RAIL-WHEEL CONTACT RESEARCH AT THE UNIVERSITY OF NEWCASTLE

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ABSTRACT

This paper presents a review of state-of-the-art research on rail-wheel contact at the University of Newcastle, UK. The research centres on rail wear and rolling contact fatigue, integrating these processes and their interactions to model the entire life of the rail from installation to final failure. Also included are processes that determine the life, such as rail-wheel adhesion and lubrication. Better understanding of these processes and the factors affecting them will lead to solutions, such as improved coatings, or predictive tools to assist maintenance of the railways, ultimately reducing costs and increasing capacity.

Wear and crack initiation. Wear and crack initiation are modelled as a ratchetting (accumulation of plastic deformation) process taking place over thousands of contact cycles. Material which accumulates an experimentally determined critical strain is defined to have failed. Where this occurs at the rail surface material may be removed as wear debris, and good correlation of the predicted wear rates with field tests has been found. Failed material deeper inside the rail cannot break away and is therefore taken to represent a crack, providing a quantified assessment of crack initiation.

Rolling contact fatigue crack growth. Recent work in crack growth modelling has combined rail-wheel contact stresses with residual stress, continuously welded rail stress, and the possibility of wheel contacts running either side of the crack as well as directly across it. This has generated greater understanding of the factors which may cause a crack to turn up towards to the rail head, or down into the rail. Modelling contacts which are offset from existing cracks shows that growth rates can be slowed dramatically by just a few millimetres change in contact position, offering the possibility of new ways of planning grinding and maintenance strategies.

Rail bending and multiple cracks. As cracks grow longer they begin to be driven by bending of the rail under the action of multiple train wheels, in addition to contact stresses. If multiple cracks are present they interact, and results from multi-crack models of the rail in bending are significantly different from those of single crack models.

Low-adhesion leaf films. The rail-wheel interface friction level is crucial for safety and timekeeping, particularly if it is too low. Recent work will be presented on the investigation of low-adhesion leaf films that form during the autumn.

Coatings. The application of coatings to the regions of the rail under greatest stress offers new possibilities for wear and rolling contact fatigue life extension. Investigations have been conducted to examine wear and rolling contact fatigue of coated rails, indicating real possibilities for rail life extension.

1 INTRODUCTION

This paper presents a review of state-of-the-art research on rail-wheel contact at the University of Newcastle, UK. The research centres on rail wear and rolling contact fatigue, integrating these processes and their interactions to model the entire life of the rail from installation to final failure. Also included are processes that determine the life such as rail-wheel adhesion and lubrication. Better understanding of these processes and the factors affecting them will lead to solutions, such as improved coatings, or predictive tools to assist maintenance of the railways, ultimately reducing costs and increasing capacity.

2 WEAR AND CRACK INITIATION

When a rail is first installed it can undergo both wear and crack initiation, both of which can start without prior damage to the rail. These processes are grouped together because the same mechanism is the primary driver of both failure mechanisms. Both wear and the crack initiation considered here are surface based, i.e. wear can only occur at a surface, and cracks must also lie at the surface of the material if they are to become larger by the mechanisms described in Section 3. The crack lengths considered are from virtually zero up to around 100 microns internal length growing into the rail. Wholly internal cracking, or cracking at the foot of the rail are not considered in this work.

