Predictive Preventive Grinding Model to Control Rolling Contact Fatigue in Rails is Tested on BNSF Railway

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Abstract Summary
This paper chronicles the efforts of BNSF Railway, a North American heavy haul railway, together with its grinding contractor, to further optimize grind cycles and metal removal requirements to most economically control RCF damage. A new grinding methodology called Predictive Preventive Rail Grinding (PPG), developed by National Research Council Canada (NRC), is tested on a portion of the railroad. Detailed measurements from eight grind cycles over the course of 2 years are used to compare actual rail surface conditions vs. the PPG model.

1 Introduction

Rail profile maintenance by rail grinding is a necessary maintenance practice on heavy haul railways to ensure long life of their most expensive asset [1]. By definition best practice preventive rail grinding is undertaken on tonnage based intervals to: maintain optimized transverse rail profiles; maintain the rail surface rolling contact fatigue (RCF) to shallow depths; maintain optimal contact conditions with the rolling stock wheels; maintain a smooth longitudinal profile in order to: prevent high dynamic loads; reduce lateral forces in curves; prevent hunting; and reduce wear of both rails and wheels.

Knowing the relationship between track curvature, accumulated tonnage and RCF growth rates is highly beneficial to a railroad on two important levels. The first level occurs during the grind planning and execution phase whereby only the requisite metal is removed from the rail. Grinding a rail to a near crack-free state without removing too much metal, and thereby reducing the rail life, is a delicate balance. By knowing the RCF crack depth in a rail, the work effort in terms of grinding passes, speeds and applied power for each individual rail can be predetermined.

The second level of benefit comes from being able to predict, based on an economic justification, when a section of track should be ground. By knowing at what rate the damage is developing over a given section of track the grinding can be planned to balance the cost of grinding with the cost of rail life to minimize the total investment in rail maintenance.

2 Background

Preventive rail grinding as a rail maintenance strategy was first developed by the National Research Council Canada’s Centre for Surface Transportation Technology (NRC-CSTT) in the late 1980’s [2] and has been recognized since then as the industry best practice for rail grinding. Preventive rail grinding was demonstrated to produce significant benefits to BNSF Railway in a two year test program on their Pacific Northwest territory between 1998 and 2000 and was subsequently cascaded to the entire BNSF system by 2001 [4, 4].

The preventive rail grinding model was designed to remove RCF cracks using a single pass at high grinding speed with a production rail grinder when the cracks were still shallow and their rate of propagation was slow.

Research theory, in-track measurements and practical experience demonstrated that RCF cracks initiated faster in increasing degrees of rail curvature. The preventive grinding method cycled the rail grinder based on traffic density (tonnage) and curvature ranges of tangent, mild curves and
sharp curves. Best practice rail grinding in North America [1, 5] sets the tangent grinding cycles as multiples of mild curve and sharp curve cycles. For example, a high production grinder will grind the track “out of face” (all the track) in the territory in cycle 1, all the sharp curves in cycle 2 and all the mild and sharp curves in cycle 3 and then repeat the process. Preventive grinding intervals used by North American railways to preventively maintain their rail range from 13.6 to 22.6 mgt (15 to 25 MGT) for curves less than 582 m radius (greater than 3°) with premium steel up to 90.7 mgt (100 MGT) for tangent rail with premium steel.

The shortcomings of the current preventive grinding model include:

- the logistics of staying on cycle for railway subdivisions with a high percentage of sharp curves that are hundreds of kilometers from subdivisions with predominantly mild curves,
- one-pass grinding of all curves in the mild and sharp curve categories at the same grinding speed (even though RCF cracks propagate at different rates in high and low rails for each curvature range),
- the inability to handle annual tonnages that are not constant across each subdivision,
- some grinding cycles eventually need multiple grinding passes on some sharper curves when RCF cracks are too deep to control with one pass,
- not knowing how deep the RCF cracks are at the start of grinding and subsequently not knowing if they have been completely removed when grinding was finished,
- the inefficiency of multiple-pass grinding in terms of the uncertainty of grinding speeds and total passes for grind planning and predicting traffic interruptions.

