ROLLING CONTACT FATIGUE STUDY OF RAILWAY RAILS

P. García[1]*, M. Panera[1], J. Belzunce[1], E. Fidalgo[2], J. Arancón[3]
[1] ITMA Materials Technology, Parque Empresarial Principado de Asturias, Avilés, Spain
[2] ICube, Parque Científico Tecnológico de Gijón
[3] ArcelorMittal, Global R&D Asturias

ABSTRACT

This work analyses the wheel-rail interaction in terms of rolling contact fatigue (RCF). For this purpose, a full scale testing machine was designed and built in order to apply the loads and boundary conditions appearing in the railway (up to 30 tons per wheel, application of lateral load in bends, inclination, angle of attack, presence of dust, water…)

Eight tests were performed under different load conditions and rail grades and RCF cracks were generated after 50000 to 100000 cycles. The occurrence of cracks was determined by magnetic particle inspection at regular intervals in the course of the tests. When the non-destructive inspection showed the existence of cracks, the test was stopped and the rail longitudinally and transversally cut to perform a metallographic analysis in order to know the nature, growth direction, shape and size of the cracks.

The cracks generated in the laboratory tests were identical to those seen in RCF affected railways and significant variations were found in the behavior of the different rail grades. The proposed test was able to simulate the damage produced in rails by RCF and allows the comparison of the fatigue behavior of different rail grades under highly controlled conditions.

KEY WORDS: Rolling contact fatigue, railway, rail.

1.- INTRODUCTION

Over the last two decades traffic density, axle loads and speeds of rail transport have increased notably because its advantages: an inexpensive, fast and reliable mode of transport. However, the new requirements cause higher wear rates and fatigue failures that restricts the axle loads, speeds and increases the inspection and maintenance costs [1].

Rolling contact fatigue (RCF) is one of the mayor causes of in-service failures of rails, therefore it is a critical factor that reduces rail lifetime. The typical failure due to RCF is called “head check”: small cracks that nucleate on the rolling sub-surface and grow under fatigue loads. The cracks grow horizontally in the first stage, then turn progressively until a nearly vertical direction until attaining their critical crack length, where brittle facture takes place. This rail catastrophic fracture may cause severe accidents [2].

The parameters that influence crack propagation are the operating conditions (loads by axle, speed, rolling stock characteristics…); track configuration and geometry (curvature radii, rail inclination…) and rail and wheel materials properties. Moreover, environmental factors, like temperature or humidity, can speed up the propagation process [3].

Despite preventive and corrective maintenance measures, over recent years a significant effort was made in order to improve rail properties and geometry to optimize the lifetime under RCF.

In this work, a full scale testing facility was designed and built to reproduce the conditions where RCF appears. The equipment achieves satisfactory results as it is able to generate rail cracks similar to those found in railways. Different rails grades were studied.

2.- METHODOLOGY

2.1.- Testing machine design

Tests were done in a multiaxial test rig composed by a 4x2.5 m T-slotted table, a portal frame and three servo-hydraulic actuators of 50, 100 and 250 kN of load capacity.

Numerous components were designed to adapt the test rig to this application, where the test configuration maintains the wheel axle fixed while the rail is moved alternatively, forward and backward. As can be seen in figure 1, the test layout is composed by the following components:

a) A wheel supporting beam. One end is attached to a fixed part of the rig by a pin joint, and a vertical load is applied by a hydraulic actuator to the other end. The wheel axle is mounted on the middle of the beam, therefore the lever ratio is 2:1.

b) Moving table. Mounted over a high rigidity roller type liner guideway, allows the reciprocating movement and withstands the reaction loads over the rail with a high accuracy, reliability and low friction.

