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Effect of normal load on the wear and rolling contact fatigue behaviour of AAR class B wheel against R350HT rail in a twin disc simulator

Tshenolo P. Leso[1*], *Charles W.* Siyasiya[1], *Roelf* Mostert[1] and *Joseph* Moema[1,2]

[1] The Department of Materials Science and Metallurgical Engineering, University of Pretoria, Lynnwood Road, Hatfield, South Africa
[2] Advanced Materials Division, Mintek, 200 Malibongwe Drive, Randburg, South Africa

Abstract. The normal load at the wheel-rail contact interface plays a significant role in wear and rolling contact fatigue (RCF) performance of both wheel and rail steels. In recent years, there has been an increase in axle loads due to increased demand for railway services. This study investigated the effect of normal load on the wear and RCF behaviour of the AAR class B wheel versus R350HT rail using a twin disc wear simulator. The mass loss, surface damage and depth of deformation were used to assess wear and RCF, respectively. From the mass loss results, wear maps were obtained to identify different wear regimes being mild, severe and catastrophic at different contact loads and slip ratios. Scanning electron microscopy was also used to assess the surface damage of wheel and rail steels in order to identify the wear regimes with surface cracking and delamination being observed at higher contact loads indicating severe and catastrophic wear. Furthermore, the RCF crack density was found to be higher on specimens evaluated at higher normal loads with more cracks evident and crack branching forming.

1 Introduction

There has been an increased demand for railway services increasing the axle load and train speeds to meet increasing demand [1]. This has resulted in problems associated with wear and rolling contact fatigue (RCF) decreasing the lifetime of wheel-rail systems as a result increasing maintenance costs. Wear is a process in which material is gradually removed from surfaces that are in contact due to mechanical, chemical, or physical factors [2, 3]. Many parameters, such as sliding, rolling, impact, corrosion, erosion, or cavitation, can cause it. Wear can cause a metal's mechanical qualities to degrade, shorten its lifespan, and ultimately cause the component or system it is employed in to fail. RCF is a phenomenon where pressure and creep forces are applied repeatedly in the rail/wheel contact area, drastically reducing the durability of the contacting surfaces [4]. During rolling and sliding of a wheel on rail, there is repeated loading at the contact surface of the two which may result in plastic deformation. Repeated loading causes the material to flow plastically when the load applied is greater than

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* Corresponding author: tshenolophinah@gmail.com

the elastic limit due to contact stresses exceeding the yield stresses of the contacting materials [5]. In heavy haul railway lines severe plastic deformation is mostly observed where extreme wheel loads are experienced causing incremental plastic flow known as "ratchetting" due to repeated loading [6]. Ratchetting has been found to cause nucleation of voids and microcracks below the wheel-rail contact surface [6]. The microcracks/voids grows as repeated loading is applied resulting in initiation of fatigue cracks [6]. During plastic deformation, work hardening occurs which is an increase in material surface hardness due to an increase in dislocation density because of strain hardening. The load exerted on the wheel-rail contact affects both wear and RCF properties. That influence of load is studied in detail to understand the influence axle load has on wear and RCF as experienced during movement of a train on rail. A study by Zhong et al. [7] has found out that loading conditions at the wheel-rail contact affects the rate of plastic deformation at the contact. When the axle load was increased from 16 tonnes to 25 tonnes there was an increase in plastic deformation [7]. The plastically deformed layer thickness is an indication of how much wear has taken place, the thicker the layer the higher the wear rate. The depth of plastic flow also depends on the initial hardness of the wheel and rail materials as well as the contact conditions.

In South Africa, there are two main subsectors contributing to its rail industry being passenger services and freight services. The rail industry contributes significantly to South Africa's economy by creating employment and generating income, with the freight rail sector being its largest contributor. The freight rail sector is responsible for transporting a wide range of commodities such as minerals (coal, iron ore, manganese), agricultural products, manufactured goods, bulk liquids, containerised freight and automotive. The rail network in South Africa is regarded as one of the largest and most advanced rail networks on the African continent [8]. Therefore, the aim of this work is to investigate the effect load has on wear and RCF performance of the class B wheel and R350HT rail steels using the twin disc simulator. This wheel-rail combination is the most used by the local rail industry and therefore, these research results are beneficial to both the local and other rail operators worldwide using such a combination