Loram Maintenance of Way (Loram) commissioned a study by the NRC-CSTT to evaluate the return on investment (ROI) of corrective and preventive rail grinding strategies with respect to RCF crack growth and propagation on a typical North American heavy haul railway. BNSF Railway was asked to partner in the study by supplying historical geometry, defect, tonnage and rail lubrication information for two of its subdivisions. BNSF Railway selected the Lakeside and the Thayer North subdivisions, with concrete and wooden sleepers, respectively, as the locations for the ROI study as these are typical of their toughest regions for geography and track geometry. Loram supplied the rail grinding history and the metal removal rates for the rail grinders.

Several factors were considered important to a new model:

1. Detail fractures with respect to tonnage between grinding cycles per track km per MGT in one BNSF Railway subdivision for preventive grinding at 13.6 mgt cycles (15 MGT) versus corrective grinding at 45 to 63.6 mgt (50 MGT to 70 MGT cycles) increased; from 0.0039 to 0.0081 for curves, and; from 0.0023 to 0.0038 for tangent [6].
2. Deep seated shells (DSS) require the appropriate gauge corner relief especially in well lubricated subdivisions [5, 7]. Appropriate tonnage intervals (MGT) were calculated by NRC-CSTT for tangent and each degree of curvature from 1 to 8 degrees to be 45 mgt (50 MGT), 40 mgt (36 MGT), 29 mgt (32 MGT), 25 mgt (28 MGT), 22 mgt (24 MGT), 19 mgt (21 MGT), 16 mgt (18 MGT), 14.5 (16 MGT) and 12.7 mgt (14 MGT) [6].
3. Rail wear rates based on approximately 454 mgt (500 MGT) for tangent, high and low rails between 0 to 269 meters radius (0 to 6.5 degrees) for rail grinding wear and rail wear caused by wheels was calculated from BNSF Railway track geometry car records. A wheel wear and metal removal index was developed per 90.7 mgt (100 MGT) of traffic.
4. Rail lubrication levels influence the RCF initiation rates by reducing the tangential stress at the wheel/rail surface, thereby increasing the number of contact cycles by wheel loads before RCF initiates.

3 RCF Crack Propagation Curves

The growth rate of three types of RCF defects are considered for the new model [1]:

1. RCF initiated by plastic flow of metal at the rail surface and subsurface until the material’s ability to shear is exhausted.
2. RCF initiated 5 mm (0.2 inch) below the gauge corner of the high rail by the combination of residual shear stress and a stress raiser (inclusion).
3. RCF initiated at the rail surface in the martensitic layer.

NRC-CSTT developed the generic RCF crack propagation curve (RCF curve) for heavy haul track from an extensive literature review (Figure 1) [6, 8, 9]. This curve shows the relationship between crack depth and accumulated tonnage and was calibrated for heavy haul traffic on BNSF Railway using their current rail sections. Each degree of curvature from 3492 to 269 meter radius (0.5 to 6.5 degrees) and each rail position (tangent, high or low rail) has a representative RCF curve calibrated for crack depth at the center of the rail head as a function of tonnage. The calibration was determined based on actual track geometry car and Loram rail grinding data for wear rates due to wheel wear and rail grinding wear.

![Figure 1: Variable rate of crack growth expressed in terms of crack depth (generic RCF crack propagation curve) for tangent and low rails (left), and tangent and high rails (right).](image)

These curves provide a number of attractive features expected from a crack growth model. First, damage occurs more quickly on high rails as opposed to low rails or tangent rails. Second, as the degree of curvature increases the rate at which damage occurs also increases. These features are coherent with what would be expected from the way these rails handle loads.

Additionally, there are features which are not necessarily expected, but worthy of note. One is that there is an initial period of rapid crack growth on a rail that has no cracks whatsoever. Then, after a period of slow growth, crack growth accelerates. Intuitively, from these features, it is beneficial to grind before crack growth begins to accelerate too rapidly.

4 Predictive Preventive Grinding

NRC-CSTT developed a new grinding methodology called predictive preventive grinding which is based on the RCF crack growth rate curves for each specific track curvature and rail position. This model relies on actual data from the railway to which it is to be applied at a subdivision or territory level [6].

The proposed method of assessing the grinding requirement is with a ROI model that prescribes metal removal using factors such as MGT, curvature, rail position (high / low / tangent), state of lubrication, grinder metal removal rates, rail type, rail size, and others.

