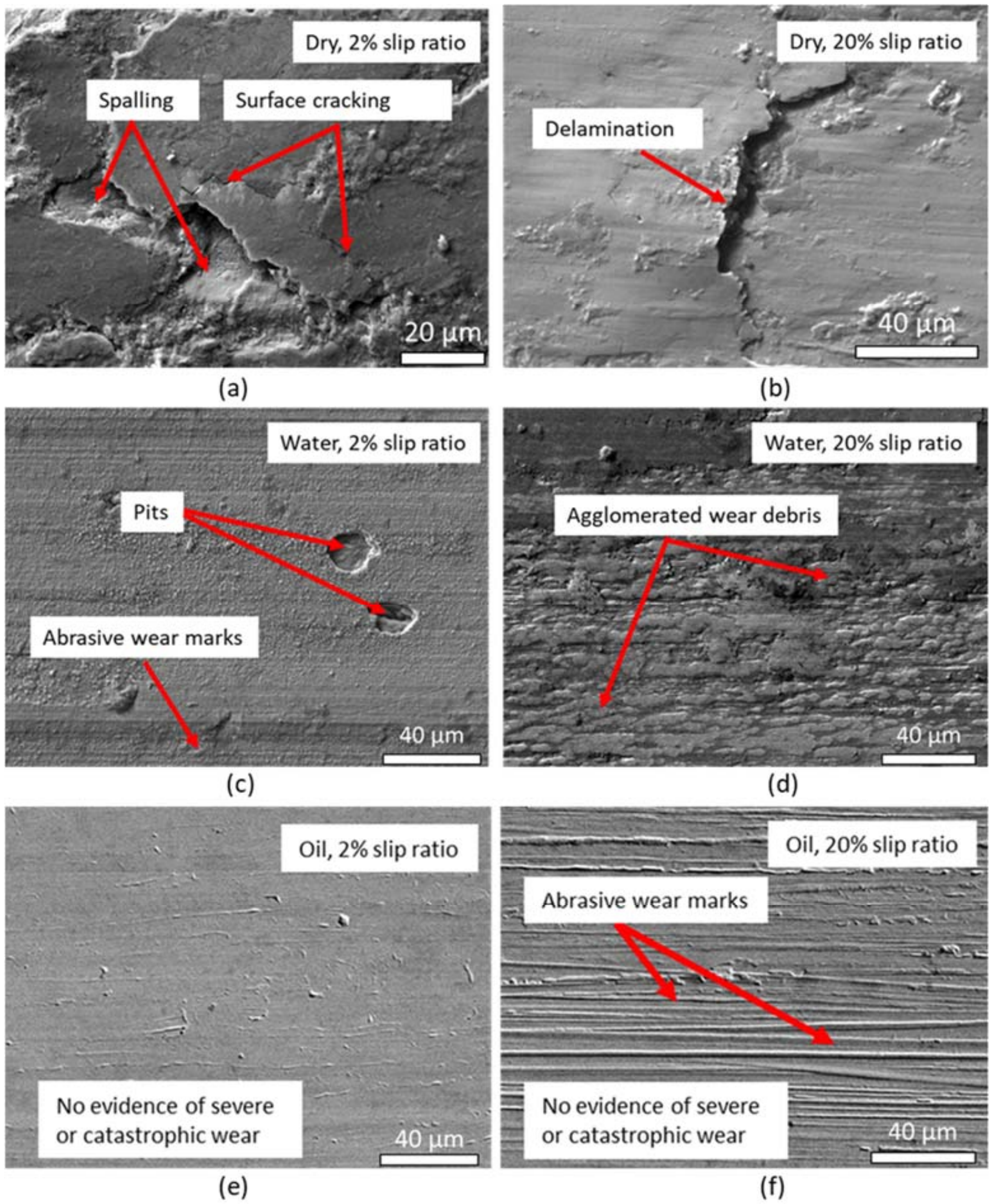

Figure 5: Scanning electron microscopy micrographs of class B wheel specimens showing worn surface morphologies after testing under different contact conditions; (a) dry contact at 2% slip ratio and (b) dry contact at 20% slip ratio; (c) water contact at 2% slip ratio and (d) water contact at 20% slip ratio; (e) oil contact at 2% slip ratio and (f) oil contact at 20% slip ratio.

