Evaluation of rail wear characteristics on heavy haul track section using measurement data

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SUMMARY
The rail is a structural component of track that serve as the running surface, guiding element, load carrier and distributor. The wear of rail is of great interest since it is known to be an important degradation mode that can limit the performance of rail, reduce its life span and significantly increase the life cycle cost of track if not well managed. It is therefore pertinent to study the wear behaviour of rail under increased loading condition and adopted grinding strategy. In this paper, the analysis of rail profile measurement data collected between 2008 and 2013 has been carried out. This is used to evaluate the wear characteristics of curves with different radii on the Swedish iron ore line to provide engineering insight for improving maintenance for better rail performance. The result shows that the average natural wear rate on sharp curves is about 2 times the wear rate on the mild curves and 5 times the wear rate on the tangent tracks. In addition, the typical total wear on sharp curves after 6 years is over 250 mm² which is about 1½ and 2½ times the wear on mild curves and tangent tracks respectively.

INTRODUCTION
The rail is a structural component of the track that serves as the running surface, guiding element, load carrier and distributor. It is in contact with and support the wheel of the rolling stock, and at the same time spread the individual wheel load to other structural elements down to the formation (1). In the common track loading conventions, rails are subjected to combination of vertical, lateral and horizontal loads as a result of wheel-rail interaction and thermal loading from ambient temperature variations (1,2). The dynamic effects of track irregularity, wheel defects, speed, and stiffness variations add to the mentioned loading conventions on rail. These accelerate the degradation of track and rail damage if not well maintained.

The continuous growth of freight traffic with more axles, higher axle load, increased wagon weight and greater speed requires better performance of rail and other track components in general. There has been continuous engineering development to improve the performance of rail in order to support the demanding loading conditions.

In modern track structure, rails are expected to meet some of these requirements; high resistance to wear, fatigue, brittle fracture and compression. In addition, they are expected to have good surface quality, good observance of profile and low residual stress (3). Rail wear is of great interest since it is known to be an important degradation mode that can limit the performance of rail, reduce its life span, cause failure of other elements and significantly increase track life cycle cost if not well managed. It occurs at any point on the track however it is dominant in curved section where wheel flange contacts the gauge corner of the rail head, leading to abrasive wear of the rail by the wheel (4).

It is therefore pertinent to study the behaviour of rail with focus on loss or displacement of material under increased loading condition and adopted grinding strategy. The study herein presents the evaluation of wear on curves with different radii on the Swedish iron ore line using rail profile measurement data. This is basically intended to follow up the modernisation and improvement carried out on the line to accommodate longer trains with heavier axle loads and increased traffic volume. This knowledge about rail wear behaviour will enhance decision making for future re-investment and relevant maintenance activities.

RAIL WEAR
The stress environment of the rail is complex with contact stress, bending stress and thermally induced stresses. From the viewpoint of maintenance engineering, the contact stresses must be well managed since a lot of fatigue or wear related rail failure modes are connected to contact stresses.

Natural rail wear is the loss of metal due to the abrasive action of wheel on the rail during interaction. Wear of rail is directly related to wheel-rail interaction in terms of the load, complex stress field and configuration of the contact (1). The main wear mechanisms in wheel-rail sliding or rolling contacts are adhesive, abrasive, fatigue driven,
thermal and oxidative wear processes (4). Further, rail wear occurs at the top of the rail as head (top) wear, or at the side as gauge face wear or can be described to occur in the form of combined head and side wear. Wear area is another measure of wear in terms of material loss or displaced at the head area in relation to a reference profile. The profile of rails under heavy traffic condition gradually change owing to wear, contact fatigue cracks and plastic flow as a result of high contact stress as shown in Figure 1.

The key factors that affect the rate of rail wear from literature include: track curvature, layout, rail grade, metallurgy, profile, train speed, wheel profile, axle load, traffic characteristics, lubrication, contaminations and other environmental conditions (1,4). It is reported in literature that the ideal wear rate is between 0.01 and 0.02mm/MGT narrow curves while medium radii and transition curves are lower by $1/3$ and $2/3$ (3). The maximum allowable vertical wear is 14 mm for UIC 60 rail while the limit for lateral wear is between 10 and 16mm depending on the line speed (3).

