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CORRELATIONS BETWEEN RAIL WEAR RATES AND OPERATING CONDITIONS IN A COMMERCIAL RAILROAD

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ABSTRACT

The rail wear rates per traffic unit (mm/MTon) in the curves of a 4.5 km-long commercial line over a period of 9 years were measured and related to specific operation conditions. The rail corrugation was analysed using a Corrugation Analysis Trolley (CAT) and visual inspection was carried out in order to identify the defects in the railroad. Since Rolling Contact Fatigue (RCF), artificial abrasion and corrugation were found to be the most important issues the grinding procedures used during maintenance of the railroad were evaluated to assess their effectiveness on removing the defects from the rail surface. The results showed that the wear rates in the studied railroad were several times higher than those typically found in the literature, mainly as a consequence of inappropriate grinding regimes. White layer formation and only partial removal of cracks emerged as the most relevant drawbacks of rail grinding procedures.

KEYWORDS: Corrugation, Crack Growth Rate, Rail Grinding, Rolling Contact Fatigue, Wear Rate.

1. INTRODUCTION

Wear of railroad systems costs millions of dollars around the world. The total annuity cost per meter for rail maintenance of a non-lubricated 12 MGT transportation system is US$ 54, becoming as high as US $ 1.5 Million a year for a 30 km line [1]. The wear of the rail can be divided into that occurring on the gauge and that on the top of the rail. In sharp curves, the wear of the gauge is very important. In tangent track, the wear of the top is more significant. However, in both regions, the most important sources of overall material removal are delamination wear caused by cracks nucleating at the surface and propagating to produce laminar wear debris [2], and artificial abrasion caused by rail grinding.

Generally speaking, it may be said that Rolling Contact Fatigue (RCF) is the most common failure mechanism since it promotes crack growth and material damage as a result of high loads transmitted between two surfaces rolling relative to each other [2]. There are several types of defects caused by RCF: a squat is the name given to a characteristic hollow on the rail head. In this case, the fracture initiates in the running band and propagates horizontally just below the rail surface, detaching an area of the running band from the rail [3]. Head checks are typically seen on a substantial length of track that exhibits a very fine array of small, closely spaced, nearly parallel cracks [4].

On the other hand, rail corrugation is another damage mechanism that causes a wave-like deformation on the top of rail. It can lead to destruction of the track due to excessive damage of the rails and pads, as well as side effects such as loose fasteners, deteriorated sleepers and pulverized ballast [5]. Rail corrugations are divided into several types depending on wavelength: short wavelengths from 30 to 80 mm, and long wavelengths from 100 to 800 mm [6, 7].

Grinding of rails has been performed in commercial railways since the 1980's to remove surface defects such as head checks and corrugations, as well as to preserve the rail's profile [8]. Rail grinding is currently carried out by trains equipped with rotating grinding wheels driven by electric motors; the rail's roughness after grinding depends on the characteristics and condition of the abrasive grinding wheels, the applied pressure and the speed and angle between the grinding stones and the rail [9]. Reprofiling of rails and wheels helps remove damage such as RCF cracks and correct the effects of wear, but leads to high maintenance costs for metros, subways and heavy haul transportation systems. In order to reduce the material removal required during grinding operations, it is important to measure wear, RCF and corrugation in the field in order to propose optimum grinding operations.

In this work, the most relevant damaging mechanisms of a commercial line were studied in order to propose solutions to control wear in the field. To do so, the rail wear rates per traffic unit (mm/MTon) measured in the curves of a 4.5 km-long commercial line over a period of 9 years were analysed and related to specific operating conditions and maintenance tasks. Wear data were given in terms of material loss from the rail and the results were compared with the values typically found in the literature. Also, several grinding procedures were studied to make recommendations for field maintenance tasks based on the analysis of ground rails.

2. EXPERIMENTAL PROCEDURE

The transportation system studied is composed of multiple units such that every unit has three vehicles with only one locomotive at the front end. The vehicles are comprised of three passenger coaches where the first and the last apply the traction. The dimensions of the car body are 3.2 x 22.8 x 3.8 m (width/length/height) and its mass ranges from 44 to 50 tons. The bogies are nonarticulated with two axles and the bogie frame is an H-shaped single rigid body. The central pivot and the air springs support the car body loads, which are transmitted to the suspension element located in the axle box. The traffic is about 7 MGT per year and trains pass every 4.7 min with a maximum velocity of 80 kmh^{-1}. For straight sections and curves with R>900 m the profile is CPC in both rails. In medium curves (400 m < R < 900 m) the profiles are CPG (high rail) and CPF (low rail) and for tight curves (R < 400 m) the profiles are HRC (high rail) and CPF in low rail. In all the analysed curves the rails are R260 grade.

2.1 Material removal/damage assessment

2.1.1 Rail profile measurements

The rail profiles measured in the 22 curves of a 4.5 km-long commercial line during 9 years using Miniprof system were analysed. The measured profiles were compared to either a reference shape or a previously measured profile. The superimposed profiles after the analysis are shown in Figure 1a. The cumulative losses in the head of the rail due to all damage mechanisms present were obtained and labelled as W_1 (see Figure 1b for reference).

In all cases, the same alignment criterion was used to superimpose the rail profiles. After the measurements, the cumulative W_1 values were plotted against the cumulative traffic in the line and the mean slope of a fitted straight line was taken as the mean wear rate of the rail. Figure 2 shows an example of the data obtained in the high rail of 4 different curves. In most cases, coefficient of determination (R^2) of the linear fit was at least 0.9. The overall material removal rates were related to curvature radius, mean slope and train velocity.

