Planning Rail Grinding Using Crack Growth Predictions*

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Abstract
Rail grinding is a widely used rail industry technique for maintaining the quality and safety of railway track. Rail grinding can be used to restore the profile of the rails, remove surface plastic damage and remove or reduce in size very early stage surface breaking rolling contact fatigue cracks. This paper focuses on the use of rail grinding to extend the safe life of a rail that would otherwise be limited by rolling contact fatigue (RCF) defects. The optimum grinding strategy for a variety of conditions has been investigated using a model that predicts the growth of surface breaking cracks in rails loaded by rail vehicle wheel contacts, taking into account natural wear of the rail and rail grinding. It was found that a grinding strategy which removes incipient cracks in a specific period of time without being over-conservative and producing excessive material loss must take into account all traffic using the line, not just the traffic perceived to be most damaging. A mixed traffic case is modelled, revealing the potential for interaction between different vehicle types in determining maintenance requirements.

Key words: Rail Grinding, Crack Growth, Prediction, Maintenance, Scheduling

1. Introduction
Rail grinding is a widely used rail industry technique for maintaining the quality and safety of railway track. Rail grinding can be used both to reduce the size of cracks in the rail and to maintain, or alter, the profile of the rail to improve wheel-rail contact conditions and vehicle dynamics. This paper focuses on the use of rail grinding to extend the safe life of a rail that would otherwise be limited by Rolling Contact Fatigue (RCF) defects (Fig. 1).

Grinding aims to remove plastically strained material approaching ductility exhaustion at the rail surface, early stage surface based crack growth, and to correct deterioration of rail profile taking place through wear. All these failure processes are driven by the high contact stress typical of the rail-wheel contact, although residual stresses internal to the rail may also influence crack growth, and will themselves be modified by plastic deformation of the steel. If not corrected surface fatigue damage in the contact area can lead to large cracks that may grow to threaten the integrity of the rail. The grinding strategy defines the depth of material removed around the rail profile at each grinding operation and the frequency with which grinding is carried out. It represents a compromise between factors including the necessity to treat surface based fatigue damage and incipient cracks, reduction in the wear
life of the rail caused by removal of material, the cost of the maintenance procedure, and the value of the extension of the safe life of the rail. This paper deals particularly with the removal by grinding of small, early stage fatigue cracks, whereas an approach which focuses on surface plasticity is presented by Vasic et al. (1).

In the UK grinding is typically scheduled based on inspections of the rail to assess rail profile deterioration or crack formation, previous experience and broad guidelines on grinding typically required for tangent track and curves. To avoid unnecessary grinding and to define an ‘optimum’ grinding strategy it is first necessary to define the objectives of the grinding programme. For example, the aim may be to maximise rail life, to minimise life cycle cost of the rail, to remove plastically deformed material to a certain depth (1) or to eliminate defects over a particular size within a certain period of grinding. The optimum grinding strategy necessarily varies with this definition according to the priorities of the operator, and no single ‘optimum’ can be identified to suit all cases. The disruption to traffic and the efficient use of grinding machines and other maintenance equipment is also likely be a consideration in identifying the best strategy.

Nomenclature

\( P_0 \) : maximum Hertzian contact pressure
\( \mu \) : traction coefficient

2. Modelling Approach

Fletcher et al. (2) developed a model capable of bringing together natural wear rate, rolling contact fatigue crack growth rate predictions, and grinding. The approach taken here is similar with the exception that the method has been extended so grinding interval is independent of traffic. The model takes a “high resolution” approach, suitable for a detailed study of a small number of specific locations (for example at a curve with rolling contact fatigue problems), but is less well suited to application over large distances of track. The inputs to the model are briefly described below, taking the specific case of the UK East Coast Main Line as an example, for which five vehicle types dominate traffic. The specific values of contact pressure and other parameters will vary with location, but this is not the primary concern here, since broad trends and the interaction between different vehicle types are of greater interest.

2.1 Representation of surface breaking crack growth

Crack growth data which forms an input to the grinding model has been generated using the “2.5d” approach developed by Fletcher and Kapoor (3). The 2.5d model represents the rail as a half space containing a semi-circular crack (in this case inclined at 30° below the rail surface), loaded by a wheel represented as a Hertzian contact pressure, and
generates crack growth data using a linear elastic fracture mechanics approach. The crack initiation phase (very small cracks dominated by rail surface plasticity) is not considered, and simulations typically assume the presence of a crack of 1.5 to 2mm radius as a starting point. The grinding model is effectively independent of this crack growth model, and alternatives could be used to supply the crack growth input data for the grinding model.