![Figure 1: Wear, RCF cracks and plastic flow of rails in curves (5).](image)

**GRINDING**

The continuous interaction between wheel and rail leads to alteration of the rail profile through wear, surface and near surface defects, or plastic flow. This require intervention such as grinding to avoid shortened life span of track components, safety issues, increase noise and vibration etc. Rail grinding is the artificial removal of metal from the surface of the rail head using for instance rotating grinding wheels that are operated by hydraulic or electric motor. The removal of metal happens as the abrasive grain particles of the grinding wheel touches the rail metal and removes chips from the rail surface.

Initially, rail grinding process was a remedial action that is focussed on elimination of defects such as corrugations and wheel burns after they have appeared using several passes (1,5). The engineering of rail grinding has improved such that rail defects can be removed at the early stage or controlled with light passes before they become critical. The basic target of this improvement is to maintain a work hardened layer, control surface fatigue and maintain defect free surface with low but sufficient removal rate. Furthermore, grinding has been extended to rail profile grinding to control and maintain the shape of the rail head and the associated wheel-rail interface. This method helps to control gauge face wear, corrugations and gauge corner fatigue.

Another important concept in rail grinding is the principle of magic wear rate for the maximisation of rail life. The practice of this principle tries to balance fatigue and wear by controlling wear rate such that it equals fatigue damage accumulation rate (3,5). A well planned preventive grinding is often used to compensate the natural wear to achieve this balance.

The grinding strategy on the northern part of the Swedish iron ore line (IOL) used to be one campaign in a year for curves and every third year for tangent tracks. In recent development, the strategy has been modified to 2 grinding cycles annually for sharp curves, once in a year for other curves and every third year for tangent tracks. The minimum material removal for each grinding is 0.2 mm but the material removal for curves is around 0.6-0.8 mm yearly. Continuous improvement of the grinding operation on IOL is ongoing by a project group.

**IRON ORE LINE**

In connection with the need to improve railway performance for the operation of heavy and long hauls, a major investment on infrastructure was initiated in 2006 basically in the northern section of Swedish iron ore line from Riksgränsen to Kaisepakte. The investment entailed complete track renewal with change of rail from 50 kg/m to 60 kg/m, and from hard wood sleepers to concrete sleepers. The fastening system was changed from heavy-back system to elastic fastener. The travelling speed in the loaded direction was increased from 50 km/h to 60 km/h. In addition to the investment on infrastructure done by the infrastructure manager, the major freight operator LKAB also replaced the old DM3-locomotives and UAD-wagons to Iore-locomotives and Fanno-wagons respectively (see Figure 1 for the Iore-locomotive). This investment was followed by measurement campaigns that started in 2007 to understand the behaviour of track components in different layout under increased loading to improve track maintenance.
Rail profile

There are three main rail profiles on the main track of the IOL namely the 60E1, MB1 and MB4. The MB4 rail profile is used for switches and crossings and also as standard profile for tangent. Narrow curves have the MB1 on the high rail and the 60E1 in the low rail (6). Figure 3 shows a sketch of the three profiles to point out some of the differences. Basically, this profiles differ on the gauge side, the MB1 have the largest gauge corner release, the 60E1 has the least, and the MB4 is between the two profiles.

Recent development is the new test profile MB5 that is adapted to worn wheels and for the low rail in sharp curves (< 650 m) with gauge widening problem. The MB5 profile is close to the 60E1 profile but 0.4 mm higher on the field side and 0.1 mm higher on the gauge side. This gives a wider running surface as shown in Figure 4, to solve the emerging RCF problem on the low rail.

Rail defects

Some examples of surface fatigue and other defects from the IOL are presented below with their respective codes from rail defect catalogue (7). Figure 5 shows low rail in a curve with shelling on the running surface due to narrow running surface that is caused by wide gauge.

Figure 6 shows a low rail with the initiation of another type of surface defect on the IOL called HH-corrugation occurring with running surface shelling.

Figure 7 shows a squat close to the border of the running surface. The squat is small and can be treated in two or three grinding cycles.
Figure 7: Tangent track with a squat close to the edge of the contact band, code 227.

Figure 8 shows a defect on the high rail gauge corner. However this was too large to be removed with grinding, thus the rail was to be replaced.

Figure 8: High rail with point defect, shelling of gauge corner, code 2222.

CASE STUDY

The descriptions of the study sections on the IOL in terms of location, curve types, length of curves, and measurement procedure are given in this section.

