Two-Material Rail Development to Prevent Rolling Contact Fatigue and to Reduce Noise Levels in Curved Rail Track

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Abstract

Results from the European 5\textsuperscript{th} frame research project “INFRA-STAR” are presented. The goal of the project is to prevent rolling contact fatigue (RCF) and to reduce squeal noise in curves by applying an additional surface layer material on the top of the railhead, resulting in a two-material rail. A dynamic train-track interaction model is used to provide the contact forces. Wheel-rail profiles, wheel-rail friction, vehicle data, track data and operating conditions are included to calculate the wheel-rail contact forces and spin moments, contact positions and load distributions in the contact patch. The contact pressure, friction coefficient, coating thickness, material properties of the coating and the rail material are used to calculate the shakedown limit, which is then used to predict the rolling contact fatigue performance of the system. The presented paper will detail the above proposed work as well as the work on theoretical modelling, twin disc testing and metallurgical research completed to date. The development of the surface layer application methods that are used and the further objectives of the INFRA-STAR project will also be discussed. The presented paper will account for interesting and industrially relevant RCF- and noise related research work. We believe that it will be of great importance in the future development of reliable and durable rail infrastructure.

\textit{Keywords:} rolling contact fatigue; rail surface coating; FE simulation; shakedown limit; crack initiation; train-track interaction model

1 Introduction

Rolling contact fatigue (RCF) is one of the major current limitations of railway infrastructure productivity. Squats, Tache Ovals, Shelling and Head Checks are all forms of RCF, but Head Checks are prevalent in curves and switches where flange contact towards the gauge corner may result in increased slip and decreased wheel-rail contact area. These surface-initiated cracks can ultimately lead to complete failure of the rail (Figure 1). In addition to RCF, high noise emission (up to 100-110dB) caused by stick-slip at the wheel-rail interface is one of the main environmental problems in Europe.
The focus of the INFRA-STAR project is on improving the durability and lifetime of the rail, and also on reducing noise emission, along stretches of track with narrow and moderate radius curves, high traffic volumes and high axle loads by applying a surface coating to the railhead. The main goal of the project is to develop a railhead with an additional surface layer (the INFRA-STAR two-material rail) which prevents rolling contact fatigue and reduces noise emissions in narrow radius curved rail.

Two application technologies for processing two-material rail are studied in the project: rolling technology for application to new rail during the production process, and laser cladding technology for application to the existing infrastructure or in the production process of new rail.

In the Corus rolling application process (Figure 2), the additional surface layer is rolled in during rail production. To achieve this, the surface material is welded/cladded onto the bloom before rolling. Before cladding, the area is cleaned and the bloom is pre-heated. Position and thickness of the welded surface layer is calculated according to the desired position and target value of the surface layer on the final rail surface (today from 1 to 4mm). After welding the additional surface layer, the standard rolling operation on the bloom and the standard finishing operation on the rail are performed.
The Duroc laser cladding technology (Figure 3) is a surface and materials treatment process by which alloying materials, and even ceramic additives, in the form of powder materials can be combined to produce unique materials. Certain demands are imposed on the materials in components and on surfaces to provide the desired tribological properties.

Figure 3, the Duroc laser cladding application process.

The choice of coating is very important. Two sample layer materials prepared by Duroc have been tested for RCF resistance, bonding and traction coefficient in the laboratory and the results are presented below. However, to remove the need to test every new potential layer material (either in the laboratory or in the field), the theory of coated rails is being developed. This requires a model of track dynamics at the gauge corner, railhead stress determination, and an understanding of two-material railhead response to such severe loading.

1 Laboratory Results

Laboratory testing of two types of Duroc laser-cladded rail steel was carried out at the University of Sheffield on the SUROS twin disc test machine (described in detail by Fletcher and Beynon [1]). The outer diameter (i.e., the running surface – see Figure 4) of the specimens was 47.3mm, and the coating thickness on the rail discs was typically 0.6-0.7mm. The base material of the rail disc specimens was cut from a UIC 900A rail, while the wheel disc material was cut from a B5T wheel.