Using the “2.5d” model, crack growth rate data for a range of crack sizes was pre-calculated for each vehicle type modelled, taking account of differences in contact pressure and traction levels (Table 1). Contact data were calculated using the Vampire vehicle dynamics software taking account of suspension characteristics, track curvature, vehicle speed and other factors, and represent a location on the UK East Coast Main Line (4). Rail residual stresses and the modification of the residual stress surrounding the crack by grinding were not considered since data were not available. The crack growth data forms an input to the grinding model (see Table 2 for an example of the crack growth data) and rates do not need to be repeatedly calculated as crack growth, wear and grinding modify the crack size. Instead, growth rate for a crack of any size can be found by interpolation from the pre-calculated input data, greatly speeding calculation.

Table 1. Contact data for the traffic types modelled.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Contact pressure (MPa) and traction coefficient</th>
<th>Wear rate / nm per wheel pass</th>
<th>Assumed proportion of traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 43 diesel locomotive</td>
<td>$P_0=1739$ $\mu=0.28$</td>
<td>1.99</td>
<td>2</td>
</tr>
<tr>
<td>Class 91 electric locomotive</td>
<td>$P_0=1934$ $\mu=0.28$</td>
<td>2.44</td>
<td>1</td>
</tr>
<tr>
<td>Mark 3 coach</td>
<td>$P_0=1460$ $\mu=0.33$</td>
<td>1.96</td>
<td>8</td>
</tr>
<tr>
<td>Mark 4 coach</td>
<td>$P_0=1725$ $\mu=0.29$</td>
<td>2.04</td>
<td>9</td>
</tr>
<tr>
<td>Class 365 electric unit</td>
<td>$P_0=1295$ $\mu=0.29$</td>
<td>1.05, 0.79*</td>
<td>8</td>
</tr>
</tbody>
</table>

* For class 365 units, the standard wear rate was 1.05nm/wheel pass, with a special case of wear reduced to ¾, referred to as 365X.

Table 2. Pre-calculated crack growth data for Class 91 locomotive, extracted from table of over 120 data points used in the modelling.

<table>
<thead>
<tr>
<th>Crack radius / mm</th>
<th>Crack growth rate / nm per wheel pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>1.5</td>
<td>7.4</td>
</tr>
<tr>
<td>4.0</td>
<td>16.7</td>
</tr>
<tr>
<td>6.5</td>
<td>28.6</td>
</tr>
<tr>
<td>7.7</td>
<td>30.4</td>
</tr>
<tr>
<td>8.9</td>
<td>29.2</td>
</tr>
<tr>
<td>10.2</td>
<td>26.5</td>
</tr>
<tr>
<td>12.6</td>
<td>20.5</td>
</tr>
<tr>
<td>15.1</td>
<td>15.7</td>
</tr>
<tr>
<td>17.6</td>
<td>12.3</td>
</tr>
<tr>
<td>20.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>
2.2 Representation of grinding

To represent grinding the model considers only the crack size reduction through rail surface removal, and does not take account of other effects of grinding such as re-location of the contact patch across the rail head, or change in contact pressure as a result of any change in rail profile (these will be considered in future versions of the model). Each grinding event is represented as a discrete wear event occurring independently of traffic.

The grinding process is taken to remove a specific depth of material from the rail surface (see Fig. 1) thereby ‘shortening’ the crack. In cases where cracks remain after grinding, the wear process effectively cuts a chord across the semi-circular crack, leaving the remainder of the crack to continue developing during subsequent wheel passes. With grinding depths in the region of 0.2mm, and crack sizes in the range of 1.75 to 20mm radius, the remaining crack is close to semi-circular, and in modelling its subsequent growth the assumption was made that it continues as a semi-circular crack with a radius determined by the length to the surface from its deepest internal point.

