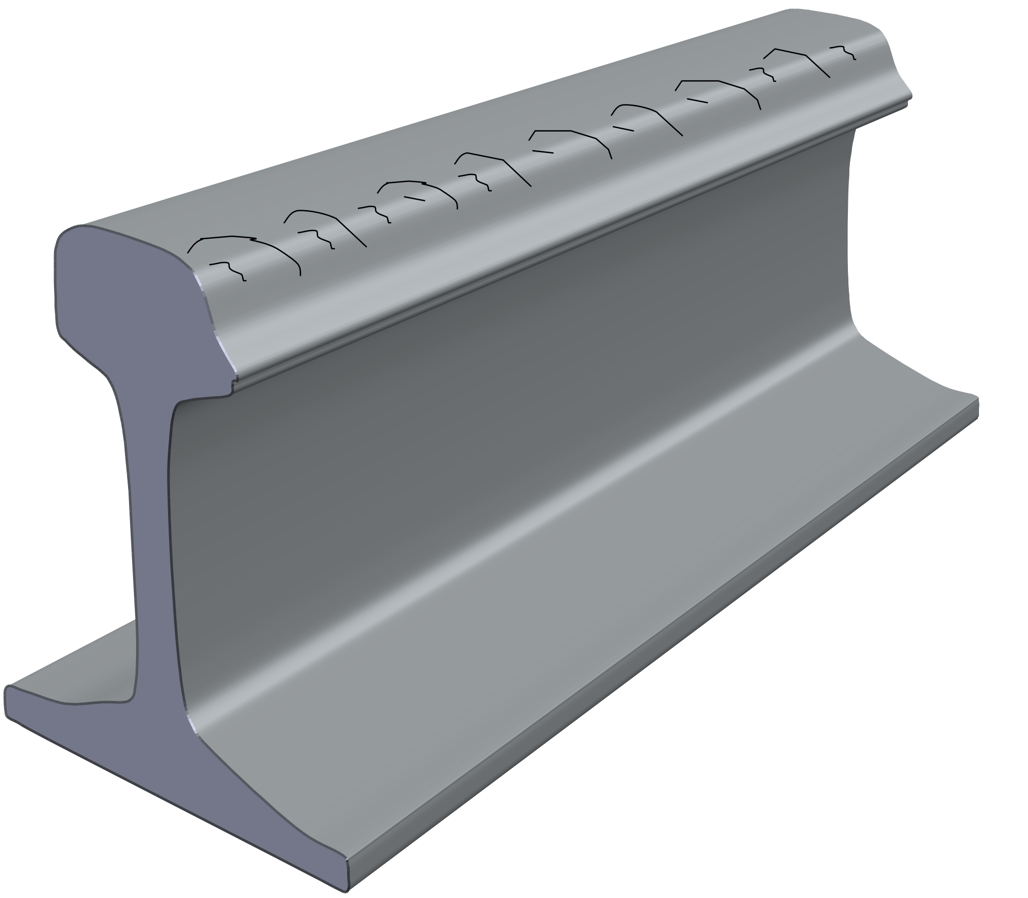
INNOTRACK
Innovative Track Systems

SIXTH FRAMEWORK PROGRAMME

INNOVATIVE LABORATORY TESTS FOR RAIL STEELS



Deliverable report D4.3.8

Guideline

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1. Executive summary

There is a need for laboratory tests of rail material by railway operators as well as by manufactures. The tests should represent operational conditions for the rail material. They should allow withdrawing less valuable products from far more expensive field tests.

This guideline is based on the experience from the WP4.3 partners with respect to laboratory tests for rail steels.

As the operational demands on rail material may differ from site to site (with respect to the curvature etc.), a suitable preparation of the laboratory tests is necessary. It should start with a definition of the conditions to be tested, e.g. with a testing matrix.

According to present knowledge, related tests can be done at twin disk test rigs or at specialized full-scale linear test rigs. Full-scale roller rigs are not recommended because the fixing of the samples is difficult and the preparation of the rail material requires a huge effort.

After testing the wear, RCF and deformation should be evaluated in accordance with a consistent evaluation scheme. Metallographic investigations could be applied especially with respect to quantifying material deterioration.

The compliance with the pre-defined requirements should be monitored throughout the test since contact conditions may vary due to profile wear and specific test rig deviations. If such deviations occur, the test conditions should be re-evaluated through numerical simulations. Thus, the effect on the test results may be estimated.

The results of testing on twin disk tests as well as those on a linear test rig can provide results suitable for practical use. An evaluation of the different tests including a rough estimate of effort is given.

2. Introduction

The activities of WP 4.3 have been focused on the reduction of cost for testing of new rail and switch materials, which is of practical importance for railway infrastructure operators as well as for the rail industry. Such tests are usually being performed as field tests on specific rail sites. The reasons for establishing laboratory tests within the INNOTRACK program are:

1. As the programme focuses on LCC reduction, laboratory tests could provide a link between metallurgy and rail–wheel contact mechanics that would affect future rail steel developments in order to reduce rail maintenance cost.
2. Controlled tests in the laboratory will enable extrapolation of the observed site results to a greater range of duty conditions.
3. The cost and the time required for laboratory tests can be easily estimated.

