CETRA 2014

3rd International Conference on Road and Rail Infrastructure
28–30 April 2014, Split, Croatia

Road and Rail Infrastructure III

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ROLLING CONTACT FATIGUE ON TRAMWAY'S RAIL

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Abstract

Head checking cracks as a special type of rail defects become more frequent recently on the high-speed railways. Partly similar defects were observed at the starting and stopping locations of the vehicles' driving axle at urban tram stops. In these places fatigue defects are appearing parallel to the track on the rail's running surface. These defects were first observed by the author of the abstract in Budapest, along tram Line 49. The most significant defects were discovered on sections of that tram line, where only old carriages run without slip protection equipment. On those sections, where other types of the carriages also run, the defects were less frequent. Measurements of eventual defects were performed using Eddy current sensor, digital microscope, wheel mounted inertial sensor and high-speed camera. Measurements with Eddy current sensors were carried out on the running surface of rail. They did not show cracks but average depth of defects could be determined. Surface deformations were detected by a digital microscope and their dimensions were also measured. Images made by digital microscope (from "micro-slip") showed similarity to the "comet-shaped" rail surface corrugation caused by high-intensity acceleration ("macro-slip"). Based on this fact, the author assumed that probably the slip plays an important role in the formation of defects. Slip values recorded by a high-speed camera during start and stop of tram carriages were found equivalent to the length of the defect under consideration. Further investigations were made to determine the exact value of the slip during the start and stop of the tram carriage under operating conditions. For that purpose, wheel- and vehicle-mounted accelerometers and the speed acquisition device of the tram carriage were used. Assessing the results of the experiments, it is concluded, that the wheel slip is responsible for the defects discovered, but further investigations are needed.

Keywords: *rolling contact fatigue defect, wheel slip, wheel-rail contact, special rail corrugation, micro-slip*

1 Introduction

Some special defects were observed during a condition survey of Budapest tram lines carried out by the author. This condition survey was based on consultations with professionals of BKV (Budapest Public Transport Plc.) and photos taken during the perambulation of tram lines and the performed investigations. Fig. 1 shows some typical defects.
One of the observed defects was distinguished, in order to analyse its causes in detail. This defect is a special corrugated longitudinal one, attributable to rolling contact fatigue appearing on the rail tread. Fig. 2 shows it in Sections 1.1.

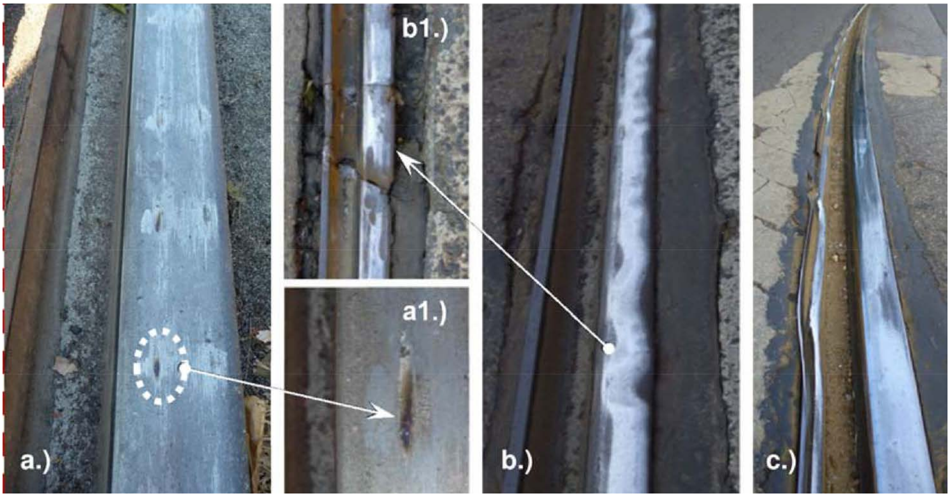

Figure 1 Special rail corrugation and defects: a) The pitch of rail corrugations was cut by electromagnetic rail-brake; b) "Winding-shaped" wear on the running surface, later broken; c) Special corrugated rail side wear of grooved head in curve

