Effect of Traffic on Crack Initiation in Rails*

Gordana VASIČ**, Francis J. FRANKLIN**,
David I. FLETCHER*** and Ajay KAPOOR****
**School of Mechanical & Systems Engineering, Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK
E-mail:Gordana.Vasic@ncl.ac.uk
***Department of Mechanical Engineering, Sheffield University, Sheffield S1 3JD, UK
****Swinburne University of Technology, PO Box 218, Hawthorn, Victoria, 3122, Australia

Abstract
This paper describes a method to predict wear rates and time until fatigue crack
initiation. A computer simulation of ratcheting wear is used to model the
accumulation of plastic shear deformation in the rail and predict the wear rate,
based on wheel-rail contact conditions. Contact data for two types of high speed
trains at two sites on the East Coast Mainline, U.K., have been obtained from
multi-body simulations of train-track interaction. Material microstructure has been
modeled as grains of pearlite and ferrite in order to represent the real rail steel.
Results showed that the wear rate increases as the proportion of Class-91/Mark-4
vehicles increases. Conditions for crack initiation arise at Harringay within 10,000
wheel passes. At Sandy, conditions for crack initiation do not arise until after
100,000 wheel passes, and arise soonest when traffic consists of only
Class-91/Mark-4 vehicles. Together with fracture mechanics models for larger
cracks, these models provide guidelines for rail grinding in order to optimize rail
life and safety.

Key words: Rail Wheel Contact, Wear, Crack Initiation, Computer Simulation,
Ratcheting Failure

1. Introduction

Rails are subjected to repeated loading by the action of passing train wheels. The
contact stresses, and how well the rail steel resists deterioration by wear and cracking,
depend on several factors: the geometry of the wheel/rail contact patch, the wheel and rail
materials, the geometry and substructure of the track, vehicle characteristics (load,
suspension, etc.), type of traffic, and wheel/rail contact conditions (friction).

Wear and crack growth are not independent. Surface-breaking cracks are truncated by
wear, and short cracks can be removed by wear or grinding. Wear can therefore be
beneficial for rail life, but too much wear also shortens the life of the rail. Another
consideration is the change of rail profile as a result of wear, which affects vehicle
dynamics and passenger ride quality, so that rails have to be ground to correct the profile. In
addition to correcting the profile, short cracks at the surface are removed, and longer cracks
are shortened. However, since grinding removes material from the surface, excessive
grinding shortens the life of the rail.

The most usual way to model wear is to use Archard’s wear law, which states that wear
rate is proportional to load and inversely proportional to (rail) hardness; the wear coefficient
(i.e., the ‘constant’ of proportionality) depends on other operating conditions, especially the
sliding (or ‘slip’) velocity between wheel and rail. Wear maps of the wear coefficient have
been determined by Jendel(1) and Lewis and Olofsson(2). Emblo and Berg(3) simulated
traffic using a numerical wear model based on Archard’s tribological model and compared
results with site measurements; the predicted wear rates, relative to MGT of traffic, were

*Received 30 Oct., 2009 (No. 09-0647)
[DOI: 10.1299/jmtl.3.100]
Copyright © 2010 by JSME
higher than the measured wear rates, but the main trends could be seen. However, such wear modeling does not indicate severity of crack initiation and growth. Another approach to modeling wear and RCF in rails is to use the T-gamma method; the ‘wear number’, the product of applied traction (T) and creepage (gamma) is energy input into the rail, per unit length, and a proportion of this energy goes into plastic deformation and crack growth – see Lewis and Olofsson\(^2\) and Clayton\(^4\). By correlating predicted wear numbers (based on vehicle dynamics simulations) with field observations of wear and RCF, an empirical formula has been developed by Evans and Burstow\(^5\) for the U.K. rail network where 220 grade pearlitic rail steel is prevalent. For high values of the wear number (more than 170 N) wear is the dominant damage mechanism, whereas RCF is dominant for wear numbers from 170 N down to 20 N. However, the formula does not necessarily translate to other rail networks where different rail and wheel materials are in use. Changes in wear behavior can, to some extent, be predicted for different steel grades – see, e.g., Clayton\(^4\) – but crack initiation is very sensitive to microstructural properties, so RCF prediction is complicated. The model used in the current paper is a computer simulation of plastic ratcheting, i.e., subsurface accumulation of plastic shear deformation, used to predict both wear and crack initiation simultaneously, and thus wear-fatigue interaction is modeled automatically; the simulation allows microstructural details of the rail steel to be simulated.