Laboratory tests have been planned and carried out at different test rigs by voestalpine Schienen GmbH (VAS), University of Newcastle upon Tyne (UoN) and Deutsche Bahn AG (DB). All tests aimed to induce RCF and wheel/rail wear under defined contact conditions. Numerical simulations were used in order to allow an understanding of specific features of the test rigs and quantify the test conditions in an objective manner.

It was the aim of WP 4.3 to provide a set of rail material laboratory tests that reflect the expected performance of rail steels in service better. From these tests, the material features that characterize the behaviour of the materials in situ should be derived.

The challenge was to identify which material parameters are of relevance for the rail integrity. Therefore, the link between metallurgy and rail–wheel contact mechanics needs to be justified mechanistically rather than empirically if the industry is to target future rail steel developments. In this context, it is important to examine the micro structural changes that occur due to stresses introduced by passing traffic and their association with rail grades and the presence of RCF cracks.

3. Planning and performing laboratory tests

3.1. Constitution of the testing matrix

A testing matrix should be established in order to define comparable conditions for the laboratory tests, especially when they are being performed at different rigs.
The conditions should refer to the operational conditions on a specific site or with respect to a specific kind of railway operation as e.g. acceleration. They should also consider the axle loads and the bogie construction of cars typically passing the track site. Table 1: gives an overview on parameters to be defined.

Table 1: Testing matrix

Parameter	Definition (examples)
A: Profile pairing	
Rail profile/inclination	e.g. 60 E2 / 1:40 n/a for twin disk test
Wheel Profile	e.g. S1002 n/a for twin disk test
B: Other contact conditions	
Angle of attack	e.g. 0.25° n/a for twin disk test
Longitudinal Slip	e.g. 1%
Lubrication	Dry conditions or water/lubricants at an interval of … sec.
C: Load	
Vertical load	e.g. 100 kN per wheel substituted by equivalent contact pressure for twin disk test
Lateral load	e.g. 10 kN, n/a for twin disk test
load cycles	total number of passes or total load in MGT
D: steel grades	
Wheel steel grade	e.g. R7
Rail steel grade	e.g. R350 HT

It should be noticed that:

- Twin disk test rigs are restricted to rather simple cylindrical contact without any lateral forces or lateral slip. Here, equivalent conditions must be derived from Hertzian contact calculation based on profile pairing.
- Lubrication, especially wetness plays an important role in rail wear and RCF. Nevertheless, the tests performed within WP 4.3 indicate that tests under dry conditions generate results with lower scatter.

3.2. Output definition

The test output has to be defined in advance to the tests. The test report should contain the results regarding wear, RCF and microstructural changes during testing such as:

- Measurement of the wheel and rail profiles at the start and the end of the tests. In case of twin disk tests, the wear is being measured by weighting. In case of full scale tests the profiles should be measured e.g. using Miniprof equipment
- Photographic documentation of the surface. It is recommended always to document both contact partners, i.e. also wheel surfaces.
- Eddy current measurements at the surface (even during testing, if possible) in order to early determine the initiation RCF cracks
- Final metallurgical examination of the material properties. The samples should be prepared in the standard metallographic way as e.g.: mounted in Bakelite (conducting if examination in SEM is required), surface grinding carried out to ensure parallel surfaces etc.
- Analysis by electron back scatter diffraction technique (EBSD) on cross sections can establish the depth of damage in test rig samples and compare them to findings from the track. The overall EBSD analysis appears to be a promising technique for assessing depth of damage and is able to discriminate between rail grades.

The Appendix contains a detailed description of the methodology for measuring and evaluating of RCF under laboratory testing conditions.

4. Testing methodology

4.1. Twin disk testing

4.1.1 Testing configuration

Twin disk tests use cylindrical disk specimens cut from rail and wheel sections. Related tests were performed by UoN at the SUROS (Sheffield University Rolling Sliding) twin disk machine.
Usual disk dimensions are 47mm diameter and 10mm track (running) width for the (Figure 1). These are maximum measures suitable for machining disk specimens from real rail and wheel sections. Other machines may use different dimensions.

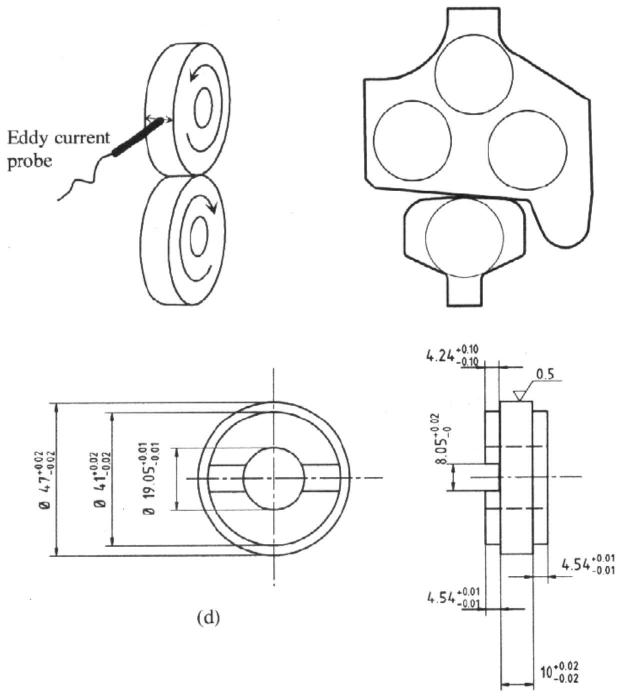


Figure 1: Disk specimens (example) for twin disk tests at SUROS test machine.