1.1 Longitudinal defects appearing on the rail's running surface

Defects apparently similar to head checking cracks (HC) were observed at starting and stopping location of the driving axle at tram stops. At these locations fatigue type defects appearing on the running surface are parallel to the track. It should be noted that longitudinal surface defects occur most frequently on the full width of rail head (Fig. 2c). However, the defect in other rail sections has a shape of corrugation (Fig. 2a). It shows similarity to the impact of unstable high-frequency bogie movement which can occur mainly on rails of high speed railways. The wheel probably slips at the moment of start and stop. This slip leads to the hardening of the rails' running surface which results failures occurring on the rail tread due to cyclical fatigue load. This type of defects was first observed by the author in Budapest, along tram line 49. The most significant defects were discovered on sections of that tram line where only aged carriages run, without slip protection equipment. These defects appeared less frequently on sections where other types of tramcar also run.

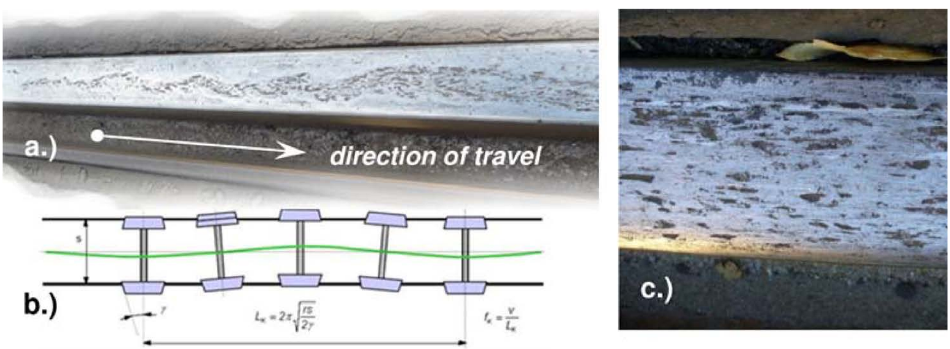

Figure 2 a) Corrugated shape of failure; c) Longitudinal fatigue defects on the whole cross-section of running surface

It has to be noted, that both, TATRA and GANZ made rigid-axle articulated tramcars run on the studied tram line 49, but the latter type does not have slip protection equipment and torque control in the engine. Aiming to discover the characteristics of the defects, the following measurements were performed.

1.1.1 Testing of rail surface deformation using Digital microscope

Images of digital microscope showed inelastic deformation ("micro-slip"). The microscope was controlled by a computer, which immediately recorded the photos taken with appropriate lateral overlap, so the microscopic pictures can be joined easily by using an appropriate software. Fig. 3c shows a panorama photo of the discovered defect. Surface deformation of the displayed microscopic failure (Fig. 3c) shows similarity to the "comet-shaped" rail surface macro corrugation caused by high-intensity acceleration, where the direction of the movement can be also determined easily (Fig. 3b).

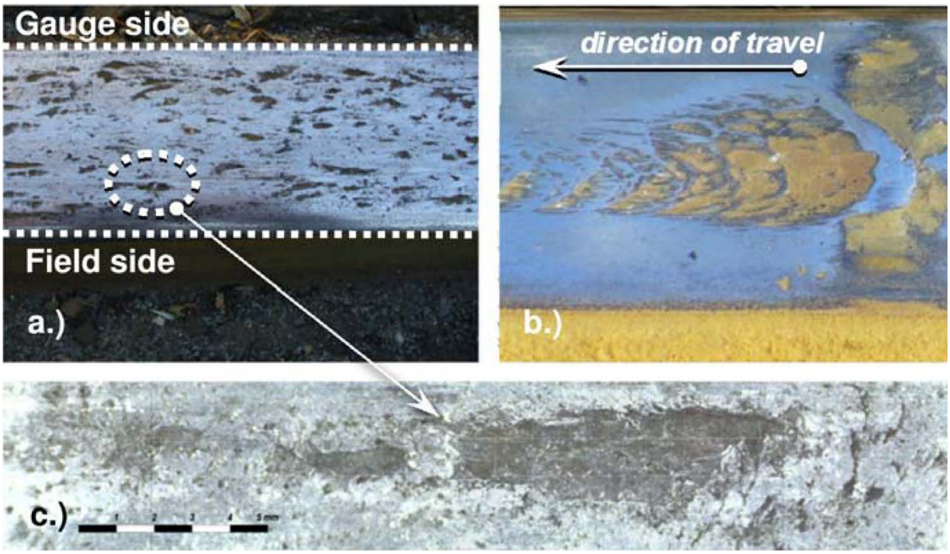

Figure 3 a) The longitudinal failures; b) macro "comet"- shaped defect on the rail running surface c) Panorama photo of digital microscope

