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Topic:  System integration and interaction – wheel/rail interface

Title of paper:  An investigation of rail squats from several perspectives

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Introduction

A rail squat is a crack growing below the running surface of a rail, leading to a depression in the rail surface, caused by plastic flow above the crack. Squats are a major problem on track in a number of countries, such as France and Australia, and have become more common in recent years. Severe grinding or more commonly replacement of the rail affected is needed to deal with the problem, incurring significant maintenance costs. In Australia, the Co-operative Research Centre for Railway Engineering has funded a project to investigate the factors influencing the formation and growth of rail squats. The problem is being approached differently at three institutions. Metallurgical investigations of squat cracks at the University of Queensland indicate the presence of a thin brittle white etching layer (WEL) on the rail surface, resulting from severe local transient heating of the rail due to wheel slip. This is only about 30 microns thick, but does help initiate cracks. At Central Queensland University vehicle dynamics studies have being conducted to identify failure indices indicative of the formation of rail squats, in situations such as in a transition into a curve. As well, experiments are underway to detect the white etching layer on track using eddy current measurements. Crack initiation can only occur if wear does not remove flaws rapidly enough, so a failure criterion must account for this trade-off. Crack growth of squat cracks is being studied at Monash University and at the University of Queensland. Progress includes the first accurate measurement of the growth of cracks shorter than 1mm in rail steel, enabling identification of a crack growth law for short cracks in rail steel. This law is appropriate in the fatigue regime applying during early growth of a squat crack, a situation where Paris law cannot be used. The effect on crack growth of entrapped fluid in short cracks in rail steel is also being studied experimentally, and is found to be quite significant even with use of a SENT test specimen. Growth of squats on track is being monitored by ultrasonic measurements in several locations in Sydney by Railcorp.

The present paper only outlines some of this work, in the order (a) metallography, (b) fracture mechanics studies and (c) detection of WEL. The outcomes of this work are expected to be collation of a knowledge base on the key factors in squat initiation and growth, and development of software to predict squat growth. In particular, industry partners will be provided with practices for classification, detection, measurement and minimization of squats.

1 Metallography of squats

Each squat consists of two main cracks, a leading one, which propagates in the direction of travel, and a trailing one, which propagates in the opposite direction to that of traffic. The depression on the running surface associated with squats increases the vertical impact wheel loadings applied to the rails, and exacerbates the deterioration of both track and some vehicle components, in a similar way as dipped welds, rail corrugations and rail joints.

Muster et al [8] studied the rolling contact fatigue in head hardened rail steel and found that because of the higher yield point, these steels are quite resistant to fatigue damage. Clayton et al. [1] reviewed a metallurgical research program at British Rail on surface-initiated rail problems. Longitudinal/vertical sectioning of rail specimens showed surface-initiated cracks branching downwards, and reaching a critical size leading to brittle fracture. It was found that the fatigue life of rails is reduced as contact pressure is increased, and that creepage played an important role. Garnham et al [2] found the volume of pro-eutectoid ferrite as the main factor in crack initiation and proposed that minimal presence of pro-eutectoid ferrite increases fatigue life and avoids RCF crack initiation, and that propagation was facilitated by sulphide inclusions (MnS). Devanathan et al [3] studied the rolling sliding behavior of bainitic rail steel. It was found that wear behavior of bainitic rail steel is similar to that of pearlitic steel, and that an increase of contact pressure increases the wear rate.

The presence of a white etching layer (WEL) on the rail surface is potentially important because it may initiate rolling contact fatigue damage. The WEL is a particular steel microstructure that derives its name from its white appearance when an etch polish section is viewed with an optical microscope. The mechanism of formation of white etching layer and its structure have been studied by numerous authors.
[4-10]. Osterle et al [6], Chou et al [11] and Jiraskova et al [5] indicated that the WEL has a martensitic microstructure with high dislocation density. Whereas, Lojkowski et al [7] and Baumann [8, 12] proposed that the WEL is nano-crystalline α-Fe with the grain size ranging from 15 to 500 nm, and Zhang et al [13] found that the WEL was composed of severely deformed pearlite, nano-crystalline martensite, austenite and cementite. Newcomb et al [4] reported that WEL is a martensitic phase and is formed by super saturation of carbon during repeated severe plastic deformation. In a similar situation, Torrance [14], examining grinding of steel, found the WEL is a phase-transformed layer where austenitization occurs due to rapid heating and cooling combined with the high pressure generated by the action of the tool. Overall, researchers suggest that either WEL is a martensitic structure or a nanostructure.

