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The potential for suppressing rail defect growth through tailoring rail thermo-mechanical properties

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ABSTRACT

Thermal damage of rails can occur through brake lock-up, or traction control system failure to prevent wheel spin. In most cases the damage produced is shallow and takes the form of a "white etching layer", usually thought to have a martensitic structure, formed as the steel is heated above its eutectoid temperature and then rapidly cooled as the wheel moves away. In many cases such layers are benign, but there is evidence of crack initiation at their interface with the sub-surface layers of the rail in "stud" defects. The metallurgical transformation during the formation of white etching layers leads to a volume change for the steel, leaving not only a transformed microstructure, but also locked-in stress. The influence of this additional locked-in stress on development of an initiated crack is studied in this paper, and the work extended to consider how alternative materials which react differently to the thermal input may offer a means to suppress crack development through locking in beneficial rather than problematic stresses.

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1. Introduction

This paper presents an extension to previous research investigating thermal influence on crack growth in rails. The origin of the work is in building understanding of "stud" type defects which have been identified on railways and metros worldwide [1]. These have superficial similarities to squat defects, but are almost always associated with severe thermal input evidenced through the presence of thin (~100 μm) white etching layer at the rail surface above the defects. Fig. 1 shows the morphology of a typical defect of this type.

White etching layer on the rail surface can be formed either through extreme mechanical work [2] or by a thermal process [3] often due to brake lock-up, or traction control system failure to prevent wheel spin. Evidence from defects cut open for examination is that plastic damage is almost completely absent in stud defects [4], so thermal input in the generation of the WEL has been examined. Severe thermal input has three main consequences, which last over different durations: (i) temporary thermal expansion of the steel, (ii) permanent metallurgical transformation of the steel to WEL, and (iii) permanent locked-in stress produced by the change of material volume associated with the metallurgical transformation. In the previous investigation [5] only additional stress due to cause (i) was considered for its effect on stress intensity factors (SIFs) describing growth of an already initiated defect. In this paper the change of volume (cause iii) is brought in as an additional phenomena in the modelling, opening up two routes of investigation. First, taking expansion characteristic of current rail steels undergoing transformation to WEL and examining the influence of the additional stress produced by this expansion. Second, using the same model in a design capacity to assess the most beneficial expansion (or contraction) which a heat affected area may exhibit if it is to suppress crack growth, i.e. assuming that initiation of damage still occurs, how can a future rail material be created to suppress the growth of the initiated defect. A wheel running temperature of 300 °C is considered, separate to the prior severe thermal event [6].

2. Modelling method and conditions

Modelling was conducted using a boundary element (BE) analysis in the Beasy software package [7] and considered cracks of 1 mm to 15 mm long, 1 mm deep, parallel to the surface of a rail. This crack configuration was chosen as a simplified representation of the "stud" crack type shown in Fig. 1. This type of crack is found in undeformed steel, and the crack sizes modelled were large relative to the microstructure dimensions, hence the model was of stress controlled crack growth, which was quantified by fracture mechanics. Microstructural anisotropy which would be important if there was extensive shear of the steel (typically affecting cracks much closer to the rail surface) was absent. The model (Fig. 2) used

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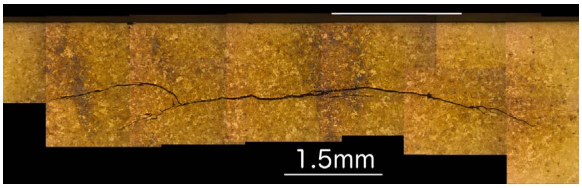

Fig. 1. Example of “stud” defect morphology below the running band in a longitudinal cross-section from a high speed mixed traffic line. The central portion of the crack is close to horizontal and lies at approximately 1 mm below the rail surface in an undeformed microstructure. The white marker above the rail surface indicates the location of a patch of white etching layer on the rail surface. The surface depression and plastic deformation characteristic of a “squat” defect are absent.

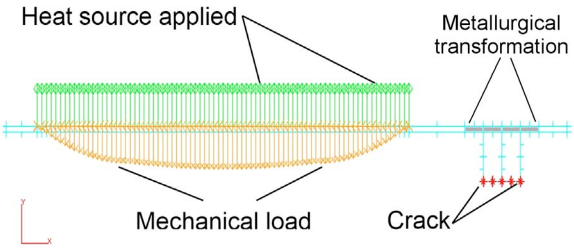

Fig. 2. BE model of rail–wheel contact with horizontal crack of 1 mm located 1 mm below the rail surface. 2 mm length of metallurgically transformed layer with 100 μm thickness from a previous thermal event is shown grey. The heat source moves together with the contact load traversing the rail surface.

