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Fatigue of railway wheels and rails under rolling contact and thermal loading—an overview

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Abstract

An overview of rolling contact fatigue phenomena occurring at wheels and rails is given. The paper outlines mechanisms behind the various phenomena, means of prediction, influencing parameters and possible means of prevention.

Keywords: Rolling contact fatigue; Railway wheels; Railway rails; Thermal loading; Martensite formation; Residual stresses

1. Introduction

Considering a number of criteria such as capacity, speed and environment, railway is a superior mean of transportation. Specifically, it has gained a crucial role in limiting traffic congestion in heavily crowded regions. In this perspective, rolling contact fatigue (RCF) of railway components is a most crucial subject. RCF-caused accidents may not only cause personal injuries and economical costs, they may also tend people to commute by car, which further increases traffic congestion, causes environmental problems and eventually may lead to an increase in personal injuries since car traffic is significantly more unsafe than railway transportation.

In this concept, also non-catastrophic RCF failures are of importance since they cause unplanned maintenance which eventually causes decreased capacity and delays in the train traffic.

The current paper is aiming at an overview of RCF failures. Topics covered are failure mechanisms of railway components, possibilities and means of numerical modelling and prediction of RCF, and possibilities to prevent RCF.

2. Specific issues in rolling contact fatigue

The analysis of rolling contact fatigue differs from the ‘classic’ fatigue analysis in several aspects:

- The rolling contact loading causes a multiaxial state of stress with out-of-phase stress components and rotating principal stress directions.
- As they grow longer, cracks subjected to a multiaxial loading normally deviate into a Mode I dominated growth (or follow a weak path in the structure). This is not the case in rolling contact fatigue, due to the large confining pressures under the contact which normally suppresses any Mode I deformation of the crack in the absence of trapped fluids, etc., see Section 3.2. Instead cracks propagate mainly in a mixed Mode II–Mode III.
- In a predominantly compressive loading, the validity of traditional fatigue models may be questioned. As an illustration, Paris’ law predicts zero crack growth under compressive loading in its original form since it employs the range of the Mode I stress intensity factor, cf the above point.
- Due to the compressive loading, crack face friction will control the crack propagation, cf [1]. The magnitude of operational crack face friction is, however, hard to quantify.

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- A similar effect of the compressive loading is that crack face deflection increases with crack length and may cause complete locking between the crack faces for part(s) of the crack [2–4].
- Occasional overloads may slightly accelerate crack growth, in contrast to the behavior in tensile loading, see [5,6]. This may lead to non-conservative fatigue life predictions.

For railway components, the issue is further complicated by the fact that there are major randomness (and systematic deviations) in acting loads [7], contact geometries and fatigue strengths (the latter due to the influence of material defects [5,8] and the large stressed volumes).

Overviews of rolling contact fatigue in general and of railway components in particular can be found in Refs. [9–23].

3. Surface initiated cracks

Below is a summary of mechanisms behind the initiation and growth of cracks from the surface of a component in rolling contact (with focus on railway wheels and rails). Some influencing factors are discussed.

3.1. Crack initiation due to surface plasticity

When a railway component in rolling contact is subjected to repeated applications of high friction loads (due to traction, braking, curving, etc.), the surface material will deform plastically, see Fig. 1. If the deformation occurs in a dominant direction, the microstructure will show clear signs of being “rolled out”, see Fig. 2a. If material hardening and residual stresses are not sufficient to prevent further accumulation of plastic strains, cracks will eventually form when the fracture strain is exceeded. This fracture strain is far above that of tensile tests, the reason being the beneficial influence of the compressive stresses, cf [24]. Such a mode of fracture is referred to as ratchetting, and is frequently studied in twin-disc tests (although it has also been studied by biaxial testing [25]). The ratchetting strain has been shown to be a non-linear function of contact pressure and number of contact cycles, see [26].

In the case of alternating directions of frictional loading (for instance due to alternating traction/braking), the material will not ratchet in the same manner since plastic deformations will occur in both directions causing the accumulated plastic strain to be close to zero. Failure will instead be caused by low-cycle fatigue. For combinations of low-cycle fatigue and ratchetting, fatigue and ratchetting can be seen as competitive mechanisms [20,27].

The theory of crack initiation due to plastic deformation of the surface material has a strong support from metallographic studies of fractured surfaces, see Fig. 2a. In rails surface initiated fatigue typically occurs at the gauge corner, whereas on wheels the surface fatigue damage can be spread all over the tread, see Fig. 2b.

3.2. Crack growth

Surface initiated cracks initially grow into the material at a shallow angle (corresponding to the texture of the plasti-

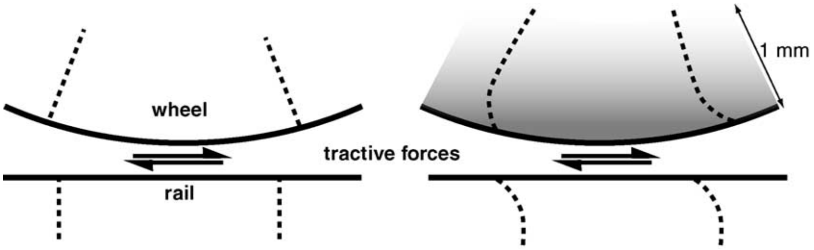

Fig. 1. Schematic sketch of plastic deformation of the surface material in a railway wheel. The dashed lines indicate material planes before and after deformation.

