EFFECTS OF SLIP RATIO ON WEAR PERFORMANCE OF CLASS B WHEEL STEELS AGAINST SOFTER R260 RAIL STEELS USING THE TWIN DISC SETUP

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ARTICLE INFO

Article details
Presented at the 23rd Annual International Conference of the Rapid Product Development Association of South Africa (RAPDASA) Institute for Industrial Engineering, held from 9 to 11 November 2022 in Somerset West, South Africa

Available online 11 Nov 2022

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DOI
http://dx.doi.org//10.7166/33-3-2805

ABSTRACT

A train experiences different slip ratios at the wheel/rail contact point as it moves along the rail track, which influences the rolling contact fatigue (RCF) and wear properties of wheel and rail materials. This variation in slip ratios is caused by a change in contact area between the wheel and rail head at curves, as the slip ratio increases compared with when a train is moving on a straight track. When the train is moving on a straight track, the wheel is found to be in contact with the rail head; but that changes when moving around curves, as the wheel flange will now be in contact with the gauge corner of the rail, affecting the severity of wear. Therefore, more research needs to be done to understand the role that slip ratio plays in the wear performance of wheel and rail materials in order to be able to develop models or systems that could be used to predict preventive maintenance. The aim of this work was to investigate the effect of the slip ratio on the wear performance of class B wheels against softer R260 rail steels under rolling and sliding conditions, using a twin-disc setup developed at the University of Pretoria. The results showed that the severity of wear was heavily dependent on the slip ratio – i.e., it increased with the slip ratio, with class B wheels performing better than the softer R260 rail.

OPSOMMING

’n Trein ervaar verskillende glipverhoudings by die wiel/spoor-kontakpunt soos dit langs die spoorlyn beweeg, wat die rolkontakmoegheid (RCF) en slytasie-eienskappe van wiel- en spoormateriaal beïnvloed. Hierdie variasie in glipverhoudings word veroorsaak deur 'n verandering in kontakarea tussen die wiel en spoorkop by kurwes, aangesien die glipverhouding toeneem in vergelyking met wanneer 'n trein op 'n reguit spoor beweeg. Wanneer die trein op 'n reguit spoor beweeg, word gevind dat die wiel in kontak is met die spoorkop; maar dit verander wanneer om die trein om kurwes beweeg, aangesien die wielflens nou in kontak sal wees met die spoorhoek van die spoorstaaf, wat die hoeveelheid slytasie beïnvloed. Daarom moet meer navorsing gedoen word om die rol wat glipverhouding speel in die slytasieprestasie van wiel- en spoormateriaal te verstaan, ten einde modelle of stelsels te kan ontwikkel wat gebruik kan word vir die voorspelling van voorkomende instandhouding. Die doel van hierdie werk was om die effek van die glyverhouding op die slytasieprestasie van klas B-wiele teen sagter R260 spoorstaal onder rol- en glytoestande te ondersoek, met behulp van 'n tweeskyf-opstelling wat by die Universiteit van Pretoria ontwikkel is. Die resultate het getoon dat die erns van slytasie baie afhanklik was van die glipverhouding - dit wil sê, dit het toegeneem met die glipverhouding, met klas B-wiele wat beter presteer as die sagter R260-reling.

1. INTRODUCTION

The wheel-rail contact interface is a very complex system, as it involves several factors such as wheel-rail geometry, lubrication influenced by humidity and precipitation, and a variety of loading conditions that influence wheel/rail wear [1]. Some of the lubricants affect the coefficient of friction at the interface, causing braking problems by increasing the braking distance [2]. The demand for high axle loads and high-speed trains has added problems to the complexity of the wheel-rail contact conditions, making it difficult to study the interface. The wheel/rail contact area is small, usually around 1 cm^2, and varies as the train moves along the track, owing to different rail-wheel profiles and the degree of curvature of the rail track [3]. Both sliding and rolling occur at the wheel/rail contact, with the rail experiencing up to 2 GPa maximum compressive contact stresses [4, 5]. A field study by Olofsson and Telliskivi [6] has shown that the wheel/rail contact changes from wheel tread/rail head contact to a wheel flange/rail gauge face contact, resulting in a significant increase in contact pressure when the sliding velocity is increased [6]. Olofsson and Telliskiv [6] have also shown that the wear rate at the rail gauge is 10 times larger than at the rail head. The change in contact conditions at the wheel/rail causes a variation in slip ratio. For a twin disc setup, the slip ratio is given by equation 1.