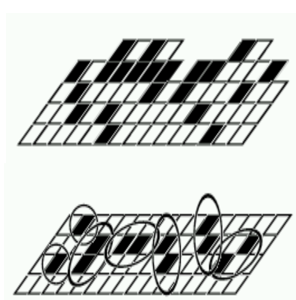
2.1 Wear modelling

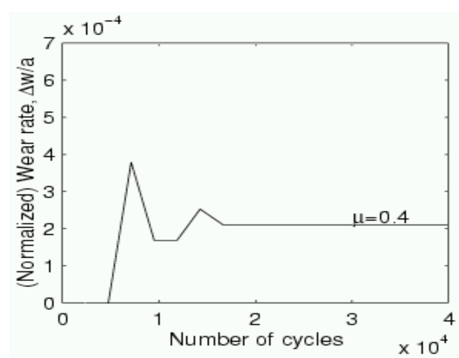
Wear is modelled as a ratchetting (accumulation of plastic deformation) process using software developed for rapid assessment of the thousands of cycles over which failure typically takes place. Small variations of material properties within the microstructure are measured and included to accurately represent the rail steel. Material which accumulates an experimentally determined critical strain is defined to have "failed", i.e. it can no longer sustain further stress and cannot support the material around it. Where this occurs at the rail surface the failed material may be removed as wear debris. Modelling rail deterioration in this way has shown good correlation of the predicted wear rates with field tests.

Mechanical properties of the rail steel such as hardness and ductility have variations of the order of a few percent with position within the rail (see Dowling [1]). To represent these properties the rail to be modelled is divided into an array of "bricks" each with mechanical properties slightly different from its neighbours. It should be noted that this array is not a finite element model of the rail.

As a simulation is conducted rolling / sliding contact loads are applied to the rail by passing wheels. Elements (bricks) in the array representing the rail accumulate damage at slightly different rates from one another because of their differing mechanical properties. Currently the ratchetting mechanism of damage accumulation is implemented, but there is nothing to prevent other damage mechanisms being considered.

Failure by ratchetting of an element in the array is defined as the accumulation of a critical strain. This strain was previously determined in experimental work on rail steels by Tyfour et al. [2]. Because mechanical properties vary between the elements, some reach failure before others, as shown in Figure 1(a).





(a) (b)

Figure 1. Modelling wear driven by ratchetting. (a) Failed elements at the surface are allowed to break away as wear debris. This allows the prediction of wear rate, and also surface roughness development. Failed sub-surface elements which are adjacent to one another can be identified as crack-like flaws. (b) Wear rate is initially low, followed by an unstable period, and later a steady state wear rate.

In Figure 1(a) it can be seen that failed elements at the surface of the rail have broken away, generating wear debris and leaving a rough surface. Validation of the wear rates generated by this model has recently been carried out, showing good agreement with those found on the track [3]. Additional validation work has been carried out by comparing the wear rates predicted by the model with those measured during twin disc testing by Tyfour et al. [4]. This work has the advantage that the conditions could be more closely controlled than is possible during field trials, and the wear rate can be measured more accurately and more frequently. The comparison showed that both the model and the experiments gave similar trends in wear rate, with a low initial rate followed by high and unstable wear rates, and finally a steady wear rate after around 17500 contact cycles, as in Figure 1(b). This evolution of wear can be linked to different rates of strain accumulation at different depths below the contact surface [5].

2.2 Crack initiation modelling

The development of small cracks in a new or crack free rail begins with accumulation of strain to the point at which material fails, just as takes place in the generation of wear debris. However, while failed material at the rail surface is lost as wear debris, material deeper inside the rail cannot break away. This weakened material cannot sustain further stress, and can therefore be taken to represent the presence of a crack. The development of such failed sub-surface and surface breaking regions can be analysed using image analysis on the visual representations of results from ratchetting failure models, providing a quantified assessment of crack initiation.

Also shown in Figure 1(a) is a representation of the rail similar to that shown for wear modelling. However, in this case failed elements are below the surface of the rail, and cannot break away. In images such as this (generally containing many more elements than in these schematic examples) the failed elements have been identified as cracks using an image analysis technique. This allows crack initiation through ratchetting to be quantified and correlated with the rates seem in the field or in the lab [6].

