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Dry and lubricated wear of rail steel under rolling contact fatigue - Wear mechanisms and crack growth

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ABSTRACT

In this work, the dry and lubricated wear behavior of rail steels (R370CrHT) under Rolling Contact Fatigue (RCF) conditions was studied in laboratory. A twin-disc rolling-sliding machine was used to reproduce contact conditions under high contact pressure (1.1 GPa) and high creepage (5%) with the aim of accelerating RCF failure. Two different types of tests were performed, namely dry and lubricated with a friction modifier, to simulate the mechanisms that cause RCF. The results showed an increase of the wear rate in the tests where a friction modifier was added after an initial stage of 4,000 dry cycles. The damage of the surface proceeded by cracks formation during the dry stage followed by accelerated crack growth and flaking due to the effects induced by the friction modifier entering into the original cracks. After several thousand cycles, the flakes were detached from the surface causing high wear rates. The cracks morphology was observed under SEM. The cracks depth and angle with respect to the contact surface were reported and some correlations were made with the mass loss results.

1. Introduction

The wear on rail systems is a serious problem for the competitiveness of transport industry. A global trend to address wear issues is the use of friction modifiers (FMs) at the interface between wheel and rail. Bower (1988) [1], Kaneta and Murakami (1985) [2–4], and others have studied rolling contact fatigue (RCF) to gain understanding of the behavior of the FM when entering the cracks and to evaluate its influence on wear and cracks growth [5–9]. Bower [1] proposed three mechanisms of crack growth assisted by fluids based on the experimental results of S. Way (1935): (i) the cracks only propagate if a fluid lubricant is applied to the surfaces in contact, (ii) the cracks always propagate in the direction of motion of the load over the surface, and (iii) if there is some relative sliding between the two contacting surfaces, cracks only propagate in the driven surface. Although it is acknowledged that a FM can minimize friction between the crack faces and promote crack growth through the Mode II (shear), it is also well known these days that no fluid is required to grow a crack; regarding (iii), it has been found that the cracks grow in both wheel and rail.

A research in Australia found that the total annual maintenance cost of a 12 Million Gross Tons (MGT) railway system can be as high as USD $ 34 per meter of rail. The costs and the wear rates are influenced by the curvature radius of the railroad, the planning intervals of rail grinding (Rail grinding refers to a controlled wear operation used to eliminate cracks before they reach a critical length at which its growth rate sharply increases) and the use of a suitable FM at the interface, among others. The total annual cost/meter of the rail maintenance in a non-lubricated 12 MGT transport systems is USD $ 54, whereas with lubrication savings could amount around 60% of the total value [10].

A survey released by the *Engineering Research Programme* in 2003 [11], where the information gathered from 35 rail networks was analyzed, concluded that effective lubrication can reduce wear on wheel and rail and the noise levels. The rails life can be increased by a factor of two, the wheel life by a factor of five and in some cases depending on the radius of curvature and grinding intervals by a factor of four. However, today many of the steps and principles that govern the phenomenon of RCF in the presence of a FM are not entirely known. Several studies carried all over the world have helped understand some of the principles that govern the phenomenon of RCF and other problems related to the tribology of wheel/rail contact such as the type of predominant defects, nondestructive techniques for inspecting rails, among others [12–18].

In this work, the dry and lubricated wear behavior of rail steels under RCF conditions was studied in laboratory. A twin-disc

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Table 1
Chemical composition of rail and wheel (wt%).

	C	Si	Mn	P	S	Cr	Al	V	Cu	Ti	Ni	Mo
R370CrHT	0.762	0.394	1.062	0.011	0.015	0.506	0.000	0.002	0.038	0.002	0.058	0.019
ER8	0.542	0.253	0.734	0.011	0.006	0.141	0.027	0.006	0.165	0.002	0.120	0.048

rolling-sliding machine was used to impose controlled contact pressure and creepage conditions that led the tribological pair to a severe wear regime. The study was done to evaluate the effect of the application of a FM to the interface when cracks are already formed at the surface of the rail.

2. Materials and methods

Rail specimens were extracted from R370CrHT rail sections, manufactured by the company *Voestalpine Schienen GMBH-Austria*, and wheel specimens were extracted from a railway wheel grade ER8. The chemical composition measured by optical emission spectroscopy and relevant mechanical properties of the rail and wheel, in line with European standards EN 13674-1:2011 [19] and EN 13262:2004 [20], are shown in Table 1 and Table 2 respectively. The hardness of the wheel was 291 ± 17 $HV_{31.25kgf}$.