2.3 Representation of natural rail wear

Each wheel pass of ordinary traffic causes a small amount of rail surface wear. This was considered in the same way as the grinding events, i.e. removal of a small amount of the crack at the rail surface. Wear values were taken from predictions made by the Dynarat model developed by Franklin and Kapoor (5), although as with crack growth data, the grinding model is capable of taking data or measured values from any source. Table 1 shows a summary of the natural wear rates for each of the traffic types, it being assumed that these rates remain constant throughout the simulation, and that in mixed traffic cases there is no wear rate variation attributable to interaction between traffic types. The main difference between the natural wear produced by rail traffic, and the artificial wear taking place during grinding is in the magnitude of rail material removed, which is much lower for each wheel passage of ordinary traffic. In addition, it is considered that normal traffic produces both a wear increment and a crack growth increment, whereas grinding produces wear only.

For the class 365 electric multiple unit a special case was modelled using a wear rate of 0.75 times the value predicted by Dynarat simulation. This could for example represent a replacement for the class 365 that reduces rail wear but is otherwise similar, and was used to examine the sensitivity of the modelling outcome to a change in wear rate. In Section 3 results for this case have been labelled 365X.

2.4 Combining crack growth, wear and grinding

Each simulation was conducted assuming an initial crack of 1.75mm radius to exist inclined at 30° below the rail surface. Modelling proceeds in an iterative fashion one wheel pass at a time, with each wheel able to produce both crack growth (calculated by interpolation from pre-calculated values produced by the 2.5d model) and wear with consequent crack size reduction. As described above, grinding events are simply severe wear events without any accompanying crack growth, which take place after a pre-determined numbers of wheel passes. The model sums the net effect of wear and crack growth with each wheel pass, proceeding iteratively through any required pattern of traffic.

The modelling method described could be applied at any location, and to any mix of rail traffic, but this paper is based on vehicles using the UK East Coast Main Line. This line is dominated by fast passenger services and high volumes of commuter services, using a mix of diesel and electric locomotives, coaches and multiple units. Table 1 shows the proportions of each traffic type simulated in mixed traffic cases. In a mixed traffic case the
different wheel profiles, suspension characteristics, speeds and other variables are accounted for in the vehicle dynamics software used to calculate the contact data. The different traffic may produce different running band positions, and a wide spread of defect locations could develop, or if only a single defect exists, the lateral offset between the contacts and the defect would affect its growth rate. However, in the current model it was assumed that all traffic is driving the growth of a single rail surface defect, representing a worst case scenario.

2.5 Optimisation of grinding

Grinding processes have many variables, including the depth of material removed, the frequency of grinding, the number of grinding stone passes in a single operation, and the rail profile the grinding is aiming to achieve. In the current simulations the depth of grinding was fixed at 0.2mm, and the effect of frequency was investigated, first for each train formation individually and then for a mixed traffic case. The class 365 electric multiple unit was simulated as a single vehicle type, but for other train formations a locomotive and coaches were simulated by iterative application of a number of wheel passes representing the vehicles in the formation.

To define a common point between the simulations, it was decided to identify for each traffic type the frequency of grinding required to remove an initial defect of 1.75mm radius after 3 million wheel passes. This could then be viewed as the ‘optimum’ grinding frequency for that traffic type, and these individually determined grinding strategies were then applied to the mixed traffic case, and in addition, the ‘optimum’ for the mixed traffic case was determined. As discussed above, the ‘optimum’ grinding strategy depends upon the aim of the grinding and the initial crack size considered, therefore a wide range of alternative ‘optimum’ strategies are possible depending on the criteria selected, with the case modelled here being an example.

3. Results

For each train formation considered, a series of grinding intervals was modelled. Results are presented as plots of crack size against number of wheel passes for up to 5 million wheel passes, starting from an initial defect of 1.75mm radius. In addition to pre-determined grinding intervals, the grinding interval required to remove the pre-existing defect by 3 million wheel passes was calculated. This gave a common point for comparison of the different traffic cases.

3.1 Class 365 multiple unit

The class 365 electric multiple unit had the lowest predicted rail-wheel contact pressure of the vehicle types examined, leading to low crack growth expectations, and also the lowest natural wear rate. Fig. 2 shows that even without grinding, the natural wear dominates crack growth, and the initial defect of 1.75mm radius is worn out after 1.2 million wheel passes. If grinding had been applied, the defect would have been removed earlier, but in no case would the defect persist to 3 million cycles.