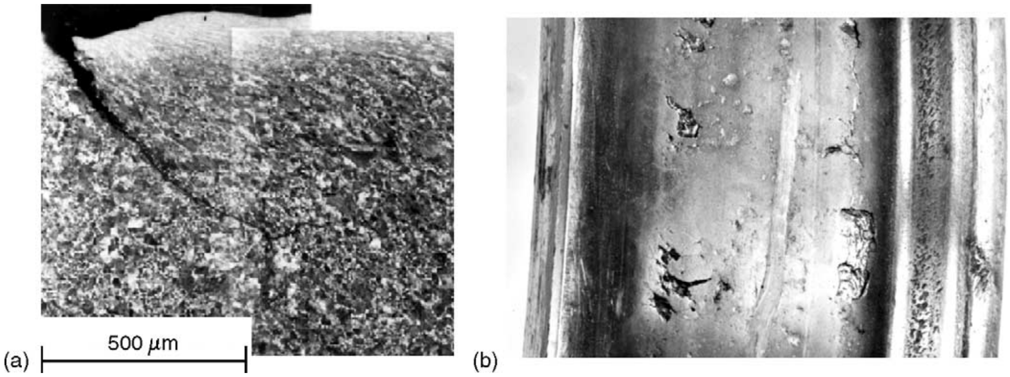

Fig. 2. (a) Deformed microstructure and crack growth in rolling contact. (b) Surface damage due to surface initiated fatigue (from [3]).

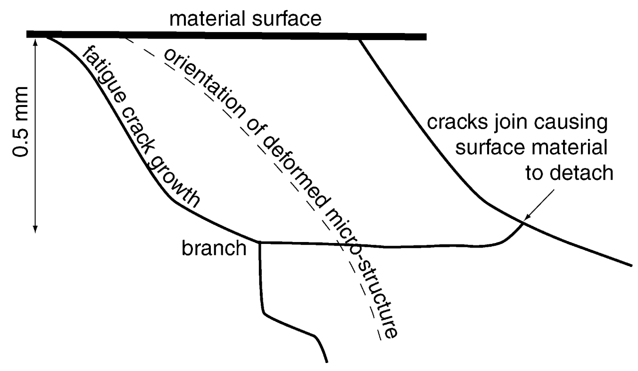

Fig. 3. Schematic representation of growth of surface initiated fatigue cracks in wheels. Once initiated, the crack will deviate to an almost radial direction. At a depth of about half a millimeter, the crack will tend to deviate (or branch) towards a circumferential growth. Final fracture will typically occur as deattachment of a piece of the surface material when the cracks deviate towards the surface.

cally deformed surface material) which soon deviates into an almost radial direction. In railway wheels, the cracks then normally deviates (or branches) again and continues to propagate in a circumferential direction at depths of some 0.5–5 mm, see [3] and Fig. 3. Final fracture typically occurs as a branching of the crack towards the surface, breaking off a piece of the surface material, see Figs. 2b and 3. A more uncommon failure mode is radial growth towards the hub of surface initiated cracks. Such a mode is promoted by high thermal loading, see [28] and Section 3.6.

In rails, surface cracks typically propagate a longer distance before deviation to vertical growth occurs. It is also not uncommon that surface cracks continue to propagate downwards until a complete failure of the rail occurs. Such a transverse fracture is promoted by global bending and tensile bulk stresses in the rail (for instance due to cooling of a welded track).

Branching of multiaxially loaded test specimens was studied in [29]. The resulting proposal was that branching of rail cracks are governed by the effective stress intensity range and the degree of overlap between the loading modes (shear and compression). Further experimental studies of the propagation of shear loaded cracks are reported in [30]. Also here, the control of mode overlapping was found to be very important to get cracks to grow in shear.

In general, crack propagation under rolling contact loading is very influenced by crack face friction [1,31]. In this context, compressive overloads may be detrimental in crushing crack face asperities and thus reducing the crack face friction [6].

3.2.1. The influence of lubrication

There are different theories on the mechanisms behind surface crack propagation. Most theories emphasize the influence of lubrication on crack growth. Lubrication is here used in a wide sense including all fluid matters that may enter the crack, e.g. water, grease, oil, etc.

Three possible mechanisms to explain the role of lubrication have been put forward, see [32]:

- Crack face lubrication which decreases crack face friction and increases the crack driving forces. This effect has been confirmed by numerical (finite and boundary element) simulations, see [1,33].
- The influence of a fluid forced into the crack distributing the contact pressure acting on the fluid at the crack mouth to a ‘hydraulic pressure’ on the crack faces. This effect will also prevent crack closure.
- The influence of a trapped fluid as shown in Fig. 4. This effect causes a marked increase in the Mode I stress intensity factor.