The samples were polished for metallographic analysis by using emery papers and (6 to 0.25 μm) diamond paste. After fine polishing, the samples were etched with Picral (100 ml ethanol + 4 g picric acid). A JEOL 5910LV SEM was used to evaluate the microstructure and the worn surfaces using Secondary Electrons (SE). For the longitudinal sections and EDS mapping a FEI Inspect F50 was used, located at the Brazilian Nanotechnology National Laboratory (LNNano). To differentiate the inclusions from the cracks Backscattered Electrons (BSE) images were taken.

The wear tests were carried out in a Twin-Disk testing machine installed at the Tribology and Surfaces Laboratory in the National University of Colombia, Medellín. Constructive details about the machine can be found elsewhere [21]. The Twin-Disk machine is used to simulate either dry or wet contact in wheel/rail tribosystems [22]. For each condition, two replicas were performed on different (new) samples to evaluate the repeatability. In this study, the lubricated condition was provided by the addition of a FM to the contact interface. In the test rig, two rolling discs are loaded upon each other and the relative speed, contact pressure and slip percentage (creepage) are precisely controlled. Fig. 1 shows a schematic of the testing device.

Cylindrical specimens were extracted from actual wheels and rails by cutting and lathe turning. The rail specimens were extracted from the rails head (Fig. 2a). Both rail and wheel specimens have the same dimensions, with a diameter of 47 mm and a rolling width of 10 mm. The experiments were designed to be aggressive enough to cause RCF under severe wear regime, so a slip percentage of 5% and a contact pressure of 1.1 GPa were chosen. The wheel specimens were rotating at 401 ± 1 RPM, and the rails specimens at 380 ± 1 RPM. As the samples rotate at different RPM they are subjected to different fatigue cycles; for the diagrams the cycles were calculated according to the wheel disc revolutions (i.e. 400 RPM). The slip percentage was defined according to Fletcher and Beynon as [23]:

$$\mathrm{Slip}(\%) = 200\left(\frac{R_W N_W - R_R N_R}{R_W N_W + R_R N_R}\right) \tag{1}$$

where N are the revolutions, R is the radius of the disk specimens, and W and R indicate wheel and rail respectively.

In order to accelerate the cracks growth, a dry pre-fatigue period was implemented before applying the FM. As it was shown by Fletcher and Beynon in a R260 rail steel [23], the number of dry cycles must be carefully controlled since high tangential forces cause the cracks to grow rapidly and severe flaking may occur after 5000 cycles, so the nucleated cracks are lost. The number of dry cycles was set equal for all samples, since Tyfour *et al.* [8] demonstrated that this has a notable effect on the final fatigue life in dry-wet contact.

Table 2
Mechanical properties of the rail.

	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness HV (HB)
R370CrHT	1373	767	10	387 ± 17 (366.4)

Accordingly, in this study, 4,000 dry cycles of pre-fatigue were used based on the results of J.F. Santa [24]. Without stopping the test, after 4,000 dry cycles a commercial FM (Sintono Terra HLK, based on synthetic oils) was added to the surface of the wheel specimen by using a brush. The amount of FM added was weighed to ensure that 0.02 to 0.03 g would be applied to the wheels surface. The application was repeated every 400 cycles. Once the FM is applied, the coefficient of traction (COT) drops sharply to reach a stable value after a few tens of cycles.

Three different numbers of cycles were selected to evaluate the effect of the FM on RCF: 9,000, 14,000, and 24,000. For comparison reasons, dry tests with equal number of total cycles were also performed. For each condition two replicas were prepared, and before each test the samples were washed and weighed to measure mass losses. The tests were performed using separate sets of samples for each number of cycles to be tested. This is because stopping the tests would induce a new *running-in* period during the re-start due to misalignment, changes in real contact area and roughness accommodation. W.R. Tyfour *et al.* show how the COT never reaches a stable value if the tests are stopped and re-started with the same pair of samples [25].

At the beginning of every test the applied load and contact area were verified by carefully watching the contact path in the samples with the applied load. After turning the motors on, the friction torque was corrected to zero, the load was applied and the test started. Once the test ended, the samples were washed with degreaser, submerged in acetone and cleaned in ultrasonic bath to remove the residues of FM. Finally the samples were weighed to measure the mass losses and to obtain the wear rates.

3. Results and discussion

The nomenclature used hereinafter has the first letter related to the interfacial condition (H for HLK and D for dry), followed by the slip percentage and the number of wet cycles. As an example, a test run with the addition of HLK with 1.1 GPa, 5% creepage and 10,000 wet cycles, is named “H5% 10 K”.

3.1. *Effect of the use of a FM on the RCF*

In Fig. 3 the COT reaches a maximum of 0.63 at the beginning of the test and then it decreases to values below 0.60. The running