A large proportion of the overall life of a typical fatigue crack is consumed in the earliest stages during which the crack is small and growth is slow. Crack formation during ratcheting strain accumulation effectively bypasses this stage of crack development, greatly shortening overall crack development time. Figure 1 was generated using a fracture mechanics simulation of rolling contact fatigue (RCF) crack growth including the effect of rail wear\(^6,\)\(^7\), and demonstrates the dramatic acceleration of crack growth produced by initial defects which may be generated through ratcheting of the rail material.

![Fig. 1 Crack size development with increasing numbers of wheel passes for a Class 91 locomotive, including rail wear. The initial radius of defect drastically changes crack progression.](image)

This accelerated crack growth caused by the early plastic deformation and damage means the rail can sustain less traffic before crack management (e.g., grinding). Cases of grinding management for long cracks are discussed by Hyde and Fletcher\(^7\).

Different vehicles have different dynamic loading characteristics and damage the rail to a greater or lesser extent. The effect of traffic on the earliest stages of rail damage – plastic ratcheting of a ductile metal leading to wear and crack initiation – can be studied using the ‘dynarat’ computer simulation\(^6\).

2. Modeling

Plastic shear strain accumulates over thousands of load cycles, and the deforming material is modelled as a mesh of rectangular elements (‘or bricks’) that lie in a plane (i.e., a cross-section through the rail) parallel to the direction of traction (Fig. 2). In order to model
variation of material properties at a microscopic level, each element is assigned individual material properties, such as initial hardness and the critical plastic shear strain at which ‘failure’ occurs.

Fig. 2 Variation of shear stress in the material depth for a low coefficient of friction. The shaded region indicates where the shear stress exceeds the shear yield stress, so plastic flow occurs and there is an increment in plastic shear strain. Elements are increasingly strained until failure occurs(8).

This approach is used to construct a microstructural model of rail steel, where elements are defined as pro-eutectoid ferrite (at the prior-austenite grain boundaries) or as ‘pearlite’ (a composite structure of ferrite and cementite). A sample image from a rail section is given in Fig. 3(a), in which the prior-austenite grain boundary can be seen clearly.

Fig. 3(a) Scanning electron microscope image of a cross-section through a rail sample from Harringay. (b) Input microstructure: 256×256 pixels, each pixel determines a 1µm×1µm element in the model; the colour of the pixel determines the material selected for the element (light grey for ‘pearlite’, dark grey for ferrite).

Figure 3(b) shows a 256×256 pixel two-colour image which is used as an input to the model. Each pixel represents a 1µm×1µm element of the material. The two colours represent two different materials, in this case the darker grey is pro-eutectoid ferrite and the lighter grey is ‘pearlite’; to model the two constituent elements of pearlite separately would require a very fine mesh, so instead the pearlite is treated as a single material.

Once the accumulated plastic shear strain reaches the critical plastic shear strain, the material element is considered to have failed as a result of ratcheting failure(9). Failed material is considered to be ‘weak’, i.e., unable to support tensile stresses and a potential site of crack initiation. Material at the surface which fails can be removed as wear debris, and thus the wear rate over time can be predicted; also, by examining elements which fail subsurface, the simulation can estimate the number of load cycles until the initiation of a ‘significant’ crack, i.e., a crack which is sufficiently long that further growth will be driven by the contact stresses rather than plastic strain accumulation (although crack growth may be accelerated by further plastic strain accumulation).