1.1 A case study of a rail squat

A damaged rail was cut from curved track in the Hunter Valley region located 160 km north of Sydney, Australia. The samples were taken from the high rail of a wide curve with radius of approximately 2000 m. This portion of track is unidirectional and trafficked mainly by DMU and XPT passenger cars of <23T axle load at up to 140 km/h. It also carries Intermodal freight services of 23 Tonnes axle load at up to 115 km/h, and occasionally carries loaded coal trains of 30 T axle load at up to 80 km/h. Three cut sections were subjected to metallurgical investigation at The University of Queensland. Each section was about 250 mm in length, of standard 60 kg per meter rail.

Figure 1: The start of a squat crack at the edge of a WEL. Transverse section, inverted. Rail sample 2.

Cut section number 2 provided a clear picture of a crack initiating at the edge of a WEL - See Figure 1, a transverse cut of material above the crack, having the rail surface as the lower edge, showing a WEL of 10 to 30 microns thickness, which has a Vickers hardness measured as 1000 to 1100. This crack bifurcates into multiple cracks, after growing more than one mm (Figure 2). Cracks observed tend to show secondary cracks, branching up, as illustrated by the longitudinal section of a forward-growing crack in rail sample 3 in Figure 3.
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Figure 2: Longitudinal section of rail sample 2, showing branching of cracks.

![Figure 2](image)

Figure 3: Longitudinal section of rail sample 3, showing secondary cracks branching up.

Rail sample 2 was broken to examine the fracture surface of the squat, near its initiation. Figure 4, obtained using scanning electron microscopy (SEM), shows a forward growing crack with a smooth surface and a rearward-growing crack with a rougher, more chaotic surface. This suggests that the forward crack grew in shear, and the rearward crack grew in tension.

![Figure 4](image)

Figure 4: View from below of the surface of squat crack, near the initiation of the crack. The arrow indicates the direction of traffic.

2. Fracture mechanics studies

2.1 Review of fracture mechanical modelling of squats

Many attempts have been made by researchers to find how a squat grows under a moving wheel-rail contact load. Most studies have focused on variations of stress intensity factors (SIFs). A crack in a semi infinite body has been studied by Datsysyn et al. She has shown SIFs are related to: the crack length, crack angle respect to the running surface, size of the contact patch, friction coefficient between faces of the crack and entrapped liquid (e.g. rain water), which pressurizes both faces when a contact load passes over the crack. It is demonstrated that a crack with 30° angle with respect to rail surface will turn down inside the rail if the crack-face friction coefficient exceeds 0.1 [15], although residual stress may prevent this. An investigation by Seo et. al. shows that if a braking contact traction passes a crack, it will be
opened in mode I as the wheel leaves. The opening mode due to negative traction force can dominate the shear mode. $K_I$ and $K_{II}$ make opposite cycles during braking compared to usual rolling conditions [16, 17]. In another study a two dimensional plane-strain FE model was created with a Hertzian contact pressure that moves over a crack [18]. Considering an elastohydrodynamic (EHD) contact pressure profile and liquid entrapped between the crack faces, both $K_I$ and $K_{II}$ increase significantly, because of the liquid’s pressure. However, reduced crack-face friction lets the crack faces slide over each other, and the shear mode of fracture takes place at lower SIFs. A study done by Bogdanski et. al shows the magnitude of $K_I$ under an EHD contact pressure is almost 250% greater than a similar dry contact condition [18]. The hydraulic pressure profile of the entrapped liquid has been calculated by Bogdanski et. al. [19]. This pressure profile is a function of initial crack geometry (length and angle), time (due to a moving load), viscosity of the liquid, and the relative velocity of opening/locking crack face [20]. Also Fletcher [21] and Bogdanski [19] in separate works found that SIFs at crack tip are not only related to the contact maximum pressure, but is also associated with the size of the contact patch. At a fixed maximum Hertzian contact pressure, a wider contact patch leads to higher SIFs. Fletcher et al found that any rise in traction or crack-face friction decreases the amplitude of $K_I$. But $K_{II}$ is more sensitive to traction rather than to crack-face friction. The amplitude of $K_{II}$ is proportional to traction, while it is inversely proportional to crack-face friction [22].