Predictive preventive grinding is based on an ROI analysis that has the following features:
- Grind the rail to the shape of a set of optimized rail profiles. The set includes mild and sharp curve profiles that alleviate development of RCF DSS defects [7].
- Preventive grinding intervals are derived from calibrated RCF crack growth curves for each degree of curvature, prevailing hardness of the rail in the track, lubrication standards, etc. Thus each curvature (from tangent to sharpest curves) has its own ideal preventive grinding interval.
Choice of preventive grinding cycle is based on a ROI analysis that maximizes rail life based on rail replacement and rail grinding costs. As the rail grinder circulates over a selected territory on the preventive grinding cycle, each track segment (whether tangent or curve) is either skipped, ground with one pass or multiple passes based on metal removal needed to remove RCF. Therefore the ideal preventive grinding interval will be the one that provides the best return on investment for each track segment.

5 Validation of RCF Crack propagation Curve

Validation tests of the theoretical RCF growth rates began in February 2008 on BNSF Railway’s Lakeside subdivision located in Eastern Washington State. The Lakeside subdivision provides several curves of varying degree of curvature within relative close proximity to each other on single track with moderate to flat grade. The traffic over this route is predominately mixed freight with approximately 70% of the loaded traffic traveling in one direction. The annual tonnage over the test area varied from a high of 87 mgt (95.8 MGT) in 2008 to a low of 77.5 mgt (85.4 MGT) in 2009. In all, over 218.6 mgt (241 MGT) passed over the test sites through the final grind cycle ending in November 2010.

The test was to be of a non-destructive nature meaning that rail samples would not be cut from track for the sole purpose of examining crack growth. Therefore, with no means to accurately measure crack depth, a strategy of closely monitoring accumulated wear rates from wheels and grinding combined with visual observations of surface cracks was employed. In order to validate the crack growth curves it was necessary to grind a rail to a crack free state and then on the subsequent grind cycle an amount of metal close to the prescribed theoretical value was removed. If cracks remained in the rail then it could be concluded that the crack growth curve was too conservative and, if the rail was crack free, the crack growth curve was too liberal.

5.1 Test Locations and Methods

A total of 21 curves and tangents were included in the study ranging from tangent track to 291 meter radius (6 degrees) in curvature as detailed in Table 1. Where practical, 3 test sites were monitored on each rail equally spaced throughout the body of a curve or tangent section. For shorter curves two locations were monitored on each rail. Throughout the course of the study a number of rails were replaced, allowing the progress of RCF initiation and growth to be monitored from a new condition. These instances were considered as separate test sites from their original sites and are included in Table 1.

Table 1 Test site distribution

<table>
<thead>
<tr>
<th>Curve Category</th>
<th>Minimum Curvature m R(°)</th>
<th>Maximum Curvature m R(°)</th>
<th>Number of Curves</th>
<th>Number of Rails</th>
<th>Total Unique Test Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent</td>
<td>0.00</td>
<td>0.00</td>
<td>3</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td>0.5° to 1.5°</td>
<td>1746 (1.00)</td>
<td>1647 (1.06)</td>
<td>6</td>
<td>13</td>
<td>37</td>
</tr>
<tr>
<td>1.5° to 2.5°</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.5° to 3.5°</td>
<td>582 (3.00)</td>
<td>549 (3.18)</td>
<td>3</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>3.5° to 4.5°</td>
<td>436.5 (4.00)</td>
<td>417 (4.19)</td>
<td>3</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td>4.5° to 5.5°</td>
<td>349 (5.00)</td>
<td>349 (5.00)</td>
<td>1</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>5.5° to 6.5°</td>
<td>288 (6.06)</td>
<td>268.6 (6.50)</td>
<td>5</td>
<td>16</td>
<td>46</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>21</td>
<td>54</td>
<td>152</td>
</tr>
</tbody>
</table>

5.2 Test Measurements

Measurements at each of the test sites were collected prior to and just after each grind cycle. The following information was collected for each pre-grind measurement: rail hardness, track...
super elevation, track gauge, high rail lubrication observations, a rail surface condition photograph, dye penetrant or magnetic particle photograph and a MiniProf rail profile measurement. Post grind information included a MiniProf rail profile measurement and a rail surface condition photograph. Throughout the course of the tests over 1800 rail profiles were collected.