Both 2D cases, such as twin-disc contact, and 3D cases, such as train wheel on rail, can be simulated. In 3D, a cross-section through the deforming material, parallel with the
direction of motion, is simulated. Since loading of rails is never known precisely, the model has been calibrated using twin-disc data from Tyfour et al.\textsuperscript{(10)} and Garnham et al.\textsuperscript{(11)}.

The material properties of ferrite and pearlite currently used in the model were derived from nano-hardness measurements and metallography of controlled twin-disc experiments\textsuperscript{(11)} using samples machined from ‘normal’ grade (Grade 220) rail steel. Both materials are modelled as strain hardening asymptotically up to a ‘final’ limit. Ferrite has a nano-hardness of 250kgf/mm\textsuperscript{2}, and hardening ratio (i.e., ratio of final to initial hardness) 1.48. Pearlite has a nano-hardness of 370kgf/mm\textsuperscript{2}, and hardening ratio 1.55. The initial shear yield stress, $k_{0}$, is related to the hardness according to:

$$k_{0} \approx 0.8 \times 10^{6} H_{n}$$

where $H_{n}$ is the nanohardness. When material properties are assigned to elements, they are sampled from Gaussian distributions; the standard deviations of the initial hardness and critical shear strain are 15% and 5% of their respective means.

3. Results and Discussion

During Rail Safety & Standards Board’s Project T355\textsuperscript{(6)}, vehicle dynamics simulations were performed using VAMPIRE with four vehicle types – Class 43 locomotive, Mark 3 coach, Class 91 power car and Mark 4 coach – at two curves (a 1250m-radius curve at Harringay and a 3000m-radius curve at Sandy) on the East Coast Mainline (ECML) in the U.K. (Class 365 was modelled also, but is not included in the present study.) This provided data on contact patch area (the contact patch is approximated as an ellipse) and forces – sufficient for calculation of peak pressure, traction coefficient and contact stresses – for one wheel each on the high rail at three locations at these two sites. This was used as an input to the ratcheting simulation.

At Harringay, for both coaches and locomotives, the longitudinal and lateral creep forces were approximately equal at all three locations. At Sandy, the forces were generally lower, and for the Mark 4 and the Class 43 at Location 888.939 (F) the longitudinal force was in the direction of motion (representing a slight braking effect). Creepage, or slip ratio, calculated here as the wear number (‘T-gamma’) divided by the vector sum of the longitudinal and lateral creep forces, is presented in Table 1.

By grouping contacts for different vehicles it is possible to simulate the passage of trains, so that $2 \times 4 \times$ Class 43 (i.e., two locomotives with four wheels each) + $9 \times 4 \times$ Mark 3 (i.e., nine coaches with four wheels each) – a total of 44 wheel passes – represents an Intercity 125, and similarly $2 \times 4 \times$ Class 91 + $9 \times 4 \times$ Mark 4 represents an Intercity 225. (This is summarized in Table 2.) In this way it is also possible to model both trains and vary the proportion of each in the total traffic.

In the results presented below, proportions are indicated by the percentage of Intercity 125 traffic, with total traffic remaining constant. Simulations are run for 4,000 trains (176,000 cycles), which is approximately 2 million gross tonnes (MGT), at each of the three locations at Harringay; and for 8,000 trains (352,000 cycles), at each of the three locations at Sandy (see Table 1). Accumulated shear strain and wear rates are calculated in each simulation.
Table 1. Vehicle speed and creepage (slip ratio), and identifiers (A-F) used for each track location studied.

<table>
<thead>
<tr>
<th>Location (Identifier)</th>
<th>Harringay (85mph)</th>
<th>Sandy (125mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>2179.03 (A)</td>
<td>871.057 (D)</td>
</tr>
<tr>
<td>Mark 4 Coach</td>
<td>0.30%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Mark 3 Coach</td>
<td>0.27%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Class 43</td>
<td>0.30%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Class 91</td>
<td>0.28%</td>
<td>0.12%</td>
</tr>
</tbody>
</table>

Table 2. Vehicles comprising trains.