Figure 4, test disc specifications (dimensions in mm).
Of the two coatings tested, one was marked Duroc 508, the second Duroc 222. Both proved to have excellent rolling contact fatigue and wear resistance under wet conditions with a Hertzian peak contact pressure of 1.5GPa (an applied load of approximately 7.18kN) at –1% slip. These experiments started with 1,000 dry cycles, a technique normally useful for initiating cracks which would subsequently be propagated, followed in one case by 20,000 wet cycles and in another case by 200,000 wet cycles. The lubricant was distilled water and applied at the rate of two drips per second. In each case the eddy current probe detected no signs of cracking of the rail disc. A similar experiment carried out on an uncoated rail disc resulted in a gate-triggering crack after 1,000 dry cycles and a mere 3,000 wet cycles.

Traction coefficient was measured for the duration of each test (see Figure 5). In the reference test with the uncoated rail disc, the traction coefficient rose to 0.44 during dry cycling, and steadied at 0.21 during wet cycling. The dry traction coefficient for the 508 coating was 0.42-0.43, effectively the same as for the uncoated specimen, while the traction coefficient during dry cycling for the 222 material was 0.39. However, traction behaviour during wet cycling was markedly different for the two materials. During the first 40,000 wet cycles of the long duration test with the 508-coating, the traction coefficient rose to a maximum of 0.33, accompanied by rusting of the surface; subsequently it dropped gradually, accompanied by de-rusting of the surface, reaching 0.21 after 200,000 cycles. With the 222-coating, on the other hand, the traction coefficient peaks at 0.30-0.32 after 5,000-7,000 wet cycles, but steadies at 0.16 by 20,000 cycles. Therefore in both dry and wet cycling, the 222-coating showed the lower coefficient of traction of the tested samples.

Figure 5, traction coefficient vs. number of cycles. Left (1,000 dry + ≈50,000 wet) DUROC 508 and DUROC 222. Right (+150,000 wet) DUROC 508 only.
After the twin disc experiments the rail discs were analysed using metallographic methods. The running surface (Figure 6) was examined using a scanning electron microscope, metallographic specimens of both transverse and longitudinal cross-sections were examined. Vickers hardness measurements were carried out on these samples.

![Figure 6, running surface rail disc (DUROC 222, 1,000 dry + 55,000 wet cycles).](image)

Results from the metallurgical investigation were:
- Contacting Surface (508 & 222 samples): micro-crack formation was not observed (neither at the surface nor at the interface). Depth of the plastic deformation of the coating surface material varied between 2 and 18µm. After the same testing parameters, depth of plastic deformation for a untreated rail disk is about 0.3 – 0.4 mm.
- Interface (508 & 222 samples): the interface bonding quality showed excellent behaviour. For none of the examined discs, micro-crack formation or delamination was observed.
- Rail base material (508 & 222 samples): the heat affected zone (HAZ) consists of a predominant tempered martensitic or bainitic structure directly at the interface, gradually transforming into annealed pearlite and finally to an all pearlite structure away from the interface.

2 Theory

One objective of the INFRA-STAR project is to analyse two-material rails with respect to RCF performance. The material that is cladded to the railhead surface (i.e., the coating) has higher hardness, higher yield stress limit and, ideally, lower friction than the rail material (i.e., the substrate). These coating characteristics reduce (or prevent) plastic flow, and thus head checks, in the railhead. The RCF performance of the two-material rail is further influenced by the thickness of the coating and by the combination/interaction of coating and substrate material properties. In the INFRA-STAR project, the analysis comprises three steps:

1. For any train traffic situation: calculation of wheel-rail contact forces, spin moments, contact positions, contact loads distributions and contact patches using train-track interaction models.
2. The results from Step 1 are used in a finite element (FE) tool developed for RCF analysis of railway rails. In the FE tool, arbitrary train traffic situations can be simulated and analysed for RCF.

3. The rail stresses calculated in Step 2 are used to carry out shakedown calculations, study RCF performance for different coatings and train traffic situations, and to determine the risk of RCF crack initiation.