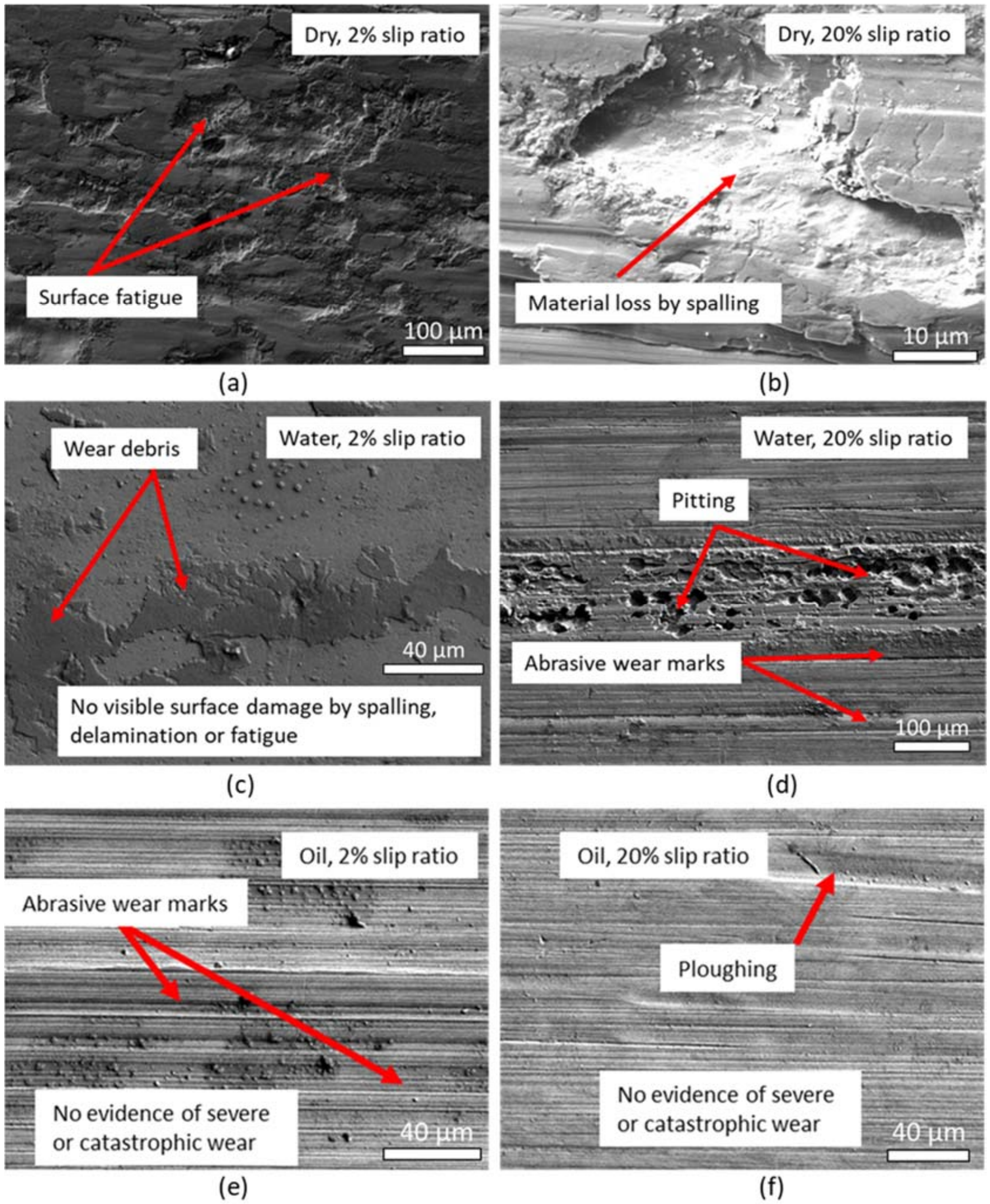

Figure 6: Scanning electron microscopy micrographs of R350HT rail specimens showing worn surface morphologies after testing under different contact conditions; (a) dry contact at 2% slip ratio and (b) dry contact at 20% slip ratio; (c) water contact at 2% slip ratio and (d) water contact at 20% slip ratio; (e) oil contact at 2% slip ratio and (f) oil contact at 20% slip ratio.