A portable coordinate measurement machine was used to align rail and wheel according to the desired parameters (angle of attack and rail inclination). The table movement is provided by a high speed hydraulic actuator.

c) Lateral load actuator. In order to simulate the rolling conditions on a railway turn, a hydraulic actuator applies a load to the external side of the wheel flange by means of a conical roller, as can be seen in figure 2. As the wheel axle is not fixed in the axial direction, the wheel moves laterally and the point of contact against the rail changes.

d) Rotary actuator. The test rig is also equipped with a 32 kN•m hydraulic rotary actuator that can be coupled to the wheel axle. Then the rail and wheel movements can be synchronized to obtain a controlled grade of slippage, as occurs when train accelerates and brakes.

Two types of test were done: unidirectional and bidirectional tests. In the last one, the moving table moves repeatedly forward and backwards while the vertical and lateral loads are constantly applied.

In unidirectional test the loads are applied only in the forward stroke; in the backwards stroke the wheel is raised until there is no contact between rail and wheel. Notice that in the second case the wheel rotates completely and its entire perimeter is tested. However, in the bidirectional test only one wheel portion is tested against the rail and overheating problems can occurs (a thermography camera was used to control the temperature in the course of the whole test).


Figure 1. Test rig adapted to perform RCF tests


Figure 2. Detail of moving table and lateral load actuator.

2.2.- Test conditions

A total of 8 tests were performed using different rail grades and testing conditions. The first six tests were done in bidirectional mode with a short stroke (the rolling length was only 140 mm). The first test was performed also without lateral load, locating the rail 8 mm away from the wheel-flange interaction point (simulating the rolling conditions existing in a straight track). Tests nº 7 and 8 were performed in bidirectional mode with a long stroke (350 mm).

The rest of the test conditions were not changed during the study: vertical load of 20 t, no rail inclination or angle of attack, dry conditions and rolling speed of 0.3-0.4 m/s. All parameters are shown in table 1, while table 2 shows the rail grades used on every test.

Table 1. Testing parameters

Parameter	Test nº1	Test nº2 to nº6	Test nº7 and nº8
Vertical load	20 t	20 t	20 t
Lateral load	0 t	4 t	4 t
Slippage	No	No	No
Rail inclination	0º	0º	0º
Angle of attack	0º	0º	0º
Environmental conditions	Dry	Dry	Dry
Displacement speed	0,4 m/s	0,4 m/s	0,3 m/s
Type of test	Bidirectional	Bidirectional	Unidirectional
Rail length tested	140 mm	140 mm	350 mm
Wheel geometry	H-36	H-36	H-36
Wheel grade*	C	C	C

Table 2. Rail grades tested

Test nº	Rail Grade
1	R65-R260
2	136SS-A
3	136SS-B
4	136HH-A
5	136HH-B
6	136HSLA
7	136SS-C
8	136HH-C

Stops for damage inspection were done at regular intervals, using magnetic particle test to detect superficial and sub-superficial defects. When cracks were found, the test is considered finished and metallographic examination was done in the cracked sections to analyze the shape and size of cracks.

3.-RESULTS AND DISCUSSION

Table 3 shows the number of runs applied until cracks appeared (in the case where no defects were found in the particle magnetic examination, it shows the total number of runs of the test). Notice that every cycle in the bidirectional test has two runs, however a unidirectional test has only one run per cycle.

The first test, the only one without lateral load, withstanded 200.000 cycles and any crack or defect were found.

On the rest of the bidirectional tests with lateral load, a corrugated deformation appeared on the rail shoulder due to plastic deformation and high wear, as can be seen in figure 3. This phenomenon can be explained by the fact that the rail is always in contact with the same wheel portion that also has similar deformation morphology.

As the first test reached 200.000 cycles without cracks, the inspection interval used in the next test (test nº2) was increased and the first inspection was done at 100.000 cycles. Unfortunately cracks were found in the first inspection, therefore this test result can not be representative because the inadequate inspection interval (also confirmed by the other tests results).

Cracks on the rail rolling surface were found in all rails tested above 50.000 runs. Most of cracks were parallel to the rail longitudinal axis and had a length between 5 and 20 mm.

