STUDY ON THE WEAR AND ROLLING CONTACT FATIGUE BEHAVIOR OF RAIL STEEL GRADES USING A TWIN DISC LABORATORY EQUIPMENT

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ABSTRACT
The wear resistance and the rolling contact fatigue (RCF) behaviour of different rail steel grades versus a railway wheel steel is analysed in this work. For this purpose, a twin-disc test was setup, in order to replicate the in-service damage suffered by the rails due to the contact pressure appearing in the rail and to analyse the wear and RCF behaviour of the rail steel in a quick and efficient way. Different rail steel grades have been studied under different test conditions and the influence of the applied load and the sliding rate on the wear and RCF behaviour of these materials has been analysed. At the end of the tests, the specimen mass loss was determined and degradation phenomena assessed by metallographic characterization. The nature, shape and size of the cracks were analysed and compared to those obtained in the tests carried out with the same materials at a pilot plant scale. It has been demonstrated that the proposed Twin-Disc tests are able to predict the behaviour of the different steel grades in rail-wheel systems in a quick and easy way.
KEY WORDS: Rolling contact fatigue, RCF, wear, rail, pearlitic steel grades, free carbide bainitic steel grades.

1.- INTRODUCTION
Rail wear and fracture due to rolling contact fatigue (RCF) are serious problems on railways worldwide. Both phenomena are due to repeated wheel contacts under normal stresses and tangential traction which, combined, reach values above the material yield strength [1].
There are different ways to deal with the study on the wheel-rail contact, wear phenomena and cracks initiation and growth due to rolling contact fatigue. One of them is studying the fracture mechanisms involved on the breakage of rails that, unfortunately, still happen nowadays. Other options, used to predict the behavior of new steel grades, are the use of tests carried out in rail circuits, specifically designed for this purpose, or in full scale test benches. This last type of tests allows the simulation of the damage mechanisms acting in the in service conditions, but are very expensive and time consuming.
Since the mechanisms by which RCF cracks initiate and grow are complex, it is convenient to study them in laboratory scale equipments, able to reproduce the damage mechanisms in an inexpensive and quick way.
This work describes the tuning of a laboratory twin-disc test, able to reproduce the damage mechanisms in small-size samples extracted from rails and wheels. The effect of the different test conditions, such us the contact pressure or the sliding rate,

on the wear and the RCF behavior has been analyzed. The obtained results have been compared to those previously obtained in a full scale test bench [2].

2.- EXPERIMENTAL PROCEDURE
2.1.- Equipment description

Tests have been performed in a twin-disc test machine designed for this purpose. This equipment is able to carry out rolling and rolling-sliding tests by using two separate 5 kW motors that drive two shafts, at the end of which the disc specimens are placed. Normal load, up to 15 kN, is applied on the line contact between the discs by a hydraulic piston, and is measured by a load cell mounted in line with the piston. Torque due to rolling-sliding contact between the specimens is measured by a transducer attached to the drive shaft of the rail specimen (Figure 1).
One of the shafts keeps fixed and the other one can be moved by the action of the hydraulic piston. The distance between both shafts ranges from 70 to 120 mm, so different test samples and configurations can be adopted.

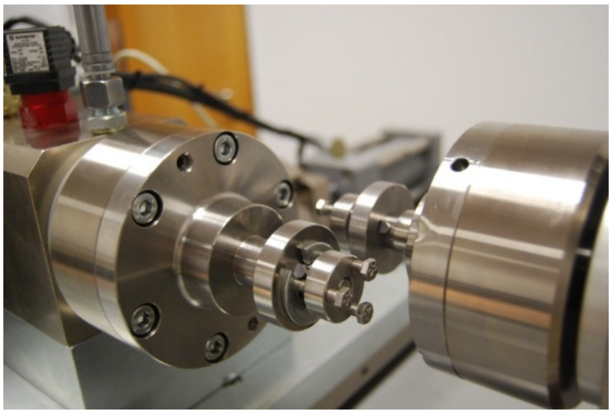


Figure 1. Detail image of the test configuration.

All the tests were performed using twin discs with the same size (47 mm diameter and 10 mm thickness).The rail specimen was mounted on the fixed drive shaft, connected to the torque transducer, and the wheel disc on the mobile one. Figure 2 shows the location of sample extraction on the rail and wheel. The relative motion of both discs and the loads involved in the test will be explained in Figure 5 below.