$$slip\ ratio = \left(\frac{V_w - V_r}{V_w - V_r}\right) \times 200\% \qquad (1)$$

where V_w and V_r are the rotational speed of the wheel and rail discs in rpm respectively [7].

Slip/creep has a relationship with the tractive force or coefficient of friction (COF), as shown in Figure 1. Increasing the creep results in an increase in tractive force until a point where full slip at contact is reached, and creep is limited by the COF for a given applied normal load [3]. As creep increases, the slip region increases while the stick region decreases, resulting in a rolling–sliding contact until pure sliding appears, when adhesion equals the frictional force between two contacting bodies under pure sliding conditions [8].

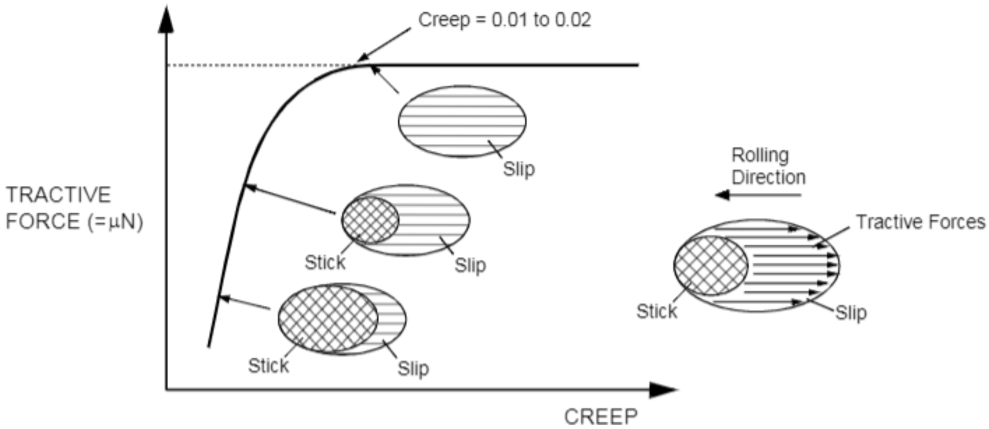

Figure 1: Relationship between traction and creep/slip in the typical wheel-rail contact coefficient of friction ranges for dry rail, friction modifiers, and lubricants [3].

Studies have been conducted to find out the effects that the slip ratio has on the wear properties of wheel and rail materials. Makino *et al.* [9] found that increasing the slip ratio increased the friction coefficient at the wheel/rail contact in AAR class C wheel steels under a twin disc setup, which in turn reduced the fatigue strength of the materials. This is a problem, as a reduction in fatigue strength causes a rapid increase in crack initiation, which might result in rolling contact fatigue (RCF) [10, 9]. This agrees with the work done by Ma *et al.* [11], who found that increasing the slip ratio increases the coefficient of friction as well as the surface hardness of the wheel/rail material after testing using the twin disc setup. This increase in surface hardness is as result of work hardening. The same study by Ma *et al.* [11] observed that increasing the slip ratio also transformed the wear mechanism from mild oxidation wear to severe fatigue and spalling, which causes RCF and can result in failure.

Wang *et al.* [12] also observed that increasing the slip ratio significantly reduced the fatigue life of rail materials that were tested using the Sheffield University Rolling Sliding (SUROS) twin-disc tester. The reduced fatigue life was the result of an increase in the growth angle of cracks and the transformation of the damage mechanism from mild surface crack to severe fatigue [12]. Wang *et al.* [12] also found that the depth of deformation layers and the size of branch cracks increased at the same time as the slip ratio increased. This increase was found to be detrimental to RCF, as it reduced the fatigue life [12]. In the same study it was found that an increase in the slip ratio also increased the wear rate on both wheel and rail materials. The same behaviour was observed in the study by Seo *et al.* [13], who found that at a low slip ratio of 0.1% to 0.3%, surface cracks caused by spalling had developed, while increasing the slip ratio to 1.5% resulted in plastic flow and the appearance of fine surface cracks. From the same study, spalling was also observed at a high slip ratio, which was an indication of fatigue.