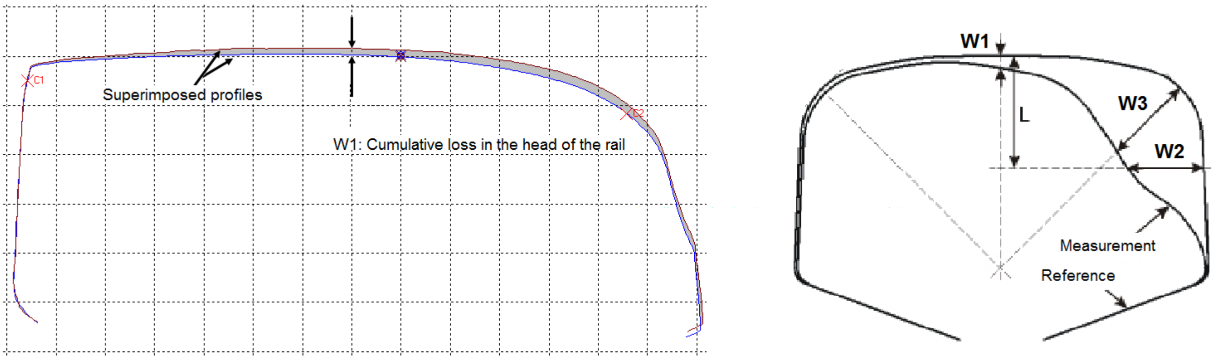


Figure 1. Measurement of overall material removal rate by profile variation with time. a) Example of superimposing of rail profiles to calculate the amount of material removed, b) Definition of W_1, W_2, and W_3 parameters. W_1 is known as the vertical rail head wear.

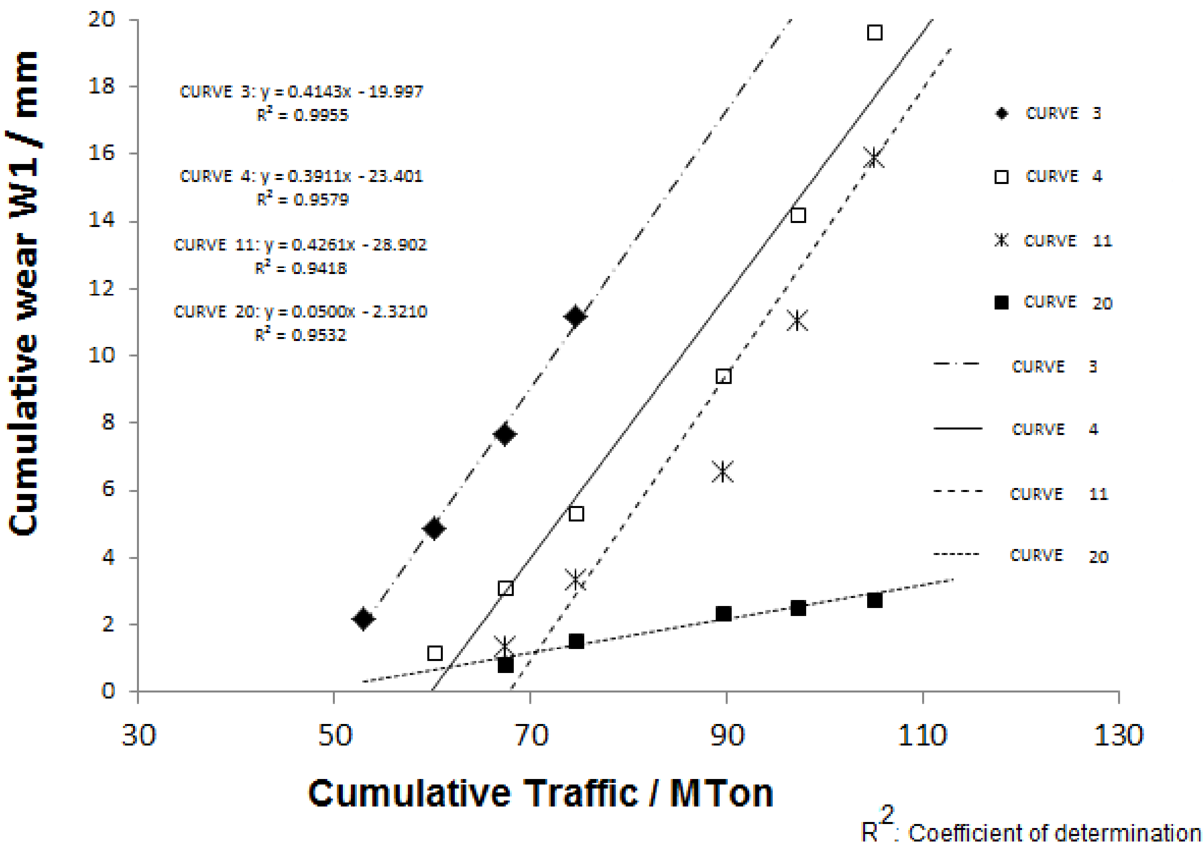


Figure 2. Measurement of overall material removal rates from the evolution of profiles with cumulative traffic. See figure 1b for definition of W_1.

2.1.2 Corrugation analysis

Measurements of corrugation were carried out using a Corrugation Analysis Trolley (CAT). The CAT data were taken from several curves of the line when corrugation was evident on the surface. The identification of predominant frequencies was achieved by spectral analysis through Fourier transform and the results were discussed in terms of the possible causes of the irregularities in the rails according to the literature. The curves with the top-five higher overall material removal rates were analysed and only the most relevant results are presented in this article.

2.1.3 Visual inspection

Several inspections were performed periodically over the ninth year of monitoring of the railroad in order to identify the most prominent defects on the surfaces. The mean time between detection of cracks was recorded as well as the mean time for corrugation to appear on the surface.

2.2 Inspection of sections of fatigued rails extracted from the commercial line

Fatigued rail samples were extracted from a 200 m radius curve of the line. The surfaces were inspected with the aid of Nikkon stereoscope and JEOL 5910LV Scanning Electron Microscope (SEM) and then the samples were cut to evaluate the depth, length and orientation of the cracks found. Based on the analysis of the results, rail grinding procedures were designed and performed to properly remove the affected material from the rails' surface.