2.1 Calculation of wheel-rail contact conditions and loads on the rail

The curving performance and wheel-rail contact conditions in two different cases of railway operation are simulated using commercial software for multibody dynamics and contact mechanics. One case treats the heavy-haul traffic on Malmbanan in the northern part of Sweden. A non-lubricated circular curve that is suffering from severe RCF is investigated. The operating conditions at the test site include a curve radius of 595 m, axle load 25 tonnes and train speed 40 km/h. The standard three-piece bogie design used on Malmbanan is illustrated in Figure 7. The second case studies commuter traffic in the Paris metro in a sharp radius circular curve where squeal noise levels are high. Here the curve radius, axle loads and train speed are 75 m, 9 tonnes and 40 km/h, respectively. Lubrication is supplied through lubricators mounted on the wheelsets.

Figure 7, Ore-wagon bogie design: three-piece bogie of type Ride Control [5]

Vehicle motion, wheel-rail contact forces, creepages and where contact occurs on wheel tread and railhead are predicted using the commercial computer code GENSYS [2] for simulation of dynamic train-track interaction. In GENSYS, Hertzian contact mechanics assuming elliptical contact surfaces and FASTSIM (Kalker’s simplified theory) for the tangential contact solution are combined in order to shorten simulation times.
However, wheel-rail surface profile curvature can change significantly within one contact patch. This is a violation of the assumptions made in Hertzian contact mechanics. Locally this leads to higher contact stresses and requires a more precise analysis. Such an elastic analysis of normal and tangential contact load distributions can be performed using the commercial software CONTACT. Based on contact locations, contact forces, contact geometry and creepages supplied from GENSYS, more detailed stress distributions on the contact patches are calculated. In certain cases when contact occurs between the wheel flange and the rail gauge corner, half-space theory and linearly elastic material behaviour may no longer be valid. Then normal and tangential contact load distributions have to be calculated by use of a time-consuming finite element analysis instead of using CONTACT. This time-consuming FE-analysis involves elasto-plastic material models and use of restraint conditions to find the contact region and contact pressure.

Wheel and rail profiles change substantially during operation due to wear and plastic deformation. During maintenance on Malmbanan, all wagon wheels in a train are not replaced or reprofiled (turned) simultaneously. The wheels on a certain wagon may even have a number of different wheel profiles. Instrumented wheelset measurements on different three-piece bogie designs have been reported [3]. These measurements showed large variations in lateral force levels depending not only on curve radius and coefficient of friction in the wheel-rail contact, but also on the actual individual curve. The importance of matching measured wheel and rail profiles in order to obtain good agreement between measured and simulated contact forces was emphasised.

Thus, in order to perform a robust analysis of RCF, the scatter in wheel and rail surface profile and the resulting wheel-rail contact loads must be accounted for. A sensitivity analysis in order to investigate the influence of different measured worn wheel and rail profiles on maximum normal contact pressure, contact position and dimensions of contact patch have therefore been performed. In total, 12 different combinations of wheel and rail profiles have been investigated.

The lateral contact position of the leading outer wheels in the two bogies of one ore wagon was stable around 20-25 mm from the top of the railhead (towards track centre) independent of wheel-rail profile combination. This is in good agreement with observations made at the modelled test site regarding the location of RCF cracks. The highest normal and tangential contact loads occur for the outer wheel of the leading wheelset in each bogie. Full sliding occurs in this contact patch. The maximum normal contact pressure according to Hertzian contact mechanics (ellipsoidal contact pressure distribution) varied between 2.5 and 4.1 GPa when the six different worn wheel profiles and new UIC60 rails were adopted. When both wheel and rail profiles were worn, the maximum normal contact pressure dropped to 0.7-2.1 GPa.

