APPLICATION OF FRACTURE MECHANICS TO RAILWAY COMPONENTS – AN OVERVIEW

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ABSTRACT

The paper gives an overview on the most relevant fracture mechanics issues for railway components. The topics addressed include safety relevant railway components such as axles, wheels and rails.

1. INTRODUCTION

Since its early days the development of railway systems has been an important driving force for technological progress. From the very beginning it inspired substantial developments in many areas such as steel production, engine construction, civil engineering, communication systems, etc. The stunning progress had, however, also its price. The new railway components were subjected to loads, which in magnitude as well as in characteristics were completely unknown by that time. Breaking railway axles, wheels and rails as well as exploding pressure vessels caused accidents with disastrous consequences for life and property. It was those accidents, which actually promoted the birth of the new research fields of materials testing and fatigue. The problems of the early days of railway technology were overcome long ago. However, increasing demands for high-speed services and higher axle loads account for quite new challenges with respect of material and technology as well as safety issues. In this paper, a brief introduction is given to crack problems of the safety relevant railway components axle, wheel and rail. For a more complete overview the reader is referred to a review paper published in [1].

2. RAILWAY AXLES

Traditionally, railway axles are designed for infinite life based on the endurance limit of the material. While this philosophy is in general sufficient a small number of axle failures occur in practice. E.g., Smith [2] specifies the failures per year on the UK railway network to 1.6 axles per year over the last 25 years, out of a population of 180,000 axles. Frequently, fatigue cracks initiate in the press fitted parts of the axles by fretting fatigue, however, crack initiation may also occur at other locations such as the transition region between the two principal diameters (Fig.1). Traditionally, railway axles are designed as solid shafts but for high-speed systems it has become common to make them as hollow shafts in order to save weight. Typically a semi-elliptical surface crack grows into the wall thereby changing its depth-to-length ratio. In a hollow axle, failure may be assumed when the crack at its deepest point reaches the hole or a fraction, e.g. 80%, of the wall thickness. Note, that this event usually does not refer to fracture. The crack will further extend until it reaches its critical depth However, the time from breaking through to fracture is usually so limited that the exact knowledge of the final crack size is not particularly important for determining the residual lifetime.

Railway axles are classical examples of a damage tolerance analysis the aim of which is to establish inspection intervals. A worked example is given in Fig. 2 [3]. As the result the depth of the surface crack is defined which non-destructive inspection (NDI) has to detect under service conditions. This size corresponds with a given inspection interval. The rationale behind the analysis is that the crack must be small enough that it cannot extend to its critical size before the next inspection. Note, however, that NDI crack detection is a statistical issue with the probability of detection increasing with crack depth [4]. Further work on damage tolerance on axles is reported in [4-10].

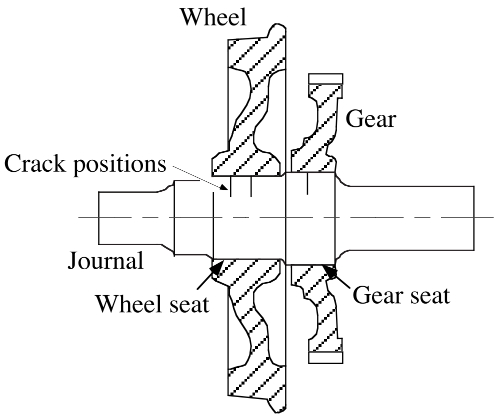

Fig.1: Typical crack positions in a railway axle.