Because crack morphology, rail deformation and wear did not match the in-service failure appearance observed in real rails, test conditions were modified increasing the stroke to 350 mm and testing in only one rolling direction (unidirectional test). Under these conditions, test nº 7 and nº8 were performed.

Tests nº7 and nº8 get satisfactory results, obtaining cracks similar to those seen in railway rails affected by RCF damage. A detail exam was done on the rails to analyze the nature, growth direction, shape and size of the cracks. Two zones were analyzed per rail: the start and the center of the rolling area; on both zones two metallographic samples were cut to analyze longitudinal and transversal sections of the rail using optical microscopy.

It was observed that the depth of cracks was about 1 mm, as can be seen in table 4. Rail nº 8 has longer and deeper cracks, however it was submitted to 75.000 runs, 50% more than rail nº 7. The length of the crack visible on the surface is about 5 mm on both rails (figure 4), that meets the relation 1:5 between crack depth and visible length observed by others authors [4]. Figure 5 shows cracks in a transverse section of the rail, while figure 6 shows cracks in a longitudinal section. The spacing, morphology, grow direction and depth of cracks agree with data provided by other authors [5, 6 y 7].

Crack differences between the start and center of the rolled area can be explained by the settlement among rail and wheel when loads and displacements are applied at the start of every run. In this case, lateral and longitudinal slippage takes place and leads to a higher crack growth rate.

Moreover, under the rolling area, a significant deformation of the pearlitic microstructure of the rail was noticed. Consequently, strain hardening takes place under the rolling surface, raising the hardness from 400 HV to 500 HV in rail nº 7; while the hardness of rail nº 8 increased from 430 to 600 HV, as shown in figure 7.

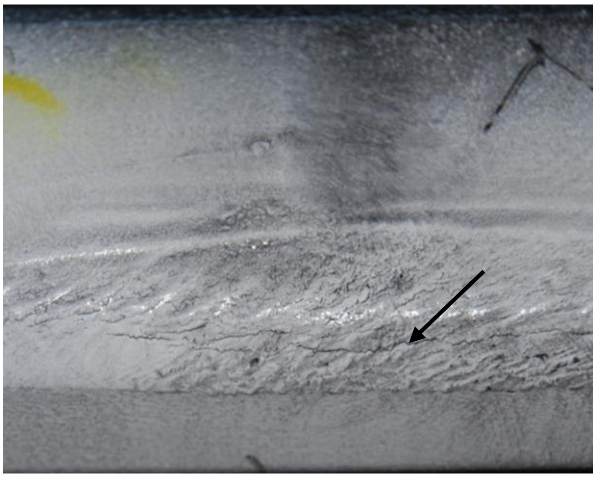

Figure 3. Detail of rail nº4 surface at the end of the test. Corrugation and superficial cracks.

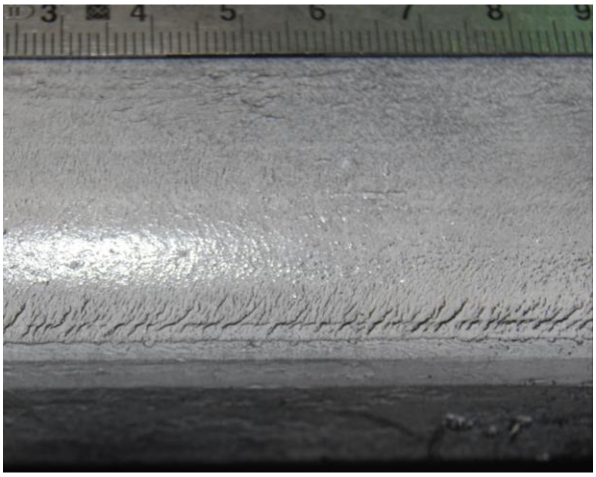

Figure 4. Detail of the surface of rail nº7 at the end of test.

