The impact of rail grade selection and friction modifier application on rail degradation.

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1. Introduction

With the increase in traffic and axle loads in recent years, rolling contact fatigue (RCF) remains a serious problem for many railway and infrastructure operators. Because of the serious consequences and also the costs associated with RCF, developing a theoretical understanding of the factors that influence its onset and progression under practical wheel/rail contact conditions has been of high importance to the industry.

2. Shakedown Theory

The shakedown theory can be used to explain the formation of surface and subsurface damage in repeated rolling contact [1,2]. According to figure 1 there are several parameters that influence the formation of rolling contact fatigue (RCF) in the wheel rail contact.

![Shakedown Map](image_url)

On the y axis the load factor consists of two parameters:
- \( p_0 \) – the maximum contact pressure between wheel and rail
- \( k_e \) – the shear yield strength of the rail/wheel material

\( p_0 \) can either be influenced by the load itself or by optimising the rail and wheel profiles without changing the load – a more conformal contact will reduce \( p_0 \) and thereby has the potential to reduce the damage in the system.

The material parameter \( k_e \) is directly related to the rail hardness. Premium rail grades, produced by accelerated cooling of the rail head have increased hardness properties (350HB – 450HB) compared to the European standard non head hardened grade (R260) and thereby providing higher RCF and wear resistance. The corresponding toughness properties however remain almost unaffected. A series of different head hardened rail grades have been developed by the industry for different track conditions.
Challenge G: An even more competitive and cost efficient railway (e.g. axle load, curvature etc). This paper compares the non-heat treated R260 grade with the heat treated R350HT grade. According to EN 13674-1 the general properties of the R260 and the R350HT grades are listed below ($R_m =$ tensile strength, $A_5 =$ elongation):

<table>
<thead>
<tr>
<th>Name</th>
<th>Hardness [HB]</th>
<th>$R_m$ [MPa] min.</th>
<th>$A_5$ [%] min</th>
</tr>
</thead>
<tbody>
<tr>
<td>R260</td>
<td>260-300</td>
<td>880</td>
<td>10</td>
</tr>
<tr>
<td>R350HT</td>
<td>350-390</td>
<td>1175</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 1: general properties of the tested rail grade according to EN 13674-1

On the x- axis of the shakedown diagram the traction coefficient $T/N$ (Tangential over Normal force) determines the degree of damage in the rail wheel contact. The maximum possible $T/N$ value is limited by the coefficient of friction (COF). The COF in turn is determined by the yield stress of the Third Body (interfacial) layer between the wheel and rail, which may be influenced by the application of a friction modifier or lubricant. Control of friction at the wheel tread / top of rail interface with specialized dry thin film friction modifiers (FM) is a relatively new technology. These materials are finding increasing use in heavy haul railways for lateral force, rail wear and energy reductions [3]. These materials are also used to reduce curve squeal and flanging noise, largely in metro and tram applications. More recent work has demonstrated the ability of friction modifiers to significantly mitigate the onset of short pitch corrugation in curves [4]. In contrast there has been relatively limited investigation of the impact of FM on RCF.

The key properties of a TOR FM include establishing a dry film on the rail, which combined with the naturally occurring 3rd body materials (e.g. wear particles and iron oxides) provides the following key attributes in the wheel / rail interface:

a) Intermediate coefficient of friction (0.3-0.4) between the wheel and rail [3,5], such that braking and traction are not affected.

b) Positive relationship between traction and creepage (“positive friction”) [6]

3. Experimental

3.1. Full Scale test rig
Experimental work was carried out on a full scale rail wheel test rig at voestalpine (Figure 2). This equipment was developed to provide a quick and reproducible test capability for rail wear and RCF.

Figure 2: Full scale rail wheel test rig at voestalpine Schienen GmbH
A full size freight wheel loads a 1.5m long piece of rail attached to a carriage moved back and forth by hydraulic cylinder. Vertical loads up to 100 t and lateral loads up to 10 t can be applied to the rail wheel contact. Friction conditions can be adjusted by applying a lubricant through a nozzle to the wheel flange, by spraying a water-air mist directly into the rail wheel contact or by spraying a Friction Modifier to the rail surface. The FM application device was specially developed by Kelsan Technologies to provide the flexibility to cover the whole rail surface or only parts of the surface (TOR, GF – Gauge Face) with an atomised spray. Additionally the test rig is capable of adjusting the rail cant through a base plate or wedge underneath the rail. Curve running can be simulated by forced lateral rail wheel contact (by adjustment of relative lateral and vertical forces), and by angle of attack (AOA – 0.25° or 0.5°) between the wheel and rail. The test rig can operate in uni- or bi-directional movement mode with a maximum test speed of 0.5m/s allowing approx 30.000 loading/testing cycles with in 24h.