2.3 Rail grinding tests

The grinding procedures were performed in a low density traffic line using a Harsco Track Technologies TG8 rail grinding machine. The samples were fatigued sections of rails extracted from a commercial line, which were placed in the low density traffic line using rail joints. The grinding machine has 8 heads (4 on each rail) and several grinding patterns can be selected. Each grinding wheel can be adjusted to an attack angle between +45° and -40° and the position can be adjusted from +50 to -38 mm. Travel velocity can be varied between 1.6 and 13 kmh-1 and the grinding pressure is qualitatively related to the power consumption of the grinding machine.

During rail grinding tests, the diameter of the grinding wheel was 152 mm and a coarse grit size (16 grit) was used for all tests. Twelve passes were applied to remove 0,5 mm from the rails' surface. The pressure applied during grinding was kept constant (see table 1 for details) while the grinding wheels were moving along the rail surface, except for the last two passes applied to the gauge corner when the pressure was reduced to half for every given pressure. The grinding time for every rail section was around 8 minutes and the grinding wheels moved from the rail head to the rail gauge corner.

Four rail grinding procedures were developed using two different velocities and two grinding pressure levels, as shown in table 1. According to the findings of the inspection of fatigued rails extracted from the field, and based on the operator's experience, the grinding tests were designed to remove 0.5 mm from the surfaces following the procedures routinely adopted by the operators in the field. Photographs were taken before and after the tests to study the changes introduced by the grinding operation.

Table 1. Details of grinding procedures

Grinding procedure	Power/ kW *	Velocity/ kmh^{-1}
D1	14	3.5
D3	8	3.5
D4	14	7.5
D6	8	7.5

* The power consumed by the hydraulic motor attached to the grinding wheels is related to the actual contact pressure applied to the rail during grinding operation. No direct measurement of such a pressure was made. Instead, the high-pressure condition is associated to a power consumption of 14 KW and the low-pressure tests correspond to 8 KW.

The rail profiles were measured before and after the rail grinding tests in order to evaluate the dimensional changes. The measurements were carried out by using a Miniprof system and the changes in parameters W_1, W_2 and W_3 (as described in figure 1b) were reported for each rail grinding procedure. The initial profile of the rail in every measured position was superimposed to the ground profile to determine the changes in every parameter and the rails were aligned using the same criterion. More details of the reprofiling procedures can be found elsewhere [10].

3. RESULTS

3.1 Wear assessment

3.1.1 Wear rates and correlation with operating parameters

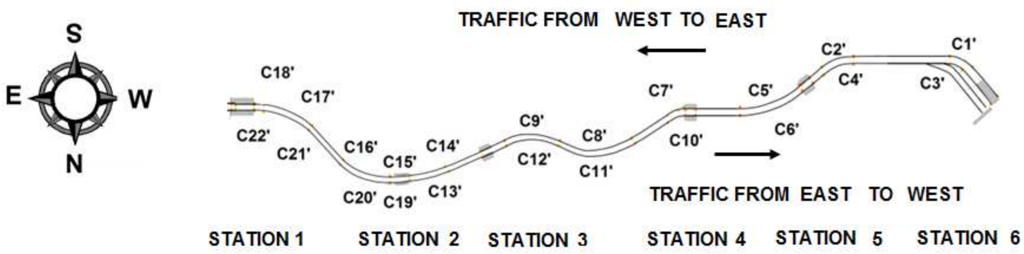
Figure 3 shows the overall material removal rates of the entire line. As mentioned in section 2.1.1, both the natural and artificial wear rates were measured by evaluating the changes in the rail profiles before and after known periods of operation and rail grinding operations performed in the field. As it was shown elsewhere, the artificial wear rates are around ten times higher than the natural wear rates [9]. Competitive relationship between fatigue crack damage and rail wear has been observed previously by some authors [11, 12]. This is particularly important when twin disk tests are performed to simulate wear of rails and wheels. However, in the railroad analysed in this work, given that artificial wear caused by rail grinding is ten times higher than wear caused by rolling sliding, competitive relationship between fatigue crack damage and rail wear is not relevant.

Depending on the magnitude of the overall material removal rate (WR) mild, medium and high wear regimes were defined. Wear regimes were defined according to different wear rates found for the rails. The proposed regimes were based on the premise that in all cases considered the same wear mechanisms were causing mass losses from the surface of the rail. Particularly, for the rails studied, artificial abrasion during rail grinding is the most important wear mechanism. Mild wear regime corresponds to WR < 0.06 mm/MTon, medium wear regime is defined when 0.06 mm/MTon < WR < 0.2 mm/MTon and severe wear regime occurs for WR > 0.2 mm/MTon. The measured wear rates are two to six times higher than those reported by several authors for passenger systems with similar operating conditions [13,14,15] although no explicit reference is made by these authors regarding the type of wear rate (natural or artificial) analysed. One of the most important issues related to wear rates of rails is that authors use different parameters to estimate wear in the field including area, volume and linear distance (vertical, horizontal or oblique) measurements, which hinders the comparison with other railroads. In this article the vertical wear was used since it is the most common parameter used in the field to determine if a rail must be replaced.

Figure 3 shows the overall material removal rates measured in all the curves of the line both eastbound and westbound, while Figure 4a shows the correlation between wear rates and curve radius for the high rails. Generally speaking, the overall material removal rates were higher in curves with smaller radius and in the line traveling from east to west. This behaviour can be explained by another important parameter of the railroad illustrated in Figure 4b, where the overall material removal rates are plotted against the local height differences of the curve and the next section of the railway, which can be taken as a mean slope. It can be seen that the highest overall material removal rates were found in those curves with the highest mean slope. The data inside the ellipse is for curves where the velocity of the train (from 20 to 40 kmh^{-1}) is very low compared with that of the rest of the curves (from 40 to 80 kmh^{-1}). It is worth noticing that when the train is travelling westbound the traction force is circa 33% higher since the train is ascending, whereas form west to east it is mostly braking.

