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Rolling contact fatigue: Spalling versus transverse fracture of rails

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A R T I C L E   I N F O

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A B S T R A C T

Rolling contact fatigue (RCF) defects in the running band of the rail may develop, as a function of born tonnage, either superficially and spall off, or penetrate into the subsurface. In practice, the first type is found to occur notably (but not exclusively) on heat-treated pearlitic rails. Both possibilities involve an essentially different operational risk with respect to transverse rail fracture and require therefore different inspection and maintenance regimes. This study presents a validated hypothesis that explains both similarities and differences of spalling defects and classical squat defects that develop also in depth. It is shown that their microstructural/-mechanical initiation mechanism is different and not necessarily governed by the local tangential stress history in the case of spalling. A model is set up and validated for subsurface crack propagation directivity, distinguishing a spalling and a transverse fracture domain for development of running band defects for both straight track and high and low legs of curves. This model allows for understanding and recognition of the nature of running band defects and for adjustment of control actions.

1. Introduction

Rolling Contact Fatigue (RCF) is a crucial damage mechanism that governs the service life and life cycle costs of the rail in those cases where profile wear is not dominant. RCF can have different forms of appearance, depending on the transverse position at the rail surface and the corresponding local history of the tangential contact stresses exerted by the rolling stock. Notably, head-checks occur on the rail gauge corner and squats in the running band of the rail. Both head-checking defects and leading cracks of squats (see refs. [1,2]) may give rise, in case of uncontrolled growth, to potentially catastrophic rail fracture. Recently however, on the Dutch network an increasing amount of running band defects have been observed that are visually similar to squats, but show a different behaviour: they systematically spall off instead of growing deep into the railhead (Fig. 1). These kind of early defects are found to concentrate on head-hardened rails that have undergone heat treatment during production and perform, during their service life, in the RCF regime. In several cases, an initiation in relation to abusive rail grinding could be established, such as has been discussed in earlier work [4]; however in other cases different factors seemed to govern the initiation process. Similar defects have also been reported in the scientific literature, notably by Grassie and designated by him as 'studs' [5,6]. An example of a longitudinal cross-section through a 'stud' defect with a thermal origination route in the absence of plasticity is shown in Fig. 2.

Although both defects, squats and early spalling defects, are rather similar in appearance and to some extent even in nature – as will be discussed in this paper, both defect types implicate an essentially different operational safety risk. It is therefore of paramount importance to be able to recognise rail defects and the way they develop at an early stage, also in view of adequate maintenance choices, especially as both defect types and differences in their behaviour are known and to some extent also documented in recent literature, but not yet fully understood.

The main contribution of the present work is that it proposes a novel model that explains both differences and similarities in nature between defects that propagate into the subsurface and those that spall off. At the same time the model is capable of predicting the subsurface crack path of surface-breaking RCF cracks in the running band of the rail, distinguishing two spatial propagation domains: a spalling domain and a transverse fracture domain. The proposed model is developed on the basis of earlier work with respect to RCF and squat formation in different track conditions, addressing both microstructural features and three-dimensional crack morphology [7], and on observations on rail defects on the Dutch network.

The structure of this paper is as follows. Section 2 discusses, as a background, properties of spalling defects on the basis of a case study; classical squat defects are not included here as they have been documented in earlier work [1,2,7] and other scientific

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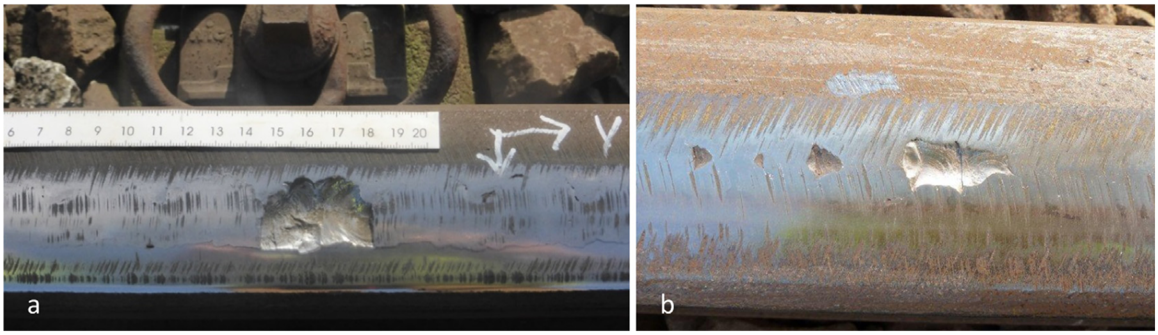

Fig. 1. Spalling defects on grade R370crHT (type MHH) according to classification [3].