<table>
<thead>
<tr>
<th>Train</th>
<th>Locomotive</th>
<th>Coach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercity 125</td>
<td>2 × Class 43</td>
<td>9 × Mark 3</td>
</tr>
<tr>
<td>Intercity 225</td>
<td>2 × Class 91</td>
<td>9 × Mark 4</td>
</tr>
</tbody>
</table>

3.1 Crack Initiation Prediction

The probable depth of initiating cracks can be estimated from the accumulated shear strain. When the shear strain reaches the critical strain for failure, the material is regarded as ‘weak’, unable to support tensile stresses, so crack initiation in this region is likely. The current simulations have a 1024×2048 mesh (approximately 1mm horizontally × 2mm depth). At each depth below the rail surface, according to the microstructure model – the pattern in Fig. 3(b) repeated – a proportion of the elements have been given properties of ferrite, and the remainder have been given properties of pearlite. Figure 4 shows the accumulated shear strain, averaged at each depth separately over (Fig. 4(a,c)) the ferrite elements, and (Fig. 4(b,d)) the pearlite elements, for Location A at Harringay (after 4,000 trains) and for Location D at Sandy (after 8,000 trains). Pearlite is harder than the ferrite and accumulates shear strain more slowly.

For both locations the shear strain is clearly greater when the traffic is Class-91/Mark-4 compared to when the traffic is Class-43/Mark-3. For Location A at Harringay the traction coefficient is relatively high, and close to the surface (i.e., within 0.5mm) there is considerable shear strain in the harder pearlite as well as in the ferrite. For Location D at Sandy the traction coefficient is low and the accumulated shear strain is larger subsurface than at the surface.

For these two cases, the shear strain reaches the critical shear strain for failure (γ<sub>c</sub>=11) only at Harringay, and only in the top 0.5mm of the ferrite fraction. Figure 4 indicates that after 4,000 trains (irrespective of type), cracks of depth 0.5mm (or, at least, initiation of damage to this depth) would be expected at Location A at Harringay, but no cracks are indicated at Location D at Sandy, even after 8,000 trains.

Snap-shots of the simulation at Location A after 20,000 cycles are shown in Fig. 5. The snap-shot in Fig. 5(a) is the internal representation, which does not indicate the accumulated plastic shear strain. When the shear strain is considered (see Fig. 5(b)), the ferrite grain boundaries (where failure occurs soonest) are elongated and can become natural paths for crack initiation and propagation. Unlike the regular hexagonal microstructure used in earlier versions of this model<sup>8, 11</sup>, the irregular structure does provide some resistance to crack.
growth, especially when both crack and microstructure are treated as three-dimensional; however, 3D microstructure is not modelled here.

Crack initiation can be predicted by using image analysis techniques to identify clusters of failed elements in the simulation matrix\(^{(12)}\).

Another approach to predicting crack initiation depth is to use percentage ‘damage depth’: the simulation calculates the maximum depth at which, e.g., 10% of elements have failed in one layer, which suggests that crack initiation to that depth is likely to happen\(^{(8)}\).

At Harringay, at Locations A and B the “10% Damage Depth” (10DD) jumps from 25\(\mu\)m to about 200\(\mu\)m after 8,800 cycles (200 trains) – regardless of the traffic mixture. At Location C, for only Class-43/Mark-3, the 10DD jumps to 200\(\mu\)m earlier, after 7,040 cycles (160 trains); and for only Class-91/Mark-4, the 10DD jumps to 198\(\mu\)m later, after 10,560 cycles (240 trains). At this location, therefore, the time until crack initiation is likely to reduce as the percentage of Class-43/Mark-3 increases.

Fig. 4 Accumulated shear strain with depth, averaged across the ferrite and pearlite elements separately at each depth. (a-b) Harringay: Location A. (c-d) Sandy: Location D.