The finite element (FE) method has been employed in most studies to investigate how a crack can propagate under a rolling contact load. Limited 3D modeling has occurred, notably prediction of an increment of growth of a crack of assumed shape by Bogdanski [23]. There is also a lack of correlation of FE results to test data.

2.2 A crack growth law for short cracks in rail steel

Paris Law does not work for short cracks of 1mm or less. However, this early crack growth must be predicted accurately to determine a fatigue life for a squat. Growth of short fatigue cracks in a head hardened rail steel that was taken from a standard One Steel 60 kg/m rail has been measured. The rail was cut to create a number of 320 mm long by 39 mm wide and 7.5 mm thick SENT (single edge notch tension) specimens with a 0.5 mm radius semi-circular edge notch of on one side, see Figure 5. The specimens were tested using hydraulic grips. Specimen number 1 was subjected to a peak remote stress of 475 MPa with $R = 0.15$.

![Figure 5: Geometry of the SENT test specimen](image)

The crack length history was then predicted by integrating a growth law for short cracks taking the form of equation (1) – a Generalized Frost-Dugdale growth law [24].

$$\frac{da}{dN} = C^* \left( a_i^{(1-\gamma/2)} \frac{(\Delta K)^{\gamma}}{(1-K_{max}/K_c)} \right) + \frac{da}{dN_0} \quad (1)$$

using forward integration, viz:

$$a_{t+1} = a_t + (N_{t+1} - N_t) C^* \left( a_i^{(1-\gamma/2)} \frac{(\Delta K)^{\gamma}}{(1-K_{max}/K_c)} \right) \quad (2)$$

where $C^*$ and $\gamma$ are material constants, $a_i$ and $\Delta K$ are crack lengths and the range of the stress intensity factor at cycle $N_t$ respectively, whilst $\frac{da}{dN_0}$ was set to 0.0. Jones, Chen and Pitt [25] revealed that many rail steels have a value of 3. Consequently in this study it was assumed that $\gamma = 3$. As a result there were only two unknown parameters, i.e. $C^*$ and $K_c$. Their value was chosen so as to fit the experimental data.
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This yielded a value of $C^* = 1.5 \times 10^{14}$ and $K_c = 85$ MPa $\sqrt{m}$. The resultant predictions for the entire crack length history are in good agreement with the experimental measurements, see Figure 6.

![Figure 6: Measured and predicted crack length history](image)

Two other specimens were tested giving similar results. Note these tests do not account for fluid in a crack. Preliminary testing with fluids shows that even in a tensile test, such as used here, there is an acceleration of the growth of short cracks.

### 2.3 Implications for Fleet Management

Since the rail steel follows the Generalised Frost-Dugdale crack growth law it follows that the equation for the crack growth per tonnage (or time) carried in that load block, $da/dT$, is:

$$
da/dT = \left( \tilde{C} \cdot a^{1/2} \cdot K_{max} - da/dT_0 \right) / (1.0 - K_{max}/K_c) \quad (3)
$$

where $\tilde{C}$ is a constant, $K_{max}$ is the maximum value of the effective stress intensity factor in a block (excluding rare overloads), $K_c$ is the apparent cyclic fracture toughness and $da/dT_0$ reflects both the fatigue threshold and the nature of the initial defect/discontinuity under block loading.