The following rules should be obtained at twin disk testing:

- The “rail” disk is usually driven at fixed speed by the lathe, while an A/C motor drives the “wheel” disk.
- The pressure forces between the two disks are applied by a fixed and a pivoted bearing where the latter is loaded by a hydraulic piston.

- The speed of the wheel disk, and thus the relative (longitudinal) slip, should be controlled and monitored precisely by a measurement system.
- The torque acting on both drive shafts is monitored by the measurement system too.
- During testing, an eddy-current probe scanning system should be used to check for cracks.
- Water or other lubricants may be applied during testing.

A detailed description of the test situation can be found in INNOTRACK report D4.3.1. [1].

4.1.2 Evaluation of twin disk testing

The ability of twin disk tests to quantify wear and RCF of different rail steels could be shown within WP 4.3. Trends such as the decrease of wear and RCF with increasing strength could be established.

The twin disk tests represent a good way of testing materials under closely controlled conditions, however, when using the laboratory results to understand real field behaviour of rail steels several points should be kept in mind. First, the twin disk conditions represent extreme cases, for example, of wear under completely dry and clean high friction conditions, or of continuous wet running. In reality, rails are rarely completely clean, and even in rain, the first wheel of the leading bogie will displace most water from the rail, and later wheels will see less water at the rail-wheel contact. Second, the twin disk simulation cannot be used to study the effect of rail–wheel profiles, since these are not present in the test.

The extreme and rapidly repeated conditions in twin disk testing help to reveal differences between the materials, but in translating the results to the field it should be remembered that such severe conditions are rarely encountered repeatedly over long periods. The great value of twin disk data is for input to modelling rather than direct translation to field behaviour.

4.2. Full scale testing

4.2.1 Testing configuration, VAS linear test rig

Full-scale tests use wheel and rail samples with profiles at the size of the original or sized down by not more than 50%. This ensures the influence of the profile shapes on RCF and wear to be considered during testing.
A linear test rig configuration was provided by VAS. The test stand consists of a 1.5m piece of test rail, which is attached to a carriage. The carriage moves hydraulically underneath a common locomotive or freight wheel, see Figure 2. For more details, see report D4.3.1. [1].

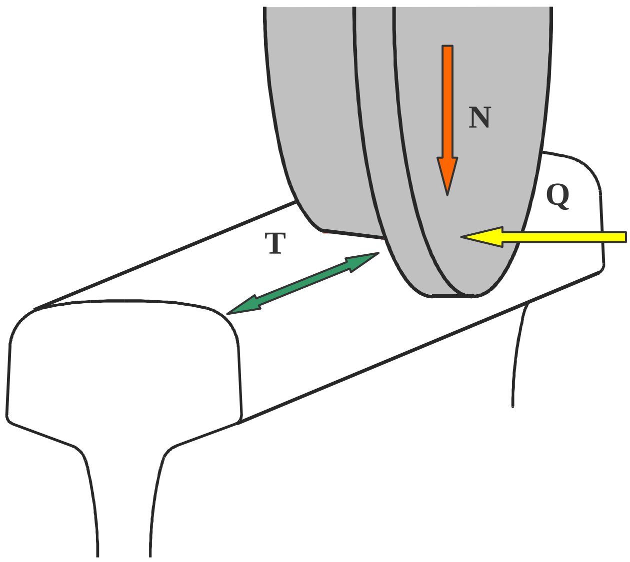


Figure 2: Linear test rig loading conditions – forces

It is recommended to simulate uni-directional running. Then, the wheel is lifted up while the rail carriage is returning at the end of a pass, and then gently set down on the rail to start another rolling cycle.
The following rules should be obtained at full scale testing:

- The rail section and the wheel should correspond to regular operational conditions.
- The vertical, lateral, and longitudinal forces (see Figure 2) should be regular, i.e. at least a vertical load (N) of 100 kN per wheel.

- The forces must be measured within the hydraulic cylinders.
- Rail inclination and angle of attack should be applied
- Water or other lubricants may be applied during testing.
- Rail and wheel positions should be recorded in all three dimensions as well as air temperature and air humidity.

4.2.2 Evaluation of full-scale testing

Within WP4.3, it could be shown that the linear full-scale rail wheel test rig was able to demonstrate that an increased wear resistance comes along with an increased RCF resistance of pearlitic rail steels. This corresponds with experience.
A number of differences between real track conditions and the test rig could be identified. They concern

- the lack of a second wheel which would stabilize the chamber angle.
- the influence of laboratory conditions (e.g. closed environment, low humidity, no rain) on friction coefficient,
- the fact that only one wheel contacts rail, which “unnaturally” influences the profile changes.

4.3. Tests at full-scale roller rig (DB)

A tests on the DB full-scale wheel-on-roller test rig with a rail roller made of a bended rail head was performed over a total load of 20 MGT. The attempt to establish a stable test procedure with exchangeable rail material on a roller rig has failed because of excessive requirements to the fixing of the rail.
Nevertheless steady contact conditions could be established during the tests, which could be evaluated by contact simulations and material investigations. For details, see INNOTRACK report D4.3.3. [2]

4.4. Amount of work

In Table 2, an estimate of the effort for the different test methods is given. It is based on the time to be consumed for preparing and performing the test and for the time needed for data collection. It should be noted that preparing the specimen for the tests needs a specific effort. Nevertheless, twin disk testing seems to be the method with lowest overall cost while full-scale roller rig tests need expensive preparing of rail profiles.