Calculations for head radius, area lost and wear measurements were extracted from the MiniProf rail profiles. Coincident with the NRC-CSTT crack growth prediction models, the primary value used from the MiniProf profiles was the vertical wear (W1 in MiniProf software).

Lubrication observations for high rails were classified as 1) Poor if there were no signs of any lubrication 2) Moderate if lubrication was present but evidence existed of pitting on the gauge face, indicating a poor lubrication condition at some time in the recent past and 3) Good if there was lubrication present and there were no signs of pitting on the gauge face. Throughout the course of the trial high rail lubrication was deemed to be primarily “Good” with the classification of Moderate or Poor used only at the onset of the test and on a handful of curves midway through the test period.

Tonnage information was obtained through monthly reports issued by BNSF Railway.

5.3 Classification of Surface Conditions

The post-grind photographs were used to classify the surface density of RCF cracks remaining in the rail after the rail had been ground. Although the photographs cannot be used to determine the depth of the cracks they can be used to determine if any cracks exist or to what extent cracks were removed compared to the pre-grind photographs. The post-grind photographs were categorized on a scale of 1 to 4 based on the probable work effort required to remove any remaining surface defects. A rail classified as 1 signified a clean rail while rails classified as 4 were judged as requiring a significant amount of additional grind effort to achieve a crack free state. Classification levels 2 and 3 were determined to reside equally between a Class 1 and Class 4 state. Examples of the four levels of classification are shown in Figure 2.
Figure 2: Shows a) Example of Post Grind Classification 4 – Severe, b) Example of Post Grind Classification 3 - Moderate, c) Example of Post Grind Classification 2 - Mild, d) Example of Post Grind Classification 1 - Clean.

6 Analysis of Test Results

Prior to the onset of the first grind cycle the Lakeside subdivision had not been ground since June 2007 and the rails had accumulated over 60 mgt (66 MGT), resulting in significant RCF damage and metal flow in many of the rails, particularly those on curves sharper than 582 meter radius (3°). The first order of business was to remediate that situation over several grind cycles. It was of no use trying to account for RCF growth from an unknown starting point. The existing damage at the start of the test was sufficiently deep that a catch-up mode was employed on the sharper curves in order to not remove the work hardened layer during any one grind cycle. By the 4th grind cycle a sufficient number of curves were in a condition to begin experimenting with varying depths of cut during subsequent grind cycles.

An example of the test results are shown in the left side of Figure 3 for 291 meter radius (6°) high rails. The model was assumed to be correct for instances in which the rail condition was returned to a clean state after grinding and the depth of cut was at or above the depth predicted by the PPG RCF crack growth model or the rail condition deteriorated and the depth of cut was below the depth predicted by the RCF crack growth model. Those instances where the rail condition improved but the depth of cut was below the model depth or where the rail condition deteriorated and the depth of cut was above the model prediction were assumed to be incorrect model predictions. In this case the model was correct 18 out of 25 times or a 72% success rate.
Figure 3: Test results for 6° high rails (left) and tangent rails (right)

An example of an instance where the model clearly breaks down is shown in the right side of Figure 3. In this case the model is fairly accurate in the lower tonnage ranges but practically no correlation for extended tonnage cycles exists. Similar results were found when extending the grind cycles on 1° high and low rails. Practical BNSF Railway field experience dictates that factors other than RCF growth rates need to be considered when extending grind intervals on standard carbon rail in tangent track. Some of these factors include the onset of truck hunting due to profile degradation, flashbutt weld dipping and increased detail fracture rates [6].

An overall summary of the results is shown in Table 2. The data has been broken out to show areas where the model seems to fit with the trial results and areas where it clearly does not as noted in the previous two examples.

