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On the accuracy of the pressure measurement film in Hertzian contact situations similar to wheel-rail contact applications

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ABSTRACT

Experimental investigations and finite element simulations on the measuring error of Prescale pressure measurement films of the mono-sheet type ‘S’ were done with perfect Hertzian contact bodies in contact situations similar to the wheel-rail contact. The sources of the systematic error were identified and quantified.

1. Introduction

In the contact zone between a railway vehicle wheel and the rail a load of approximately 100 kN is distributed over a contact area of about 1 cm^2, which leads to a maximum nominal contact pressure that exceeds 1000 MPa. The size, shape and pressure distribution of the contact area influence all relevant aspects of the wheel-rail contact, namely wear, rolling contact fatigue and tangential traction forces. In earlier times the contact area was usually calculated using the Hertzian contact formula. This formula leads to elliptical contact areas, but is valid only for constant principal contact radii [1]. Most wheel and rail profiles have cross sections that are designed from several curved sections with different constant radii or of additional straight sections. So, when due to the pressure the contact area exceeds the boundaries of one section, it no longer lies within the range of one constant principle radius. Also due to the dynamic effects of the wheel-rail system, the position of the wheel on the rail changes continuously. This can lead to a situation when a contact point matches a boundary point between two sections or can even lead to two-point contact. In all cases the Hertzian requirement of constant principle radii is violated and the contact area and the pressure distribution can only be calculated numerically or be measured [2].

Current research shows that the possibilities to measure the contact zone between the wheel and the rail are very limited. Experiments using Prescale measurement film of the mono-sheet type ‘S’ have been executed in the recent years for this purpose [3,4] (Fig. 1). Prescale pressure measurement films are easy to use on real components without any substantial need of modification to the experimental setup. Moreover, the experiment results of the films are easily readable as well as reproducible by using the accompanying scan software, without any reading errors or the need for calibration.

Results of experimental and numerical scientific investigations on the error in the measurements with Prescale film have been published by Hale et al. [5], Wu et al. [6], Liau et al. [7,8] (all in the biomedical field) and by Hoffmann [9,10]. In all these published investigations, the applied maximum pressure was in the range between approximately 10 MPa and 130 MPa with the use of Prescale two-sheet type ‘W’. Aymerich et al. [11] pressed steel spheres with radii of 20 mm, 30 mm as well as 50 mm against a steel plate of thickness 9 mm and compared the contact area as measured by the Prescale HS film against that measured by the ultrasonic method. None of these published results can be qualitatively employed for the wheel-rail contact situation.

In the wheel-rail contact area, the principal contact radii of standard wheels with S1002 profile lie between approximately 420 mm (worn) and 460 mm (new) in direction of travel, which is the wheel radius and between approximately -100 mm to ∞ perpendicular to the driving direction, if only the wheel tread is considered. For the standard rail UIC 60E2, the principal contact radius perpendicular to the driving direction is 70 mm or 200 mm in the tread area, while that in travel direction is ∞. This leads to a substitutional contact radius of approximately 450 mm in travel direction and between approximately 100 mm–300 mm perpendicular to the driving direction in Hertzian calculations [12].

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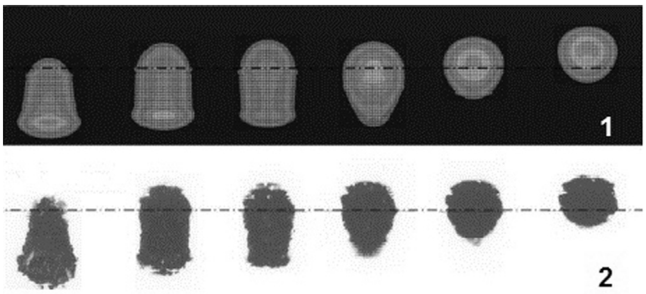

Fig. 1. Area of the contact between a standard wheel (diameter = 920 mm) with profile S1002 and a 60E2-rail at different relative positions at forces of 100 kN; 1: finite element results, 2: experimental results measured with Prescale HS film.

The imperfect Hertzian shapes of wheel and rail are not suitable for systematic error measurements. Therefore, in the present work, experimental measurements with Prescale films MS, HS and HHS were done with perfect Hertzian contact bodies in contact situations similar to the wheel-rail contact. The first aim was to quantify the systematic errors by the usage of this measurement method. In a second step the contact situations with film were simulated with the finite element method and sources of the systematic errors were identified and accordingly, conclusions for the application of Prescale pressure measurement films in the wheel-rail contact were drawn.