Table 2: Rough estimate of effort for one test

	samples & material needed	test preparation and follow-up *	duration of the test **	measurement and data collection ***
Twin disk, SUROS	special test sample, ∅47 mm	one hour	one hour	one hour
Linear test rig VAS RSP	rail segment, 1500 mm single wheel with new S1002 profile	3 man-day	5 days	2 man-days
Roller test rigs DB, C and A	2 rings of rail material newly profiled wheelset with bearing, new 1002 profiles	3 man-days	1 week	2 man-days

* includes all objects needed for performing the test, i.e. the samples to be tested and their counterpart.

** includes the man-time needed for establishing one test configuration at the rig

*** includes the man-time needed for doing measurements, storing and evaluating data etc. This does not include the time needed for an overall evaluation of results.

5. Accompanying numerical analysis

A physically sound approach to compare test conditions (between each other or towards field conditions) is to translate the conditions to an equivalent measure that correlates to the studied deterioration measure; in the current study the RCF life of the rail samples. Two configurations that have the same magnitude of this equivalent measure are then considered as equivalent and RCF lives for other configurations can be evaluated from interpolation.

For test evaluation, it is recommended that the subsequent numerical analysis as carefully as possible consider the worn profiles, the acting forces, the point of contact, the coefficient of friction in the contact *etc*.

The tests done within WP4.3 have indicated that the real test conditions may deviate from nominal conditions due to profile changes, deflections of test samples *etc*. Further, several parameters have been found difficult to assess, such as friction coefficients, point of contact *etc*.

Within INNOTRACK innovative and physically sound methods of evaluating equivalent measures and thereby compare test (and operational) configurations have been developed. These methods of evaluation are outlined below. Detailed descriptions are available in WP4.3 deliverables D4.3.4 [4] and D4.3.5 [5].

5.1. Evaluation of elastic contact conditions

The evaluation of the contact conditions has been based both on elastic analyses and of elasto-plastic FE-analyses. The latter case is described in section 5.3 below.

For an analysis of elastic contact stresses, the following facts need to be considered:

- Actual measured wheel and rail profiles need to be adopted. Note that there may be deviations in profiles along the rail (around the wheel). Preferably, these should be accounted for either by adopting a "mean profile" or by sensitivity analyses.

- Smoothing of the measured rail profiles is normally needed to avoid extreme peaks in the evaluated contact pressure.

- The simulations regarding the contact conditions need to account for the conformal contact if such exists. In such cases hertzian contact theory is not sufficient.
- The calculations should consider a wide range of friction coefficients, if it cannot be determined exactly. It should be verified that the maximum shear stress is within a reasonable order of magnitude and that the location of the maximum shear stress is in agreement with actual measured head check location.
- The contact patch size and position should correlate with the measured wear band on the rail profile. Note that the effective rail inclination of full-scale rigs may differ from the design configuration due to deformation in the load chain of the rig.
- If numerical evaluations of the test conditions are to be performed, varying operational conditions over a single test in the form of intermittent lubrication, varying load magnitudes *etc.* should preferably be avoided. The reason is that such test conditions will significantly complicate the numerical evaluation, not only regarding the contact conditions, but also regarding RCF life prediction, see section 5.2.

5.2. Comparison of theoretically predicted and experimentally found RCF lives

As stated above, it is needed to define an equivalent measure that correlates to the RCF life in order to compare test conditions. In INNOTRACK the measure that has been employed is the fatigue index, FI_{surf}, which is based on the shakedown map. FI_{surf} was employed under the presumption of full slip at measured/estimated levels of maximum coefficient of friction. Further, contact patch sizes were taken from non-Hertzian contact analyses as discussed in section 5.1. FI_{surf} can under these conditions be expressed as

$$FI_{\mathrm{surf}} = f - \frac{2\pi kA}{3F_{\mathrm{n}}} > 0 \tag{1}$$

where f is the traction coefficient, k the yield limit in shear of the rail material (in the current study adopted as k = 300 MPa), F_n the normal force between wheel and rail, and A the contact patch area.
Other possible equivalent measures ($T\gamma$, τv_{slip} etc) pose difficulties under conformal contacts due to the problem of combining non-hertzian contact analyses with simulations of dynamic wheel–rail interaction, which are needed to evaluate γ and v_{slip}. Further, in partial slip conditions FI_{surf} looses its validity.
To establish that FI_{surf} is physically sound, FI_{surf} magnitudes are plotted versus measured fatigue lives, N_f, in a log-log-scale in Figure 3 (the two points for each test configuration represent high and low estimates of friction). A Wöhler-like relationship would correspond to a straight line. The grey line represents a least-square fit given by the relationship

$$FI_{surf} = 1.78(N_f)^{-0.25} \qquad (2)$$

In relation to the description above, the recommendations regarding comparison of RCF lives are summarized in the following practices:

- Describe the equivalent measure adopted and how the various parameters have been measured/estimated/evaluated. In particular it is important in noting limitations in employed numerical models and/or measurement techniques.
- If a parameter is estimated to be within a range, perform an analysis of the sensitivity.
- Plot equivalent measure against fatigue life in a log-log-scale. A physically sound measure should show a decreasing fatigue life with increasing magnitude of the equivalent measure. Ideally the relation should be close to a straight line.