The main aim and objective of this work was to study the effects that the slip ratio has on the rolling and sliding wear performance of a Class B wheel against R260 rail steels, as they are some of the materials currently used in the local rail industry. The literature [12] has demonstrated that, as the wheel moves along the rail track, it experiences different slip ratios caused by changes in the contact conditions.

2. METHODOLOGY

A twin-disc test rig developed at the University of Pretoria was used for this work. The test rig used two identical rotating cylinders (discs) that were in contact under an applied load at specified opposite angular velocities. Both discs were connected to some pivoted shafts run by independent 3 kW motors to create both rolling and sliding contact. Each motor was connected to its own 4 kW variable speed drive (VSD) to control the speed over a range of 0-1400 rpm. To measure torque, the lower shaft was mounted with strain gauges connected to the TorqueTrak 10K-LP Torque Telemetry system, and the measurements were used to determine the coefficient of the friction values. The rotational speed of the rail disc was kept constant at 340 rpm, while the wheel disc speed was varied to achieve slip ratios of 2%, 5%, 10%, and 20%. To obtain the coefficient of friction (μ) from the torque measurements, equation 2 was used:

$$\mu = \frac{T}{PR_r} \tag{2}$$

where T is torque (Nm), P is the applied load (N), and Rr is the radius of the lower disc (m). For the contact load measurements, a 10 kN C9C compressive load cell was used. The test matrix is shown in Table 1.

Table 1: Test matrix

Contact load (kN)	Number of rolling cycles	Rail disc speed (rpm)	Wheel disc speed (rpm)	Slip ratio (%)
1	62 000	340	347	2
1	62 000	340	358	5
1	62 000	340	376	10
1	62 000	340	416	20

AAR M-107/M-208 [14] Class B wheels were used for the wheel discs, while BS EN 13674-1:2011 [15] R260 rail steels were used for the rail discs; their chemical compositions and as-received microstructures are shown in Table 2 and Figure 2 respectively. Their chemical compositions were obtained through spark emission spectrometry. The as-received Vickers hardness values of the wheel and rail steel were 348 ± 3 and 298 ± 6 HV 10 respectively, conducted using a Struers Duramin-40 machine under a load of 10 kgf. All tests were done in dry contact conditions. Before and after testing, the discs were cleaned in an ultrasonic bath to obtain the mass losses. The worn wheel and rail discs were cut in cross-sections, then ground and polished to be observed using optical microscopy and scanning electron microscopy to analyse the morphology of the worn surfaces and the sub-surface cracks, and to investigate the depth of the plastic deformation and work hardening.

Table 2: Chemical composition of wheel and rail steels

Material	Wheel	Rail
Standard	AAR M-107/M-208	BS EN 13674-1:2011
Grade	AAR Class B	R260
Element	Chemical composition (wt%)	
C	0.67	0.70
Mn	0.81	0.91
P	0.020	0.025
S	0.0078	0.0049
Si	0.347	0.354
Ni	0.065	0.045
Cr	0.150	0.036
Fe	Balance	Balance