WEAR RATE OF RAILS / $mmMTon^{-1}$

Curve number	18	17	16	15	14	9	8	7	5	2	1
Wear rate of high rail	0.05	0.01	0.07	0.03	0.17	0.07	0.19	0.02	0.07	0.11	0.10
Wear rate of Low rail	0.03	-	0.04	0.05	-	0.05	0.11	0.03	0.04	0.07	-
Curve radius	600	2500	360	1500	754	304	300	3500	300	304	200
Curve mean slope	0.0	-0.7	0.0	0.7	-3.5	-11.8	-6.8	0.0	-11.2	-5.1	-15.1
Velocity / Km h -1	80	75	40	20	55	80	80	72	45	80	30

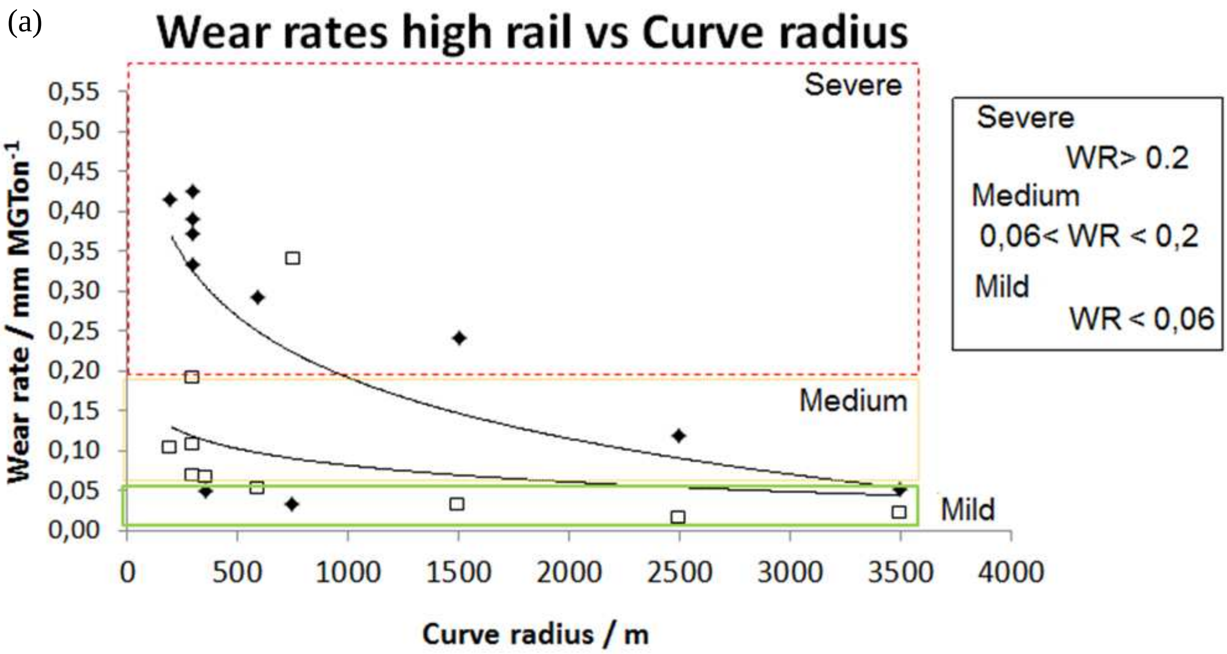


Curve number	22	21	20	19	13	12	11	10	6	4	3
Wear rate of high rail	0.29	0.12	0.05	0.24	0.03	0.37	0.43	0.05	0.33	0.39	0.41
Wear rate of Low rail	0.13	0.02	0.03	-	0.03	0.08	0.06	-	0.05	0.05	0.32
Curve radius /m	596	2496	364	1504	750	300	304	3496	304	300	200
Curve mean slope	0.0	0.7	0.0	-0.7	3.5	11.8	6.8	0.0	11.2	5.1	15.1
Velocity / Km h -1	80	80	45	20	65	80	72	52	30	80	35

SEVERE
MEDIUM
MILD

Figure 3. Overall material removal rates of the curves of the entire line

(a)



(b)