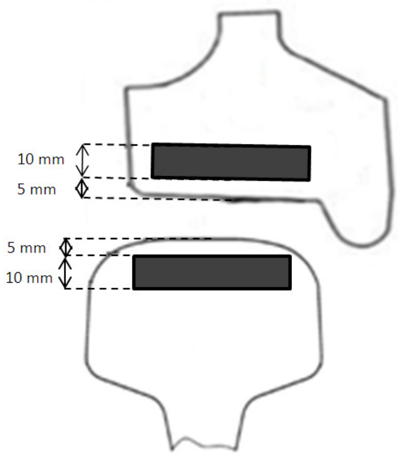


Figure 2. Sample discs extraction.

2.2.- Materials

Different rail steel grades have been tested versus a R7 rail wheel steel, according to the American standards. Three pearlitic rail steels (P1 to P3) and one experimental carbide-free bainitic steel (B4) were included in this study [3]. Table 1 collects the different tested materials, their nominal hardness and a short description.

Table 1. Tested materials.

Code	Description	HB Hardness
P1	Pearlitic steel rail	>260
P2	Head hardened pearlitic steel rail.	>350
P3	Experimental hypereutectoid pearlitic steel grade.	>390
B4	Experimental carbide-free bainitic steel grade.	>390

2.3.- Test conditions

In order to analyse the influence of the different test conditions on the wear behaviour and crack initiation and growth due to rolling contact fatigue, several tests have been carried out. Table 2 collects the analyzed test conditions.

Table 2. Test conditions.

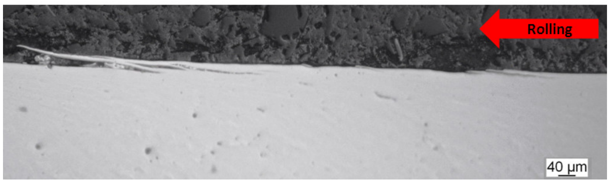
Test No.	Tested material	Contact Pressure (MPa)	Slip rate (wheel/rail) (%)	Rail disc speed (rpm)	Cycles	Lubrication (yes/no)
1	P1	900	1	400	10.000	No
2	P1	900	1	400	21.000	No
3	P1	900	1	400	50.000	No
4	P1	900	5	400	50.000	No
5	P1	1.500	1	400	10.000	No
6	P1, P2, P3, B4	1.250	1	400	30.000	10 kcyles dry/ 20 kcycles water

At the end of the experiments, sample discs were characterized by mass loss determination and metallographic characterization. Discs were diametrically cut at their middle section and the length and depth of cracks were determined by optical microscopy techniques.

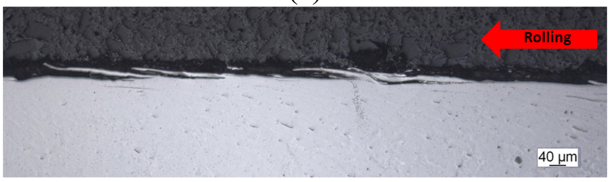
3.- RESULTS AND DISCUSSION

3.1.- Test condition influence

Figure 3 shows micrographs of the P1 steel grade samples after twin-disc tests performed under different experimental conditions.



(a)



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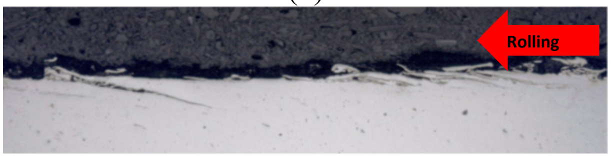

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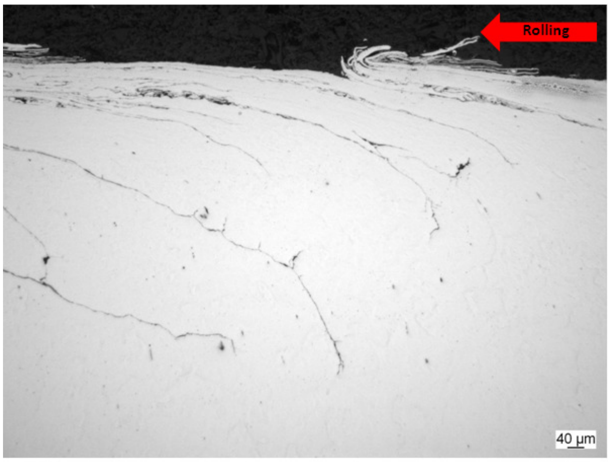

(d)

Figure 3. P1 Steel grade. Test condition 3, 4, 5 and 6 (a, b, c and d respectively).