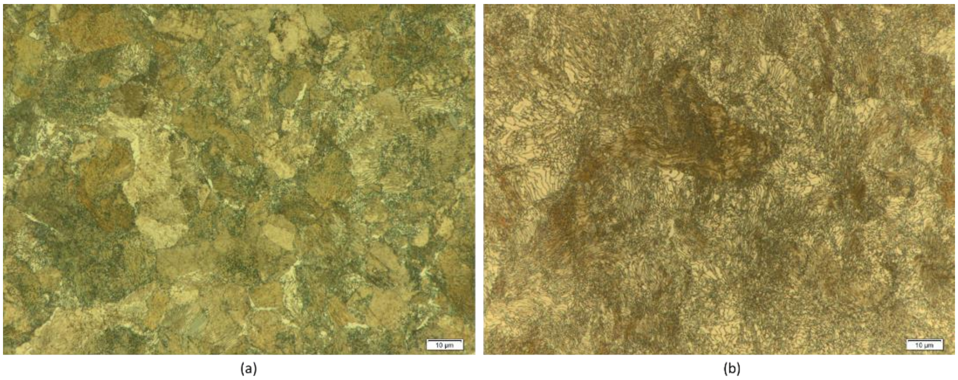

Figure 2: Optical microscopy micrographs of the as-received (a) Class B wheel specimen obtained at the rim, and (b) R260 rail head specimen showing pearlitic microstructures

3. RESULTS AND DISCUSSION

The coefficient of friction was found to increase with the number of rolling cycles, up to a point where it became stable after reaching a steady state, as seen in Figure 3a. At the steady state, adhesion equalled the frictional force between the two contacting discs. The coefficient of friction was substantially dependent on the slip ratio. In other words, increasing the slip ratio resulted in an increase in the average value of the coefficient of friction, as seen in Figure 3b. The literature [16, 17, 18, 19] has shown that friction plays a significant role in the wear performance of wheel and rail steels, with the slip ratio affecting the severity of the wear. From Figure 5 it can be seen that the severity of the wear increased with the slip ratio, with more evidence of sub-surface damage by cracking and loss of materials by spalling being observed at a higher slip ratio of 20%. At a lower slip ratio of 2%, sub-surface damage was mainly caused by peeling, in which a layer of material is removed from the surface. At a lower slip ratio, the wear was mainly the result of abrasion, which was evident in abrasive wear marks (ploughing) that indicated mild wear, as seen in Figure 4a; while at a higher slip ratio (20%), the wear was mainly the result of a loss of material by spalling in both wheel and rail steels, as seen in Figure 4b and Figure 4d. Spalling is an indication of severe wear, which the literature has identified as the cause of failure in both wheel and rail materials. Delamination was also observed on the R260 rail steel at a slip ratio of 10%, as seen in Figure 4c, which is an indication of severe wear.

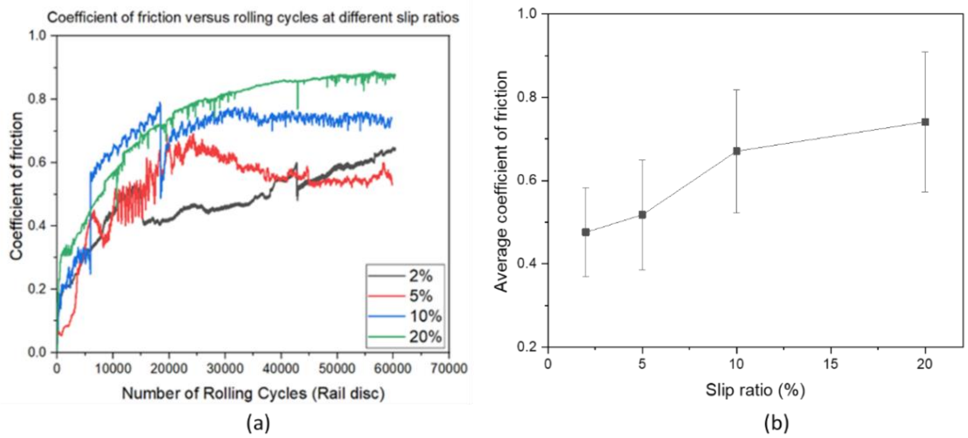

Figure 3: (a) Coefficient of friction as a function of the number of rolling cycles at different slip ratio;s and (b) average coefficient of friction vs slip ratio under an applied load of 1 kN and dry contact conditions