Geometric dimensions of a defect could be also determined from the pictures taken by a digital microscope. The length of the observed failure is varying between 5 and 25 mm (Fig. 3c) and the dominant wavelength of the displayed wave-like defect shown in Fig. 2a is between 0.10 and 0.30 m. A difference exceeding two orders of magnitude appears when this value is compared to the theoretical wavelength derived from the calculation based on Klingel's formula [3] Eq. (1):

$$\lambda = \frac{2\pi}{\sqrt{\frac{2\mathrm{tg}\gamma_e}{e \cdot r_0}}} = 14.1\,\mathrm{m} >> 0.1 - 0.3\,\mathrm{m} \tag{1}$$

where:

$\mathrm{tg}\gamma_e$=0,05=1/20	Equivalent Conicity = wheel profile cant (1:20);
e=1500 mm	Nominal rolling radius distance;
r_o=670 mm	Nominal rolling diameter.

This result can't be explained by the traditional sinusoidal motion theory. It should be noted that Klingel's theoretical wavelength refers to the motion of one single wheelset rather than the motion of the whole carriage. For the sake of the calculation, it was assumed, that the wheel and rail profile are to be in perfect condition and shape. Although smaller values of wavelength can also occur if the profiles of the wheel and rail are worn out. Values of wavelength obtained from Klingel's formula are actually falling between 1 and 40 meters.

1.1.2 Detection of cracks in railhead by using Eddy current sensor

Eddy current sensor is used to detect and determine the depth of crack-like damage in the gauge corner of the rail. Devices applied for this measurement are continually improving, so cracks under the running surface can be detected in a reliable way up to a depth of 3-4 mm by using this technique, depending on the Eddy current excitation frequency. Determination of crack's depth is very significant for traffic safety and for specifying the maintenance work to be carried out on the rails of high speed railways. Identical method was used by the author to discover cracks under the running surface near the observed defects.

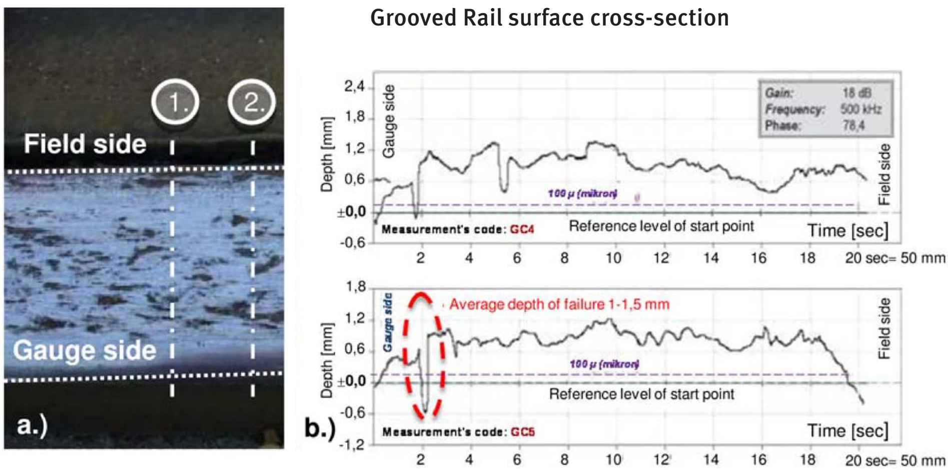

Figure 4 Testing result of two cross-sections by using Eddy current sensor

Measurements were performed using Hocking Locator 2, a single frequency device. The Eddy current test method is based on the principle of magnetic induction. The primary magnetic field of the excitation coil (sensor) induces a secondary magnetic field in the rail. Measuring the changes of this magnetic field the location of sub-surface cracks and material failures can be determined. The sensor is moved with constant speed transversally on the rail's running surface (the width of a rail head is measured in 20 seconds). This timebase mode crack detection test was performed in those cross-sections, where the size of the defects was the greatest (Fig. 4a). In the time-base mode the Y component (depth) is represented against time. Near-surface cracks were not discovered by using Eddy current sensor.