With respect to testing, the following practices are recommended:

- Before the testing start, documentation practice in general and the definition of what constitutes “rolling contact fatigue initiation” in particular should be decided.
- The planned numerical evaluations should be decided beforehand so that relevant parameters can be (as much as

possible) monitored throughout the testing. Note that this also includes items indicated in section 5.1.

- The test conditions should cover a sufficiently large span of RCF lives so that the evaluation in Figure 3 is possible.

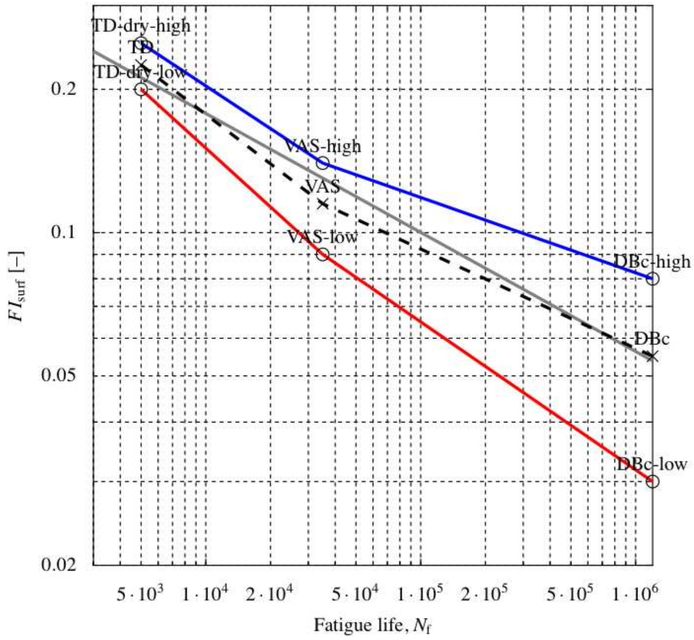


Figure 3: Theoretically evaluated fatigue index FI_{surf} plotted against measured rolling contact fatigue initiation lives for three different test rigs.

5.3. Elasto-plastic analysis of contact stresses and RCF life

To explicitly analyse the plastic deformation in the contacting surface, elasto-plastic FE-simulations may be adopted. Based on the experience in INNOTRACK [5], the following recommendations are given:

- Actual wheel and rail profiles should be adopted.
- The relative position of the wheel and rail (or alternatively, the point of first contact) is needed to establish correct contact conditions.
- The constitutive model of the rail steel should preferably be calibrated towards cyclic test data. In that calibration it is

important to consider which stage of the stress–strain relation that is important to mimic (first cycle or after many cycles, strain range or absolute strain magnitude etc).

- At least three and preferably five cycles need to be carried out to stabilize the stress–strain response in terms of peak magnitudes. To stabilize the strain increment during a load cycle, significantly higher number of cycles are needed.

If rolling contact fatigue life is to be evaluated, a ratcheting criterion is suitable. See [5] for a discussion.
The experience from INNOTRACK is that FE-simulations of conformal elasto-plastic wheel–rail contact corresponding to test conditions is on the limit of what commercial codes currently can manage. That situation is however likely to improve.

6. Conclusion

Twin disk tests as well as linear test rig tests represent a good way of testing rail materials under closely controlled conditions. In transferring the laboratory results to field conditions one has to consider that the twin disk configuration represents extreme conditions due to permanent slip under dry and clean high friction conditions and because the influence of the profile shapes cannot be taken into account.

Real contact conditions can be established by full-scale tests such as the VAS test rig. The test results should be reviewed afterwards by metallographic analysis as well as by numerical analyses. Such an analysis facilitates a comparison of test results with field conditions.

7. References

References to be found in INNOTRACK KMS

[1] INT D4.3.1: Testing Matrix Definition. Responsible: DB, author: Ullrich, D, published: Aug. 2007.

[2] INT D4.3.3: Results of first tests. Responsible: DB (with contributions of UoN and VAS), author: Ullrich, D, published May 2008.

[3] INT D4.3.7: Innovative laboratory tests for rail steels . INNOTRACK WP4.3 final report. Published August 2009.

[4] INT D4.3.4: Contact stress and wear. Responsible: TUD, author: Li, Z., published Oct. 2008.

[5] INT D4.3.5: Simulation of material deformation an RCF, Responsible: Chalmers, author: Kabo, E/ Ekberg A., published July. 2009.

8. Appendix: Measurement of RCF under laboratory testing conditions

(Final version: Carroll R, Corus)

General

To allow accurate and consistent measurement of rolling contact fatigue (RCF) cracks during laboratory testing, a methodology is required which can be followed by all partners. This document discussed within WP4.3 is based on Corus and Network Rail's experience of measurement of RCF cracks during track trials.
Before any sectioning is carried out a close inspection of samples, with photographs taken (preferably with a ruler) should be carried out. A rail profile should be taken using a Miniprof or similar if appropriate. The surface of the sample should be inspected as specified in following section.