The empirical findings that support an influence of lubrication include:

- Experimental findings concluding that lubrication (preceded by a number of, more or less, dry cycles) is essential for surface cracks to grow, see [24,34–37] and references in [11,17,32]. Further, the crack propagation is depending on the lubricant viscosity [38].
- Surface fatigue of rails is rare in tunnels, see [36,39].
- Large seasonal variations in wheel reprofilings, see [19,40].
- Preferred growth in the direction of the motion. This is easily understood, since a contact moving from right to left in Fig. 4 will ‘squeeze’ the water out of the crack. Also crack face lubrication will cause a direction dependency as a result of the altered sequence of loading according to [32].
- Propagating surface cracks are also more frequent on the driven surface, see [36]. This can be understood by noting that a traction applied from the wheel (upper body in Fig. 4) will open the mouths of a crack in the rail (lower body in Fig. 4) before the crack enters the contact area, allowing

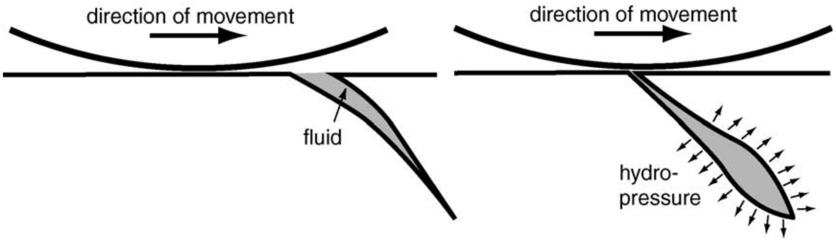

Fig. 4. Mechanism of crack propagation by the pressure of a trapped fluid.

lubrication to pour into the crack. In the same manner, cracks on wheels will be closed by a traction and opened by a braking torque. The effect has also been shown in numerical simulations, see [32].

It should be clarified that the role of the lubrication in the propagation of surface cracks does not imply that lubrication should be abandoned. Instead, a proper use of lubrication has the beneficial effect of reducing friction, which will reduce the risk of crack initiation (possibly including the growth of small cracks) and also decrease wear rates and noise radiation.

3.2.2. *Corrosion*

It could be suspected that crack growth is promoted by rust formation, which has been found to occur at the crack tip. Such a mechanism cannot explain why cracks grow in a preferred direction or the influence of traction and is not active when the lubrication consists of e.g. grease or oil. However, for deep cracks, where fluid penetration all the way to the crack tip is unlikely, the influence of corrosion may well be of interest. This effect has, to the authors' knowledge, not been studied for rolling contact fatigue, although it is well studied for plain fatigue.

3.3. *Predictive models*

3.3.1. *Crack initiation*

To predict surface initiated rolling contact fatigue, shakedown maps [17,41] may be used. These maps require as an input acting loads, contact geometry (i.e., Hertzian semi-axes, see [42,43]) and material strength in terms of the yield limit in shear (including hardening, which may be substantial in rolling contact [24,44]). The location of the work point in the shakedown map, see Fig. 5, indicates whether surface plasticity (implying surface fatigue) will occur.

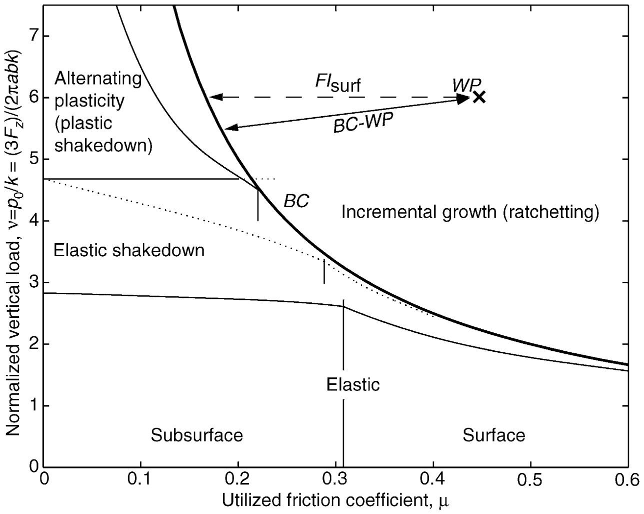

Fig. 5. Shakedown map. Surface fatigue is predicted if the working point WP (defined by the material yield stress in shear, contact geometry and applied loading) is outside the thick line.

The shakedown map is based on Hertzian theory [45]. To obtain a better prediction of acting contact stresses "exact" or "approximate" elastic modelling [43,46–49] or elasto-plastic (FE-) modelling [50] can be employed. A fatigue criterion can then be employed to quantify the fatigue impact from the evaluated stresses and strains. A combination of a multiaxial low-cycle fatigue criterion [51] and a ratchetting criterion [27] has proven to be very successful in predicting fatigue initiation in rails, see [52,53]. "Extended" uniaxial criteria can also be found in the literature, but have proven to be less efficient [20]. More simplified models have also been developed to try to relate the fatigue life to parameters such as the contact pressure. Such an approach has proven to be difficult since the relation between two parameters will depend on, for instance, the applied friction, cf [34]. An overview of some predictive models including a discussion of factors such as impact loading, thermal loading, martensite formation, etc. is given in [54].