1.1.3 Investigation of tramcar wheels

The intensity of the use of sand to prevent slip by increasing friction can play a significant role in the appearance of the defects studied. In order to check the wheels of vehicles running on the tram line 49, the tram depot was visited in order to find out whether the sand poured under the wheels, could be the cause of these defects. However, it was stated, that no crack-causing matter has been poured on the running surface of the wheel other than some contaminations in the sand itself. No wears were observed on the wheel, unlike the rail heads, as described above.

2 Wheel-slip testing

The results of these investigations (Sections 1.1.1 – 1.1.3) lead to the conclusion that the wheel micro slip (Section 1.1.1) can play a significant role in the appearance of the defect described above (Fig. 2), therefore the slip values were determined at the moment of start and stop of the tramcar, under operating conditions. The tests were performed on a back storage track of tram depot in Budapest under dry, cold weather and good adhesion condition. The tramcar used for the test runs on that line, where the observed failure is situated. (Section 1.1 refers to main parameters of the tested tramcar). Scale signs were marked up on the wheel and along the track before the measurements, therefore the slips become easily determinable by visual observation (Fig. 5).

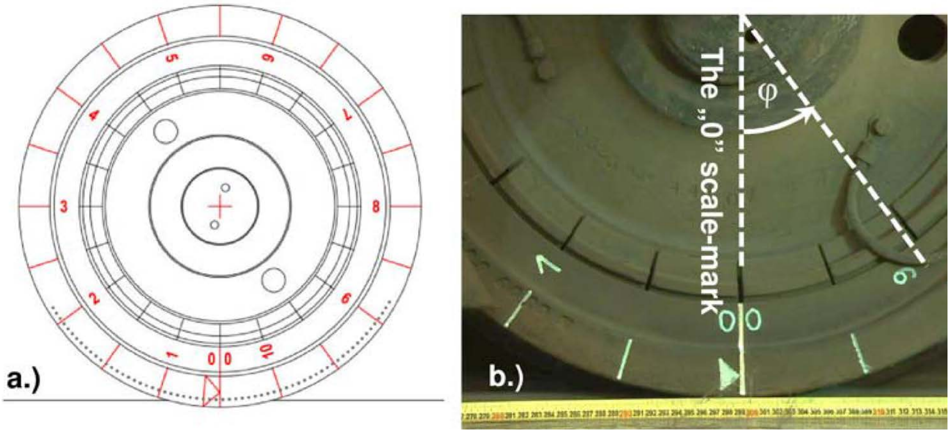

Figure 5 a) Regular scales marked on the wheel; b) the "0" scale-mark and the scale-marks placed alongside the track

2.1 The process of testing at the moment of start and stop

Testing at the moment of start: The tramcar was started according to operating condition with different intensities of acceleration, and then it was run out without braking to end of the track until it stopped. It was slowly driven back to the starting position, using only electromagnetic rail brake to stop.

Testing at the moment of braked stop: The vehicle was started from the other (side) end of the track and it was coming towards the HS camera with maximum speed (30 km/h) according to the local conditions, and it stopped using the maximum intensity of the brake. The vehicle was stopped in the visual field of the HS camera.

2.1.1 Test using visual observation and high speed camera (HS)

The position of the "0" scale-mark on the wheel related to the scale-marks placed alongside the track was read at the start location and also when the vehicle returned that same position (Fig. 5b). The slip value is the difference between the two readings. The test by using HS camera is in principle similar to that of the visual observation, but in that case the position of the "0" scale-mark is read by the HS camera. Time – distance data points of the wheel axle, and the time – arc-length data points of the angular displacement of the "0" scale-mark are determined by graphical analysis of the video recorded by the HS camera. Quadratic Least Square Regression was performed to data points where the correlation coefficient related to the set of all cases was higher than 80%.