3 ROLLING CONTACT FATIGUE CRACK GROWTH

Growth of rail cracks in the length range covering hundreds of microns to tens of millimetre is driven by a combination of fluid pressurisation (tensile, mode I) or crack sliding (shear, mode II) mechanisms. These have been extensively modelled including the effect of the rail-wheel contact stresses as the major external input to the system. However, recent work has combined rail-wheel contact stresses with residual stress, continuously welded rail stress, and the possibility of wheel contacts running either side of the crack as well as directly across it. This has generated greater understanding of the controlling factors in rolling contact fatigue crack growth, including the stress which may cause a crack to turn up towards to the rail head, or down into the rail. The ability to model contacts which are offset from existing cracks shows that crack growth rates can be slowed dramatically by just a few millimetres change in contact position, offering the possibility of new ways of planning grinding and maintenance strategies.

3.1 Mechanisms

The primary mechanisms by which small cracks generated by ratchetting can grow into larger cracks are both dependent on the presence of fluid in the crack. This may be rain water, but can also include liquid based flange lubricants or other rail contamination.

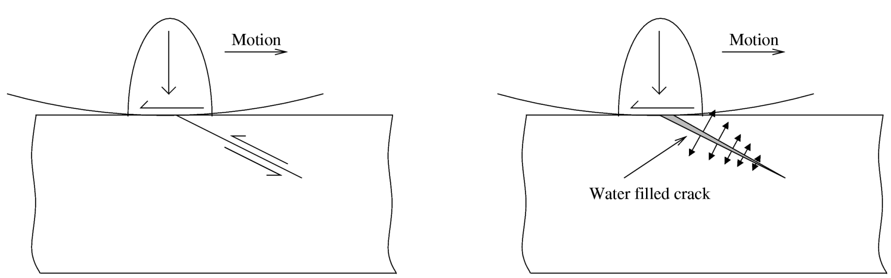
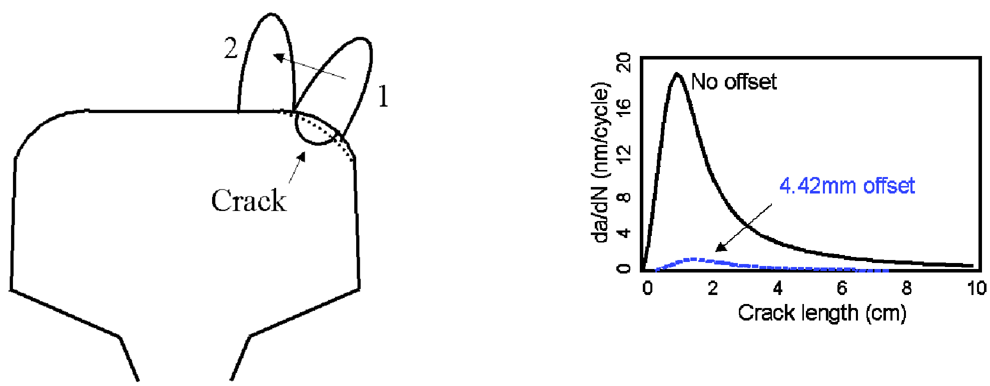


Figure 1. Crack growth mechanisms. Left - mode II shear stress driven crack growth. Right - fluid pressure assisted crack growth. In both pictures the crack lies at a shallow angle below the rail surface, which is loaded by a wheel and corresponding contact pressure moving from left to right.

Fluid was first identified at a requirement for rolling contact fatigue (RCF) crack growth by Way [7]. It may act to lubricate the faces of the crack, allowing them to slide over each other in a mode II shear failure mechanism. Alternatively, it may apply internal pressure to the crack through hydraulic transmission of the contact pressure, squeeze film effects, or entrapment within the crack. Internal pressure allows a mode I tensile failure mechanism to act even though the crack lies in the compressive stress region below the wheel contact. Figure 2 shows these mechanisms schematically. Fluid is of primary importance in controlling which parts of the cracks are open and which closed during the passage of a contact, and also controlling whether the crack faces will slide over one another or lock together if mode II failure is considered.

3.2 Additional stresses
In addition to stress applied directly at the rail-wheel contact, several additional stresses can affect the growth of cracks in the mid-length growth stage. Of greatest importance are residual stresses from rail manufacture and those generated by plastic flow of the rail during use. Also of importance are continuously welded rail, or thermal, stresses. Although these stresses are generally of a lower magnitude than the contact stresses, they have the ability to affect crack growth through changing the regions of the crack which are open or closed, and those which are sliding or locked, thereby changing the overall stress range to which the crack tip is subjected.