An interesting aspect is the analysis of contact stresses and pertinent subsurface stress field. To this end, methods based on Hertzian theory [42,45], "exact" or "approximate" elastic modelling [43,46–49] or elasto-plastic (FE-) modelling [50,55] can be employed. A problem with the non-Hertzian elastic modelling is that very localized extreme stress magnitudes may occur as a result of mismatching contact profiles. This results in unrealistically conservative fatigue predictions. On the other hand, Hertzian presumptions may be grossly violated in some cases. The third option, elasto-plastic simulations are normally to time consuming to be of practical use except for selected case studies. It should be noted that complex constitutive models are needed to reflect the plastic material response in a reliable way [56–58] in particular when ratchetting is studied. This calls for time consuming elasto-plastic simulations. A faster approach has been suggested [59] where the material response is evaluated in reference to the moving load, meaning that time-derivatives are replaced by space derivatives in the constitutive equations.

3.3.2. *Crack propagation*

For the propagation of long surface cracks, linear elastic fracture mechanics models can be employed. Analytical models, e.g. [60–62], typically include simplifications, such as 2D loading, simplified crack and contact geometry and elastic conditions. Further, simplifications (or omissions) are typically needed to account for crack face friction and the influence of trapped lubricants. To simulate more realistic conditions, FE-analysis can be used [31,33,63–66]. Overviews of work on predictive modelling of crack propagation can be found in [67,68].

3.4. *Prevention*

A surface fatigue index based on the shakedown map has been outlined in [69]. This index can be expressed as

$$\mathrm{FI}_{\mathrm{surf}} \equiv \mu - \frac{1}{\nu} = \mu - \frac{2\pi abk}{3F_z} \qquad (1)$$

Here, μ is the applied friction, a and b the semi-axes in Hertzian contact k, the yield limit in shear and F_z the vertical load magnitude. The higher the index, the higher the risk for surface fatigue. Various means of preventing surface fatigue initiation can be identified from this fatigue index. The first option is to increase the material resistance (k) and controlling the contact geometry (a, b) by the introduction of materials with a higher yield limit [70–72], grinding of rails [39,73,74], surface coating [75] and rim quenching of wheels to introduce beneficial compressive stresses [76]. Another option is to decrease the acting frictional loads (μ) by lubrication and brake controls. See also [16,19,77] for in-depth discussions on fatigue prevention.

3.5. Additional factors

3.5.1. Surface asperities

An explanation to crack initiation and growth that does not rely on the occurrence of plastic deformations and subsequent propagation under the influence of lubricants has been put forward in the literature, see [78,79]. It is proposed that cracks will form and grow in the tensile stress field that is introduced below asperities.

A material surface that appears smooth on the macro-scale will show roughness on the micro-scale, see Fig. 6a. An asperity is a small elevated part of the surface. When the two surfaces are pressed together, only the largest asperities will initially be in contact. Gradually as the load magnitude increases, the contact will spread out to smaller and smaller asperities.

However, also at higher pressures, relatively large asperities will take a larger portion of the load than the surrounding material. This may be seen as a local point load and may cause cone cracks to initiate due to the tensile radial stress resulting in the material outside the contact, see [78,79] and Fig. 6b.

The asperity model is most useful when there are no or little plastic deformation at the surface, since plastic deformation of the surface tends to smooth out the surface, cf results in [34]. Fully elastic contact conditions is normally not the case in railway applications, but rather for gear and rolling bearing contacts.

Lubrication will suppress asperity contact [80]. Whether asperity models fully explain the empirically found influence of lubrication as discussed above is questionable. As for the preferred growth direction, crack propagation towards the approaching contact will be suppressed by the global contact pressure. Traction will introduce additional stresses which will be compressive on the driving side and tensile on the driven side. This explains the influence of traction by the asperity model. However, the most useful feature of the asperity models is the explanation of the effect of surface roughness on the fatigue life [70,81]. It should be noted that similar effects occur locally on a macroscopic scale in contacts between wheels and rails with damaged surfaces, such as in Fig. 2b.

3.5.2. Surface defects

The influence of surface defects on RCF is complex. Depending on the shape of the defect, the material hardness, the lubrication etc., the defect may either be plastically deformed, worn away or act as an initiation spot for subsequent cracking, see [38,70,82–84].