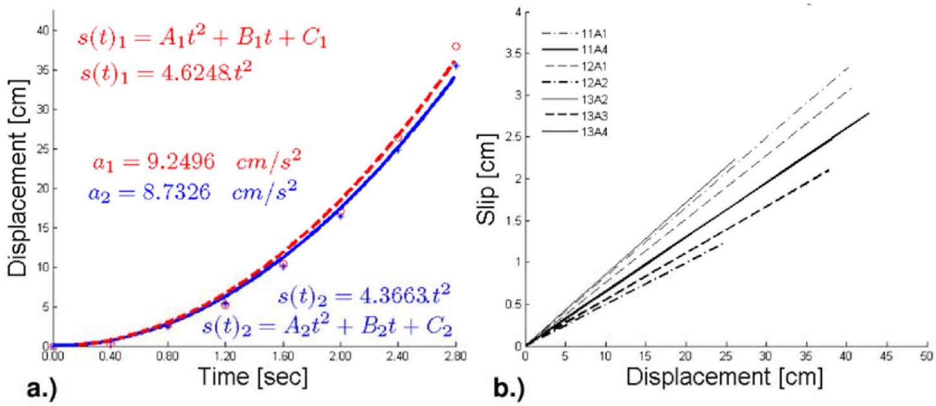

Figure 6 a) Time – distance, and time–angular displacement functions in case of starting by high intensity acceleration; b) distance – slip diagram in case starting by various intensity acceleration

Fig. 6a shows the parameters of the fitting curves in case of a start with high intensity acceleration (the Quadratic Regression Equation = ax^2). The residual values (difference between the fitting curve and the actually observed values) are caused by imperfection of reading from scale-marks alongside the track. The slip value (Δs) is determined by the difference of fitting curve Eq. (2):

$$\Delta s = s(t)_1 - s(t)_2 = A_1 \cdot t^2 - A_2 \cdot t^2 \qquad (2)$$

The measured and calculated slip values at the start reflected micro-slip that is directly proportional to distance (Fig. 6b). This could be caused by the linear engine of the tramcar, which assures uniformly accelerated motion.

2.1.2 Test using wheel – mounted accelerometer

Wheel slip testing can be improved by using wheel-mounted digital 3-axis accelerometer [2], ensuring continuous monitoring of the wheel motion (slip). This can significantly reduce the uncertainty of the previous methods (refer to Sections 2.1.1.). The accelerometers are mounted on the driving wheels and the free running wheels too. The longitudinal axis of the device is perpendicular to the wheel radius. The magnitude and the location of the slip can be determined from the measured acceleration value (Fig. 7). The process of starting and stopping corresponds to the descriptions in Sections 2.1. This methodology is worked out by the author in MATLAB software by analysing acceleration value of the accelerometers that are mounted on the wheels of bicycle.

The accelerometers are placed preferably in identical position on the wheels (they should be in equal phase – cophasal -) before starting. The magnitude of wheel slip can be determined from the “pre-start” and “post-stop” angle differences of the accelerometer positions by using accelerometer values (a_x, a_y) (Fig. 7). The directly measured acceleration data is distorted by noise, while that latter could be separated from the data by using linear-phase low-pass digital filter [4] in MATLAB. Fig. 8 illustrates the filtered signal and the acceleration, braking and coasting sections in case of a starting with low-intensity acceleration. The magnitude and location of the slip is determined from the phase shift of the measured accelerometer data read on different wheels. It can be noted that the calculation must be corrected, because of the difference between the accelerometer run circuit and the length of tread. Further tests with a properly equipped tramcar are planned to be performed in spring 2014.