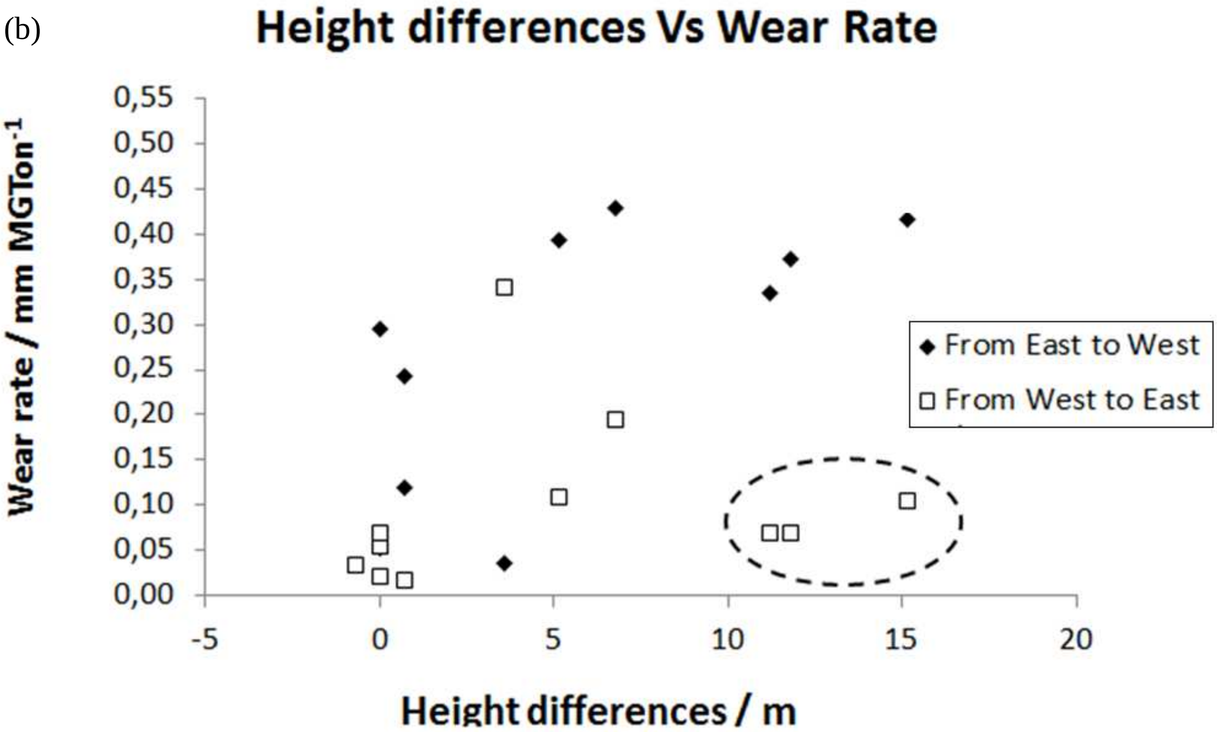


Figure 4. Relation of overall material removal rates with operating parameters. a) Material removal rates vs. curve radius and proposed wear regimes. b) Material removal rates vs. height differences.

In the particular case of the commercial line studied in this work, only vehicles of the same type were in operation during data collection. This is mainly because the line is very short and has only one transfer point to a different line. The authors would like to emphasize that, even if the same specific vehicle had been used for all the tests, there could have been registered differences in the wheel-rail contact due to local variations in system dynamics since the rail and wheel profiles are dynamically changing during operation. The effect of those differences on wear rates is, however, beyond the scope of this investigation. Given that several operational parameters (rail and wheel profile, evolution of contact patch, train velocity, vehicle dynamics, among others) affect wear of wheels and rails, the study of wear rates for complex railway lines has been done by modeling

[16,17]. It is important to model those complex systems in order to predict profile evolution caused by wear [17] and to analyze the effect of other parameters in wear rates of rails. Although there could be some other factors related to vehicle/track dynamics causing high wear rates in the analysed railroad in this work, the analysis of those factors by modelling is also beyond the scope of this article.

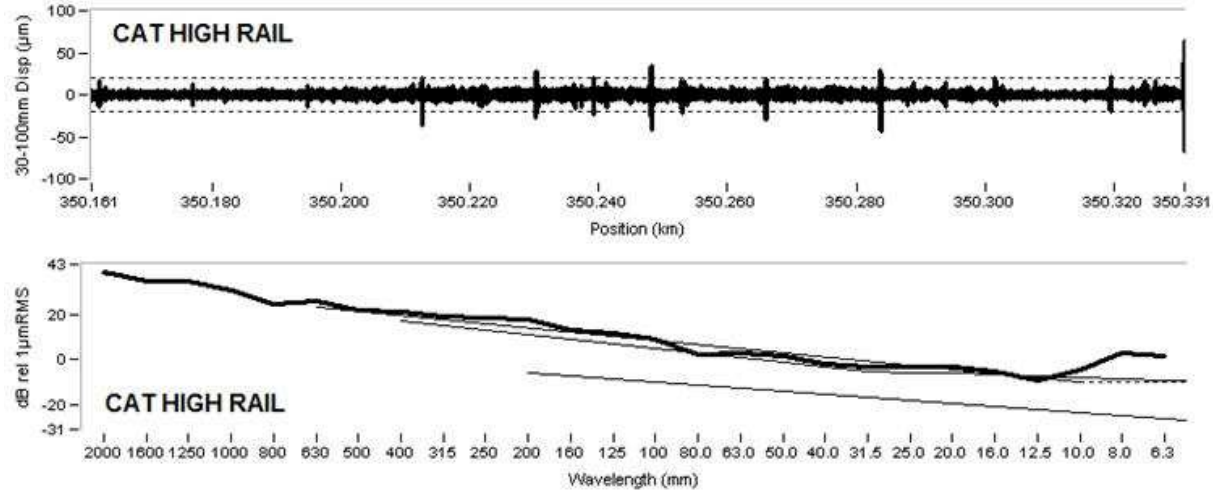
3.1.2 Corrugation analysis

The corrugation analysis was based on the results of Grassie, Kalousek and Magel obtained in 1999 [6]. The authors of that report performed CAT measurements and also measured the track's dynamic response. After performing the tests, information of corrugation wavelength and vehicle speeds over corrugation sites was used to conclude that there were two types of corrugation.