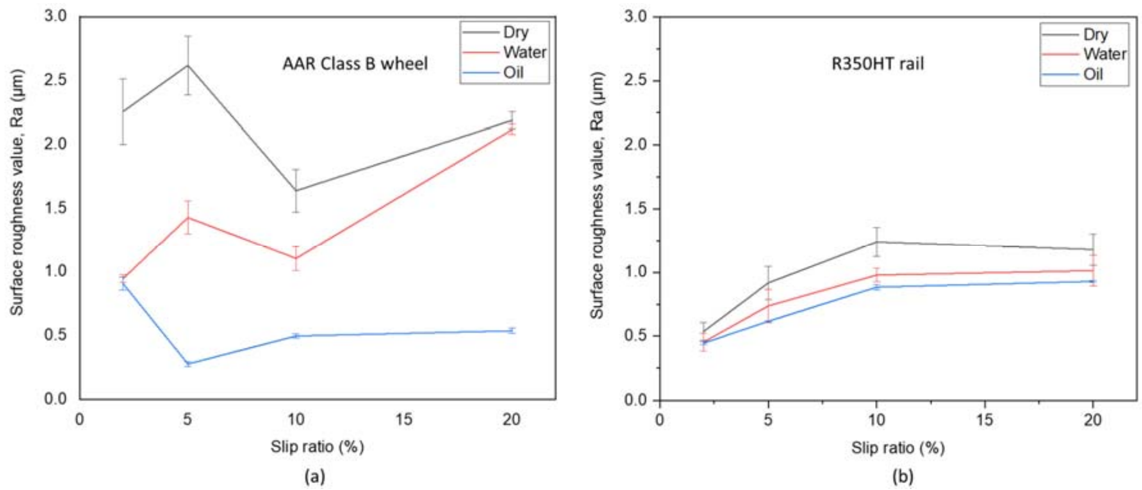

Figure 7: Surface roughness value as a function of slip ratio of (a) wheel and (b) rail specimens under dry, water and oil conditions.

Effects of lubrication on plastic deformation

The depth of deformation was found to rely more heavily on slip ratio under dry contact conditions than under water and oil contacts as seen in Figure 8 with dry contact specimens showing more plastic deformation. Keeping the slip ratio constant at 20%, dry contact resulted in significantly more deformation depth compared to both water and oil as seen in Figure 9 on both wheel and rail materials, the same was observed at 2, 5 and 10% slip ratios. For class B wheel specimens under dry contact conditions the depth of plastic deformation increased from 7 to 50 µm when slip ratio was increased from 2 to 20% with an increase of 614% compared to 80% increase under water contact and where the depth of plastic deformation increased from 5 to 9 µm for the same slip ratios. To further confirm that plastic deformation had occurred, a Vickers' micro hardness test was performed to quantify the increase in surface or sub-surface hardness. As may be seen from Figure 10 and Figure 11, there were significant increases in sub-surface hardness after testing for all slip ratios and conditions and the hardness was highest under dry contact. Slip ratio was also found to have an influence on work hardening with hardness increasing with slip ratio especially under dry contact.

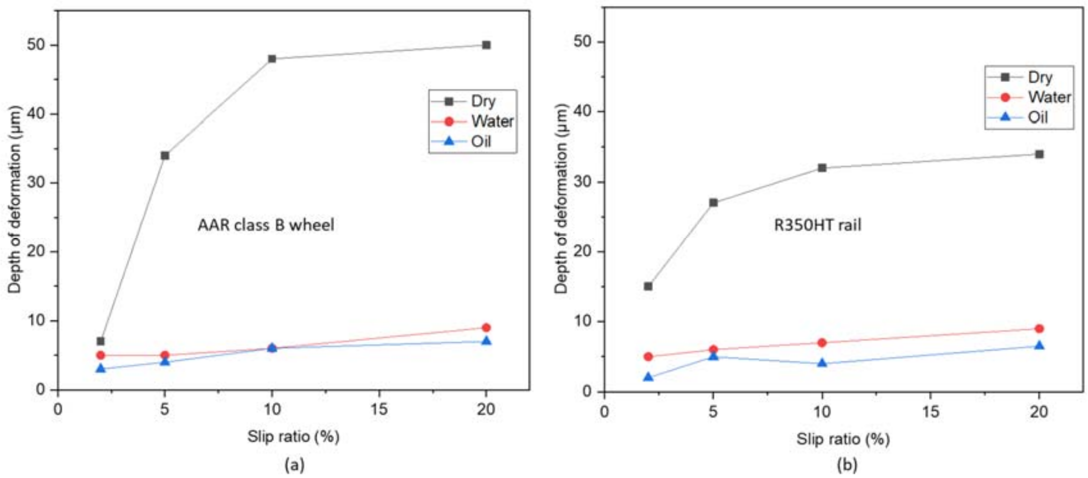

Figure 8: Depth of deformation versus slip ratio of (a) class B wheel and (b) R350HT rail specimen under dry, water and oil conditions.