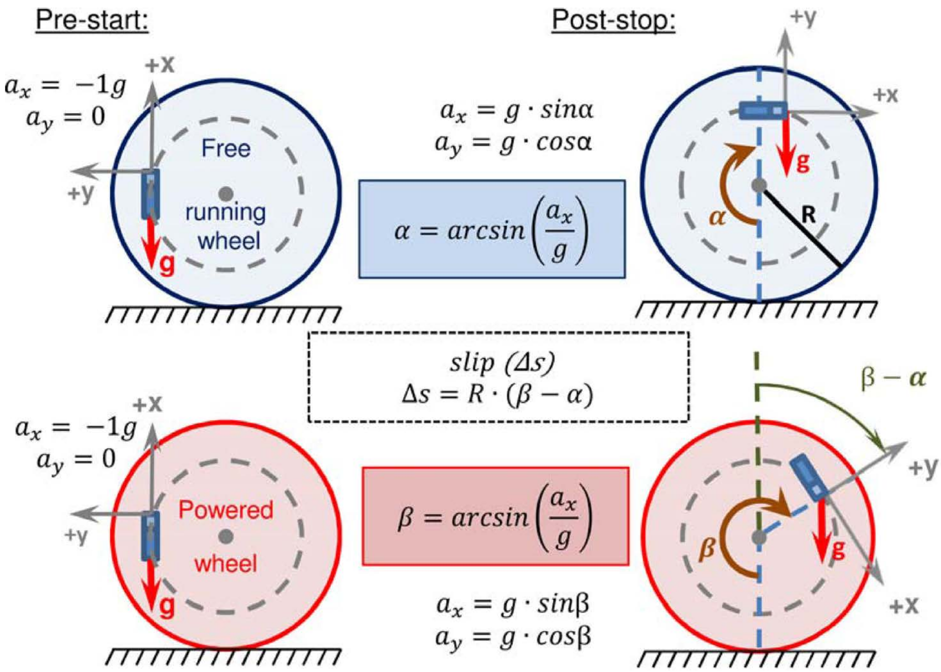

Figure 7 Wheel slip testing by using 3-axis accelerometer

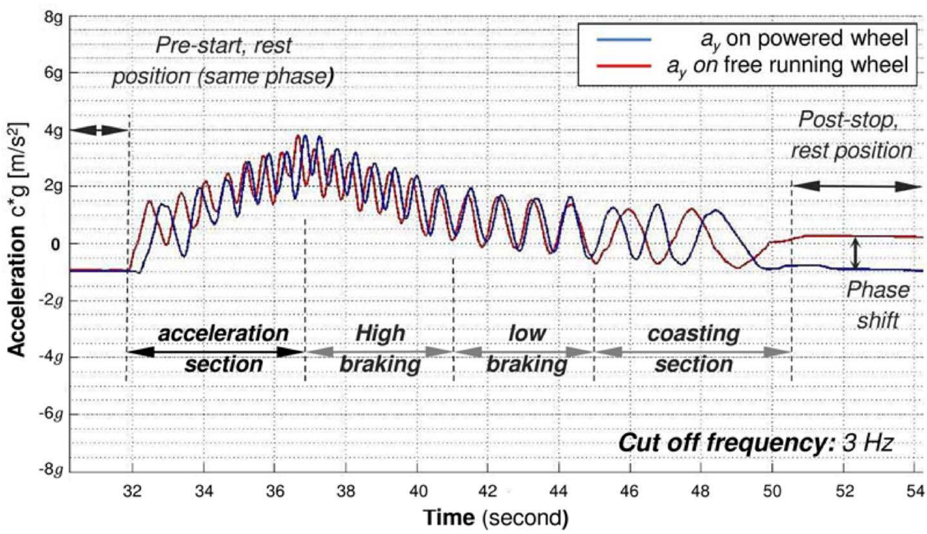

Figure 8 Centrifugal acceleration of powered and free running wheels

3 Summary

The most significant defects were discovered on those sections of the tram line stops, where the driving bogies stop. Surface deformations discovered (Fig. 3c) showed similarity to the "comet-shaped" rail surface macro corrugation, caused by high-intensity acceleration. During wheel slip testing, the tramcar does not slip in a visually perceptible manner, but the detailed investigations showed micro-slip directly proportional to distance. Furthermore, the lengths of the defects were equal to the measured slip values at the moment of start. On the base of these facts it can be assumed, that probably the slip plays an important role in the formation of these defects. The uncertainty of the wheel slip testing is reduced by applying wheel-mounted digital 3-axis accelerometer, which ensures the continuous monitoring of the wheel motion. Although the measurement methodology has already been developed, actual measurements on the field are planned to be performed in spring 2014.

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