3.3 Growth rates and contact offset from the crack
Grinding can be used to move the rail-wheel contact position on the rail head. Moving the contact just a few millimetres can dramatically reduce the crack growth rate. Figure 3 illustrates this effect.



(a) (b)

Figure 1. Effect of offsetting the contact on crack growth rate. (a) Schematic cross-section of a rail head containing a crack beneath the original running band, position 1. Grinding of the rail (shown dotted) moves the contact to position 2. (b) Crack growth rate predictions for the contact patch relocation. Relocation by just over 4mm results in a reduction of around 90% in crack growth rate for a 10-15mm length crack. Contact conditions: peak pressure 1250MPa, surface friction coefficient 0.15.

3.5 Recent developments
The initial models for crack growth in rails were developed as two dimensional representations of the rail-wheel contact [8]. These were subsequently improved by considering a three dimensional contact patch and corresponding stress field, while maintaining an underlying two dimensional crack [9]. Geometry factors can then be used to translate the results for a two dimensional crack to those for a semi-circular three dimensional crack. This approach has the advantage of moving towards a more realistic representation of the rail-wheel contact while retaining the speed of the two dimensional models.

To validate the combined 2d crack with 3d stress field model (colloquially referred to as the "2.5d model") a full three dimensional model has been developed (see Figure 4). This model considers full 3d representations of the rail-wheel contact and the crack, and includes the correct modelling of complex factors such as friction between the crack faces when they are in contact.

Following investigation of finite element and boundary element techniques the Beasy boundary element package was selected for this work. Initial results from the true 3d boundary element model (BEM) show very good agreement with the results from the "2.5d" model. This successful validation will allow a wide range of contact conditions to be rapidly evaluated with the 2.5d model, with confidence that it reasonably represents the true 3d situation.

In future work, the 3D crack growth model will also extend from the validation of the 2.5d model by examining different conditions, to see the effect this will have on crack growth rate. Variables that can be investigated further include crack radius, crack shape, contact pressure, crack face and surface friction conditions, and lateral offset of the contact from the crack. Additional stresses present in the rail such as residual and thermal (continuously welded rail) stresses will also be included in future models.

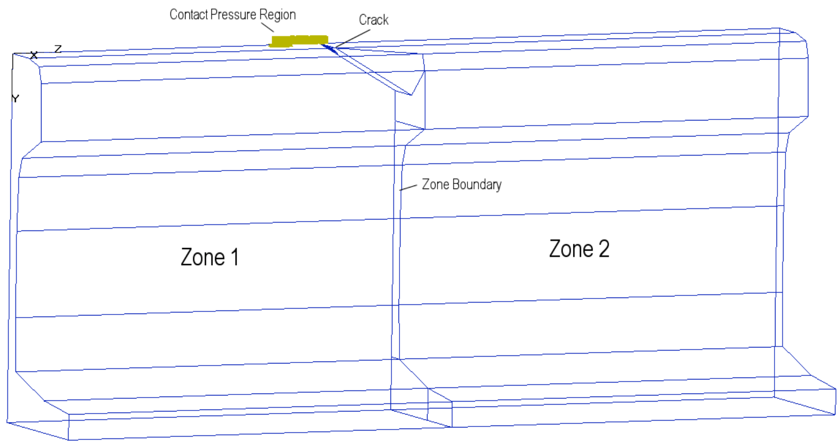


Figure 1. The 3d boundary element model splits the rail into two zones. The crack to be modelled lies on the boundary of the zones.

4 RAIL BENDING AND MULTIPLE CRACKS

As cracks grow longer (greater than around 10mm internal crack length) they begin to be driven by bending of the rail under the action of multiple train wheels in addition to contact stresses. This is illustrated schematically in Figure 5.