Fig. 5 Snap-shots of the simulation, representing a 1mm×1mm area of the cross-section. Traffic is Class-43/Mark-3 only. Shown (a) un-sheared, and (b) sheared. Elements which have failed are black; elements (at the top surface) which have been removed as wear debris are white.
At Sandy Locations D and E, the 10DD jumped from less than 10\(\mu\)m (the severely strained region close to the surface where micro-roughness causes very high stresses) to over 1.5mm, suggesting crack initiation is likely to occur sub-surface in the region where the shear stress is a maximum. For both locations, the 0% case (i.e., only Class-91/Mark-4) caused the 10DD to jump soonest, after 107,360 cycles (2,440 trains) at Location D, and after 65120 cycles (1,480 trains) at Location E. No jump occurred at Location F. At Sandy, therefore, increasing the percentage of Class-43/Mark-3 trains increases the number of cycles until crack initiation.

However, the damage depth percentage is arbitrary and the damage depth method sensitive to statistical anomalies.

### 3.2 PC-Depths

A new method is proposed here: probable crack depths (‘PC-depths’) are calculated such that in 95% of layers closer to the surface the average strain in the ferrite exceeds 10.5. PC-depths are presented in Table 3 for all locations and traffic mixtures at Harringay after 4,000 trains; at Sandy (after 8,000 trains) the PC-depths were zero. The results for Harringay are in the range 485-800 microns.

Because the definition of PC-depth is related to ferrite (which accumulates strain faster than the pearlite, and thus fails sooner), the method is also sensitive to statistical anomalies, since the ferrite fraction is low. Further, for premium grade rail steels the ferrite fraction is even lower still, to the point where the microstructure can be modelled as fully pearlitic – in which case, PC-depth will not apply. Therefore, an alternative definition based on strain in the pearlite has been found by comparing predictions for the Harringay cases; for pearlite, selecting a threshold value of 2.7 (rather than 10.5 for the ferrite) results in similar PC-depth predictions. These results are presented in Table 4 for Harringay; pearlite PC-depths for Sandy are zero again.

<table>
<thead>
<tr>
<th>Percentage of Traffic as Class-43/Mark-3</th>
<th>Harringay Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0%</td>
<td>785</td>
</tr>
<tr>
<td>25%</td>
<td>716</td>
</tr>
<tr>
<td>50%</td>
<td>687</td>
</tr>
<tr>
<td>75%</td>
<td>630</td>
</tr>
<tr>
<td>100%</td>
<td>620</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentage of Traffic as Class-43/Mark-3</th>
<th>Harringay Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0%</td>
<td>727</td>
</tr>
<tr>
<td>25%</td>
<td>703</td>
</tr>
<tr>
<td>50%</td>
<td>675</td>
</tr>
<tr>
<td>75%</td>
<td>634</td>
</tr>
<tr>
<td>100%</td>
<td>594</td>
</tr>
</tbody>
</table>

In general, the Class-91/Mark-4 creates conditions for crack initiation sooner than the Class-43/Mark-3. (It is worth noting that this ranking of traffic in terms of crack initiation can differ from their ranking for crack propagation since the mechanisms of initiation and propagation differ.) Location C at Harringay is an exception. The distributions of maximum orthogonal shear stress for Locations B and C at Harringay are compared in Fig. 6. In both these cases, three of the four stress distributions are very similar. At Location B, the stress...
distribution for the Class 91 is significantly greater than for the other vehicles, so the Class-91/Mark-4 would be expected to be more damaging. At Location C, however, the stress distribution for the Mark 4 is significantly lower than for the other vehicles, so the Class-91/Mark-4 would be expected to be less damaging. The stress distributions for Location D at Sandy are shown in Fig. 6(c). The stress distribution for the Class 91 is significantly higher than for the other vehicles, especially at the surface; but for all vehicles the stress is lower than at Harringay.