Description of study area

The study area in this article is the northern section of the iron ore line with axle load of 30 metric tonnes and annual load of about 30 MGT. The track section is one of the busiest sections in Sweden and has the largest predicted traffic increase of about 136% between 2006 and 2050 due to expansion of mining activities in the north of Sweden (8). Figure 9 shows the locations of the different sections that are studied on the line. Due to the amount of data available and to avoid inconsistency in the evaluation, sections 1 and 2 were left out in this study.

Table 1: Description of the sections on the study area

<table>
<thead>
<tr>
<th>Section</th>
<th>Station area</th>
<th>Curve Categories</th>
<th>Number of Curves</th>
<th>Total length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Stordalen-Abisko</td>
<td>B, C, E</td>
<td>4</td>
<td>2378</td>
</tr>
<tr>
<td>4</td>
<td>Björkilden-Kopparåsen</td>
<td>A, B, C, D, E</td>
<td>18</td>
<td>6582</td>
</tr>
<tr>
<td>5</td>
<td>Låktatjåkka-Vassijaure</td>
<td>A, E</td>
<td>3</td>
<td>1511</td>
</tr>
<tr>
<td>6</td>
<td>Vassijaure-Riksgränsen</td>
<td>A, B</td>
<td>9</td>
<td>5209</td>
</tr>
</tbody>
</table>

Table 2: Description of the curves types

<table>
<thead>
<tr>
<th>Category</th>
<th>Layout</th>
<th>Radius (m)</th>
<th>Number of curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Curve</td>
<td>&lt;550</td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>Curve</td>
<td>550-650</td>
<td>17</td>
</tr>
<tr>
<td>C</td>
<td>Curve</td>
<td>650-750</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>Curve</td>
<td>750-850</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>Curve</td>
<td>&gt;850</td>
<td>6</td>
</tr>
<tr>
<td>T</td>
<td>Tangent track</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Measurement procedures

The measurement of the rail profile and wear is done with handheld tool called MiniProf. The MiniProf measurement is manually done by one man and the system is capable of measuring the cross sectional profiles of the rail in addition to the track gauge. The measurement accuracy of MiniProf for rail profiles is ± 9 μm (9). Figure 10 shows the field measurements done with MiniProf on the IOL. Basically, two measurements campaigns (before and after annual grinding campaigns) are carried out annually from 2007 to 2013 between the month of June and October. The in-built function of the device estimates the vertical (W1), horizontal (W2) and 45° (W3) wear by calculating difference between the measured profile and the reference profile as shown in Figure 11.
In this article, the analysis of wear characteristics is done using the wear area from gauge to rail centre. This is estimated by dividing the area between the reference profile and the measured profile into a number of sections (dA) and these areas are displayed relative to their position on the reference profile. The device gives an estimate of the gained area lying outside the reference profile; lost area lying inside the reference profile and the difference between the two as the total area (9).

**RESULT AND DISCUSSION**

The data collected is analysed to depict the pattern of rail wear phenomenon for different curve types on the IOL. The result presented in this section gives relevant information content from the wear measurement data and practical knowledge to improve maintenance for better rail performance. Firstly, the natural and artificial wear in 2008 and 2013 are evaluated for the different curve types. Secondly, the accumulated natural and artificial wear are presented and discussed. Finally the combination of the two material removal modes are evaluated for the different curves.

Figure 12 shows the average amount of wear area at the different curve types shortly after the renewal of the track in 2008 and some years later in 2013. The box represent the mean wear area for same curve types in different locations while the interval bars represent 2 standard errors away from the mean wear area. In both cases, wear area is maximum on the sharpest curve category and minimum on the tangent tracks. This is expected for the reasons of concurrent vertical load and increased lateral flanging force due to steady state centrifugal force and dynamic supplement caused by the dynamics of wheel negotiating the curve. It confirms that the abrasive wear of the gauge face by the wheel flange is more in sharp curves, as well as the wear of the rail head top by the wheel thread. The interval bar in figure 13 shows that there is variation in the wear pattern of curves that are in the same category. This is due to the fact that the curves are not exactly of same radius and length, and there are little differences in the layout and operational factors.

An observation from the plot is that the wear in 2013 is higher than 2008 in sharp curves. This is suspected to be related to axle load increase and high dynamic force from the new locomotives in sharp curves.