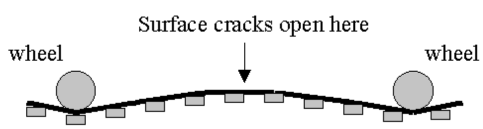
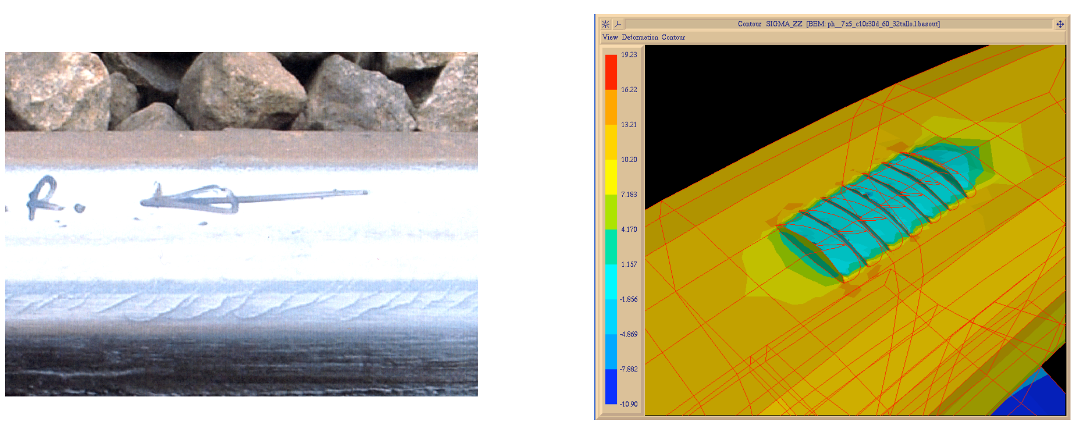


Figure 1. Multiple wheels cause rail bending. Growth of existing cracks in the head of the rail may be driven by bending.



(a) (b)

Figure 1. Multiple cracks can influence one another's growth, particularly in rail bending. (a) Photograph of a rail containing multiple cracks. (b) Modelling multiple cracks in bending.

If multiple cracks are present they interact, and results from multi-crack models of the rail in bending are significantly different from those of single crack models (see Figure 6). Recent work will be presented from investigation of these effects.

5 LOW-ADHESION LEAF FILMS

During the autumn, fallen leaves are drawn into the rail-wheel contact by the turbulent slipstream of train passage and bond to the rails. In damp conditions (dew or light rain) this layer becomes a low-adhesion contaminant film that causes havoc with time tables and leads to a higher than usual number of signals passed at danger. Although sand or Sandite, for example, can be used to increase adhesion levels, these extra particle contaminants cause other problems with track devices or in the rail-wheel contact. To combat the problem of leaf films, an understanding of the fundamental chemical and physical nature of the leaf films and their bonding to the rails is necessary. Towards this end, Vasic et al. [10] have been successful in creating low-adhesion leaf films in the laboratory.

6 COATINGS

While management of the contact position and friction levels offers the possibility of extending the life of rail steels, the application of coatings to the regions of the rail under greatest stress offers new possibilities for life extension. Investigations have been conducted to examine wear and rolling contact fatigue of coated rails as part of the EU 5th Framework project InfraStar, and field tests have had very positive results [11]. A design methodology has been developed based on shakedown maps for predicting rail behaviour at a given site, for given coating thickness and material parameters [12].

7 CONCLUSIONS

Current research at the University of Newcastle upon Tyne covers a number of areas of rail-wheel contact, primarily surface wear, crack initiation and crack propagation, and the interaction of these processes. Also covered is the problem of low-adhesion leaf films that cause accidents and time-table chaos, and lead to damaged wheels (wheel flats) and rails (wheel burns). Better understanding of these processes and the factors affecting them will lead to solutions, such as improved coatings, or predictive tools to assist maintenance of the railways, ultimately reducing costs and increasing capacity.

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