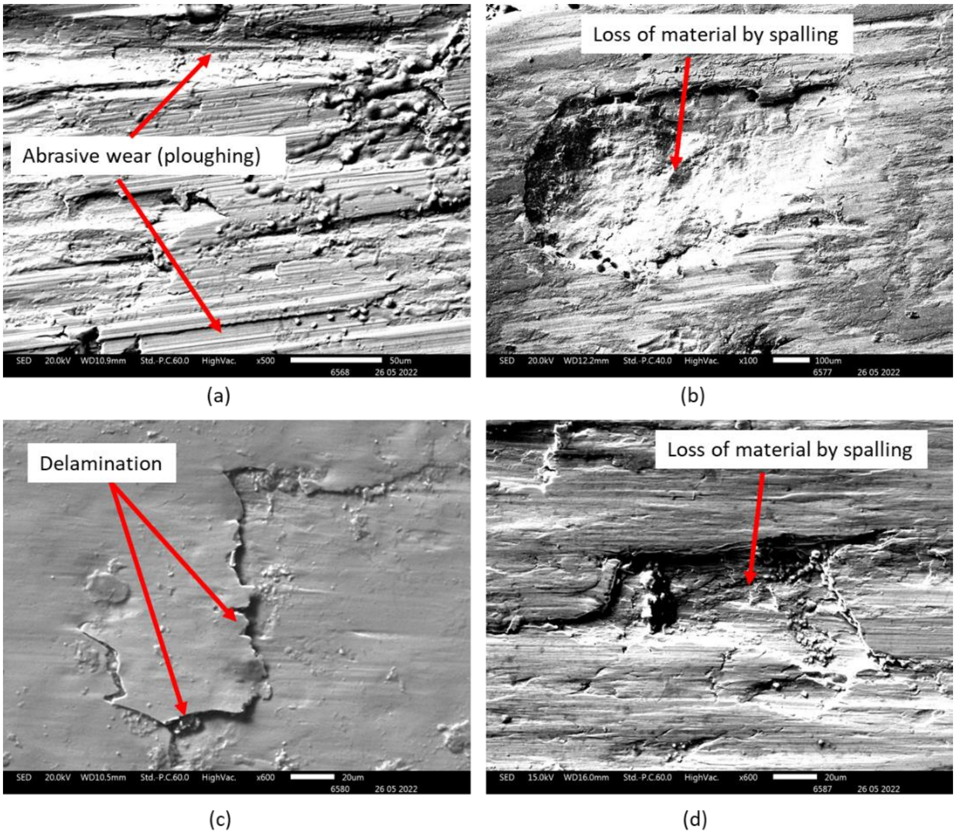

Figure 4: SEM micrographs of AAR class B wheel disc surfaces: (a) 10% slip ratio and (b) 20% slip ratio; R260 rail discs surfaces (c) at 10% slip ratio and (d) 20% slip under an applied load of 1 kN and 62 000 rolling cycles, showing different surface damage mechanisms