A special type of surface defects is caused by indentations, e.g. of gravel, see Fig. 7. Investigations of such defects on wheels indicate that they are mainly spherical indentations

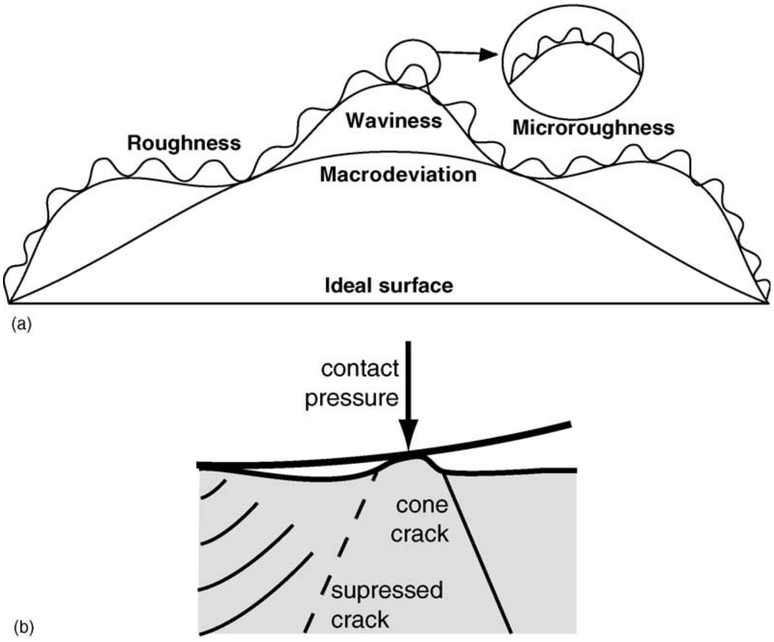

Fig. 6. (a) Roughness of a material surface on different scales. (b) Loading of an asperity causing a cone crack.

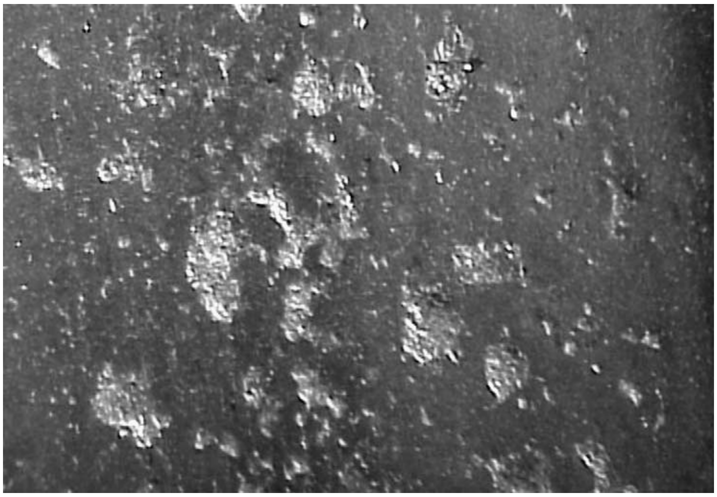

Fig. 7. Surface defects caused by gravel indentation on a railway wheel.

and likely to be benign. Another special case is the reparation of running surfaces by surfacing (i.e. additional material welded to the surface). Failures of wheels caused by such procedures are discussed in Ref. [85].

3.6. *Thermal loading*

The initiation and propagation of surface cracks is highly influenced by the presence of thermal loads, cf [86]. In railway wheels, the thermal load is normally due to tread braking. When brakes are applied, the temperature rises, causing the fatigue strength of the material to drop, see [19,87]. Thermal loading may induce cyclic and residual tensile stresses near the running surface of the wheel [88–91] which will promote both the initiation and the early growth of a surface crack. It should be noted that resulting residual stresses due to thermal loading are also influenced by the geometrical design of the wheel [92]. When thermal loading is the dominant cause to fatigue, resulting surface cracks tend to be radial. However, the point of initiation of such cracks is not restricted to the tread, but varies and even includes the bottom of the flange side, see [90]. For rails, thermal damages are more rare, but can occur as “wheel burns” when wheels are sliding at stop signals, see [18].

Martensite formation on the wheel tread normally indicates a previous history of temperatures which were high enough to austenite the material (above some 700 °C, see [93]) and fast cooling of the wheel, see [94]. However, martensite can also form due to rapid shear under impacting, see [19]. Extensive martensite is typically caused by locking and sliding of the wheel due to frozen breaks, leaves on the track, etc. More localized martensite formation (and other thermal damage) may be promoted by the formation of hot-spots, i.e. very localized, highly heated spots on the tread. Such localized martensite can also occur on high speed wheels as a result of a poorly adjusted wheel sliding protection system [95]. The martensite and the surrounding heat affected zone (HAZ) may act at initiation spots for fatigue cracks. This is further emphasized since martensite formation includes a volumetric expansion that will form high tensile residual stresses below the martensite [96]. The brittle martensite may also break off from the wheel, forming a wheel flat. Such wheel flats will cause high vertical load magnitudes which may cause secondary damage to the wheel, rail, bearings, etc. As a side-note, a possibility to avoid martensite problems may be the introduction of bainitic steels which are unable to form brittle martensite [97].