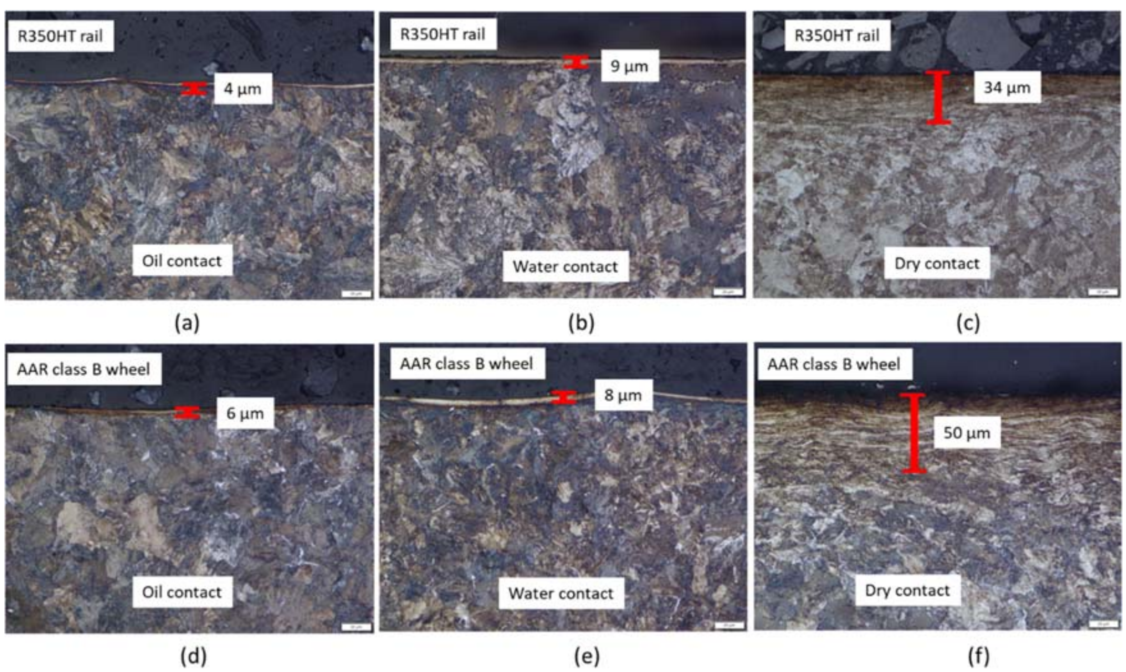

Figure 9: Optical microscopy micrographs of R350HT rail (a,b and c) and AAR class B wheel (d, e and f) specimens showing the depth of plastic deformation after testing at 20% slip ratio under different contact conditions (dry, water and oil).

