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Wear and surface residual stress evolution on twin-disc tests of rail/wheel steels

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Abstract. Twin disc tribological tests were performed in wheel and rail materials, with specimens taken from a Spanish AVE train wheel and a UIC60 rail, in a program intended to characterize their contact fatigue behavior. The X-ray diffraction technique was used to characterize the residual stress distribution at the initial and damaged stages, as well as in intermediate stages, since existing residual stresses in the surface layers of the railways steels and its evolution during contact loading can have a major influence on crack initiation and propagation.

Introduction

Rolling contact fatigue (RCF) is a kind of damage that appears in components subjected to variable contact stress. In this type of fatigue loading, failure is caused by cracks that appear not only on the surface but also under the surface of the bodies in contact, depending on load magnitude. Although most of the failures caused by RCF damage in railway transportation do not cause casualties involving loss of life, they are a matter of concern since they cause unplanned maintenance interventions, with decreased service availability and delays in train traffic.

Fatigue failures due to RCF in railway wheels and rails are mainly caused by phenomena such as heat generation, fatigue, wear and impacts [1] and can be categorized as surface initiated defects or subsurface initiated defects. Residual stresses have a major influence on surface initiated defects, since these defects are normally caused by gross plastic yielding of the wheel and rail material close to the running surface, due to repeated applications of high friction loads as consequences of traction, braking, curving, etc [1].

If that deformation occurs in a dominant direction, *e.g.* rails in double-track railways in which trains mostly run in the same direction, the material will harden and when residual stresses are not sufficient to prevent further accumulation of plastic strains and fracture strain is exceeded, cracks will eventually appear [2]. That phenomenon explains the benefits of the residual compressive stresses on the wheel tread induced during manufacture.

The work presented in this paper is part of a project where it is intended to develop a methodology to anticipate the need for repair or replacement of wheels or rails, and in particular to establish time limits for intervention on wheels or rails where one or more defects were detected. In the present paper, simultaneous studies of surface integrity (i.e. detection of surface defects), wear (i.e. mass loss), roughness, and surface residual stress were carried out aiming at the identification of time dependency of these parameters since all of them play a part in the running–in and service stages of the wheel and rail.

Material characterization

The experimental investigation was performed on samples taken from an Alta Velocidad Española (AVE) train wheel and from a UIC60 rail. It should be mentioned that the AVE train wheel, from which the specimens were taken, is a real used wheel that reached the geometrical limits for continued usage. In order to characterize these two materials, chemical composition, mechanical properties, microstructure and hardness measurements, were carried out [3]. The materials analysis revealed an ER7/ER8 grade wheel steel according to the EN 13262 standard and an R260 MN grade rail steel according to the EN 13674 standard. The chemical composition of the studied wheel and rail steels is presented in Table 1.

Table 1. Chemical composition of wheel and rail materials [% weight].

	C	Mn	Si	P	S	Ni	Mo	Al	Cr	Cu
wheel	0.49	0.74	0.25	0.01	<0.005	0.18	0.06	0.03	0.26	0.12
rail	0.72	1.1	0.35	0.02	0.01	0.02	<0.001	<0.005	0.02	<0.02

Tensile tests according to NP EN 10002-1 standard were made using round cross-section specimens with Ø10mm. The specimens were extracted from the wheel tire in the tangential direction and from the rail head in the longitudinal direction. The obtained results are shown in Table 2. Fatigue crack growth rate determination tests were also performed in order to characterize the fatigue crack propagation behaviour, as this is essential for the objectives of this project, mentioned before [3].

Table 2. Mechanical properties of wheel and rail materials.

Material	Young modulus [GPa]	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Reduction in area [%]
wheel	197	503	859	18	51
rail	191	504	950	13	19

Experimental work

Twin disc tests

Twin disc test machines are commonly used to simulate heavy loaded contacts like the wheel/rail contact and to predict materials behaviour in rolling contact fatigue. The twin disc test consists of two rotating discs in contact subjected to a constant applied load. In this type of tests the most important parameters are the discs' geometry, their rotating speed, the normal loading contact force, the presence of a lubricant and its flow rate and temperature. The main results obtained with twin disc tests are the specimens' contact surface wear, the surface fatigue cracking analysis and surface scuffing, depending on the test conditions.