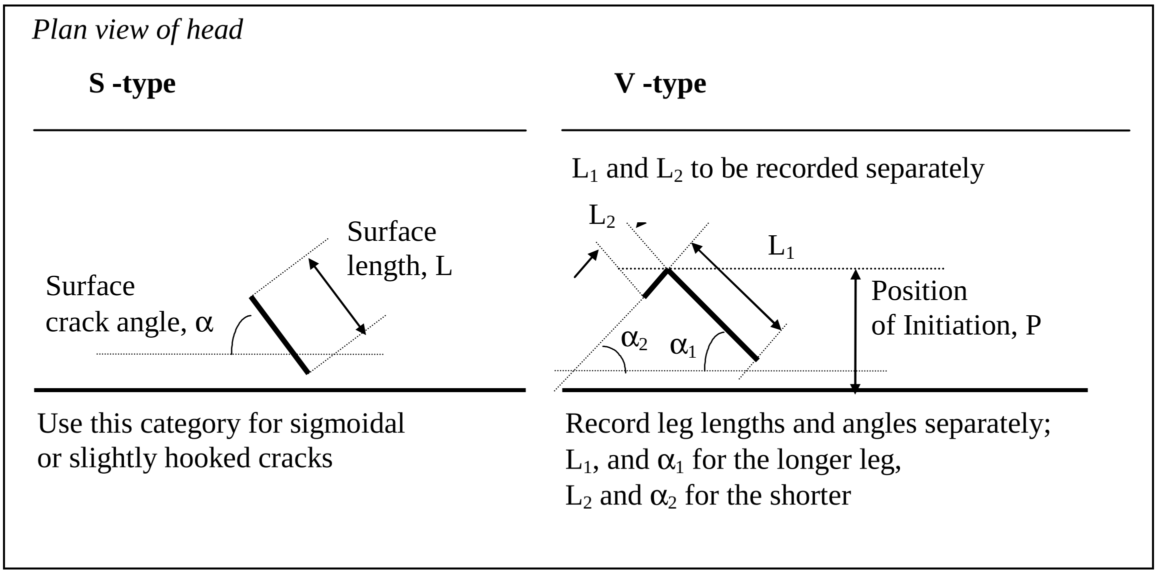
Surface Cracks

The following information needs to be recorded for all test samples. Cracks may need to be highlighted using magnetic particle or liquid penetrant inspection to aid identification.

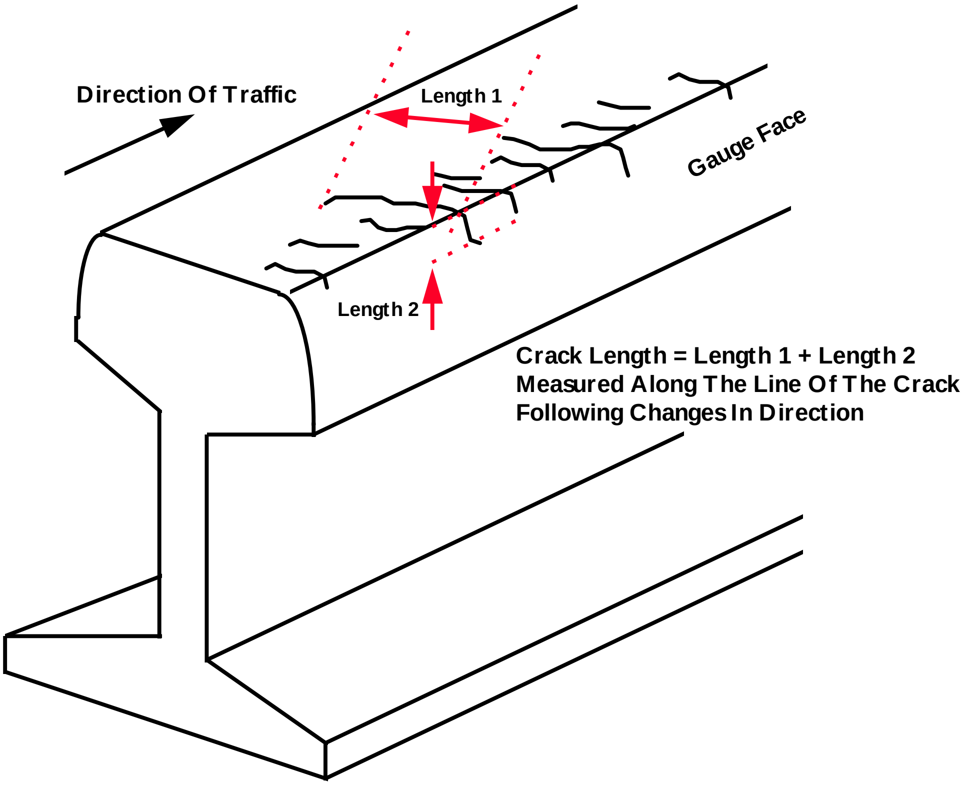
- A photograph of the surface of the sample should be taken, preferably with a ruler included against the surface of the sample.
- The lengths and angles of approximately six of the longest cracks should be recorded. If cracking extends down the gauge face, this length should also be included in the measurement of total crack length. For details, see Table 1 and the following sketches.
- Position of initiation of cracks
- Density of cracking, longitudinal spacing of the cracks.