To examine the sensitivity of the outcome to wear rate a further simulation was performed with the wear rate reduced to 0.75 times its standard value. This extended the number of cycles requires to wear the initial defect away from approximately 1.2 to 1.9 million cycles. The effect of this change in wear when the class 365 is a component of a mixed traffic simulation is discussed below.
3.2 Class 43 locomotives and mark 3 coaches

The combination of 2 class 43 locomotives and 8 mark 3 coaches makes up a high speed passenger train, and these vehicles are considered together as a train formation. It is shown in Fig. 3 that a grinding interval of approximately 193,000 wheel passes is sufficient to remove a 1.75mm radius initial defect by 3 million wheel passes. More frequent grinding will remove the defect sooner, but could represent over-grinding.

In the case where no grinding is applied, Fig. 3 shows that crack growth rate is predicted to change over time, increasing most rapidly during the first 1 million wheel
passes, and much more slowly at larger crack sizes. This is because as the crack enlarges it moves away from the highly concentrated wheel-rail contact stress into less highly stressed material, and this change is reflected in a reduction of crack growth rate at larger crack sizes. Since wear is independent of crack size, an equilibrium can be reached, or at least approached, indicated by the reduction in slope of the crack size curve. However, it should be noted that the only crack growth mechanism modelled here is contact stress driven growth of the crack, and in reality rail bending will begin to drive growth of larger cracks \(^{(6)(7)}\). Crack growth cannot be expected to slow or stop in every case as the cracks extend, and there is not necessarily any “safe” region in which cracks of a stable size reach equilibrium with rail wear. This pattern of growth was also seen in the case of class 91/mark 4 vehicles.

3.3 Class 91 locomotive and mark 4 coaches

Figure 4 shows results for the high speed passenger train formed of a single class 91 locomotive and 9 mark 4 coaches. The behaviour was very similar to that for the class 43/mark 3 high speed trains, although the grinding interval required to remove the initial 1.75mm radius defect was increased from approximately 193,000 to 245,000 wheel passes. This difference is brought about through the combination of differences in contact pressure (and hence crack growth predictions), and also differences in the natural wear rates for the vehicles.

![Fig. 4 Effect of grinding interval on crack radius for class 91 locomotive and mark 4 coaches.](image)

In this case the class 91/mark 4 train is predicted to be less damaging (in terms of allowing an extended grinding interval) than its class 43/mark 3 counterpart, even though Table 1 shows that the class 43/mark 3 train runs with lower rail-wheel contact pressures. The key to this counter-intuitive finding is in the wear rates for the different vehicle types, with the class 91 and mark 4 vehicles showing higher wear than the corresponding class 43 and mark 3. Although the higher contact pressures will drive crack growth faster, the higher wear has the effect of naturally “wearing out” any cracks.

3.4 Combined traffic

Figure 5 shows the results for a combined traffic case, assuming the traffic exists in the
ratios shown in Table 1, with the class 365 unit assumed to produce its standard rail wear rate of just over 1nm per wheel passage. For clarity the results generated at a range of grinding intervals are not presented here, but the ‘optimum’ case able to remove the 1.75mm radius defect by 3 million wheel passes is presented, along with application of the ‘optimum’ rates identified for each of the train formations individually. Removal of the initial defect in the mixed traffic case required a grinding interval of approximately 370,000 wheel passes.

Fig. 5 Effect of grinding interval for combined traffic of classes 43, 91, 365, mark 3 and 4 coaches.

From Fig. 5 the case of no grinding (effectively the maintenance requirement in the class 365 single traffic type case) is predicted to lead to development of large cracks. Although there are a large proportion of wear dominant class 365 vehicles modelled in this mixed traffic case, for the initial defect size considered the wear they produce is not sufficient to compensate for the crack growth produced by the other vehicle types. However, with these wear dominant class 365 vehicles present in the traffic mix the optimum grinding intervals predicted for the individual high speed trains are over conservative, and would lead to unnecessary wear of the rails through excess grinding. Use of these grinding strategies would lead to cracks being removed far more quickly than needed to meet the ‘optimum’ definition of initial defect removal by 3 million wheel passes.

Figure 6 presents further results for the mixed traffic case, but here the wear produced by the class 365 units is reduced to 0.75 times its previous value. This could for example represent a replacement for the class 365 that reduces wear but is otherwise similar to the original units, and is labelled 365X in the figure. In this case, the grinding interval previously identified as able to remove the initial defect in 3 million cycles of mixed traffic was applied (370,000 cycles) but rather than the initial defect being worn out, it was found to develop into a large defect, and was not controlled by the grinding process.