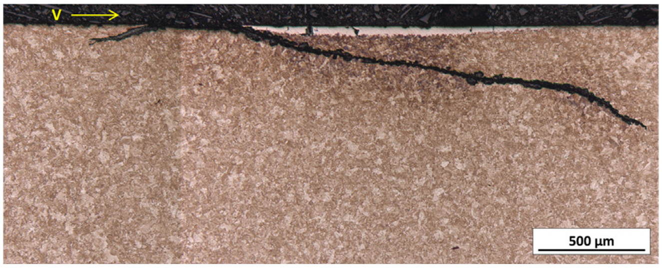

Fig. 2. Longitudinal cross-section over a 'stud' defect on grade R350HT according to classification [3].

literature. Section 3 presents some theory and discussion on surface crack initiation. Section 4 continues with subsurface crack propagation, presenting a model that differentiates between spalling and transverse defect domains. Section 5 discusses, in the framework of model validation, results of microstructural analysis. Section 6 ends with general remarks and conclusions of the work.

2. Case study: spalling defects and their properties in practice

Fig. 3 shows an example of a fully developed individual spalling defect, which, like the defect in Fig. 1a, makes part of a longer, repetitive series of identical defects on heat-treated premium rail in the upper leg of a 2240 m radius curve.

The initiation of such an early defect, in relation to white etching layers along grinding grooves in combination with roughness and harmful residual subsurface stresses induced by a case of abusive maintenance grinding, has been discussed in earlier work [4] and to some extent in the literature on roller bearings [8–10]. Here, the morphology and growth of the defect itself are of interest.

At first view, the geometry of the surface-breaking cracks is striking: the defect shows the 'wedge' shape which is characteristic for squat defects. The crack fronts (Fig. 3a and b) in the subsurface clearly 'expand' from this wedge-shaped surface crack to the other side of the rail. This process would, in the case of squats, give rise to local surface settlement and the development of two 'wings' or 'lobes' in the running band (see for example Fig. 1 in Ref. [7]). However, in this case the wedge opens toward the *field* face of the rail, whereas in the case of squats this opening is systematically toward the *gauge* face [1,7]. Fig. 4 shows another example of a similar spalling defect where this same difference is visible in the crack pattern.

A second observation from Fig. 3 concerns the exact position of the initiation of the defect. Fig. 5 shows in more detail multiple positions of crack initiation: they coincide, both in position and in alignment, with particular grinding grooves. As is particularly clear from Fig. 3c, which shows the surface of the spalled part after polishing with an etching agent (3 percent Nital), after this initiation surface-breaking cracks start to circumscribe the *deepest* area on the rail surface resulting after grinding; a demarcated zone where both individual grinding marks and corrosion are visible due to a lack of contact history under passing wheels. Since this area is the deepest, this means that more material has been removed as compared to the surrounding area, which may suggest the presence of a different (and more harmful) residual stress profile. Fig. 3b shows the internal crack face of the spalled part, where corrosion has started from the position of initiation (the 'oldest' part of the fracture surface), disappearing with increasing distance. A clear distinction is visible between leading and trailing 'wing' of the defect for each individual mechanism, where the term 'mechanism' denotes an individual defect that has fully developed and grown together with its neighbour, forming a defect chain.

It is however interesting to compare the surface-breaking crack path with that which one would expect in the case of regular RCF. Using the model in Ref. [7], one would expect longitudinal shear stresses τ_{zx} opposite to the running direction and transverse shear stresses τ_{zy} toward the gauge face. The leading crack would then initiate perpendicular to the resulting main tensile direction – which is however not the case. This will be discussed (and clarified) further in the following sections. Different causes may, individually or in combination, explain the surface-breaking crack geometry itself, given local initiation at an individual grinding groove:

i. the eventual presence of a differential residual stress profile in the subsurface;
ii. the effect of the geometrical surface irregularity on the response of the material in the top layer of the rail. This comprises a double effect:
    a) inside the moving contact patch, compression occurs in the subsurface, whereas outside this zone tensile stresses occur. The resulting stress alternation at a fixed position yields fatigue, especially if crack initiations are already present.
    b) the occurrence of transient, both normal and tangential contact stress redistribution within the moving contact zone. Such redistribution may lead to cyclic, large tangential stress amplifications along the edges of the deepest surface area with reduced contact stresses, and indeed surface-breaking cracks develop along these edges.

The simulation of effects a) and b) would require extensive and non-conventional modelling work in order to cover both the transient 'interface' effect (distribution of contact stresses, creepage and slip) and its effect on the subsurface stress and strain response. Such modelling work is outside the scope of this study and remains for future work.