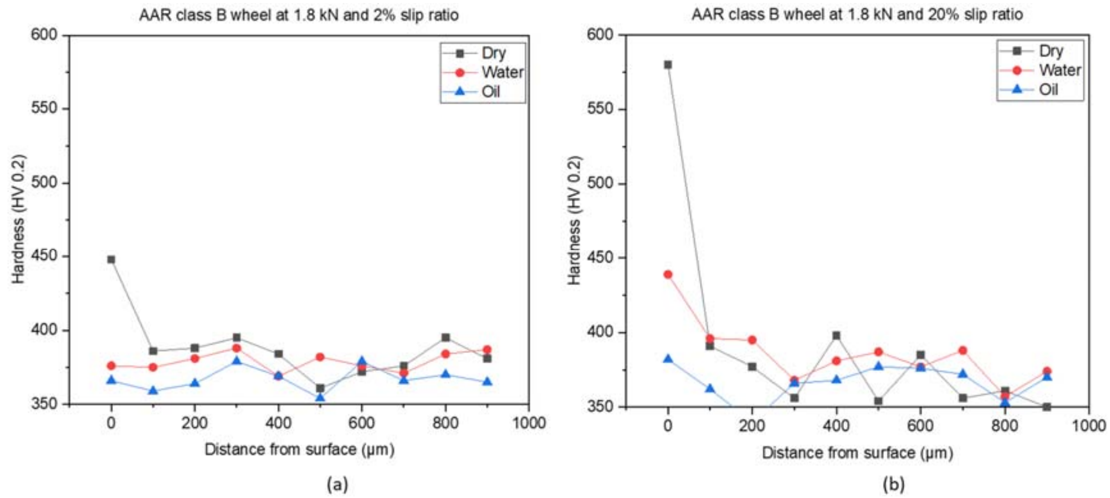

Figure 10: Micro hardness (HV0.2) variation with depth under dry, water and oil conditions for Class B wheel steel at (a) 2% and (b) 20% slip ratios.

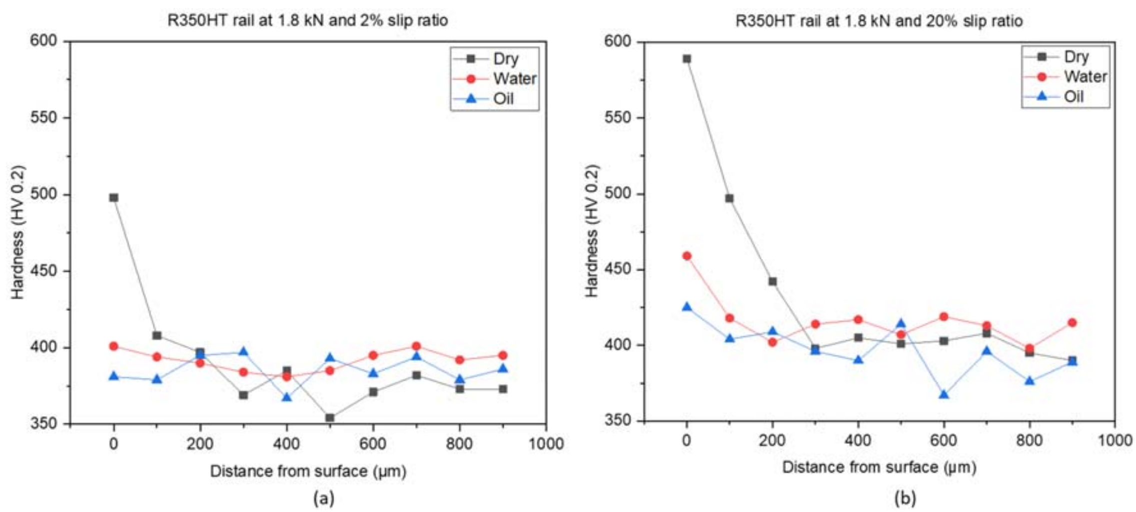

Figure 11: Micro hardness (HV0.2) variation with depth under dry, water and oil conditions for R350HT rail steel at (a) 2% and (b) 20% slip ratios.

Effects of lubrication on rolling contact fatigue and sub-surface damage

Even though oil and water reduced wear on both wheel and rail specimens, it has earlier been found that it accelerates the RCF by fluid crack pressurisation. Wear and RCF have been found to have a competitive relationship with RCF being dominant when wear rate is lower than crack growth [32] resulting in crack growth until failure occurs. In this study, water was found to accelerate propagation of RCF cracks on both wheel and rail materials where sub-surface RCF cracks with branching were observed, Figure 12c and Figure 12d. This acceleration may be due to fluid crack pressurisation and was also observed by Wang et al. [11] when water was introduced at the wheel/rail contact. Fluid crack pressurisation occurs due to a liquid being entrapped into a crack due to both rolling and sliding of the wheel on rail surface under load resulting in tearing and widening of the crack due to shear stresses. From this study, there was some form of evidence of fluid crack pressurisation having occurred, Figure 12c, Figure 12d and Figure 13a.