Due to the applied contact pressure and the traction stress, result of the relative motion of the discs, a region of maximum stress is generated a few micrometers under the surface. Cracks nucleate in this area as a consequence of fatigue mechanisms.

On the one hand, experiments carried out under dry condition (test conditions 3 to 5) lead to wear and delamination phenomena, rather than inducing any important crack. The employment of higher slip rates, such us 5% in test condition 4, leads to higher adhesive forces, that are responsible for the increase of the wear rate and the generation of wear debris from the surface of the discs. Increasing the contact pressure (test condition 5) leads to the generation of some deeper cracks, however not important differences have been found on these samples.

On the other hand, the combination of dry cycles with water lubrication (test condition 6) has led to the generation of much deeper and larger cracks, similar to those obtained after a full scale test using the same materials (see Figure 4) [2].

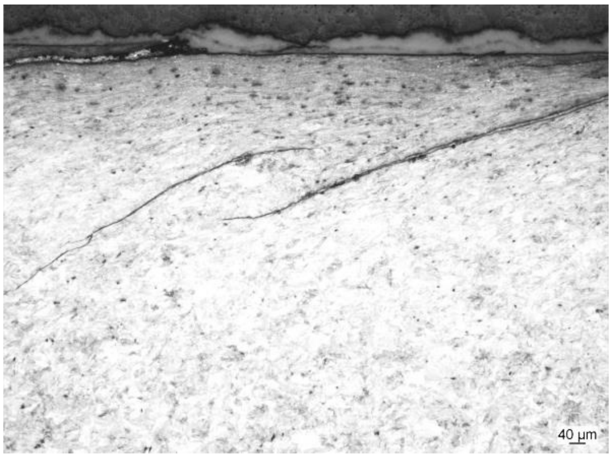

Figura 4. P1 Steel grade tested in a full scale test bench.

Figure 5 shows a schematic representation of the stresses acting in both of the discs during a twin-disc test and the crack orientation of both of them [4]. The upper disc corresponds to the rail steel grade and the bottom one to the wheel steel. Positive wheel/rail slip rates (wheel speed > rail speed) leads to compressive stresses on the output contact point of the upper disc, which causes the flattening of the surface material. Under dry condition, just a wear process takes place, but under a wet condition, water is trapped inside the crack and, as the cracks move through the contact, the entrapped fluid is pressurised, promoting crack growth (see Figure 5).

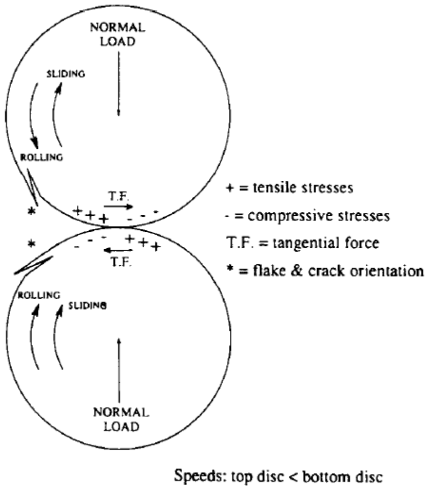

Figure 5. Schematic representation of the state of stresses in the twin-disc rolling/sliding contact. Crack orientation and sub-surface stresses on both discs are shown.

Since test condition 6 was the most demanding one, it has been selected to carry out the comparative study of the different rail steel grades.

3.2.- Wear and rolling contact fatigue study performed on the different steel grades.

Figure 6 shows a comparative graphic of the wear rates determined with the tested materials. The head hardened pearlitic steel (P2) and the experimental hypereutectoid one (P3) exhibited much better wear resistance than the conventional pearlitic steel (P1). Anyway, the experimental free-carbide bainitic steel grade give rise to the lowest wear rate of all of them.