3.2. FM application methodology
The friction modifier used in this work was KELTRACK® Hirail, a water based suspension of engineered solids and polymer composites [7,8]. This material is specifically designed for atomizing spray application. Rheological properties have been tailored to provide a sufficiently fine spray pattern to leave a uniform dry film on the rail head, without compromising other important characteristics. Previous work has described the frictional characteristics resulting when a dry film of FM exists between the wheel and rail [9]. The desired frictional characteristics are achieved when the material exists together with the other naturally occurring “3rd Body” materials, primarily iron oxide wear particles. The performance and tribological behaviour of this material have been extensively documented by Japanese researchers [10,11].

The application systems consist of a spray nozzle, compressed air connector and heater, and a reservoir equipped with a level sensor for exact consumption calculations. The spray nozzle was adjusted for these tests to cover both the top of rail and gauge corner with the FM spray. During the application of FM the wheel is lifted off the rail.

3.3. Test methodology and measurements
The parameters for these tests had been identified in previous work [12] to ensure formation of Head Checks within 100.000 wheel passes (100.000 passes are defined as the standard test length). Conditions were kept constant to provide comparable conditions (Table 2).

<table>
<thead>
<tr>
<th>Wheel type</th>
<th>Freight disc wheel, 920 mm diameter, UIC/ORE S1002 profile, grade R7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic</td>
<td>uni-directional</td>
</tr>
<tr>
<td>Vertical load (V)</td>
<td>23t</td>
</tr>
<tr>
<td>Lateral load (L)</td>
<td>4t</td>
</tr>
<tr>
<td>Cant / Angle of attack (AOA)</td>
<td>0 / 0°</td>
</tr>
</tbody>
</table>

Table 2: general test rig parameters

Each test started with a new wheel and rail with a standard 60 E1 rail profile. For all the tests reported in this paper the FM application rate was also kept constant applying an amount of approx. 0.25 ml every 250 wheel passes covering the whole contact area (including the gauge corner and the upper part of the gauge face).

3.4. Rail wear
Rail wear was monitored during each test using a MiniProf Rail instrument from Greenwood Engineering. Measurements were performed at three rail positions (R1, R2 and R3) and at two wheel positions (W1 and W2) after completing predefined number of wheel passes (0; 2.000; 5.000; 10.000; 20.000; 50.000; 75.000; 100.000).

Average wear was measured for the positions A, B, C and D on the rail, defined by the angle between their tangent to the rail surface and the horizontal line (Figure 3). Points A, C and D were defined by the authors in order to calculate wear rates perpendicular to the original rail surface in specific areas in the contact band.
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![Figure 3: Measurement positions on the rail profile]

In addition to previous work [13], a new profile alignment method was developed allowing an improved alignment of the measured profiles in relation to the reference profiles and thereby increasing the accuracy of the wear results. Furthermore a system wear parameter was also determined considering area loss of rail and wheel.

3.5. Metallography
After completing each rail test, 20 mm thick rail samples were cut at the MiniProf measurement point R2 to determine microstructure and crack depth at positions A, B, and C. Crack depth analysis was done according to the ERRI D173 procedure [12]. Surface stress micrographs were also taken at these cut positions. The surface was slightly polished and then etched. Transverse micrographs (perpendicular to longitudinal rail axis) were obtained at positions A, B and C, after which the extent of plastic flow was determined by close examination of the microstructure, quantified by reference to a scale on the image.

3.6. Magnetic Particle Imaging, Image Analysis and Rail Roughness
After each 100,000 wheel pass test, or as specified, magnetic particle imaging (MPI) was used to visualize any head checks which formed. SigmaScan Pro image analysis software was used to identify average crack length L, crack spacing W, and crack angle. Rail surface roughness measurements were performed on each rail sample, as on a new rail sample, using a Mitutoyo Model Surftest-212 surface profilometer. As the instrument uses a stylus detector, surface roughness measurements were completed in the longitudinal rail direction only. Twenty six measurement locations were used starting at the bottom edge of the rail gauge side spaced approximately every 5 mm up around the rail profile until reaching the bottom field side corner.

4. Test results
Three different series of tests were done. Standard length tests (100,000 cycles) were carried out with the rail grade R260 and R350HT under dry and FM conditions. The second series consisted of one long term (400,000 cycles) test for each rail grade under FM conditions. Finally a special test series was done to examine the effect of a dry FM on pre-existing cracks on the rail surface.