Two types of discs are being used in twin discs tests, one cylindrical and another with a 'spherical' contact surface with 35 mm radius; both discs have 70 mm diameter and 7 mm thickness, as shown in Fig. 1. These types of discs were joined in pairs composed of one cylindrical disc and one 'spherical' disc. The cylindrical discs were taken from a UIC60 rail sample and the 'spherical' ones from a Spanish AVE wheel.

Since the specimens were extracted from the real wheel and rail profiles it was decided to verify if the specimens' orientation and location has any influence in the RCF behaviour. This way, as shown in Fig. 2, the specimens were taken in different orientations and locations from these two profiles.

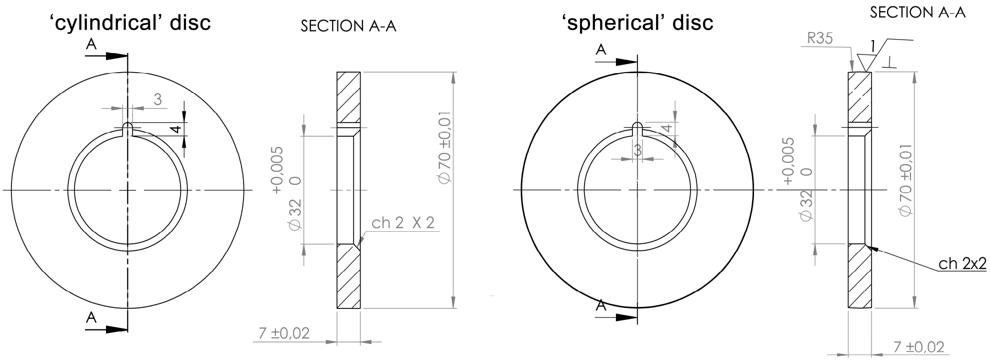

Fig. 1. Disc dimensions [mm].

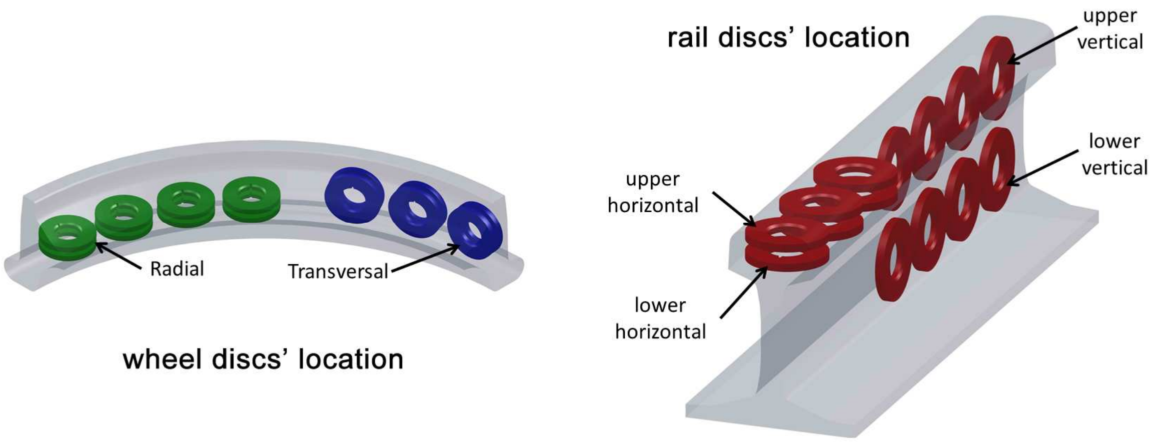

Fig. 2. Location of disc specimens extraction on the wheel and on the rail.

These specimens where tested in a twin disc machine available at CETRIB-INEGI laboratory of the Faculty of Engineering of the University of Porto, that was recently up-graded [4]. The tests were performed with an applied load of F=750 N. Due to the discs' geometry and according to Hertz theory [5] the maximum contact pressure is p_0=1.5 GPa and the contact area assumes an elliptical shape with a minimum radii of a=0.4 mm and a maximum radii of b=0.6 m. In this particular case the smallest radius is oriented in the rolling direction. The discs rolled under pure rolling conditions at a speed of v=13.4 m/s, at the contact centre. Galp TM100 oil was used as a lubricant, with no special additives. Lubricant properties are shown in Table 3. This type of lubricant was chosen because it reduces the wear, reducing its influence on the RCF and promoting the appearance of contact fatigue defects – which are the object of this study. The two disc pairs studied were composed by discs taken in different positions of the wheel and rail as indicated in Table 4.