**Figure 12:** Natural wear on the different curves as measured in the years 2008 and 2013.
The artificial wear from grinding campaigns in 2008 and 2013 is shown in Figure 13. The amount of material removed during grinding at the initial stage is small in comparison to 2013. This is due to the fact that there is about 40% increase in the annual tonnage from 2008 to 2013 requiring more metal removal as a result of increase in damage induced by traffic. In 2008, there is no clear difference in the amount of material removed on the different curve types. In 2013, the artificial wear is clearly higher on the curves with radius less than 850 m than others since the dynamic effect of the tonnage increase is probably not linear with curve radius. Further, the ratio of the artificial and natural wear is about 2 for the sharp curves (<550 m), and around 3-4 for others in 2013. This wear pattern observed in 2013 is similar to what is witnessed between 2009 and 2012.

The accumulated natural wear for 6 years is shown in Figure 14. The average accumulated natural wear area is about 85 mm² on the sharp curves and 15 mm² on the tangent track. The total natural metal loss for other curve types can be seen in the figure. An interesting observation is the exponential shape of the wear plots for all the curves (slow rate at the initial stage which eventually increases in 2010), and near-linear pattern (near constant rate) on the tangent track. The reason for the exponential nature of the plot especially for curve segments is the fact the axle load was increased by almost 30% from 24 metric tonne in 2009 to about 30 metric tonne in 2010. In addition to this, the axle load is another factor that causes this behaviour. The effect of the systematic and gradual change in axle load from 25 tonne to 30 tonne is not visible in this figure but can be seen in Table 3.

The average annual wear rate in mm²/MGT for each period is shown in Table 3 together with the overall average wear rate for each curve type. A remarkable observation is the visible rise in the wear rate in 2011 on all the curves. The rise in the wear rate is between 75% and 200%. It is not only related to increase in annual tonnage but also for the fact that 100% of the iron ore wagon are now operating with 30 ton axle load. Using the average wear rate over the entire period between 2009 and 2013, the natural wear rate on the sharp curves is about 2 times the wear rate on the mild curves (C type curves) and 5 times the wear rate on the tangent tracks.

Table 3: Average natural wear rate for different periods and curve types

<table>
<thead>
<tr>
<th>Period</th>
<th>Average natural wear rate mm²/MGT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A curve</td>
</tr>
<tr>
<td>2009</td>
<td>0.36</td>
</tr>
<tr>
<td>2010</td>
<td>0.33</td>
</tr>
<tr>
<td>2011</td>
<td>0.58</td>
</tr>
<tr>
<td>2012</td>
<td>0.63</td>
</tr>
<tr>
<td>2013</td>
<td>0.50</td>
</tr>
<tr>
<td>Average</td>
<td>0.48</td>
</tr>
</tbody>
</table>
The accumulated average artificial wear area for the curves and tangent track is shown in Figure 15. The amount of metal removed during grinding is normally optimised by pre-grinding evaluations carried out by the project group. This evaluation involves the use of rail profile measurement data, eddy current measurement data and report from technical field visit. The accumulated artificial wear on the curves is at least 1½ times that on the tangent track. There seems to be a pattern in the amount of metal removed and track curvature. This pattern is not distinct enough because of the high metal removal on the D curve type. The high metal removal on the D curve is considered to be incidental and not a definite pattern since it is only one D curve that is reported in the figure.

The findings presented so far are the average wear pattern for different categories of curves and tangent track according to field measurement data. These observations cannot be generalized for all tracks, however useful inference can be drawn from the observed trends.

Finally, the wear development from a holistic view is shown for specific curves and tangent track in Figure 16. After 6 years, the total wear on the sharp curves is over 250 mm² which is about 1½ and 2½ times the total wear on mild curves and tangent tracks respectively. In addition, it is clearly visible from the slope and rise for the different periods in the figure that more metal is removed during grinding operation than during traffic operation.
CONCLUSION

This paper presents an evaluation of rail wear characteristics on five curve types and tangent tracks on the Swedish heavy haul line. Some of the concluding remarks are:

- Natural wear rate on the sharp curves is about 2 and 5 times the wear rate on the mild curves and the tangent track respectively.
- The visible rise in natural wear rate on all the curves between 2010 and 2011 is related to both increase in annual tonnage and axle load condition.
- More material are removed during grinding operation than traffic operation.
- The typical total wear on sharp curves after 6 years is over 250 mm² which is about 1½ and 2½ times the wear on mild curve and tangent track respectively.

This study is part of a project in progress. The result achieved so far will be further used in the development of model for estimating the remaining useful life of rail. It is gives also useful information for the ongoing grinding and lubrication projects on the route.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial and technical support of Trafikverket, LKAB, SPENO, Voestalpine, Luleå Railway Research Centre (JVTC) and SWECO.

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