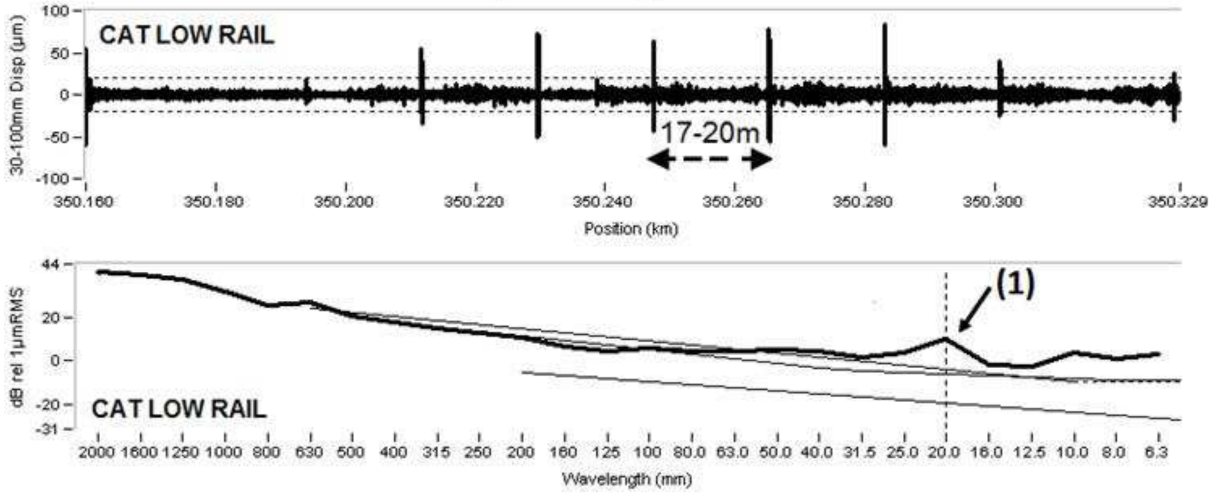
The first type arose from excitation of the vertical dynamic behavior of the vehicle/track system at a frequency of about 200- 250 Hz. From measurements of the track's dynamic response, it was concluded that large dynamic contact forces in this frequency range were associated with an almost rigid coupling of the rail and sleeper. The second type of corrugation appeared to arise from lateral excitation of the track, and was associated with an excessively rigid coupIing of rail and sleeper. From the analysis of ground rails, it was also found that an incomplete removal of corrugation may in part be the cause of the very short grinding cycle on the track since most of the time taken for a corrugation to develop is during the Initiation phase when a small corrugation exists. The results of CAT analysis showed that the most important type of corrugation occurred predominantly in curves. Some peaks at regular intervals of about 17 m (which is the length of a single rail) and several fatigue marks revealed issues with welds as it was previously reported [6].

In the field, the criterion used to grind the rails relies on the calculation of the r.m.s. amplitude of longitudinal irregularities in a set of given wavelength ranges along the track. The fraction of the track length for which the r.m.s. amplitude exceeds an specified limit is the base to prescribe a grinding operation. According to European class 1 grinding standard, the exceedence percentages applicable are 5% for 10-30 mm, 5% for 30-100 mm, 5% for 100-300 mm and 10% for 300-1000 mm wavelength ranges [6]. It is proposed in this work that the use of such strict criteria to control rail roughness and noise would have been responsible for the excessive high wear rates on low rails.

Corrugation occurred preferentially on the low rail with dominant frequencies between 100 and 250 Hz. Figures 5a and 5b show a low rail with corrugation and the corresponding high rail without damage. Figure 5b shows a peak (arrow (1)) exceeding the limits according to ISO 3095. According to the criteria used in the field, the mean time between reprofiling is 3 months for the worst curve and among 5-7 months for other curves. The predominant wavelength found indicates that the corrugation comes from the excitation of the vertical dynamic behaviour of the vehicle/track system at a frequency of about 200-250 Hz [6]. This result implies that corrugation is an important issue for the analysed railway.



a) CAT of high rail



b) CAT of low rail

c) Defects on welds

d) Corrugation on the low rail

Figure 5.CAT analysis of the commercial line. a) CAT of high rail, b) CAT of low rail, c) Defects on welds, d) Corrugation on the low rail.

3.1.3 Visual inspection

Figure 6 shows the most important defects observed in the commercial line. Head checks, corrugation and some fatigue detachments were found after twelve inspections (one per month during a year). The estimated traffic was around 7 MGT per year. Generally speaking, corrugation was observed preferentially on low rails while head checks were found on the high rail in tight curves, i.e. those with higher wear rates. Fatigue detachment (spalling) was also observed in some cases after rail grinding. The most important defects found in the field are head checks.

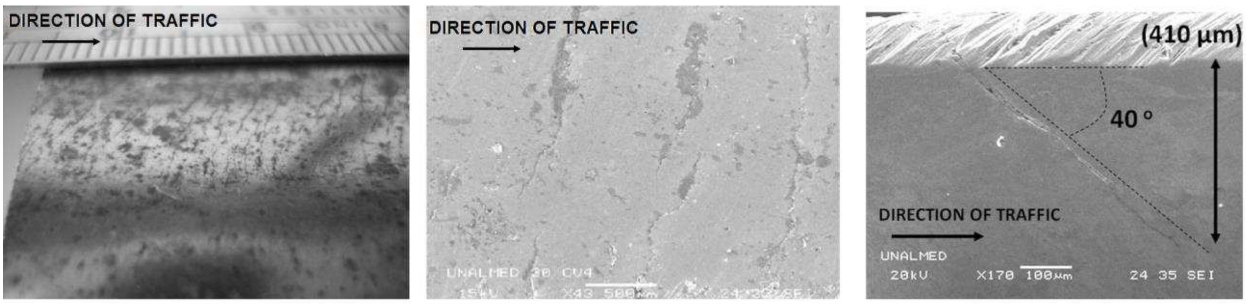
The maintenance of the railroad by rail grinding is done when the head checks are detected by visual inspection in the field. According to the operator, the mean time between grinding depends on each curve and ranges between 4 and 10 months although precise data are not easily available. However, given the cumulative traffic on the line after 10 months, it can be concluded that the mean grinding interval is very low compared with those typically found in the literature [12].

a) b) c)

Figure 6. Defects found on the inspection of railroad. a) Head checks on the rail's surface, b) Fatigue detachment due to head checks, c) Defect not removed by rail grinding.