![Fig.6 Variation of the maximum orthogonal shear stress with depth. (a) Location B at Harringay, (b) Location C at Harringay, and (c) Location D at Sandy.](image)

3.3 Wear

Wear rate predictions for the different traffic mixtures and locations are given in Table 5. Wear rates at Sandy are significantly lower than those at Harringay. Comparing different proportions of Class-43/Mark-3 traffic, only in one of the six cases (Harringay Location C) does the Class-43/Mark-3 cause a higher wear rate than the Class-91/Mark-4.

The variation of the wear rate with traffic mix is almost linear. The linear relationship
means that wear rates can be calculated for individual trains and then a weighted average of these used to calculate wear rates of different combinations of trains. However, although there is a linear relationship for wear rates, the same cannot be assumed for crack initiation.

<table>
<thead>
<tr>
<th>Percentage of Traffic as 43/Mk-3</th>
<th>Harringay Locations</th>
<th>Sandy Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0%</td>
<td>1.693</td>
<td>1.966</td>
</tr>
<tr>
<td>25%</td>
<td>1.666</td>
<td>1.869</td>
</tr>
<tr>
<td>50%</td>
<td>1.637</td>
<td>1.782</td>
</tr>
<tr>
<td>75%</td>
<td>1.612</td>
<td>1.696</td>
</tr>
<tr>
<td>100%</td>
<td>1.581</td>
<td>1.629</td>
</tr>
</tbody>
</table>

4. Conclusions

Predictions for wear of, and crack initiation in, rails at two sites, Harringay and Sandy, on the East Coast Mainline have been made for two different trains (Intercity 125, consisting of 2 Class 43 locomotives and 9 Mark 3 coaches, and Intercity 225, consisting of 2 Class 91 locomotives and 9 Mark 4 coaches) as different proportions of the total traffic.

Predicted wear rates from simulations of 2mm depth lasting 176,000 cycles (4,000 trains), at each of three locations at Harringay, and 352,000 cycles (8,000 trains) at each of three locations at Sandy showed that in three out of six cases the wear rate increased as the proportion of Class-91/Mark-4 vehicles increased, and in two cases the wear rate remained constant; in only one case the wear rate decreased. In all cases the trend was approximately linear, indicating that wear rates can be calculated for individual trains and then a weighted average of these used to calculate wear rates of different combinations of trains.

Three methods of predicting crack initiation were used. Analysis of the shear strain plots indicates that after 4,000 trains (irrespective of type), cracks of depth 0.5mm would be expected at Location A at Harringay. However, this is a visual assessment, and subjective.

At Harringay, based on the “10% Damage Depth” predictions, conditions suitable for crack initiation to a depth of about 200 microns arose after 160-240 trains. At Locations A and B, the traffic mix did not affect crack initiation time significantly. At Location C, the conditions for crack initiation arose slightly sooner as the proportion of Class-43/Mark-3 vehicles increased. At Sandy, crack initiation was predicted to occur sub-surface at a depth of about 1.5mm; the time until crack initiation was found to increase as the proportion of Class-43/Mark-3 increased.

The Damage Depth method provides quantitative predictions, but is very sensitive to statistical anomalies and the proportion of ferrite in the steel microstructure.

A new method was proposed: probable crack depths (‘PC-depths’), calculated such that in 95% of layers closer to the surface the average strain in the ferrite exceeds 10.5. The crack initiation depth predictions for Harringay are in the range of 485-800 microns. The PC-depth predicted for all locations at Sandy was zero. A complementary method of achieving similar predictions based on accumulated shear strain in the pearlite fraction (by choosing a threshold value of 2.7 rather than 10.5) was also proposed. This approach could be applied to premium grade rail steels which have a very low ferrite fraction and which are thus almost fully pearlitic.

In practice, cracks were observed at Harringay but not at Sandy. At Harringay, crack depths of the range predicted above were observed only after 1-2 million cycles (see Table 11 of Evans et al.\cite{13}). One explanation for this difference is that the model only predicts the
conditions that would accelerate crack initiation and short crack growth. Further model development is required to capture microstructural causes of, and barriers to, crack initiation and short crack growth.

References