2 Materials and methods

Wheel and rail discs were machined from AAR class B wheel and R350HT rail steels. The chemical compositions were obtained using spark emission spectrometry and the as-received hardness conformed to their respective standards being AAR M-107/M-208 [9] for class B wheels and BS EN 13674-1:2011 [10] for R350HT rail steels. The hardness values of the wheel and rail materials in the as-received state were 350 ± 8 HV10 and 385 ± 9 HV10. The Vertical Twin-Disc Rig (Figure 1), which was manufactured in-house at the University of Pretoria was used for this work. The operational details of this test rig have been discussed in a previous study [11]. The experiments were carried out under dry contact at 1, 1.4, and 1.8 kN, which corresponds to maximum contact pressures of 552, 645, and 740 MPa, respectively, according to Hertz theory [12, 13]. The tests were performed for 62 000 rolling cycles, while keeping the rail disc speed constant at 340 rpm and varying the wheel disc speed to achieve slip ratios of 2, 5, 10 and 20%. Slip ratio is defined by equation 1, where Vw and Vr are the rotational speed of the wheel and rail discs in rpm, Rw and Rr are the rolling radius of the wheel and rail discs respectively. Before testing, both the wheel and rail discs were cleaned in an ultrasonic bath of ethanol to remove any contamination and weighed to get the initial mass. During testing, the torque data was recorded and converted to coefficient of friction using equation 2. After testing, the worn discs were cleaned in an ultrasonic bath and weighed to get the mass loss. The worn surfaces were observed under a scanning electron microscopy (SEM) and optical microscopy (OM). The worn discs were sectioned, mounted ground and polished to a surface finish of 3 μm, then etched using 3% Nital to observe the depth of plastic deformation using OM and the sub-surface damage using SEM.

$$Slip\ ratio = \left(\frac{V_w.R_w - V_r.R_r}{V_w.R_w + V_r.R_r}\right) \times 200\% \qquad 1$$

$$\mu = \frac{T}{FR_r} \qquad 2$$

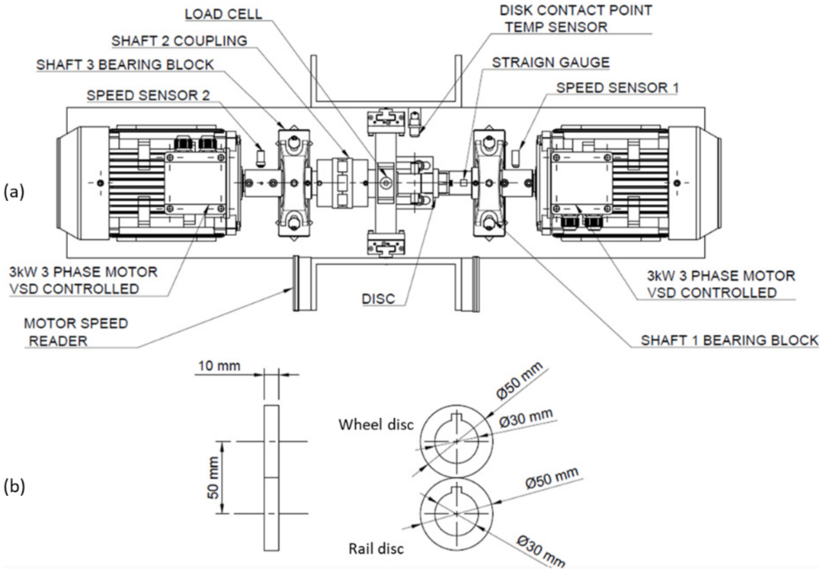

Fig. 1. A schematic diagram of the (a) University of Pretoria wear simulator and (b) wheel and rail discs.

3 Results and analysis

Figure 2a shows that increasing both load and slip ratio increased wear rates, as measured by the cumulative mass loss. In other words, more mass loss was observed at 1.8 kN contact load at a slip ratio of 20% indicating that an increase in contact load resulted in more wear rates. Figure 2b shows that the average coefficient of friction decreased rapidly when the contact load was increased from 1 to 1.8 kN. In other words, the coefficient of friction was found to be more sensitive to slip ratio at lower loads than at higher loads. This is attributed to wear debris sticking together easily at lower loads increasing the surface roughness of the wheel and rail resulting in an increase in the coefficient of friction. The decrease in friction coefficient with an increase in contact pressure was also observed by other works on twin-disc setup [14, 15, 16], confirming that the rig was able to produce reliable and comparable results.