3.2 Inspection of fatigued rails

The inspection of fatigued rails revealed the presence of parallel cracks at the surface (head checks). Head checks nucleate at the surface and can cause catastrophic rail failures so its removal by rail grinding is mandatory [2]. The amount of material to be removed during rail grinding is usually defined by considering the actual depth of head checks in the rail. Accordingly, the incubation time and crack's growth rate play a key role in artificial wear caused by rail grinding [2]. In this study, the inspected rail had an average of 3 cracks per square millimetre (see figure 7a for reference). The inspection of a longitudinal section in the central part of the contact zone (where the cracks were located) revealed that, on average, the crack depth was 0.5 mm (figure 7b). The angle between the rail surface plane and the cracks was around 35-45 degrees (figure 7c). Some iron oxides were found inside the cracks as a result of the interaction with the ambient. According to these findings and the operator's experience, the grinding procedures were designed to remove 0.5 mm from the rail surface.



a) b) c)

Figure 7. Head checks found in railroad inspection a) Head checks on the rail's head b) Top view of the head checks c) Longitudinal section of cracks

3.3 Rail grinding tests

The changes in W_1, W_2 and W_3 parameters after the grinding tests are shown in Figure 8. Based on the previously measured depth of penetration of the head checks (circa 0.5 mm), only two procedures were found to be effective to entirely remove the cracks. These successful procedures were associated with higher pressures, i.e. higher power consumption during the grinding tests. W_2

parameter is higher when a lower pressure is applied to the rail, but its variation is not significant when compared with those of W_1 and W_3. On the other hand, although grinding velocity plays an important role on the mass removing process, the greatest differences before and after the tests were obtained when the power consumption changed and the grinding velocity was kept constant. This can be verified by comparing, for instance, procedure D1 (14 KW, 3.5 kmh^{-1}) with procedure D3 (8 KW, 3.5 kmh^{-1}) in Figure 8.

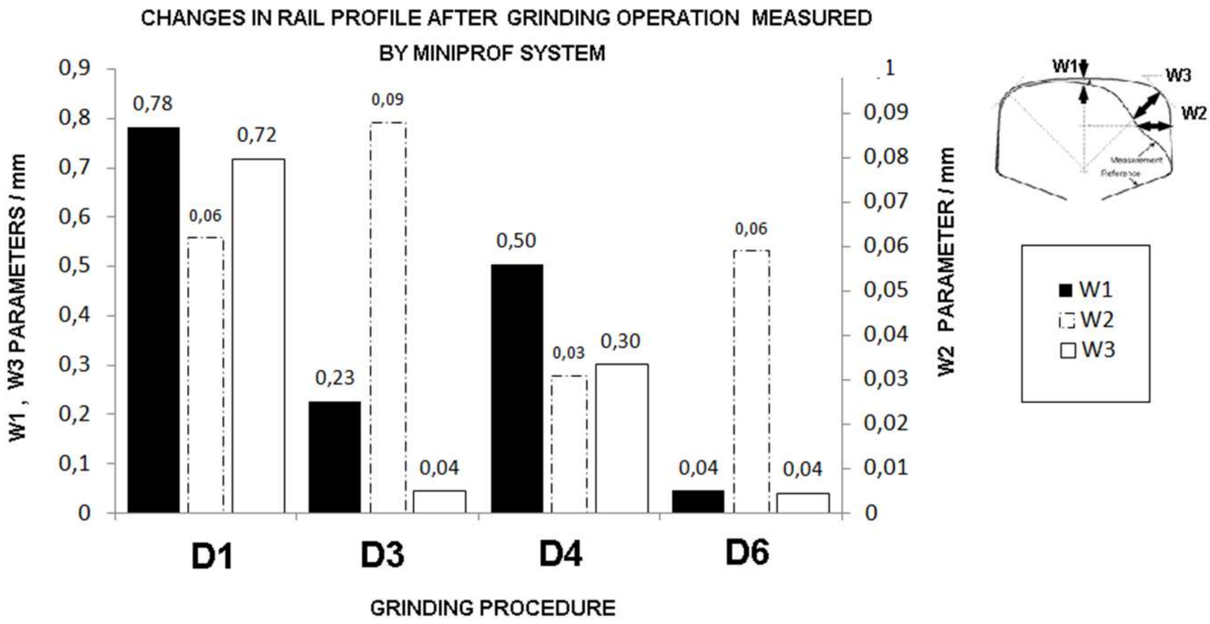


Figure 8. Overall results from rail grinding tests. See table 1 for description of grinding procedures.

Figure 9 shows the ground surfaces after procedures D1 and D3. Only D1 procedure was effective over the entire rail surface, as opposed to procedures D3, D4 and D6 that left a black zone where the wheels did not grind the rail's surface [10]. On the other hand, the marks seen after the low velocity procedures (D1 and D3) were clearly more uniform. According to these results, low velocity grinding (within the range analysed in this study) is recommended for better results in terms of homogeneity of the surface.

The metallographic inspection of the rails ground with D1 procedure revealed a hard white layer with cracks parallel to the surface (Figure 10). This layer is composed of fresh martensite formed due to localized heating and fast cooling during the grinding procedures, which has been previously reported by Chandrasekar et al [18] and Kanematsu et al [19].

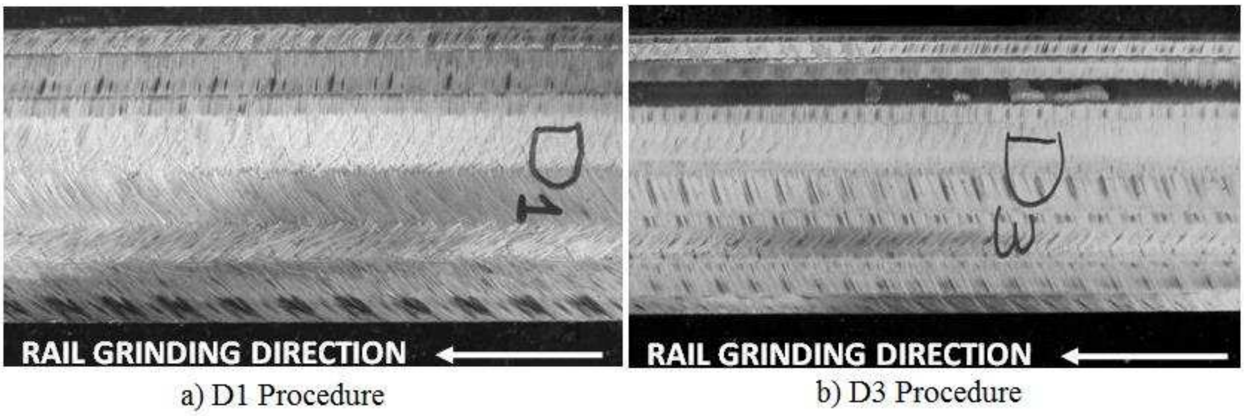


Figure 9. Aspect of rail's surface after the grinding tests. a) D1 procedure b) D3 procedure