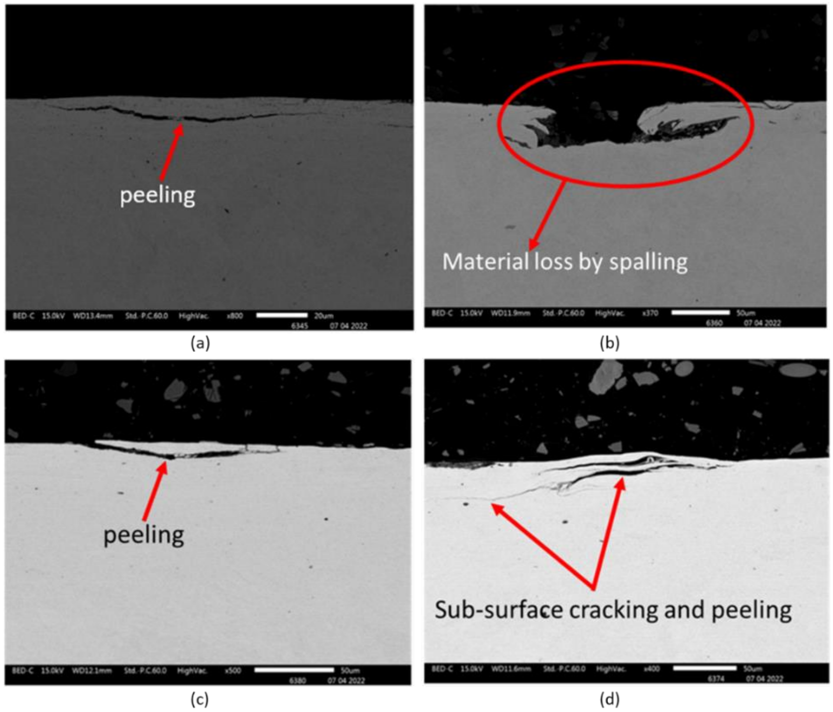

Figure 5: AAR Class B wheel specimen after testing at (a) 2% slip ratio and (b) 20% slip ratio; R260 rail specimen after testing at (c) 2% slip ratio and (d) 20% slip ratio under 1 kN applied load showing sub-surface damage

Mass loss increased with the slip ratio for both the R260 rail and the Class B wheel steels, with the rail steels losing more mass than the wheel steels, as can be seen in Figure 6. The reason for the lower mass loss by the Class B wheels than by the R260 rails could be attributed to hardness. The R260 rail was softer than the class B wheels, with a hardness value of 298 HV10 compared with the wheel's 348 HV 10. From the literature [12], the slip ratio plays a role in the rolling and sliding of the wheel on the rail as the train moves on a straight track. When the train is moving on a straight track, the wheel is found to be in contact with the rail head; but that changes when moving around curves, as the wheel flange will now be in contact with the gauge corner of the rail, leading to an increased slip ratio between the wheel flange and the rail gauge face. This causes the contact at the wheel flange and the rail gauge face to experience more severe wear than at the wheel tread and rail head.

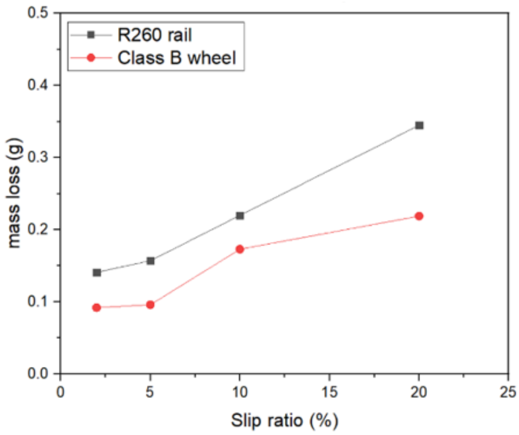

Figure 6: Mass loss in Class B wheel discs and R260 rail discs as a function of the slip ratio under an applied load of 1 kN and dry contact conditions

To study the effect that the slip ratio has on the plastic deformation and work hardening, Vickers micro hardness tests were performed using a load of 200 gf. The results are plotted in Figure 7 for both wheel and rail specimens. The results show that increasing the slip ratio also increases the rate of work hardening, as confirmed by the increasing hardness towards the surface/sub-surface region of the discs. The maximum micro hardness was observed at a slip ratio of 20% on both wheel and rail steels. This was confirmed by the micrographs in Figure 8, which show the depth of the plastic deformation for both wheel and rail specimens, with the depth of deformation increasing with the slip ratio. The same trend was observed in studies by Ma *et al.* [11] of an ER9 wheel against a U7 rail and by Rodríguez-Arana *et al.* [20] of R260 rail steels under a twin-disc setup. This increase in surface hardness with an increasing slip ratio might be caused by an increase in the dislocation density as work hardening increases.