Table 3. Lubricant properties.

Viscosity at 40°C [cSt]	**Viscosity at 100°C** [cSt]	**Density** [kg/m^3]	**Viscosity index**
100	11.1	891	95

Table 4. Disc pairs composition.

# disc pair	**material**	**position**	**reference**
V	Wheel	transversal	TRV1
	Rail	upper horizontal	DHS1
VI	Wheel	radial	RAD3
	Rail	lower vertical	DVI1

Residual stress measurements

Residual stress determination was performed by X-ray diffraction using the $\sin^2\psi$ method [6]. The experiments were carried out with a PROTO iXRD equipment available at CEMDRX laboratory of the Faculty of Sciences and Technology of the University of Coimbra, working on Ω mounting. Lattice deformations of the {211} diffraction planes ($2\theta \approx 156°$) were measured using Cr-K_α X-ray radiation, with 11 β angles (22 ψ angles), an acquisition time of 30 seconds by peak and ±2° oscillation in ψ. The stress was evaluated using the $(1/2)\cdot S_2$ X-ray elastic constant value of 5.83×10^{-6} MPa^{-1}. For the analyzed material and considering the radiation used, the average penetration depth of the X-rays was about 5 μm. The residual stresses were determined in the longitudinal direction (LD) and the transversal direction (TD) of the rolling track, on a rectangular area with a maximum width between 0,7 and 0.9 mm, at the centre of the rolling track. Residual stress depth profiles were obtained using the electro polishing layer removal method.

Results and discussion

Some interruptions of the twin disc tests were made for measuring contact surface roughness topography, mass loss (due to wear) and residual stresses, with the objective to follow their evolution during the rolling contact fatigue process. The evolution of the mass of the tested specimens is presented in Fig. 3 and Fig. 4. The evolution of some roughness parameters along these tests, such as the roughness average (R_a) and the RMS roughness average (R_q), is presented in Fig. 5 and in Fig. 6. The recorded topography roughness average (S_a) and the RMS roughness average (S_q) are also shown. These measurements were performed on a HOMMELWERKE T8000 measuring station equipped with a drive unit LV-50/50 E and a TKL 300 measuring probe. From these results it is possible to conclude that the running-in phase of these materials ends after approximately 5 million rotations.

The contact surfaces of the tested specimens were also observed by optic microscopy during twin disc tests interruptions. During these observations the presence of defects such as cracks, pits or spalls was detected, as shown in Fig. 7. These observations allowed to conclude that rolling contact fatigue cracks appear at the contact surface after 15 to 18 million cycles. The wheel material is more sensitive to defects initiation, since a large number of defects were observed at wheel specimens.

The residual stress and the X-ray diffraction peak breadth depth profiles, obtained after electro polishing layer removal, can be observed in Fig. 8, corresponding to the state before fatigue cycling. Before RCF tests, the specimens present an initial residual stress state in the surface layers essentially due to the machining and finishing of the specimens surface, since they were not submitted to any post-machining treatment. The specimens present compressive stresses near the surface, more intense in the transversal direction, followed by tensile stresses at a depth between 30 and 120 μm. The initial stress state at the surface, however, is not the same on the discs obtained from the wheel and the rail, as it can be seen in Fig. 9, due to the fact that the sequence of machining and finishing operations where not the same for the two types of specimens. It is noticed that, although Fig. 8 is based on data for a different pair of discs, the values presented for surface measurements (i.e., depth approximately zero) correspond well to the values found in the tested specimens as recorded in Fig. 9.