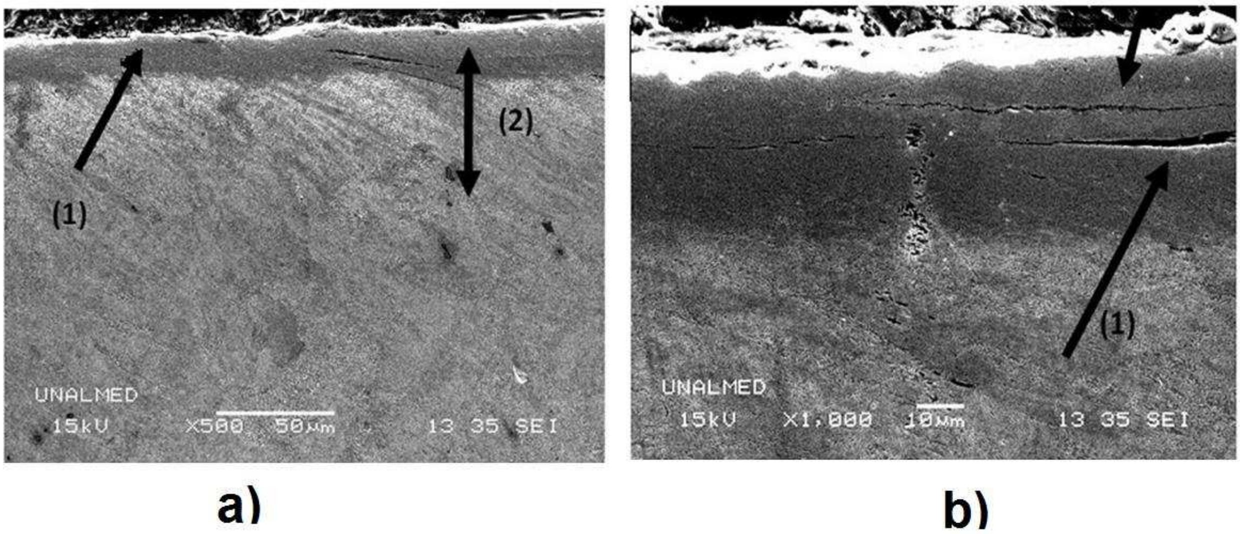


Figure 10. Rail microstructure of sub-surface white layer. Procedure D1. a) Crack observed at the surface; (1) shows the white layer, (2) shows the thickness of deformed layer, b) Detail of cracks found at or near the surface.

The detail shown in figure 10b reveals several cracks in the white layer. According to those results, the D3 procedure is recommended since it applies a lower normal force to the surface, but the number of passes of the grinding wheel over the rail must be increased to ensure that the entire surface of the rail is being ground.

4. Discussion

A number of hypotheses are proposed to explain the overall material removal rates measured in the studied line. Firstly, the demanding operating conditions found in the railway (curve radii smaller than 300 m and mean slopes higher than 3.5%) lead to very high traction loads on curves on the high rail. Those forces accelerate the cracks growing rate and demand higher reprofiling frequencies to control fatigue as it was previously shown in an analysis performed in the same railway [9]. Secondly, the dynamic response of the system leads to the formation of corrugation on low rails also requiring higher reprofiling frequencies to control vibrations and noise.

Additionally, it was found that new defects are induced in the surface during the grinding procedures. The cracks in the white layer were caused by the combination of the grinding equipment used in the field and the grinding parameters defined by the operator. However, it must be emphasized that state-of-the-art grinding should not introduce new defects during grinding. The defects observed include a white hard layer on the surface of the rails, which can significantly reduce the resistance to rolling contact fatigue of the rails since it acts as a source of preferential nucleation site for new cracks.

According to the previously described results, the use of a friction modifier is recommended in order to minimize the wear rates. As can be seen from the literature, the use of a friction modifier helps reduce wear rates and corrugation [20,21] while increases the incubation time for RCF cracks

[21] due to the reduction in the traction force. However, once the cracks are formed, their growing rate (and therefore the fatigue damage of the rail) can be increased as a consequence of the pressurization mechanism [22] although further research must be carried out in order to understand to what extent this phenomenon can be detrimental to rail's life in the field. An important matter to take into account is that friction modifiers must be applied on both rails (high and low) in order to avoid differences in the coefficient of friction that could lead to hunting in curves.

5. Conclusions

The wear mechanisms of the rails of a passenger railroad were studied and correlated with the operation and maintenance conditions recorded over a period of 9 years. The main conclusions drawn from the investigation are as follows:

Material removal from the rails was caused mainly by two wear mechanisms: Rolling Contact Fatigue (RCF) and artificial abrasion due to rail grinding. A synergistic effect was also found to be significant as inadequate rail grinding caused defects that acted as preferential nucleation sites for fatigue cracks.

Corrugation also played a relevant role in the wear of the rails since it determined the amount of material to be removed during by reprofiling. The corrugation frequencies were in the range between 100 and 250 Hz, which typically correspond to the excitation of the vertical dynamic behaviour of the vehicle/track system.

Practical-use indexes were proposed to classify the wear regime as mild, medium and severe depending on the magnitude of the measured wear rate. A direct correlation among the wear rates, curve radius and mean slope was found.

The analysis of the reprofiling procedures revealed that the greatest effects on the surface and sub-surface quality of the rails were obtained when the grinding power consumption increased and the grinding velocity was kept constant. Also, formation of a white layer at the ground surface was observed for many grinding conditions. A practical recommendation is made to remove at least 0.6 mm by reprofiling to ensure the complete removal of cracks caused by RCF.

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