An advantage of equation (3) is that it does not require knowledge of the load time history so that the analysis becomes very much simpler. Vehicle dynamics modeling and measured axle loads will be used to estimate $K_{max}$. Given knowledge of the squat growth history associated with a particular line we can determine the value of $\tilde{C}$ via a reverse engineering process and then use this constant to predict squat growth at other locations and positions. This data is being collected by Railcorp in Sydney, Australia, using ultrasonic crack depth measurements, from which crack surface area is inferred. The resulting growth data shows fairly linear growth of crack surface area with time.

### 2.4 History of stress intensity during a wheel passage

Previous studies have looked at relatively long cracks. The cycles of stress intensity at the tip of a short crack can differ from those reported. A wheel passage does induce tension in the surface of a rail, just
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before a wheel arrives, but this is small and dies away subsurface with a steep gradient, leaving mainly a cycle of shear stress, which may or may not peak subsurface, depending on the tractions present on the surface. This shear stress cycle conventionally is used to explain spalling due to rolling contact. Clearly, squat cracks are reluctant to spall, so a distinct mechanism of growth is involved. To investigate this in 2D, an XFEM model, using code adapted extensively from that of Pais [26] is used. XFEM enhances finite element interpolation, both to add a jump in displacement normal to a crack, and to introduce a singularity at the crack tip. The advantage of this approach is that a crack can grow through a finite element mesh without following element boundaries. An example of this type of analysis follows.

A plane strain model of a partial axial section of rail is loaded by pressure, and tractions distributed to represent those due to a 10 tonne moving wheel load, with a braking traction of 2 tonne, and a contact patch with semi-axis 9.2 mm. As well, the model has displacements imposed on its cut boundaries, which are those found by modelling the rail as a beam on an elastic foundation. The elastic foundation stiffness is intended to be typical of a 60 kg/m rail. 12800 finite elements were used. Two short cracks are modelled at 20° to the surface of the rail, both 1 mm long: one facing into the direction of travel, as in Figure 7, and one in the trailing direction, reflecting observed crack angles. Histories of the effective stress intensities at the crack tip during a wheel passage, are shown in Figure 8. These are found from $K_I$, $K_{II}$ and the angle of predicted crack growth $\Delta \theta$ [15]. The plots of $K_{II}$ correspond to the effective values predicted by the maximum hoop stress theory of crack growth. Those of $K_{I\theta}$ correspond to the effective values predicted by the maximum shear stress theory, as explained in [15].

It can be seen on Figure 8 that for the trailing crack, the peak to peak range $\Delta K_{II\theta}$ is smaller than, but similar to the range $\Delta K_{I\theta}$. This crack has a choice of growing in mode I or mode II. Its predicted direction of growth in each mode is shown on Figure 9. Mode I behaviour would result in spalling, but mode II behaviour would make the crack grow deeper. In practice, it keeps growing on a compromise between these directions, producing beach marks associated with periods of growth in one mode or the other. For an axle without traction, this crack is predicted to continue growing in shear without a direction change. For the leading crack, $\Delta K_{II\theta} \gg \Delta K_{I\theta}$ and growth in shear is likely. Figure 9 shows that the analysis predicts that the crack should continue to grow at the same angle if it grows in shear, as at the peak $K_{II} , K_I = 0$. However, growth in tension, would lead to subsidiary cracks growing back toward the surface, such as those observed in Figure 3. This is also in accord with experimental observations above, of a leading crack with a smooth surface and a rougher trailing crack, for a squat in a transition into a curve, but presumes a braking traction. This may be applied to slow a train entering a curve, but could also arise partly from flange contact.

![Figure 8: Histories of effective stress intensity ($K_{I\theta}$ or $K_{II\theta}$) predicted for wheel passage over a 1 mm crack at 20°.](image-url)
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Figure 9: Predicted crack growth directions.

2.5 Predictions of crack paths by element removal

The path taken by a squat crack can be estimated more simply by element removal from a finite element model, removing elements with the maximum principal stress, if several assumptions are made.