Symbol	Description
L, L_n	Surface crack length,
α, α_n	Surface crack angle measured parallel to running direction
P	Position of Initiation. Distance from gauge corner to furthest tip of crack.
D	Subsurface depth of crack perpendicular to surface
K, K_n	Subsurface crack length, distance along the crack
ϕ, ϕ_n	Angle of subsurface crack from surface

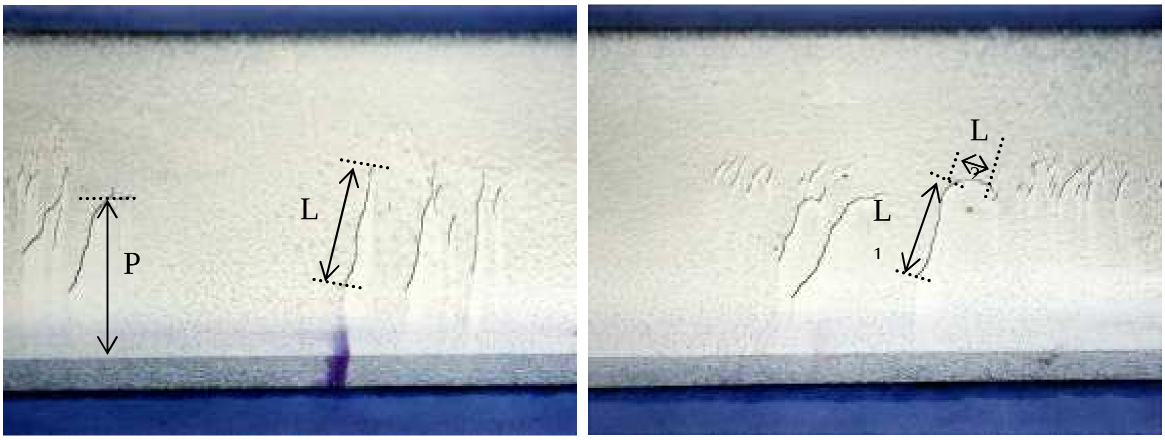
At least two different types of RCF cracks have been identified these are shown schematically in the diagrams below with a definition of the measurements required of the surface crack features for each.



Where cracks propagate below the gauge corner then the crack length reported should be the total along the surface and on the gauge face, see below.