Results from CONTACT on a specific wheel-rail profile combination indicate a maximum normal contact pressure 6.6 GPa compared to 3.4 GPa obtained from Hertzian contact mechanics. The high level of the calculated normal contact pressures means that the assumptions made both in Hertzian contact mechanics and CONTACT (elastic half space assumptions) are violated. Similar high contact stresses are reported in reference [4]. In this Reference, it is discussed that high strain rates, plastic shakedown and hardening means that admissible stresses are increased above the
normal yield stress limit. On the other hand, the calculated stresses may be reduced if the measured wheel and rail profiles are smoothened before they are adopted in the simulations (to account for measurement errors). Further investigations of the calculated stresses are unfortunately outside the scope of INFRA-STAR.

2.2 Calculation of rail stresses caused by trains running at track

A train vehicle running on track causes stresses to the rail. The stresses introduced in the rail come from two rail responses:

1. *Global response*: Stresses are introduced into rail due to global rail beam bending and torsion, which is caused by the resultant longitudinal, lateral and normal force components acting on the rail. This response is influenced by the properties of the track components, their interactions and system behaviours, and also the train-track interaction.

2. *Local response*: The local wheel-rail contact causes locally, near and at the contact zone, very high stresses and large stress gradients. The stress levels are close to, or above, the yield stress limit.

Both of these responses must be taken into account when making novel RCF analysis of rails. In Ringsberg et al. [6], it was shown that the global response affects the residual stress state by some 10 per cent (longitudinal bending stress), as compared with the local response that govern RCF damage.

A tool has been developed by Ringsberg et al. [6] that can be used to simulate train traffic situations of arbitrary track and analyse the rails for RCF. It is called the finite element (FE) tool and it consists of two FE models describing the track: (i) the track model, and (ii) the rail model. Both of the models were created in the commercial FE code I-DEAS. The FE analyses are performed in the commercial FE code ABAQUS that enables the user to employ user-supplied subroutines for more advanced constitutive material models. The FE tool is described briefly below (see Ref. [6] for a detailed description).

2.2.1 Presentation of the FE tool

The FE tool considers the global response using the track model and the local response using the rail model. A substructure modelling technique is used to account for both the global and the local response in the rail simultaneously, by using time-dependent boundary conditions (TDBC). The TDBC are calculated in the FE analysis using the track model, and then used in the FE analysis using the rail model. Hence, the stresses introduced in the rail from both the global track behaviour, and the local wheel-rail contact, is incorporated in the rail model FE analysis. Figure 8 shows a flow chart of the FE tool.
The track model is a beam element model which fully describes a track with all of its components, i.e. the ballast material, the sleepers, the pads and the rail. The material formulation for the components is elastic. The loads used in the track model analysis are calculated in the Step 1 (see Section 3.1) using the software GENSYS. The wheel loads from a running train vehicle are represented by a distribution of discrete load collectives, one for every wheel. A load collective is defined by three mutually orthogonal and, over time, constant components, corresponding to the resultant of longitudinal, lateral and normal rail force. In the dynamic FE analysis, the load collectives travel with a defined (constant) velocity along the rail in the rolling direction. No inertia or damping forces from the vehicle is considered. However, a magnification factor applied to the wheel axle load can be used to approximately include dynamic effects from the vehicle. In addition, the FE analysis using the track model is done for only one train running over the track FE model. The results from the analysis are the TDBC, which are calculated as the difference between the displacements (translations and rotations) for two rail cross-sections. In the present work and in Ringsberg et al. [6], the displacements for two rail cross-sections distanced 12cm, and positioned in the middle between two sleepers, were used to calculate the TDBC.

The rail model is a 12cm three dimensional (3D) solid element model that has an elastic-plastic material model definition (see Ringsberg and Josefson [7] and Ekh et al. [8]). The number of wheel-rail contacts and their positions on the rail are determined in the Step 1 (see Section 3.1) from calculations using the software GENSYS and CONTACT. High mesh densities are required in the contacting regions in the rail model to resolve the stress and strain gradients. The contact loads that represent the normal wheel-rail contact loads are applied as distributed pressure loads. These loads can have either a Hertzian distribution or any distribution as calculated from e.g. CONTACT [7]. Tangential contact load distributions are also applied, similarly to the normal loads. Full sliding is simulated by using friction coefficients for the longitudinal and lateral directions as weight factors multiplied to the normal contact load distribution. Furthermore, the contact loads are moved incrementally over the rail model. The TDBC calculated in the track model FE analysis are continuously updated for every contact load movement. One wheel passage, here

Figure 8, flow chart of the FE tool.
defined as a load cycle, is the passage of one set of contact loads over the rail model. The user controls the number of load cycles in the FE simulation.