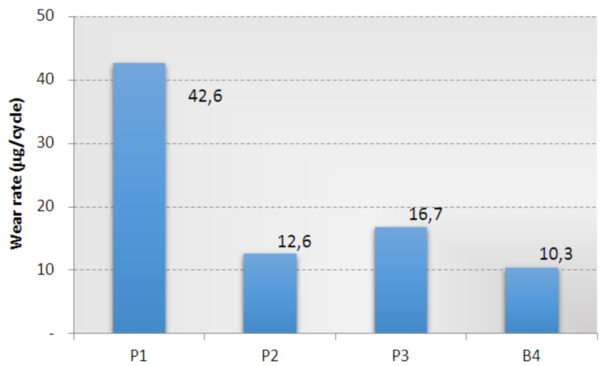

Figure 6. Wear rates of the different materials under test condition 6 (µg/cycle)

Figure 7 collects surface images and micrographs of the longitudinal sections of the discs after these experiments.

Conventional pearlitic rail steel (P1) and head hardened pearlitic rail steel (P2) have shown similar contact fatigue resistance. Cracks up to a length of 2 mm with depths of 0.8 mm were found in those two steels (P1 and P2).

In P3 and B4 samples no significant crack evolution was found. The average length and deep of the cracks were 0.2 and 0.3 mm respectively, and wear was the only failure active mechanism in these tests.

The route to improve the fatigue resistance of steel rails is through the delay of crack initiation. Crack formation in rail discs is always preceded by a considerable amount of plastic deformation. Since cracking is preceded by plastic deformation, a stronger steel grade can be expected to have a longer fatigue life. For a given combination of contact stress and creepage (slip rate), the amount of plastic deformation will depend on the shear yield strength of the steel. Stronger steels will require more load cycles to develop the same amount of deformation than weaker ones. Once cracks have initiated in a heavily deformed microstructure, their propagation can still be hindered if the paths of weakness, such us manganese sulphide inclusions and primary ferrite or cementite on grain boundaries, are reduced [4].

Hypereutectoid steels, in which cementite crystallizes in a fine and discontinue network (P3), are expected to have greater fatigue resistance than fully pearlitic and ferrito-pearlitic steels (with soft ferrite present on grain boundaries), due to their higher hardness (higher yield strength) and lack of microstructure weakness paths [5].

The presence of highly stable retained austenite between the ferrite laths provides a better wear behavior to the experimental carbide free bainitic steel (B4). Transformation induced plasticity (TRIP) effect in the subsurface region, where cracks nucleate, increases the local hardness and strength of this material, improving its wear resistance. Additionally, the formation of martensite particles in the contact line of the discs leads to an “auto-polishing” surface process which delays the evolution of cracks.