The evolution of the residual stresses at the discs' surface, during rolling contact fatigue, are shown in Fig. 9, as well as the evolution of the X-ray diffraction peak breadth. These experimental results show an evolution of the surface during the lubricated rolling contact fatigue tests, pointed out by gradual changes of the residual stress state and the X-ray diffraction peak breadth values, mainly during the running-in phase. The surface residual stresses are always compressive for both types of discs and more intense in the transversal direction, compared to longitudinal. But after the running-in we obtain a stabilized residual stress state, where the stresses are very similar for the same direction in both types of discs, even if they were very different before tests. The dependency of the in-depth residual stress profile with the number of cycles is currently under investigation.

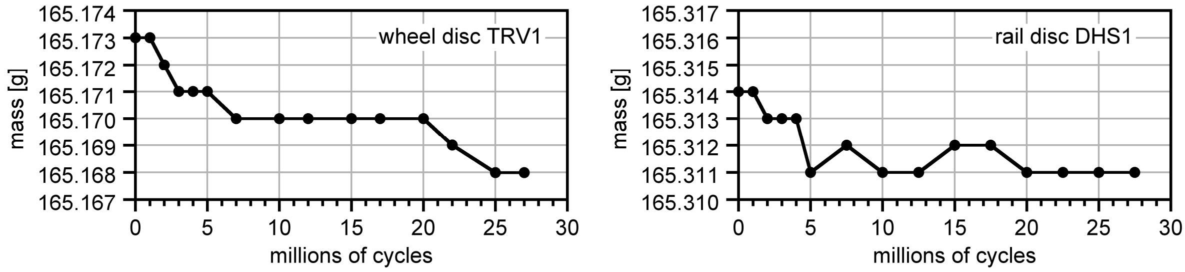

Fig. 3. Disc pair V mass evolution.

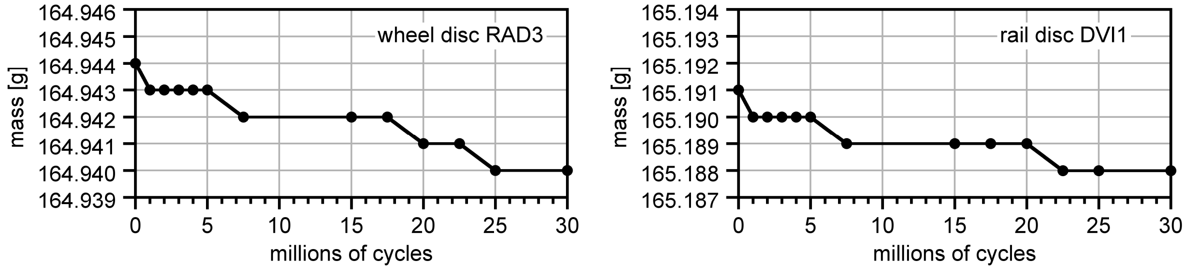

Fig. 4. Disc pair VI mass evolution.

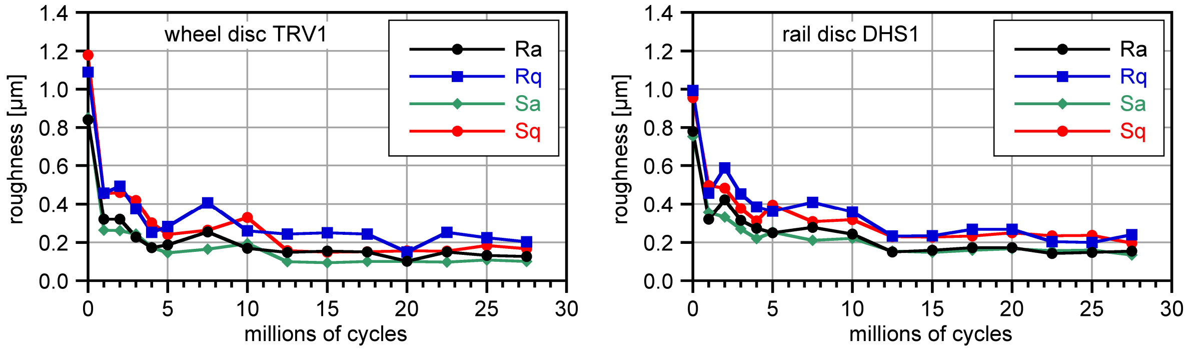

Fig. 5. Disc pair V roughness variation.