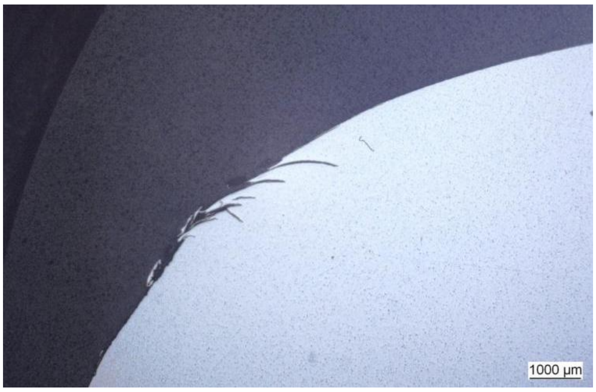

Figure 5. Transversal section of the center region of rail nº8 (12.5x). Maximum crack depth: 0.71 mm.

Figure 6. Longitudinal section of the center region of rail nº7 (12.5x). Maximum crack depth: 0.74 mm

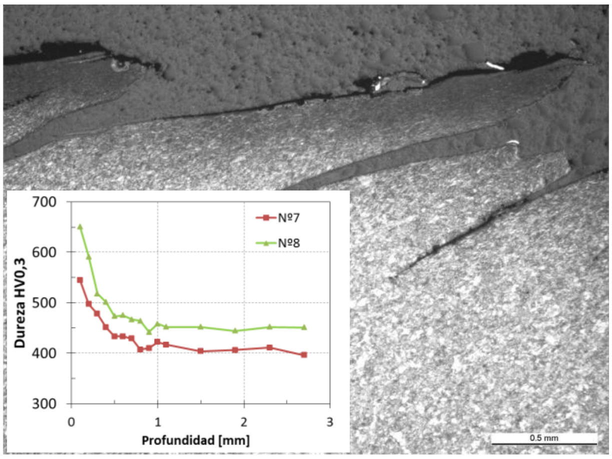

Figure 7. Longitudinal section (50x, rail nº8), showing surface deformation. Hardness profiles of rails.

Table 3. Tests results

Test nº	**Runs needed to crack appearance**
1	No cracks after 200.000
2	100.000
3	No cracks after 50.000
4	50.000
5	No cracks after 50.000
6	75.000
7	50.000
8	75.000

Table 4. Crack depth measurements on tests nº 7 and nº 8

Maximum crack depth (mm)			
Transversal samples		**Longitudinal samples**	
Nº7-Start	0.88	Nº7-Start	1.18
Nº7-Center	0.41	Nº7-Center	0.74
Nº8-Start	0.85	Nº8-Start	1.60
Nº8-Center	0.71	Nº8-Center	1.42

4.- CONCLUSIONS

The full scale rolling contact fatigue testing facility has demonstrated its effectiveness to simulate service conditions where RCF cracks appears in railways in a reliable, fast and economical way.

Bidirectional tests do not simulate properly the crack propagation process in rails because only one part of the wheel rolls onto the tested rail. Furthermore, crack propagation paths depend on the rolling direction and this type of test (it applies the same number of runs on both directions) generates interferences in the growth behaviour of cracks.

However, satisfactory results were obtained when the rolling length was increased up to 350 mm and tests were done in a single direction. Under these conditions, cracks morphology, spacing, size and direction were identical to those seen in railway rails.

It must be highlighted that hardened head rail grade (rail nº8) showed better performance against RCF than the standard strength rail grade (rail nº7).

In spite of the satisfactory results achieved, it must be remarked the limitations to reproduce exactly track conditions due to limitations as the lack of dynamic effects caused by railway imperfections and vehicle dynamics; the stability of climatic conditions (rain, temperature, presence of foreign bodies…) and, specially, because the tested rail is always in contact with the same wheel, therefore the area and pressure contact have a special evolution during the test [8], while a railway rail is in contact with hundreds of wheels with, at least, slightly different geometries and wear distribution.

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