The software CONTACT uses half-space theory in the calculation of the contact loads used in the rail model. The validity of this assumption was investigated in a comparison between FE analysis using the rail model approach and FE analysis where both the wheel and the rail were modelled by finite elements. The wheel-rail contact was positioned on the railhead top and rolling-sliding along the railhead's longitudinal symmetry line. There was very good agreement in results between the two cases, and hence, the approach used for the rail model was deemed reliable. The computational efforts using the rail model as compared with the full wheel-rail FE model were much less. The rail model approach was therefore preferred.

2.2.2 Use of the FE tool in the INFRA-STAR project

In the INFRA-STAR project, several train traffic situations will be analysed with respect to RCF performance of the two-material rail system. The contact conditions as calculated in Step 1 (see Section 3.1) will be analysed using the FE tool, to calculate the stress variations in the railhead during wheel-rail rolling-sliding contact loads. Furthermore, experiments carried out in the INFRA-STAR project show that the steady-state material behaviour is elastic shakedown (see also section 3.3) for the two-material system. Based on this observation the following calculation procedure is employed in the project.

- The contact positions and patch sizes calculated in Step 1 are used to mimic the wheel-rail contact situation using the rail FE model. The contact load distributions applied to the rail model are assumed to follow Hertzian assumptions. In Figure 9, the FE mesh of the rail model for an example of wheel-rail contact on the iron-ore line Malmbanan in Sweden, is presented.
- The material response is known to be elastic shakedown. The coating-substrate interaction is accounted for in Step 3 in the shakedown calculations (see Section 3.3). Here, small difference in the Young’s modulus (E) and the Poisson’s ratio (ν) between the two materials is assumed.
- In a separate FE analysis, using the rail model, the influence of TDBC on the rail stresses could have been used in Step 3. However, this possibility in the FE tool will not be incorporated in the INFRA-STAR calculations.
- In separate FE analyses, using the rail FE model, contact load distributions in the longitudinal, lateral and normal directions with unit maximum peak values are used. The stress results from the FE analyses are scaled in Step 3 using the CONTACT peak values of the contact loads.
- Because the material response is known to be elastic shakedown, the results from the separate FE analyses using tangential and normal contact load distributions can be superposed. Hence, several cases can be examined in detail depending on relationships between the contact loads, coating thickness, coating material and friction coefficients.
2.3 Shakedown theory, RCF analysis and performance of the system

Repeated loading of rail steels will lead either to elastic or to elastic-plastic behaviour (see Figure 10). In elastic behaviour, material recovers completely from external loading without permanent deformation. In elastic-plastic behaviour, however, there is plastic deformation (deformation beyond the elastic limit) which is irreversible, and this results in residual stresses and probably work hardening. Thus, although the early cycles may be elastic-plastic, an elastic steady state may ensue. This process is termed elastic shakedown, and the maximum load for which this is possible is called the elastic shakedown limit. Since the material deforms only elastically in the steady state, it has long life which can be calculated using approaches based on high cycle fatigue.
Sometimes elastic shakedown occurs because plastic deformation and/or wear during early cycles causes a change in contact geometry. With rails the profile after grinding is not as conformal with wheel profiles as is the profile of a worn rail. Contact, therefore, is made over a relatively small area and leads to relatively high stress (in excess of the shakedown limit) but as the rail deforms plastically and/or wears the profile becomes more conformal, the contact area increases, and the contact stress drops (to beneath the shakedown limit). This causes problems with head-hardened rails (i.e., rails heat-treated during manufacture), which are more resistant to plastic deformation and retain their original profile, and consequently the higher contact stress, for longer.