Table 1
Conditions modelled.

Case	Expansion due to transformation (%)	Rail–wheel contact temperature rise (°C)
1	0	0
2	0.8	0
3	0.8	300
4	1.3	0
5	1.3	300
6	−0.8	0
7	−0.8	300

a 2D plane strain representation of the rail–wheel contact, with a maximum Hertzian contact pressure of 1014 MPa. Surface and crack face friction coefficient was taken as 0.3, with a contact half-width of 5 mm. This pressure and contact size correspond to a wheel of 780 mm diameter and 6.5 t axle load running on a UIC60 rail worn to a slightly flatter than new condition crown radius. The 2D model was able to represent vertical and longitudinal stresses that characterise wheel motion in straight track, but could not represent the lateral forces or lateral crack growth that can be significant in curved track. This disadvantage was set against significantly lower solution times, enabling a wider range of conditions and crack sizes to be studied. The contact was taken to be fully sliding, with shear traction distribution across the contact defined by the product of Hertzian normal load distribution multiplied by friction coefficient. The conditions modelled are shown in Table 1. Metallurgical transformation of the pearlite to martensite was simulated on a macro scale through bulk expansion or contraction of the heat affected zone, not by modelling the thermo-mechanical behaviour of the microstructure itself. The expansion depends on the specific alloy composition of the steel, with two different cases considered in the paper alongside the ‘artificial’ contraction cases used for the design study.

2.1. *Density based calculation of volume change*

Values for the metallurgical transformation volume change of the heat affected area can be generated using either a density or an atomic volume based approach. To assess the change based on density, the density of pearlite was calculated by taking the density of its constituents ferrite (α iron, 7870 kg/m^3) and cementite (Fe$_3$C, 7700 kg/m^3) and their weight percentage, assuming a eutectoid composition steel with 0.77% carbon for which the weight fractions of ferrite to cementite are 8:1 [8]. This gives a density of pearlite with 0.77% C as 7851.1 kg/m^3, although this takes no account of the effect of other alloying elements on the density. The density of martensite is available from literature [9], although its value is sensitive to plastic deformation. This is particularly relevant to rail steel surfaces where plastic deformation of pearlite is common, although the increased hardness of martensite after transformation may protect it from further deformation. Density prior to plastic deformation [9] is 7790 kg/m^3, but may drop to 7785 kg/m^3 with 5% plastic deformation. Assuming the value for zero plastic deformation applies, the change from pearlite to martensite reduces density to 7790/7851.1 = 99.22% through an expansion of 0.78% in volume. The expansion would be greater after plastic work. A value of 0.8% is used in Table 1 to capture this process.

2.2. *Atomic volume change approach*

An alternative to the bulk density based approach is to use atomic volume data for steel microstructures [10]. Taking carbon as a weight percentage (C) and atomic volume in Angstroms cubed, values are pearlite (11.916), austenite (11.401 + 0.329C), and martensite (11.789 + 0.370C). Considering a carbon fraction of 0.77% this indicates a change of atomic volume from 11.916 Å^3 to 12.0739 Å^3 with the transformation from pearlite to martensite i.e. a volume expansion of just over 1.3%. Following similar reasoning the change from austenite to martensite is predicted to give an atomic volume increase of around 3.6%, which is in agreement with literature data for this transformation [11]. A value of 1.3% is used in Table 1 to capture this approach for the pearlite to martensite volume change.

2.3. *Implementation of volume change in modelling*

The exact value of volume change with transformation will depend on the steel chemistry, and also the exact thermal path taken as the steel is heated and cooled, but the methods outlined above gave a reasonable range for which modelling could be conducted to investigate the effect on cracks in a rail. To represent the expansion and contraction through transformation of a surface layer in the BE model a thermal body load was applied to the whole of the transformed layer (regardless of contact size or position) using a temperature calculated to achieve the required volumetric expansion [12]:

$$\frac{\Delta V}{V_0} = 3\alpha\Delta T \qquad (1)$$

where $\Delta V/V_0$ is the volume change ratio, α is the thermal linear expansion coefficient for the material and ΔT is the temperature difference. It should be noted that this is simply a convenient way to implement expansion or contraction within an existing structure without modelling microstructural change or applying a mechanical load. It is an artificial temperature value, distinct from the thermal boundary condition applied to represent the passing of a hot wheel over the rail with which it is combined using superposition.

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