Examples of studies on thermal loading reported in the literature include: thermal damages from more or less controlled operations [22,95,98,99], experimental evaluation of high temperature fatigue resistance of wheel steel [87], measurements of tread face temperatures in operation [100] and in brake rigs [88,101], analysis of stresses and strains due to thermal and mechanical loading [28,89,102], experimental studies of the effects of tread braking on fatigue [91,98] and the development of numerical fatigue prediction models based on continuum mechanics [28,54] and fracture mechanics [103]. As for martensite and wheel flat formation, the issue is discussed in [19,54,77,93,99]. There are reports in the literature of controlled full-scale tests of the development of wheel flats with analyses of the resulting wheel flats [93,104]. Further, analytical and numerical models of the process of martensite formation have been derived [94,105].

4. Subsurface crack initiation and growth

4.1. *Mechanisms in railway wheels*

For cases of moderate surface friction (a utilized coefficient of friction below approximately $\mu < 0.3$), fatigue cracks tend to initiate below the surface. Such an initiation is promoted by the occurrence of material defects [2,3,8,106]. An additional factor that may promote crack initiation is contact close to the field side of the wheel, see [2].

According to elastic analysis, the largest alternating shear stress in a railway wheel due to rolling contact (of nominal profiles) is typically some 4–5 mm below the surface [107]. However, the point of initiation of subsurface cracks in railway wheels may be from 4 mm down to some 20 mm [2,106,108–110]. There are several reasons for this, some of which are:

- Material hardening is more pronounced at the surface [3].
- Residual compressive stresses at the surface due to manufacturing and operational loading may tend to suppress shallow fatigue crack initiation [66].
- Material defects may cause very high localized stresses even at considerable depths [5,8,108].

The deeper the point of initiation, the more important the effect of material defects. Below some 10 mm, the global stress magnitudes are very low. Still, a material defect will introduce a very high stress concentration that may trigger fatigue initiation, see [5]. In contrast, the closer to the surface, the more important the influence of the contact geometry, cf [111]. It should be noted that since the crack grows in compression and shear, which rubs the crack faces, the material defects that acted as crack initiators may be worn away during crack propagation. In particular, this is an issue for soft material defects, such as MnS, and defects located close to the surface. This could explain the lack of material defects in some cases reported, e.g. [109]. The difficulty of finding MnS-defects is also due to their small sizes. However, they are known to form clusters [3,108] and have been found to deform to very long, needle-shaped strings [93].

At shallow initiation of fatigue cracks in wheels, the crack typically grows downward towards the wheel hub in the subsequent propagation, as in Fig. 8a. It then deviates at a depth of some 20 mm with a continous growth in the circumferential direction. When initiated at a larger depth, the crack typically continues to grow at this depth, Fig. 8b. Final fracture will eventually occur as branching towards the surface as in Fig. 8a or, more seldom, towards the wheel hub as in Fig. 8b. In both cases (and also in fatigue of rails), the crack surfaces show a characteristic ‘beach mark’. See also [2,3,15,23,106] for more information.

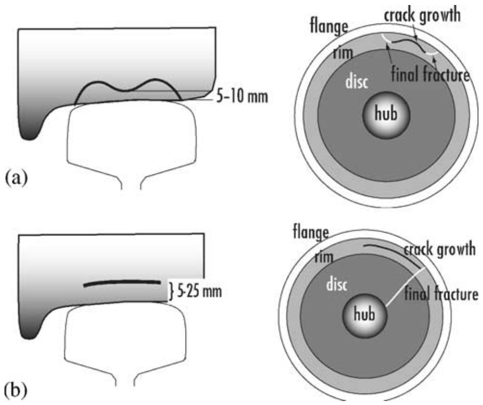

Fig. 8. Typical appearance of subsurface fatigue cracks in railway wheels: (a) shallow initiation and (b) deep initiation at a defect.

4.2. *Mechanisms in rails*

For rails, subsurface initiated fatigue is most common in heavy haul lines, predominantly in the high rail in curves [14]. The largest shear stress range in rails (as evaluated for a plane which is oriented 60° to the vertical) has been reported to occur at the gauge corner at a depth of approximately 3 mm below the surface [112,113]. Points of initiation reported in the literature are normally deeper: values of 3–15 mm below the running surface have been reported [11,14,114,115]. The reason that cracks initiate at these significant depths is likely to be the large tensile stresses here [14,115,116]. The location of initiation is typically above the depth of maximum residual tension, but may coincide with the depth of maximum cyclic tension [117]. Subsurface cracks typically occur at the gauge corner of the high rail in curves [18] due to the high loading and often small contact area. It should also be noted that the boundary effect of the gauge corner will have a detrimental effect, cf contact close to the field side of a wheel as discussed above.

There are strong indications that material defects are important for subsurface fatigue initiation in rails [14,16,18,118,119], but also reports of no large non-metallic inclusions at initiation sites [115,116] (cf the discussion of wear of material defects in the section on wheels above). Note that welds may introduce additional material defects (as well as locally high vertical loads and detrimental residual stresses) and thus may be weak points [18,39]. Further, hydrogen may have a detrimental effect in propagating cracks from subsurface defects in both wheels and rails, see [3,16,18].