More RCF cracks and crack branching were observed under dry and water contact with no observation of any formation of RCF cracks when oil was used at the contact under SEM. The reason for no RCF damage (no spalling, shelling or cracking) under oil contact when the worn surfaces were observed under SEM, even at high magnification was due to the lubricant's high viscosity. High viscosity makes the oil particles to easily accumulate elastohydrodynamic lubrication (EHL) at the wheel/rail contact [33, 34]. Elastohydrodynamic lubrication (EHL) is a type of lubrication that occurs when two solid surfaces come into contact under high pressure and are separated by a thin layer of lubricant that is thick enough to provide a fluid film but not thick enough to prevent contact between the surfaces. In EHL, the pressure between the two surfaces causes the lubricant to deform and flow, creating a highly viscous fluid film that supports the load and reduces friction and wear between the contacting surfaces. The same was observed on a study by Wang et al. [35] where the rate of crack growth was significantly reduced under oil conditions compared to water. Only the plastically deformed layer was visible under scanning electron microscopy when oil was introduced at the contact, Figure 12e and Figure 12f. The same observation of water having more RCF than oil was seen on a study by Hardwick et al. [36]. Under dry contact, sub-surface damage was observed on AAR class B wheel specimen, Figure 12a and Figure 12b where there was some indication of severe and catastrophic wear as a result of spalling and peeling. More sub-surface damage and cracking were observed at high slip ratio with crack length and crack branching increasing with slip ratio under dry contact. As seen from Figure 12c, Figure 12d and Figure 13b, the RCF cracks originated from the surface and propagated tangentially in the depth direction, eventually splitting into two branches, one extending towards the surface and the other towards the depth. From Figure 13b, larger multi layered RCF cracks formed under dry contact at 20% slip ratio, which propagated by branching, other branches propagating towards the surface causing shelling. The same phenomenon was also observed in a study by Makino et al. [13]. Shelling is an indication of fatigue and has been found to reduce the fatigue life of wheel and rail steels.