4.1. Wheel/Rail Wear
Figures 4 and 5 provide a comparison of the wear results between R260 and R350HT rail grades. In both cases for dry contact conditions there is increased wear during the first 25,000 cycles as wheel and rail profiles adapt to each other until reaching a degree of conformal contact. Nevertheless at this stage the wear values of the R350HT grade are up to 3 times lower compared to the R260 grade depending on the examination positions. After this wearing in process both grades show quite steady wear rates resulting in a final average wear ratio of 1 : 2.2 (R350HT : R260).
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In both cases, the application of FM drastically reduced the wear volume and rate, resulting in a very small initial wear for the R260 grade and no measurable wear for the R350HT grade. At position D the R260 (FM 250) also showed some amount of plastic flow (negative wear values) which was not present for the R350HT rail.

Comparing the area loss results it can be seen that the wheel wear for both rail grades under dry contact conditions is on the same level. No increased wheel wear was measured in combination with the higher hardness R350HT rail grade (Figure 6).
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It is also noticeable that the worn volume of the wheels is significantly lower compared to the worn volume of the corresponding rails. When the wheel and rail wear volumes are combined, for dry contact conditions the overall wear of R260 is 1.4 times greater than R350HT. Concerning FM conditions some values could be calculated for the R260 rail. All the wheels and the R350HT rail grade tests resulted in wear values situated below the resolution of the MiniProf device.

The long term tests for R260 and R350HT showed the same wear behaviour as the standard length tests.

4.2. RCF crack results

Both rail grades developed RCF cracks under dry contact conditions, though the crack depth and the surface crack spacing of the R350HT was significantly reduced compared to the R260 grade indicating an improved crack resistance of the premium rail grade in addition to the higher wear resistance.

<table>
<thead>
<tr>
<th>Rail grade</th>
<th>R260</th>
<th>R350HT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact - dry wheel passes</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Avg. crack length L, mm</td>
<td>6.98</td>
<td>10.00</td>
</tr>
<tr>
<td>Avg. distance between cracks W, mm</td>
<td>2.04</td>
<td>1.77</td>
</tr>
<tr>
<td>Avg. crack angle (degrees)</td>
<td>34.4</td>
<td>36.9</td>
</tr>
<tr>
<td>Head checks / linear cm rail length</td>
<td>4.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Average crack depth, mm</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 3: RCF Crack Analysis, dry contact conditions, 100,000 test cycles, grades R260 and R350HT

Rail with FM applied every 250 wheel passes from the onset of testing for R260 and R350HT rail grades developed no cracks or head checks after 100,000 or 400,000 wheel passes. A good comparison of the crack and wear results can be seen in figures 7 and 8.
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4.3. Plastic Flow
Surface and subsurface plastic flow occurring under the different conditions was examined for “dry” and all FM conditions, at position B, the location of roughly matched rolling radius where minimal or no
longitudinal creepage occurs. A manual examination method was chosen and the maximum depth of plastic flow was defined at the point where the deformed microstructure reached an angle of 45° on a micrograph image.

Figure 9 shows the plastic flow results of all (100,000 and 400,000 passes) dry and FM tests for both rail grades. The reduction of plastic flow as a consequence of the FM application for both rail grades after 100,000 cycles is clearly indicated. Additionally the R350HT grade dry shows even lower plastic flow values compared to the R260 grade with FM application indicating a higher resistance to damage.

![Plastic Flow Examination](image)

**Figure 9: Plastic flow examination for grades R260 and R350HT, standard and long term tests, dry and FM contact conditions.**

The long term tests (400,000 cycles) for both rail grades show slightly increased deformation depth but more than doubled transversal extension of the deformed structure compared to the equivalent 100,000 tests. Due to the FM application the shear loading is reduced compared to dry conditions. Increasing the test duration increases the total shear amount acting on the rail surface resulting in the higher transversal deformation extension. Once again the increased material performance of the R350HT rail grade can be seen as this grade even after 400,000 cycles shows lower deformation values compared to the R350HT 100,000 dry conditions.

The results concerning surface roughness are shown in chapter 4.4.3 table 5.

### 4.4. Tests with pre-existing cracks

Pre-existing cracks in combination with any liquid 3rd body material on the rail surface can lead to conditions that favour accelerated crack growth due to the effects of the entrapped incompressible fluid and corresponding hydropressurization [14,15]. While hydropressurization is not an issue with a dry thin film FM such as KELTRACK, another hypothesized mechanism for accelerated crack growth is reduced friction between internal crack faces [16].