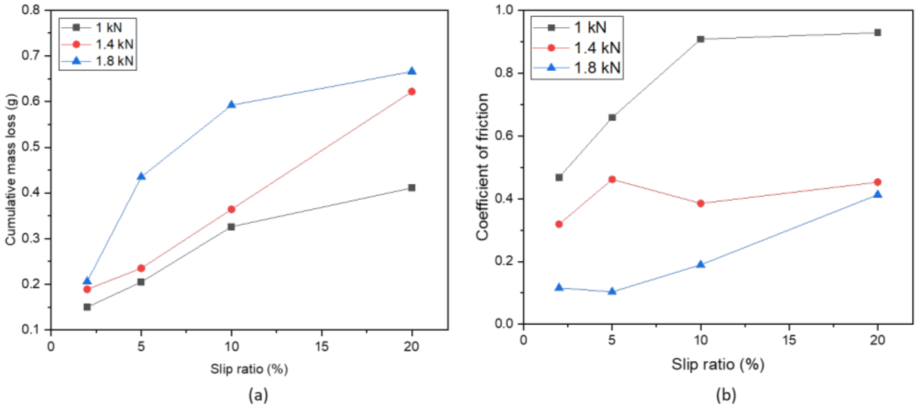

Fig. 2. (a) Cumulative mass loss (wheel + rail) versus slip ratio; (a) average coefficient of friction versus slip ratio at different contact loads.

Varying the load across the different slip ratios was found to affect wear and RCF on both wheel and rail steels. The severity of wear increased with an increase in the load and was evident from the worn surfaces, Figure 3. As may be seen at lower load of 1 kN wear was mild and mainly due to abrasive wear whereas at higher load of 1.8 kN there was evidence of severe and catastrophic wear due to delamination and surface cracking. The evidence of surface cracking and delamination has been previously discussed [17, 18, 19] as indicators for catastrophic wear. It is evident that increasing the contact load causes more damage to both wheel and rail materials. This was also confirmed by optical microscopy micrographs in Figure 4 where the depth of deformation increased with increase in contact load with the maximum depth of 45 μm observed at 1.8 kN compared to 25 μm at 1 kN.

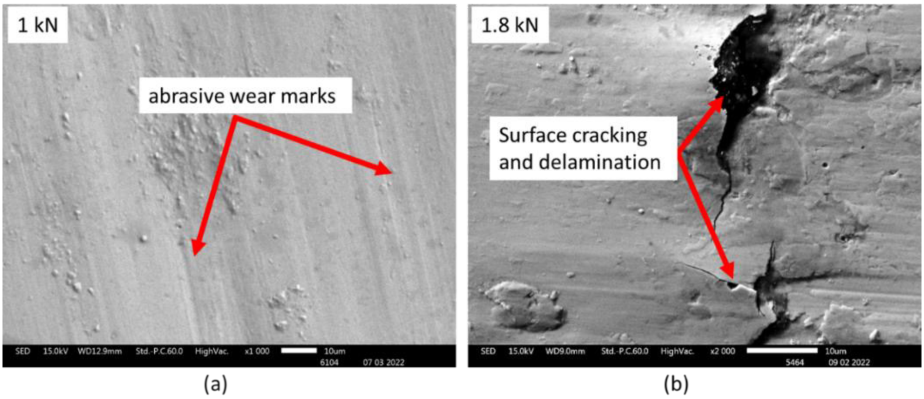

Fig. 3. SEM micrographs of rail specimens showing the contact surface morphologies at different loads: (a) 1 kN and (b) 1.8 kN.

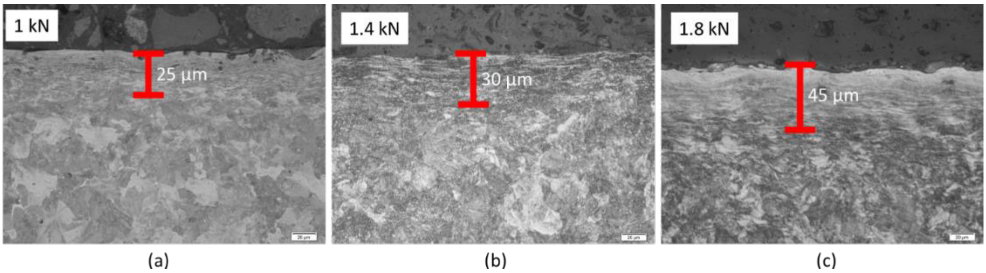

Fig. 4. Optical microscopy micrographs of class B wheels at 5% slip ratio showing the plastically deformed regions under different contact loads: (a) 1 kN, (b) 1.4 kN and (c) 1.8 kN.