Table 2 Result summary by curve and rail category

| High Rails in curves 582 m R (3°) and below | Low Rails in curves 582 m R (3°) and below | High Rails in 1746 m R (1°) curves with less than 40 mgt (45 MGT) | Low Rails in 1746 m R (1°) curves with less than 40 mgt (45 MGT) | Tangents with less than 40 mgt (45 MGT) | All rails for 1746 m R (1°) and Tangents with more than 40 mgt (45 MGT) |
| Correct Model Prediction | 39 | 20 | 24 | 25 | 37 | 4 |
| Incorrect Model Prediction | 16 | 24 | 19 | 14 | 9 | 34 |
| Model Success Rate | 71% | 46% | 56% | 64% | 80% | 11% |

Clearly from the results shown in Table 2 the predicted RCF crack growth curves are in need of refinement for low rails on sharp degree curves and extended tonnage intervals for tangent rails and both rails on shallow degree curves.

7 Economic Models

Using the theoretical predicted RCF crack growth curves, economic models can be applied to determine ideal grind cycles. Using the relationships between the W1 (vertical) and W2 (gauge face) wear rates in MiniProf software, estimates can be made for determining when a rail will be removed from service due to either vertical or horizontal wear limits. These estimates give an overall cost of rail based on relay costs for new rail. The maintenance costs in terms of grind effort can be estimated based on the required artificial wear, the productivity of the grinder and other costs associated with its operation.
The left side of Figure 4 shows the combined annual maintenance and rail life costs for a 535 meter (0.27 mile) long 578 meter radius (3.02°) curve carrying 65.6 mgt (72.3 MGT) of traffic as a function of days between grind cycles. As would be expected, the costs are extremely high for short grind cycles as the cost of nearly continuous grinding overwhelms the benefit of removing slow growing cracks. As the grind cycle is extended the cost of rail life is balanced against the cost of grinding until a minimum optimal cost is realized at a 108 day cycle. After this point the cost of removing cracks in the rail at an ever accelerating pace outweighs any benefit of delaying the grinding costs.

The right side of Figure 4 shows the annual maintenance and rail life costs for a 539 kilometer (335 mile) long territory. These costs include the optimal levels for all curves within the territory. In this case an optimal cycle is realized at 149 days. Note a difference in vertical axis scale between the two plots of 1000.

Figure 4: Cost plots for an individual curve (left) and territory (right) versus grind cycle

The new predictive preventive grinding model, in comparison with an historic style of preventive grinding on BNSF Railway theoretically saves between $US 5 to $US 7.4 million over 10 years in rail and maintenance costs for one subdivision alone. The new grinding strategy also can extend rail life a further 22% to 58% with improved grinding efficiencies.

8 Conclusions

The theoretical RCF crack growth curves were found to need refinement for some curve and rail categories. Once these refinements are completed, economic models can be used to determine optimal grind cycles for each specific territory on the railroad.

Further experimentation is needed to determine the break point between the 1746 and 582 meter radius (1° and 3°) categories. Due to the nature of the testing, the methodology employed in this validation process was time consuming and labor intensive. Existing, commercially available equipment to measure crack depths is available to measure crack length but depend on a theoretical angle of growth to be accurate. The use of an accurate and easy to use method to monitor the crack depths would be extremely useful for determining crack growth rates. To determine RCF depth accurately rail samples need to be destructively tested to determine the relationship between RCF surface length and RCF vertical depth into the rail.

9 Acknowledgements

The authors are grateful to BNSF Railway for their support and cooperation in the project and help with providing the data from past records and their participation in the field assessment process.
10 References

3. J. Stanford, P. Sroba, E. Magel, Burlington Northern Santa Fe Preventive-Gradual Grinding Initiative, AREMA, Chicago, ILL, September 1999
4. J. Stanford, J. Kalousek, P. Sroba, P., Magel, E, Transitioning from Corrective to Preventive Rail Grinding on the BNSF Railroad, Proceedings of the Seventh International Heavy haul Conference, Brisbane, Australia, June, 2001 IHHA,
6. P. Sroba, R. Caldwell, J. Kalousek, Technical background for a return on investment economic analysis on rail grinding for heavy haul lines, internal report by NRC-CSTT to Loram, April, 2007.
7. P. Sroba, M. Roney, E. Magel, J. Kalousek The Evolution of Rail Grinding on Canadian Pacific Railway to Address Deep Seated Shells in 100% Effective Lubrication Territories” World Congress on Railroad Research, Montreal, June 2006.