Due to the different fatigue mechanisms, it is convenient to distinguish between cracks initiated at fairly shallow depths and more deep cracks. In the first case, contact stresses are the dominating cause, whereas the deeper the point of initiation, the more important issues such as material defects (or other stress concentrations), global bending, residual and thermal stresses will become. The failure then turns more towards “plain fatigue”. There are even reports in the literature of crack initiation at the *lower* gauge corner [120]. The initiation then occurs at a stress concentration (typically a weld or a flow lip with a notch) and the propagation is immediately transverse due to global bending and tensile residual stresses.

Shallow subsurface induced fatigue cracks in rails typically propagate parallel to the surface up to a critical length where they may deviate and cause a complete failure of the rail if not detected in time [14,16,117]. Tensile residual stresses and (in all-welded tracks) thermal cooling will promote such a failure. A more benign failure mode is when the crack deviates towards the surface and breaks loose a piece of the rail material.

4.3. Predictive models

The initiation of subsurface cracks has been modelled by the use of multiaxial fatigue criteria of varying complexity, see [1,13,54,121,122]. As compared to surface initiation, the amount of plastic deformation is much reduced, which justifies an assumption of elastic shakedown [17] and the use of an elastic fatigue criterion.

If the Dang Van criterion is used, it has been shown [69], that the criterion for fatigue initiation (presuming Hertzian contact condition and no boundary effects) can be approximated as

$$\mathrm{FI}_{\mathrm{sub}} = \frac{F_z}{4\pi ab}(1+\mu^2) + a_{\mathrm{DV}}\sigma_{\mathrm{h,res}} > \sigma_{\mathrm{e}} \tag{2}$$

Here, F_z is the vertical load magnitude, a and b the Hertzian semi-axes, μ the traction coefficient, a_{DV} a material parameter, $\sigma_{\mathrm{h,res}}$ the hydrostatic part of the residual stress and σ_{e} the equivalent fatigue limit, often taken as the material's fatigue limit in shear.

A complicated issue is to account for the influence of material defects. To relate the amount of subsurface defects in rails to the fatigue resistance, a "shell index" has been employed in the literature [11]. This index is based on the oxide volume fraction, the oxide size and the Brinell hardness. In the literature there are also examples [2,3,123] of accounting for material defects by using the semi-empirical Murakami criterion [124]. However, it should be noted that this criterion is originally derived for uniaxial loading. Recent research indicates that adoption of such uniaxial criteria may be doubtful [125]. There are also more fundamental studies on the issue of material defects with simulations using both elastic [126–128] and elasto-plastic [5,8,129] material models.

An important issue is the effect of occasional impact loading. High transient loads may trigger the onset of crack growth and the coalescing of material defects. It may also cause a slight detrimental history effect [5]. There are also indications in the literature that the fatigue strength may be decreased when impact loading is applied [110].

The subsequent propagation of subsurface initiated cracks has been modelled by fracture mechanics models, see [1,4,108] and the overview in [68]. In contrast to surface cracks, which typically propagate predominantly in Mode I due to the lubrication induced pressure [33,63], subsurface cracks propagate predominantly due to a mixed Mode II–Mode III loading after an initial stage of Mode I propagation [108]. A complicating issue is the influence of crack face friction, which seems to have a profound effect [1,4], but is hard to quantify. This is especially important if design is to be made towards the crack growth threshold.

The issue of crack branching, has also been studied in the literature, e.g. [1,130]. An interesting finding from fracture mechanics simulations and field studies [130], was that the highest tendency to branching was achieved at a fairly early stage. At continued growth, this tendency decreased.

4.4. Prevention

For deep fatigue initiation, material defects are of high importance. It should be noted that it is the largest defect size, in contrast to some average defect size, that is of importance, see [108]. Further, overloads should be avoided since they will cause high localized stresses at material defects [5] which may trigger fatigue initiation. Here, it is the extreme load magnitudes (and not average load levels) that are of importance.

Controlling the contact geometry is vital to counteract shallow fatigue initiation, as can be seen from Eq. (2). In particular hollow wear of wheels has been found to be detrimental [109,111]. The influence is due to the resulting small contact patch combined with resulting high longitudinal creepage [131].

As for material strength, it should be of importance, but it is fairly unclear which material parameters that correlates the best to the resistance against subsurface cracks. An educated guess would be that fatigue limit, crack growth characteristics and fracture toughness [18] are of importance.

4.5. Residual stresses

Residual stresses in rails and wheels have been extensively studied in the literature. The first issue is the experimental determination of residual stress magnitudes. There are a wide range of destructive methods of determining the residual state of stress based on cutting of rails and wheels. Examples include methods where displacements of the transversely cut surface are derived from interferometry [132], from longitudinal cutting in combination with interferometry [133], by use of surface coating and heat treatment [133] or by evaluating opening displacements and deriving stresses from FE-simulations or analytical solutions [22]. To obtain the 3D state of stress, Batelle technique (consecutive sectioning into stress-free dices and rods) or oblique slicing techniques can be used [134]. Non-destructive methods include ultrasonic, magnetic and X-ray diffraction techniques, as discussed in [76,135–141]. A rough, but efficient way of identifying solid wheels that have been heavily braked and thus are likely to contain high tensile residual stresses is the use of paint that burn when subjected to high temperatures [138]. More general overviews on the subject of residual stress measurements are given in [134,142,143].