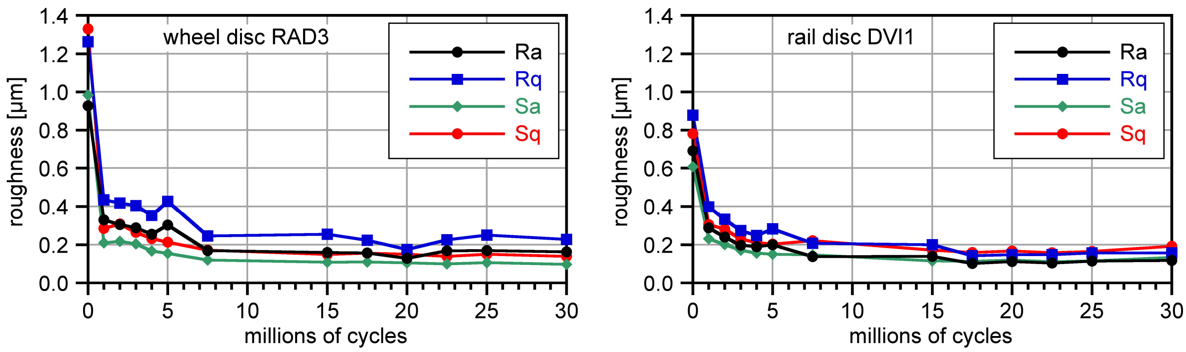

Fig. 6. Disc pair VI roughness variation.

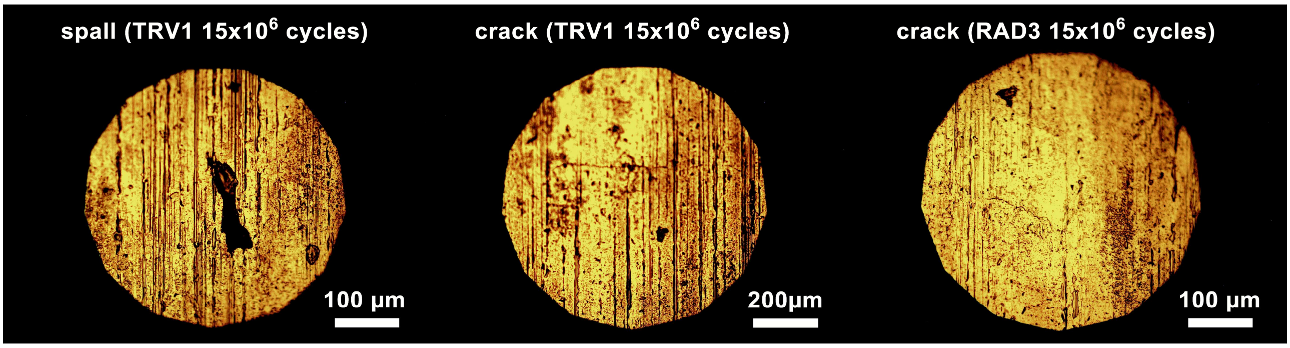

Fig. 7. Some contact fatigue surface defects detected.

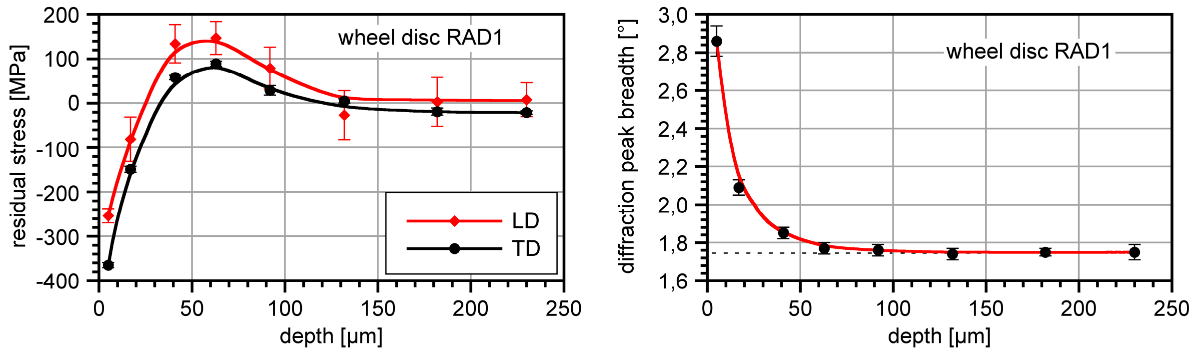

Fig. 8. Residual stress and X-ray diffraction peak breadth depth profiles before RCF.