2. Materials and methods

2.1. Prescale measuring film

A Prescale film is composed of a polyethylene terephalate (PET) polyester base, a color-developing material and a micro-encapsulated color-forming material. There are two types: The mono-sheet type 'S' is comprised of one film with the two layers coated on one polyester base whereas the two-sheet type 'W' has two films with the two layers coated on two different polyester bases. When pressure is applied, the micro-capsules break and the color-developing material turns red, with the intensity of the color corresponding to the applied pressure. The size and the wall thickness varies for different micro-capsules causing them to break at different pressures. Since all micro-capsules in the Prescale are broken at the rated maximum pressure, higher applied pressure levels are not detected since the intensity of the color (red) remains unchanged thereafter.

The Prescale type 'W' is available in five different pressure ranges from 0.05 MPa up to 50 MPa while the Prescale type 'S' is available in three different pressure ranges from 10 MPa up to 300 MPa. The pressure in the middle of the wheel-rail contact patch normally exceeds this maximum limit of 300 MPa, thus ruling out the use of the Prescale film for the measurement of the peak pressure in this case. However, the Prescale can still be used for the measurement of the size and shape of the contact patch.

In this investigation only the three different S-type films were used: the MS (pressure range 10 MPa–50 MPa), the HS (pressure range 50 MPa–130 MPa) and the HHS (pressure range 130 MPa–300 MPa). The S-type films have an overall thickness of 110 ± 5 μm. The micro-capsules in Prescale films have a cross-section of 4 μm–15 μm [13].

In most of the published papers regarding finite element simulation of Prescale films in Hertzian contact, a linear elastic material model was used with an equivalent Young's modulus of approximately 100 MPa and a Poisson's ratio of approximately 0.4 [5–8].

2.2. Experimental setup

The aim of the experimental setup was to create a contact situation similar to the wheel-rail contact which can be precisely calculated analytically. For this purpose, two contact bodies of 1.6580 steel were produced. The first (contact body I) has a spherical radius of 450 mm ($R_I = 450$ mm) and the second (contact body II) has a plane contact face ($R_{II} = \infty$). Both contact faces were finished with a high surface quality (mean roughness: contact body I = 0.11 μm; contact body II = 0.14 μm).

The two contact bodies were mounted on a test rig (Fig. 2) and pressed against each other using a hydraulic jack with forces of 25 kN, 50 kN, 75 kN and 100 kN. The deviations in the experimental setup from the assumptions of the Hertzian contact theory were negligible. Therefore, the exact contact areas are calculable using the formulas from the Hertzian contact theory (Table 1) [1].

The contact area was measured using the MS, HS, and HHS Prescale films. The analysis was done using the FPD-8010E scan software. In order to minimize the measurement error, the average value of five repeated measurements was used for the comparison with the analytical results. The roundness of the contact patches was checked and from the measured value of the circular contact area, the contact radii were calculated.

2.3. Finite element model

The experimental setup including the Prescale film was simultaneously simulated using the finite element program Abaqus 6.13.

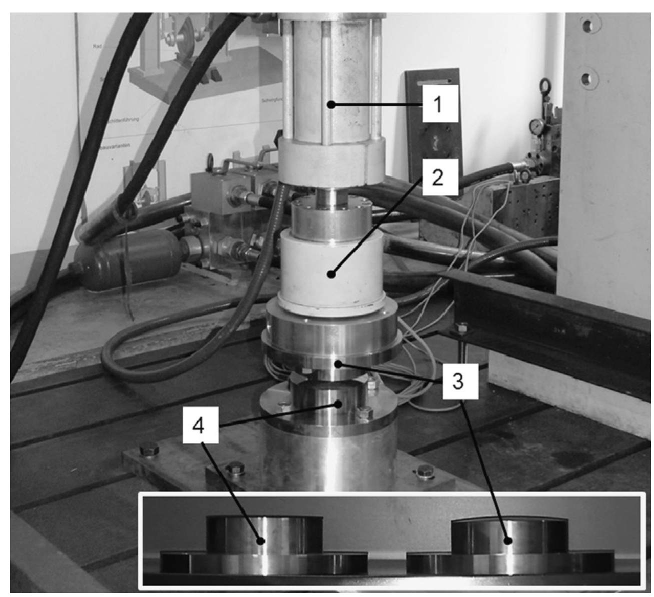

Fig. 2. Experimental setup. 1. Hydraulic jack (maximum force 100 kN); 2. load cell; 3. contact body I ($R_I = 450$ mm); 4. contact body II ($R_{II} = \infty$).

Table 1
Analytical results of the experimental setup without the film at the different loads. *F* = Force; a_H = *Hertzian contact radius*; p_0 = *maximum contact pressure*; δ = *approach of distant points.*

F (kN)	a_H (mm)	p_0 (MPa)	δ (mm)
25	4.18	682.6	0.039
50	5.27	860.0	0.062
75	6.03	984.5	0.081
100	6.64	1083.6	0.098