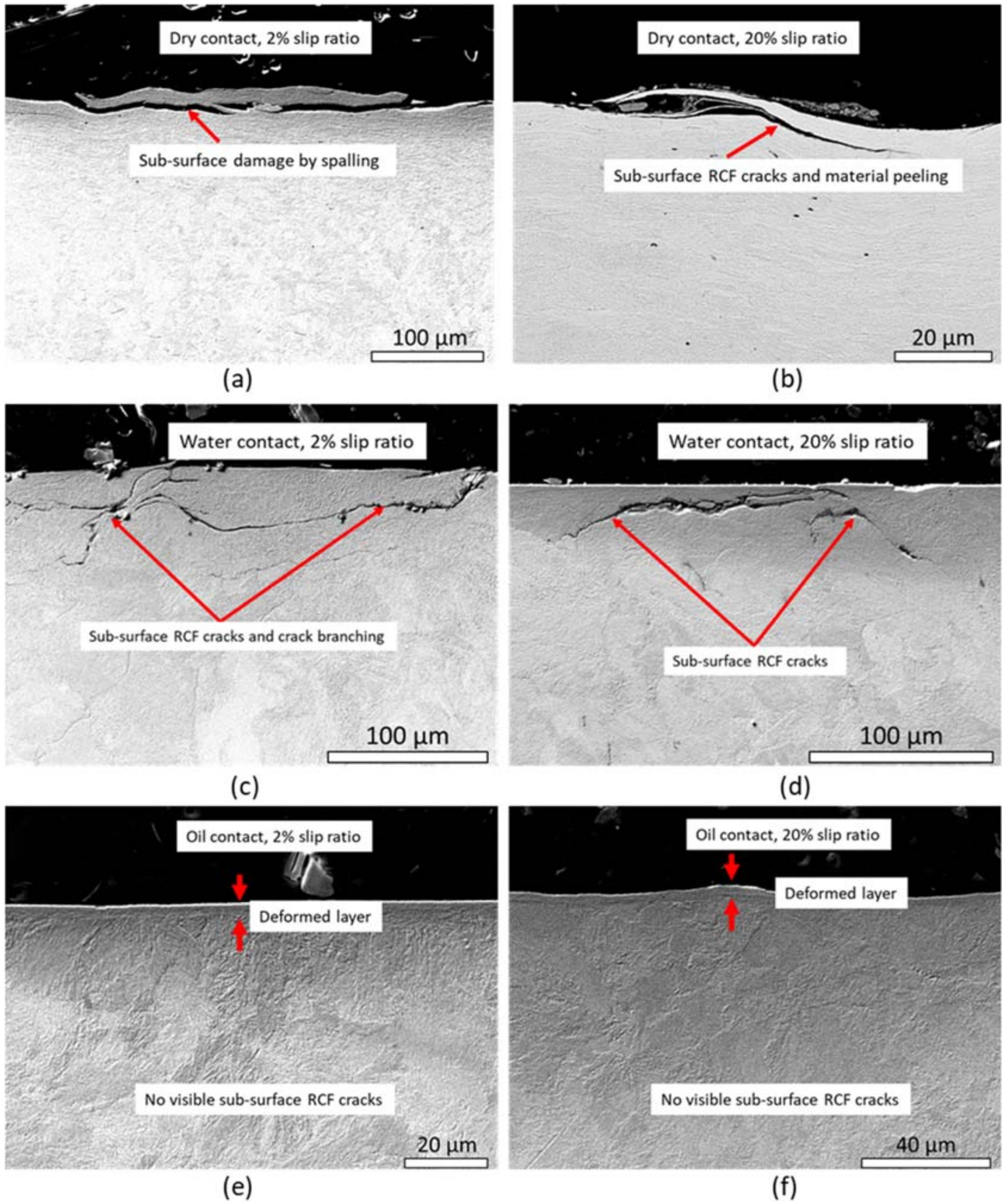

Figure 12: Scanning electron microscopy micrographs of class B wheel specimens showing sub-surface damage and RCF cracks after testing under different contact conditions; (a) dry contact at 2% slip ratio and (b) dry contact at 20% slip ratio; (c) water contact at 2% slip ratio and (d) water contact at 20% slip ratio; (e) oil contact at 2% slip ratio and (f) oil contact at 20% slip ratio.

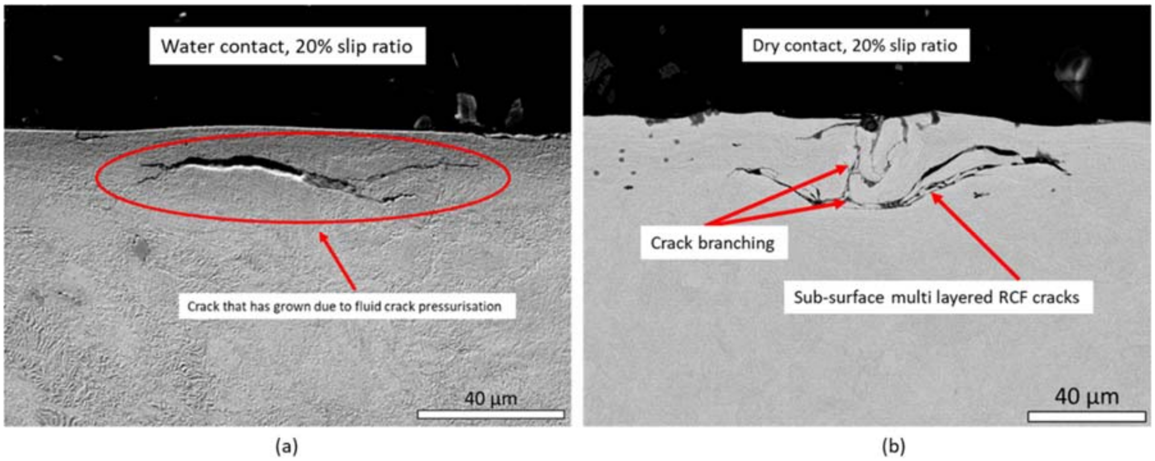

Figure 13: R350HT rail specimen showing (a) RCF crack that may have propagated by fluid crack pressurisation at 20% slip ratio under water contact, and (b) sub-surface multi layered RCF cracks with branching.

Conclusions

Lubricating the wheel/rail contact during wear testing has been found to significantly reduce wear but to result in a negative impact on RCF resistance when water was used as a lubricant. Water was found to promote RCF crack propagation and growth by fluid crack pressurisation. Dry testing resulted in increased plastic deformation on both wheel and rail steels. This effect was confirmed by measuring the depth of deformation and performing micro hardness tests. Less surface damage was observed when water and oil were used at the wheel/rail contact with only mild were being observed. Under dry contact, delamination and material loss by spalling were observed which are an indication of severe and catastrophic wear. Introducing water and oil at the wheel contact was also found to lower the coefficient.

Acknowledgements

The authors would like to thank Mintek South Africa for financial support and supplying materials.

Declaration of interest statement

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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