In order to examine the potential effects of a dry FM film on pre-existing Head Checks on the rail surface a special test sequence was developed. First 25,000 dry cycles were done until Head Checks were clearly present on the rail surface. Then the FM application device was turned on and the test was finished until reaching 100,000 total cycles. Only the rail grade R350HT was used for these tests (R260 rail grade tests failed due to equipment problems).
As a comparison another 25,000 cycles dry tests was done using the slightly worn wheel for the previous "R350HT 25,000 dry followed by 75,000 FM" test.

4.4.1. Wear and RCF results

Figure 10 shows the wear results for the combined tests. Some wear occurs during the first 25,000 cycles, and is subsequently reduced below measurement resolution due to the FM application between 25,000 and 100,000 cycles.

During the combined test no change in visual appearance of the surface cracks was noted during the FM application phase of this test. Crack depths for the R350HT 25,000 dry wheel passes and R350HT 25,000 dry followed by 75,000 FM wheel passes were analyzed using the metallographic method described (Table 4).

<table>
<thead>
<tr>
<th>Test</th>
<th>Average crack depth [mm]</th>
<th>Min crack depth [mm]</th>
<th>Max crack depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R350HT 25,000 dry</td>
<td>0.9</td>
<td>0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>R350HT 25,000 dry followed by 75,000 FM</td>
<td>1</td>
<td>0.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 4: crack length distribution for R350HT tests dry and dry followed by FM

The average crack depth results suggest that no further crack growth took place during the FM phase of the test. A closer examination of the crack length distribution (Table 8) revealed that there was one specific crack that was significantly longer than all the other cracks at “R350HT 25,000 dry followed by 75,000 FM”. Though, it is important to keep in mind that besides the FM application also factors like slightly different contact conditions due to the initially worn wheel for the “R350HT 25,000 dry” test or the metallographic examination procedure itself might produce some differences in crack depth. Further work on this topic is planned for 2011.

4.4.2. Plastic Flow
Comparing these results with the previous tests the values for the combined test in the transverse direction are increased by approximately 15% whereas the deformation depth is reduced by about 5% (figure 11).

Furthermore the R350HT results for 100.000 dry, 25.000 dry and 25.000 dry followed by 75.000 FM indicate that some saturation of the plastic deformation took place below 25.000 cycles under dry contact conditions. This saturation seen under dry conditions is not reached for both 100.000 cycles and 400.000 cycles FM tests. It should be acknowledged that the saturation is very likely influenced by both the wear rate and the material resistance against plastic deformation. Further investigation in this area will also be conducted in 2011.

4.4.3. Surface Roughness Results

The averaged surface roughness values measured within the wheel/rail contact region after each test are shown in Table 9. The wheel passes and contact conditions are listed as well. For comparison the results of R260 and R350HT grade for 100.000 dry and 100.000 FM are also shown.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Test contact conditions</th>
<th>Test wheel passes</th>
<th>Avg. Roughness (Ra: microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>n'a</td>
<td>Dry 0 FM 0</td>
<td>1.6</td>
</tr>
<tr>
<td>R260</td>
<td>Dry 100.000</td>
<td>0</td>
<td>2.42</td>
</tr>
<tr>
<td>R260</td>
<td>Dry followed by FM (every 250 passes)</td>
<td>125.000 75.000</td>
<td>1.05</td>
</tr>
<tr>
<td>R350HT</td>
<td>Dry 100.000</td>
<td>0</td>
<td>1.68</td>
</tr>
<tr>
<td>R350HT</td>
<td>FM (every 250 passes)</td>
<td>0</td>
<td>0.57</td>
</tr>
<tr>
<td>R350HT</td>
<td>Dry 25.000</td>
<td>100.000</td>
<td>2.07</td>
</tr>
<tr>
<td>R350HT</td>
<td>Dry followed by FM (every 250 passes)</td>
<td>100.000 75.000</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Table 5: Surface roughness results for all tests

It can be clearly seen that the dry followed by FM tests show roughness values that are situated between complete dry and complete FM test conditions.
5. Rail grade track results
In addition to full scale test rig studies, voestalpine has operated a number of track tests with different radii and loading conditions for several years to study the in-track benefits of head hardened premium rail grades [17,18,19]. In addition to the R350HT grade discussed in this paper there exist grades with even higher hardness that show increased wear and RCF resistance compared to the R350HT [20]. With respect to R260 and R350HT grades, test rig results show the same trends as seen in track:
- reduced wear rate with increased rail hardness
- reduced crack spacing (between head checks) with R350HT
- simultaneous reductions in both wear rate and crack depth with higher grade rails

6. FM track results
In addition to the documented reductions in wear and RCF under wheel / rail test rig conditions, friction modifier application has been demonstrated to produce simultaneous reductions in wear and RCF under full-scale revenue service conditions.