4. Discussion

The combined traffic cases presents the most interesting results, and reveal the sensitivity of predicted crack growth rates to changes in (for example) the wear rates taken for a particular vehicle. This leads to two important findings: (1) if outcomes are so
sensitive to the wear rates (and other inputs such as contact pressures may show similar sensitivity, this is to be investigated in future work) a considerable factor of safety will be needed in defining a safe grinding programme. (2) High sensitivity to factors such as the rail wear produced by a particular vehicle could have rail maintenance implications, particularly when fleets of vehicles are renewed or updated.

Fig. 6 Effect on crack growth of a reduction in wear by class 365 units to 0.75 times its standard value (labelled 365X). Grinding interval same for both cases.

The model shows that there can be major and possibly unexpected consequences of a change in vehicle wear characteristics while other factors remain constant. In the mixed traffic case class 365 electric multiple units have a beneficial effect on rail crack growth by producing more wear than crack growth, i.e. for the crack size considered they are able to wear away cracks, although this would not be the case for larger defects. Moreover, class 365 units are able to wear away not only initial defects, but also to reduce some of the crack growth produced by the high speed trains, making a much longer grinding interval possible (while still meeting the target of removing a particular initial defect size by 3 million wheel passes) than if the high speed trains ran alone.

The impact on crack growth and grinding requirements of a reduction in wear to 0.75 of its previous value for the class 365 units is minor if these vehicles are considered alone (Fig. 2), i.e. the initial crack is still removed by the natural wear of the units, without grinding. However, when the reduced wear vehicles form part of a mixed traffic pattern the impact can be much greater. In the mixed traffic case, and assuming that grinding practice remains unchanged, this small reduction in wear is sufficient to move the system from a safe condition in which defects wear and are ground out, to one in which large defects can develop (Fig. 6). Effectively, the small reduction in wear for the electric multiple units is predicted to allow the damage produced by the existing high speed trains to show through. In reality, the change in damage and crack behaviour would be likely to show up during rail inspections, and the grinding maintenance programme could be modified. Modelling such as presented here has a major role in predicting the sensitivity of rail crack growth to changes in vehicles, and providing sufficient time to increase inspection, modify maintenance procedures, and thereby prevent dangerous crack growth.

A further aspect of any maintenance programme that has not been tackled here is the variation in maintenance that will occur for operational reasons. For example, it is very
unlikely that a fixed and completely regular grinding interval could be maintained since there will be competing demands on the grinding machine time available. In addition, it is quite possible for a grinding operation to be missed due to equipment failure. The effect of these operational realities will be studied in further work which will examine how a grinding maintenance programme can be designed which is resilient to these issues, but which also avoids unnecessary rail wear.

5. Conclusions

Rail grinding is a widely used rail industry technique for maintaining the quality and safety of railway track. A grinding model was applied to investigate how the required grinding interval varies with traffic, focusing on rail grinding to extend the safe life of a rail that would otherwise be limited by rolling contact fatigue (RCF) defects. It was found that grinding strategies which remove incipient cracks in a specific period of time without being over-conservative and producing excessive material loss must take into account all traffic using the line, not just the traffic perceived to be most damaging.

Modelling a mixed traffic case while artificially modifying the natural wear produced by one of the vehicles revealed the potential for interaction between different vehicle types. This led to two important findings: (1) If the predicted grinding intervals required are very sensitive to the natural wear rates of the rolling stock (which are difficult to know with certainty) a considerable factor of safety will be needed in defining a safe grinding programme. (2) High sensitivity of maintenance requirements to factors such as the rail wear produced by a particular vehicle type could produce unexpected changes in RCF crack growth when fleets of vehicles are updated and their behaviour changes.

The current model considers grinding only in terms of reducing the size of incipient surface breaking fatigue cracks, and does not take account of other effects of grinding such as re-location of the contact patch across the rail head, change in contact pressure or change of internal residual stress as a result of any change in rail profile. These will be considered in future versions of the model, along with ways in which a grinding maintenance programme can be designed which is resilient to operational realities such as missed or delayed grinding operations, but which also avoids unnecessary rail wear.

References