Wear maps (Figure 5) can be used to define different wear regimes being mild, severe and catastrophic [14, 20]. The wear rate (µg/m/mm^2) is the weight of lost material (µg) per distance travelled (m) per contact area (mm^2). The twin-disc contact areas were found to be 2.33, 2.78 and 3.15 mm^2 corresponding to Hertzian contact pressures of 552, 645 and 740 MPa respectively. The areas are relatively similar to the ones in literature obtained by twin disc tests, for example work by Rodríguez-Arana et al. [21] the contact area of the contacting disc was found to be 3.743 mm^2 at a maximum contact pressure of 1240 MPa under a twin disc setup. The contact areas, mass loss of the wheels as well as the equivalent linear travelled distance (9.74 km) were used to calculate the wear rates (µg/m/mm^2) at different slip ratios and contact pressures, Figure 5. When the load was increased from 1 to 1.8 kN at 5% slip ratio under dry contact, the wear behaviour changed from mild to severe and when the slip was increased to 20%, it was catastrophic. This agreed with SEM observations in Figure 3. As expected, the R350HT rail showed lower wear rates compared to the wheel due to its higher hardness. Literature [22, 23, 24] has shown that hardness plays a significant role in wear performance of steels, with harder steels performing better than softer ones.

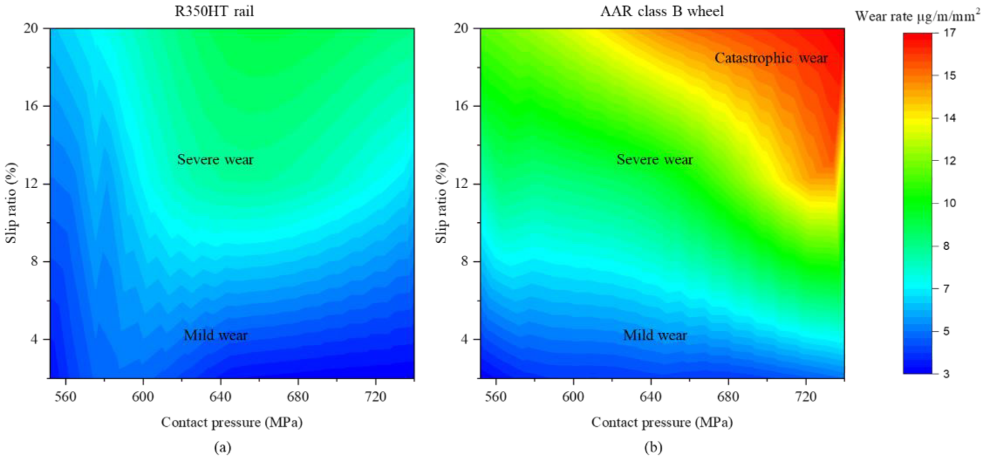

Fig. 5. A contour plot of wear rates showing 3 wear regimes for: (a) the R350HT rail and (b) the wheel at different slip ratios and contact pressures under dry contact and 62 000 rolling cycles.

Increasing slip ratio and contact load was found to promote crack propagation and crack branching, which caused severe damages such shelling and spalling an indication of catastrophic wear, Figure 6. Previous works [25, 26] have shown that micro cracks initiate at high slip ratios and contact loads which may result in crack propagation.

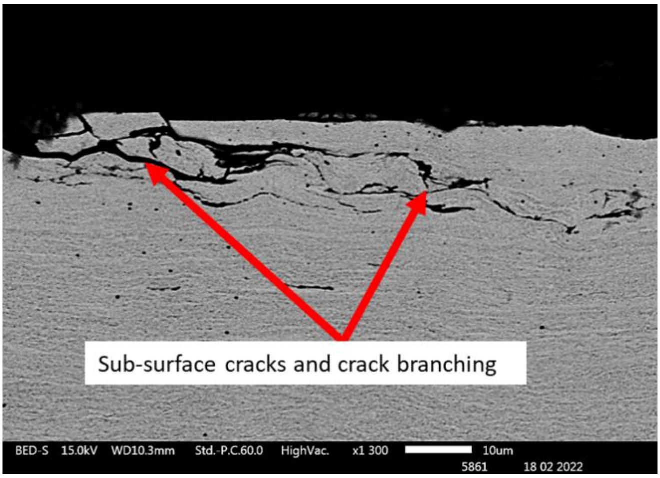

Fig. 6. SEM micrograph of wheel specimen showing RCF subsurface damage and crack branching after testing at 1.8 kN and 20% slip ratio.

4 Conclusions

This study was intended to help the local rail industries using AAR class B wheels against R350HT rail combinations to understand the wear and RCF performance under different contact conditions for the predictive maintenance. For this reason. the effect of load on the wear and RCF behaviour of the AAR class B wheel against R350HT rail in a twin disc simulator was investigated and the following conclusions were drawn:

- The depth of plastic deformation and RCF crack density increased with load across all the slip ratios with more damage and depth being seen on the wheel steels.
- Higher wear rates were observed on the wheel with some evidence of catastrophic wear at higher contact loads.

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