If the applied load exceeds the elastic shakedown limit then the ‘steady state’ will be elastic-plastic, with plastic flow occurring with each loading. If the load or contact stress is below a certain limit termed plastic shakedown limit, then the cycle of plasticity is closed and the material fails by low cycle fatigue (LCF). For a contact pressure above the plastic shakedown limit the strain cycle is open and there will be a unidirectional component of plastic flow. This unidirectional component accumulates cycle by cycle, a process known as ratchetting. The plastic shakedown limit is also known as the ratchetting threshold.

Ductility is a measure of how much plastic strain a material can survive. Ratchetting, by its very nature, leads to failure at the point where ductility is exhausted. In rails loaded above the shakedown limit, each loading results in some plastic shear, and this accumulates until a critical shear strain is reached and failure occurs. This mechanism is ratchetting failure (RF) and is discussed by Kapoor [9].

Failure/damage, whether by low cycle fatigue or ratchetting, causes wear (i.e., loss of material from the rail surface) and leads to the initiation of rolling contact fatigue cracks. The focus has shifted recently from controlling to preventing head checks, and for this it is necessary to improve operating conditions. An appropriate applied surface material will move the steady state ‘operating point’ out of the ratchetting regime and into elastic conditions. Figure 11 shows how the operating point is affected by coating thickness and contact width. Clearly the thicker the coating the better – although, cost aside, there are probably limitations imposed by the production/application method. Equally clearly, wheel-rail contact operates in a very different regime from twin disc tests, so the very promising lab results may not translate to rails in the field.
Figure 11, the curve depicts the shakedown limit which varies with the ratio of coating thickness to the semi-contact width. Larger contacts or thinner coatings result in a lower shakedown limit. If the load exceeds the shakedown limit then ratchetting occurs.

The shakedown limit in Figure 11 depends on the coefficient of friction and on the shear yield stress of both the base material and the coating. Wong et al. [10] have calculated shakedown limits of line-loaded coated materials for different ratios of shear yield stress and different coefficients of friction. For the specific case of the twin disc tests, these shakedown limits are plotted in Figure 12; the operating point (peak pressure is 1.5GPa, and coating thickness is approximately twice the semi-contact width which is 300 microns) is marked. Values of friction have been chosen as those observed (0.4 for dry; 0.27 and 0.16 for the Duroc 508 and 222 coatings respectively) and the shear yield stress has been estimated from hardness measurements (410HV and 370HV respectively, and 270HV for the base material). The operating point is well within the shakedown limit, so ratchetting should not occur – and this is in agreement with the lab tests in which no cracks were detected, even after 200,000 cycles.

Figure 12, operating point for the twin disc lab tests, and shakedown limits for the 508 and 222 coatings for steady-state dry and wet friction coefficients (μ), h = coating thickness and a = semi-contact width. Vickers hardness (HV) is 410 and 370 respectively, and 270 for the base pearlite.
Similar shakedown maps will be drawn up based on the stresses calculated in Step 2 of the theoretical model.

3 Main achievements and further objectives

In the first year of INFRA-STAR, two materials have been selected with very promising RCF resistance during laboratory testing. Field test operating conditions, contact forces and contact positions, have been calculated using a train-track interaction model. Surface coating application techniques have been optimised and prototype two-material rails (field test samples) are produced.

Currently first field-testing is undertaken on Malmbanan in the northern part of Sweden. Two-metre lengths of Duroc treated two-material rail were put in track 2nd of July 2001. In September 2001, two pieces of 20-metre long cladded rail will be installed here. The two-material rail will replace the original outer rail in a curve that is suffering from severe RCF. In 2002 full scale field-testing will start at Paris metro (RATP), focussing also on squeal behaviour.

Coating materials and application techniques will be optimised, new coating materials will be selected and tested, both in laboratory and in the field. The train-track interaction models will be validated through field measurements.

Figure 13, field trial on the Malmbanan: two-metre lengths of rail coated with Duroc’s 508 and 222 material. The type of rolling stock is four-axle freight wagons for iron ore transportation, axle load 25 tonnes.
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