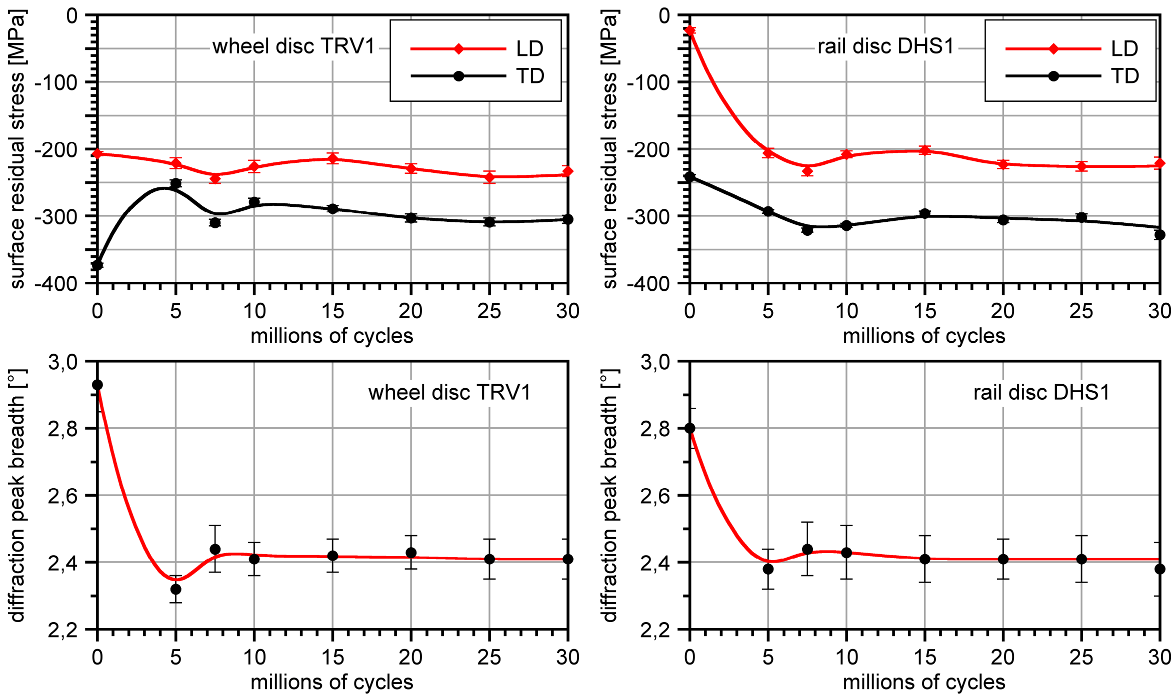

Fig. 9. Surface residual stresses and X-ray diffraction peak breadth evolution during RCF tests.

Concluding remarks

Twin disc rolling contact fatigue tests in wheel and rail materials were performed. The experimental results show an evolution of the surface integrity during contact fatigue tests. In the present experimental conditions, the running-in phase of the studied materials ends after approximately 5 million rotations and rolling contact fatigue defects appear at the contact surface after 15-18 million cycles. The wheel material presents a higher wear rate than the rail material and is more sensitive to defect initiation, since the larger number of defects was observed in the wheel specimens.

It was found that during the running-in phase, up to near 5 million cycles, there is an evolution of the surface roughness and of the surface residual stress state, however both become approximately constant thereafter. This phenomenon could be explained by the fact that during the running-in the roughness peaks were smoothed or split out. This way the reduced wear rate allowed the remaining surface material to soften, until a steady residual stress state is reached.

A more complete analysis of the evolution of residual stress fields in the twin disc machine specimens will be assessed and their influence on the evolution of initial surface cracks will be better understood by the results of the experiments. Relationship between the obtained results by the different types of tests will be studied in order to develop a methodology to better know the time for repair or replacement of the wheels or rails.

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