In a test carried out under heavy-grade operating conditions on a major heavy haul freight railroad in the western United States, two test zones were established to examine the impacts of TOR friction control when combined with optimized gauge face lubrication (versus gauge face lubrication alone). The two 16-km test zones were separated by an approximate 5 mile buffer zone. One segment was established as a control zone (gauge face lubrication only), while the other incorporated both gauge face lubrication and trackside application of TOR friction modifier. Traffic running over each zone was identical, with similar grades (2% typical) and curvatures (R = 175 m typical). Also, both gauge face lubrication and track cant were optimized in both segments to reflect industry best practices. Finally, identical head-hardened rail was laid in both areas at the same time, creating a controlled test in which TOR friction modifier application represented the only controllable test variable between the zones.

Monitoring of rail wear and surface conditions was carried out over approximately 2 years and 127 million gross tonnes of traffic. Following this period, the rail was ground to remove RCF and restore target conditions. Rail profiles collected throughout the test program demonstrated 23-60 % reductions in natural rail wear rates with TOR friction modifier application. Pre/post grinding data also suggests that the TOR zone received fewer grinding passes (~ 15 %), had less metal removed, and produced rail with better overall surface conditions.

7. Test rig vs. track test
Although the results from the test rig show the same trends as seen in track, the absolute values differ because of several differences and limitations that come along with this laboratory experiment:
- There is no wheel axle or trailing wheel present at the test rig. Therefore no steering forces will act in the wheel rail contact.
- In track the lateral wheel rail contact is determined by steering capabilities of the vehicle. At the test rig the lateral contact is forced by applying a combination of vertical and lateral loads.
- In track a certain rail segment is loaded by thousands of different profiles resulting in thousands of different contact locations on that rail segment. So wear and RCF is a result of this profile distribution. At the test rig the same wheel and the same rail are always positioned to each other in the same way during a complete test. So the wheel and rail adapt to each other according to the loads and the material properties of both partners.
- In track the climate conditions can vary from sunshine to rain resulting in changing friction conditions. The friction conditions will also be influenced by any 3rd body material in the wheel rail contact like sand, leaves, oxides… At the test rig the climate conditions are kept constant and therefore the friction conditions also stay rather constant. Additional unintended third body layer materials aside from wear debris and few oxides will not be present.
- In track there is a continuous consumption of the friction modifier caused by breaking or accelerating actions, unconditioned wheels, precipitation etc. But also factors like equipment failures and tank refill intervals influence the overall FM effectiveness. The test rig provides a closed and controlled environment where these effects are reduced or do not happen at all. As a consequence the FM effectiveness is increased compared to track conditions.
8. Conclusions
Referring to the different parameters in the shakedown map this paper shows that both rail grade ($k_e$) and friction management (T/N) will result in a reduction of damage in the wheel rail contact. Furthermore the results concerning wear, RCF crack formation and plastic flow examinations clearly indicate that a combination of these factors will result in the best rail performance.

There is often uncertainty whether increasing the rail hardness in the system will result in an increase in wheel wear. The results clearly indicate that the wheel wear was not increased when switching from R260 to R350HT under test rig conditions for the given wheel grade R7. Results with pre-existing cracks on a 350HT grade showed that crack growth was not negatively influenced by the friction modifier. There are also indications that further crack growth was stopped or at least reduced because of the application.

A series of track tests either concerning the friction modifier or concerning different premium rail grades support the findings of this paper. Premium rail grades can extend the rail life by reducing wear on the one hand and mitigating RCF on the other. By additional application of the friction modifier this rail life extension can be further increased providing a maximum benefit in cost savings for the rail track operator. Of course there is also a third factor in the shakedown map that was not analysed in this paper – $p_0$. This factor is directly influenced by maintenance activities that must be seen as a precondition to gain this rail life and cost advantage.

9. References


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[17] G. Girsch, R. Heyder, Advanced Pearlitic and Bainitic High Strenght Rails Promise to improve Rolling Contact Fatigue Resistance, 7th World Congress on Railway Research, Montreal, 2006, p. 234