(a) The crack grows according to the maximum hoop stress theory. This is debatable, as researchers have often considered squat cracks to grow in shear eg [15], and the XFEM analysis above also suggests this may be the case.

(b) The moments when the wheel arrives or when it leaves correspond to the peak effective stress intensity. This is true only if $K_I$ controls the growth, as peak values of $K_I$ occur at these moments. This assumption avoids modeling the complete passage of a wheel. Peak $K_{II}$ values occur while the wheel is over the crack mouth, inducing triaxial compression. However, if fluid in a squat causes lubrication allowing growth in shear of a such a closed crack, then this analysis may be misleading.

With these simplifying assumptions, crack paths can be predicted in two or three dimensions. A 3D prediction with an elliptical contact zone is shown in Figure 10. The predicted crack path is squat-like, although note that the stress field makes the crack grows down initially and then to change direction. In reality, elongation of metal crystals of the pearlite microstructure from repeated plastic deformation near the rail surface, tends to promote crack growth at 15 to 20 degrees to the surface initially. Note also that while for conditions close to pure rolling, this model causes crack growth in both directions, for the case with a traction illustrated, the model only predicts crack growth in the longitudinal direction opposite to the traction. Hence both accelerating and braking tractions would be needed to produce a typical squat crack, that grows a similar amount in both directions.
3. Detection of white etching layers

Using eddy current inspection, a White Etching Layer on the rail surface can be detected. Tests were first done at a 250 kHz inspection frequency, and were successful at detecting a WEL, as confirmed by sectioning and etching the rail samples afterward. One sample with the regions of WEL detected and the eddy current signal is shown in Figure 12. The original probes that were used, had a frequency range from 5 KHz to 600 KHz. Most of the White Etching Layers on the rail surface are found to have a thickness between 20 to 50 µm although thicknesses of around 200 µm have been found in some extreme cases. Because of the low material thickness of the WEL, a probe with a low depth of penetration was needed. Since the depth of penetration of the eddy current probes is inversely proportional to the frequency of the probe, a more suitable probe needed to have much higher frequency of operation [27]. The probe used to obtain Figure 12 had a frequency range of 500 KHz to 2 MHz.
Current operating frequencies for the probe are around 1 MHz with the depth of penetration of around 50 \( \mu \)m.

### 3.1 Influence of temperature and other factors on eddy current testing

The influence of temperature on the electrical and magnetic properties of steel has been studied extensively [27-29]. It is known that the increase in temperature of steel results in the increase in the resistivity of the material.

This relationship is explained in the formula [30],

\[
R = R_0[1 + \alpha(T - T_0)]
\]

Where \( R \) is the resistance, \( R_0 \) is the resistance at the room temperature, and \( \alpha \) is the temperature coefficient of resistivity. Tests on a rail sample have indicated that eddy current readings vary by up to 10% for a rise in temperature from 23°C to 60°C. Using the rule of thumb approach mentioned in [31], the average rail temperature is higher than the air temperature by 17°C or about 1.5 times the air temperature, meaning there is a chance of a 6 to 8% error in the eddy current reading under normal conditions, and steps have to be taken to minimize the error. Calibration of the eddy current, therefore, would have to take into account the changes in the rail temperature for any degree of certainty in the readings.

Further work is needed on the influence of other external factors in the eddy current inspection, especially on the influence of stresses on the rail surface on the magnetic properties of rail steel. A series of tests has been planned on the influence of the external factors on the eddy current readings. Modelling of the flow of eddy current on the rail steel is ongoing using Comsol Multiphysics.

### 4. Conclusions

Progress is being made in both microscopic observation of squat cracks, detection of white etching layers, and in prediction of the early stages of growth of squat cracks. An outline of some of this has been provided above. Work remains to further examine the effect of water in squat cracks, to calibrate eddy current detection of white etching layers, to obtain more evidence of how these cracks grow, and to quantify the stress intensities from block loading due to trains passing.

### References