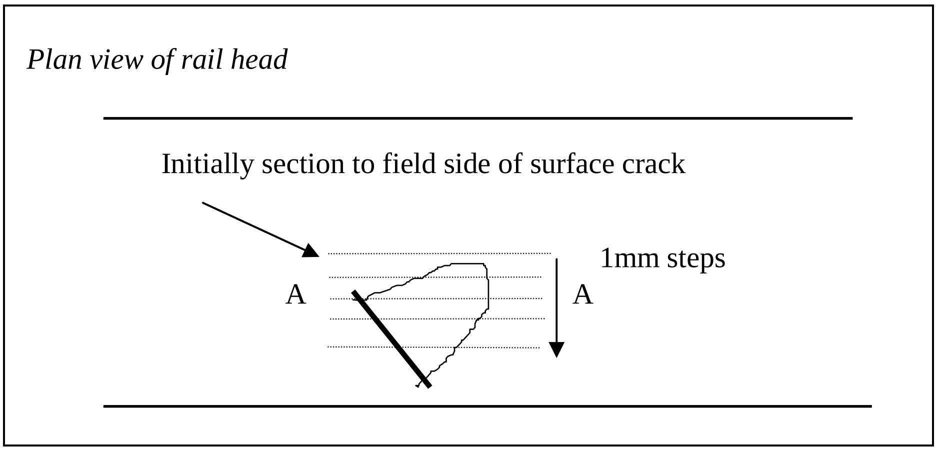


Examples of RCF cracks with measurements

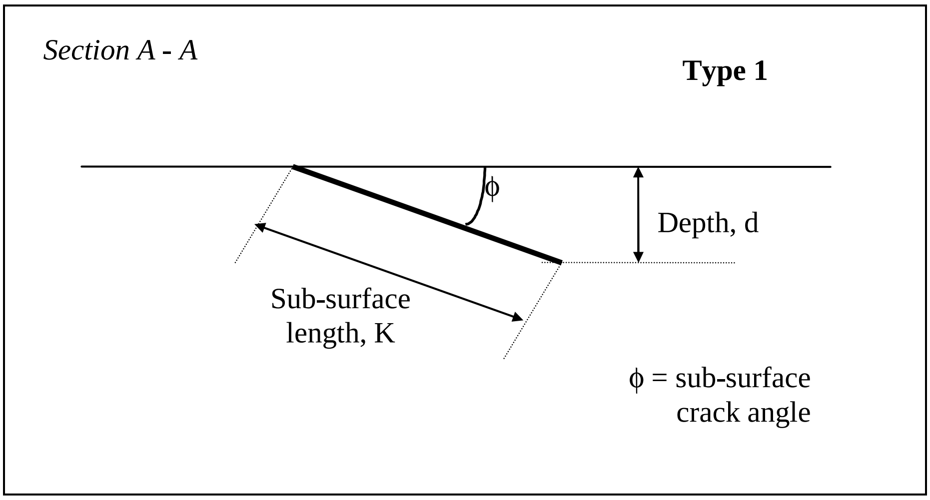


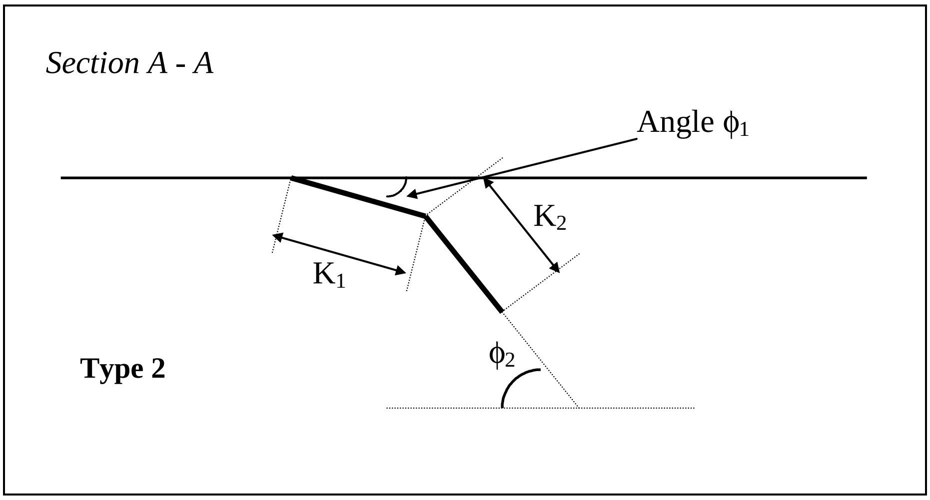
Subsurface Cracks

To study the propagation of cracks below the surface then the samples should be sectioned longitudinally; initially this should be on the field side of the surface crack. The sample should then be milled or ground in 1mm steps to reveal the location of the deepest crack.

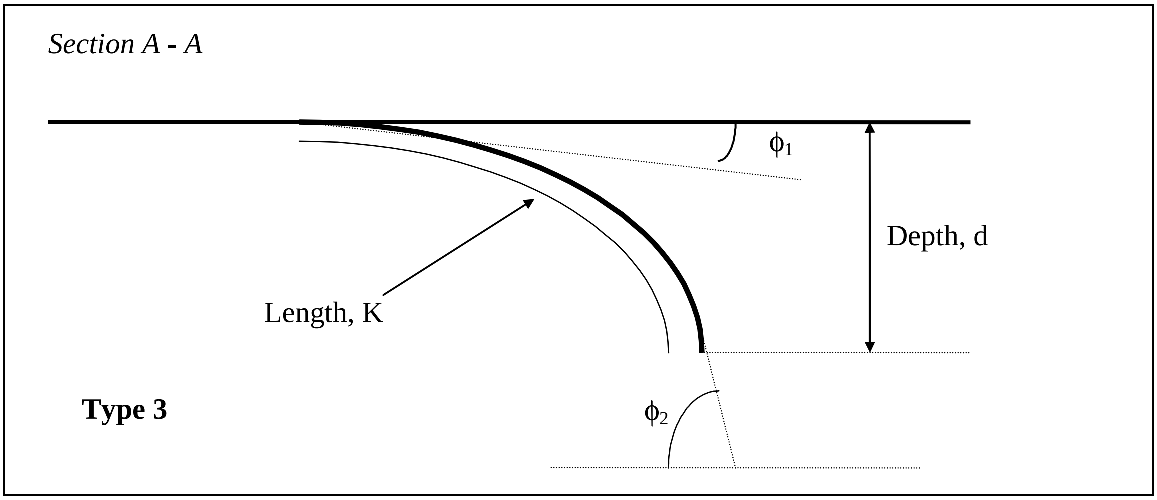


There are several ways in which cracks can propagate below the surface, the measurements required depend on the morphology and are shown below.





Samples should also be sectioned for metallurgical analysis. The samples should be prepared in the standard metallographic way as e.g.: mounted in Bakelite (conducting if examination in SEM is required), surface grinding carried out to ensure parallel surfaces etc.
The sample should be ground on SiC grinding papers. Grinding should be carried out using papers with increasingly smaller grit size e.g. starting with 120 grit and working progressively through 240, 400, 800 and 1200. The sample should be cleaned with running water between papers to remove any particles before proceeding on to the next paper. Care should be taken to reduce bevelling of edges of sample.
Once sample have been ground on finest paper samples should be cleaned using cotton wool, detergent (Teepol) solution and water before rinsing in alcohol and drying. Samples should be polished using diamond paste of 6μm and 1μm on a rotating pad. Samples should be cleaned using the same process between pads and after polishing.



The samples should be etched using 1% or 2% Nital (nitric acid diluted in methanol) for between 2 and 5 seconds and washed with copious amounts of water, dried and rinsed in alcohol.
Samples should be stored in desiccators to preserve the etch. After extended storage, samples should be repolished and etched.
Observation in optical microscope and photographs of deformed microstructure below surface should be carried out. Preferably, scale bars should be embedded into micrographs or alternatively magnification recorded.

To characterise deformation of rail material below surface then microhardness traverses using a Vickers microhardness indenter (100 or 200g) should be carried out until bulk hardness values are reached at a spacing of not less than 5× width of indent.