As for the influence of the residual stresses on fatigue resistance, it has been shown to be easily accounted for if high cycle fatigue initiation is analyzed using the Dang Van criterion, see [69] and Eq. (2). The issue is also discussed in [135]. To predict the influence on crack propagation and final fracture is more cumbersome since the residual stress field will be redistributed during crack propagation. Further, residual stresses will influence the crack face friction with simulations [33,61,66] showing a quite marked beneficial influence of a compressive residual stresses. Experimental studies, on the other hand, have shown correlations where a higher compressive residual stress leads to a shorter fatigue life, see [36]. However, as pointed out by the authors of that paper, this result is likely not to reflect the influence of the residual stress, but rather that high compressive stresses are detrimental and also will cause high residual stresses.

5. Concluding remarks

This overview has only given a brief glance at problems related to RCF of rails and wheels. There are some issues that have not even been touched upon, such as the influence of climate, the interaction between wear and fatigue, etc.

As always when trying to give an overview, there is a practical need to separate various phenomena and parameters in order to prevent complete chaos in the presentation. This often gives the false impression of a very structured discipline. In reality, this is not the case. Various phenomena and parameters interact in the most intriguing ways. To the railway engineer challenged with the task of predicting or analyzing rolling contact fatigue, this is naturally a problem. Further, physically sound predictive models found in the literature typically are too complex for general adoption. In contrast, rules of thumbs and empirical knowledge can be used to characterize, but seldom to predict or analyze problems. Engineering models presented in the literature, are typically simplistic in the fatigue evaluation criteria [144], or in the load description cf [145]. The latter can be a consequence of computationally intensive methods for fatigue evaluation, cf [146,147]. Further, the models typically focuses on a certain mode of fatigue.

In order to overcome these issues, an engineering model for RCF of railway wheels was developed with the aim that it should be

- based on a scientific understanding of occurring fatigue mechanisms,
- fast enough to be directly incorporated in a multi-body dynamics code of train–track interaction without the introduction of an unreasonable computational overhead,
- understandable and manageable from an engineering point of view.

The model defines the fatigue impact in terms of three indices corresponding to *surface initiated fatigue*, *subsurface initiated fatigue* and *fatigue initiated at deep material defects*, respectively. The fatigue indices for surface and subsurface fatigue are defined by Eqs. (1) and (2), espectively. Details are given in [69]. The model is currently implemented in commercial multi-body dynamics (MBD) codes such as GENSYS and ADAMS/Rail. An example of the use of the fatigue indices is presented in Fig. 9. In Fig. 9b the subsurface fatigue index has been derived for a train operating a corrugated track. As a comparison, Fig. 9a shows the impact of the same train on a regular track. Details of the simulations are given in [148].

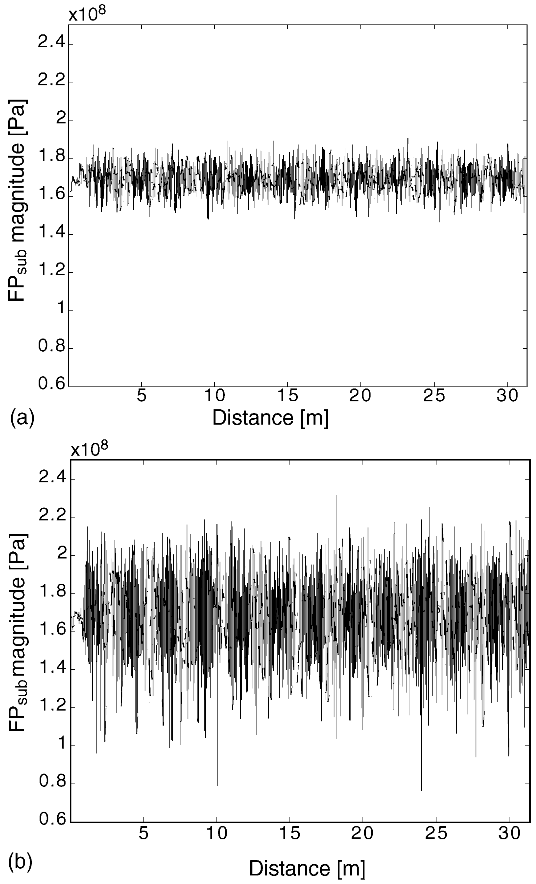

Fig. 9. Fatigue indices for subsurface fatigue according to Eq. (2) evaluated for a train operating: (a) a regular track section and (b) a corrugated track section.

With the development of this tool, it is hoped that the analysis of RCF can be an integrated part of any MBD-simulation. However, the mystery of RCF is far from solved. There are several issues that are currently not fully understood or possible to model. And finally, it should be remembered that there are more dimensions to the problem: If the cause of a RCF problem is pin-pointed to, say, friction the question still remains; what caused the friction. . .

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