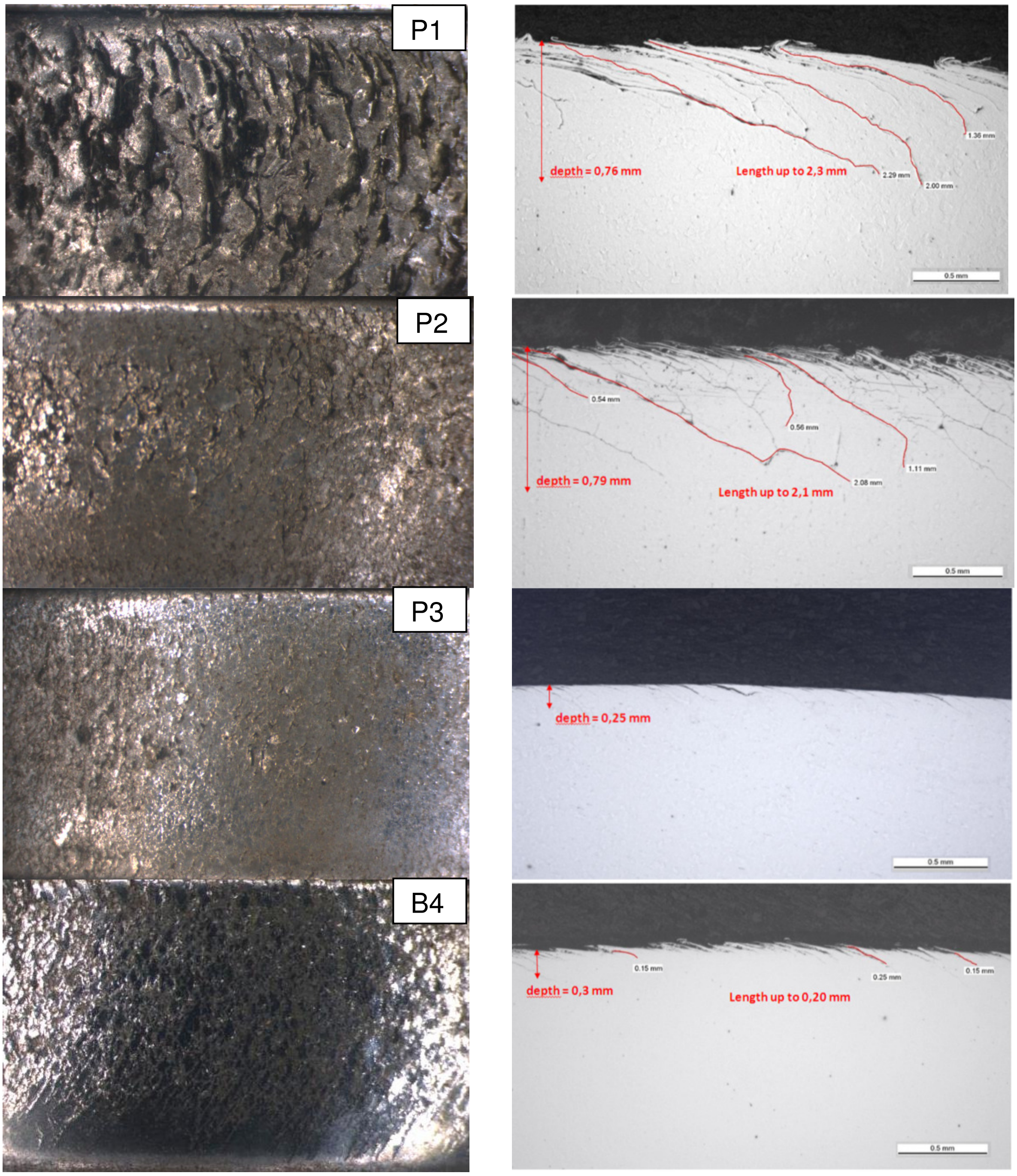

Figure 7. P1, P2, P3 and B4 steel grades. Rolling surface appearance of the samples at the end of the tests (on the left) and microstructural damage observed in the transverse section of them (on the right). Test condition 6 (Table 2).

4.- CONCLUSIONS

The setting of a laboratory scale twin-disc test, able to reproduce in an easy, quick and inexpensive way the damage mechanisms active in rail service conditions was described in this work.
The influence of different test parameters on the wear and rolling contact fatigue resistance of a pearlitic rail steel was analysed. The use of higher sliding rates leads to an increase of the adhesive loads and, consequently, an increase on the material wear rate.
Experiments performed in dry condition lead to wear and delamination phenomena, rather than producing any significant penetrating crack. Meanwhile, the combination of dry cycles with water lubrication ones, leads to the generation of deeper and larger cracks, because of the entrapment of water drops inside them. These combined tests are able to reproduce the damage induced in the course of the in-service conditions of real rails.
The wear and rolling contact fatigue resistance of three different pearlitic steel grades and a free carbide bainitic steel grade were analysed under the combined dry/water condition. The main mechanisms for the crack nucleation and growth were identified.
Head hardened pearlitic steel grade (P2) has exhibit better wear behaviour than the pearlitic conventional one (P1), because of its higher hardness and yield strength, however both materials have shown a poor rolling contact fatigue resistance and cracks up to a length of 2 mm and depths of 0.8 mm were found on both of them.
Hypereutectoid pearlitic steel grade (P3), with no continuous cementite network along primary grain boundaries, has shown a good wear behavior, but more important, its excellent rolling contact fatigue resistance should be marked.
Finally, the experimental free carbide bainitic steel grade (B4) has shown even better wear and rolling contact fatigue resistance than the hypereutectoid one (P3), the TRIP effect due to the retained austenite present in its microstructure, is the responsible for the good wear and RCF resistance of this material.

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