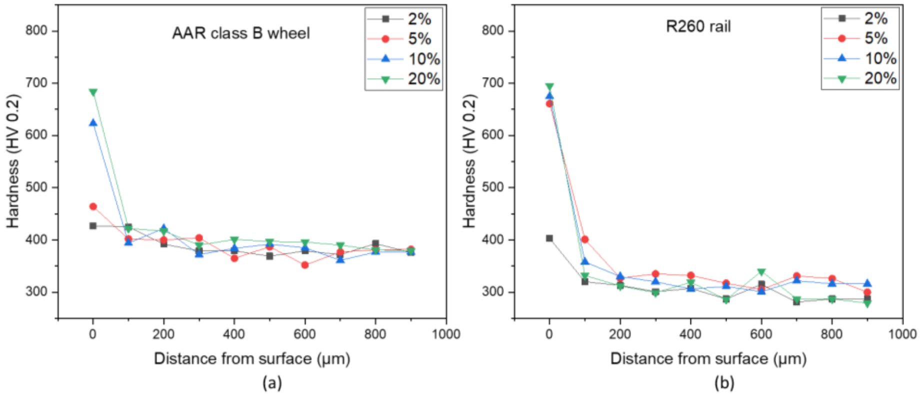

Figure 7: Micro hardness (HV0.2) variation at different slip ratios: (a) AAR Class B wheel steel and (b) R260 rail steel under an applied load of 1 kN and 62 000 rolling cycles

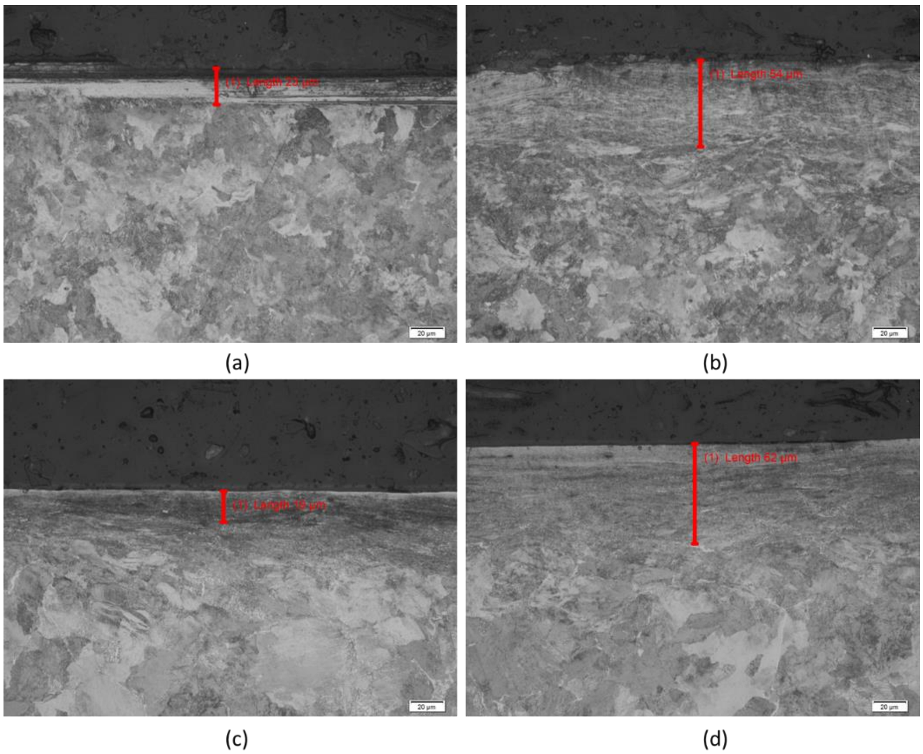

Figure 8: Optical microscopy micrographs of AAR class B wheel at (a) 2% and (b) 20% slip ratio; R260 rail at (c) 2% and (d) 20% slip ratio, showing the plastically deformed region at 1 kN contact load and 62 000 rolling cycles

4. CONCLUSION

From the results it was observed that the coefficient of friction, mass loss, severity of wear, and depth of plastic deformation of wheel and rail contacting discs increased with an increase in the slip ratio. Therefore, an increasing slip ratio was found to have a negative impact on the wear performance of both rail and wheel steels. There was evidence of severe wear at a high slip ratio of 20% as a result of spalling. The Class B wheels performed better than the R260 rail with low wear rates across all slip ratios.

5. ACKNOWLEDGEMENT

The authors would like to thank the following organisations for making this project possible: Mintek for financial support and supplying materials, and the University of Pretoria for providing the research facilities.

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