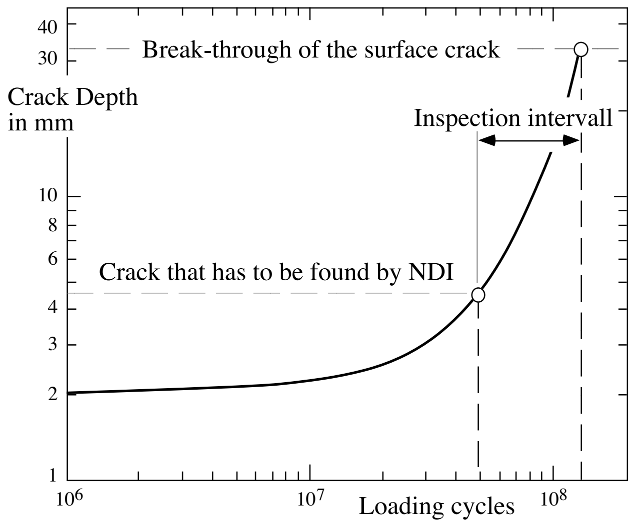

Fig. 2: Quantifying the requirements for non-destructive inspection (NDI) based on fatigue crack extension simulation [3]. (The numbers in the figure are aimed at illustrating the method and cannot be used for industrial implementation without appropriate modification.)

3. RAILWAY WHEELS

Fatigue crack growth in wheels may lead to the loss of a part of the wheel (spalling) or to radial crack extension with the consequence of the release of the press fitting between wheel and axle. The result can be damage of rails and sleepers or vehicle components or even derailment. With respect of fatigue crack initiation it has to be distinguished between wheels of block-braked vehicles and wheels of disk-braked vehicles.

Wheels of block-braked vehicles: The initiation of surface cracks in wheels of block-braked vehicles is due to cyclic thermal loads, which arise during breaking. The braked wheel tread is subjected to periodic heating due to friction with the break-shoe and subsequent cooling. An example for such thermal loading is given in Fig. 3 [11]. Note, that the heating as well as the cooling occurs non-uniformly along the circumference of the wheel concentrating in so-called hot spots. At such points the temperature increase can be in the order up to 540^{o}C [11]. The consequences of the heating episodes are thermal stresses up to peak values of 465 MPa [12], local transformation of the pearlitic to a martensite microstructure associated with local thermal expansion and residual stresses in the wheel rim. Fatigue cracks originate predominantly at sites of high tensile residual stresses, which are at the chamfer, at the tread and at the clamping rim. There are, however, also reported cases where cracks were observed at other locations such as the wheel flange or minor grooves from labelling. Sometimes these cracks grow some millimetres into the wheel material before they deviate to the surface, this way causing the loss of a piece of the tread. They may, however, also propagate in radial direction, this way damaging the whole wheel section which, in an extreme case, may cause the catastrophic failure of the wheel.

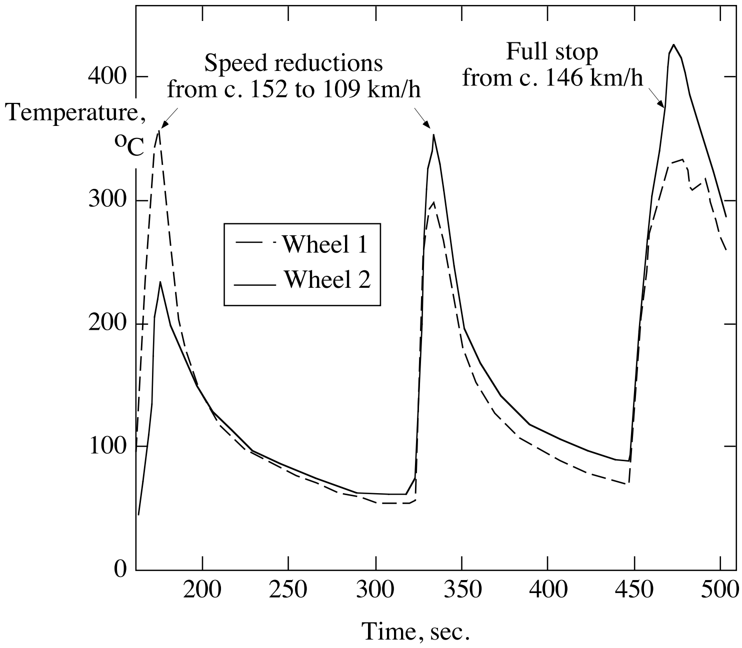

Fig. 3: Periodic heating and cooling of the tread of a block-braked wheel [11].

Wheels of disk-braked vehicles: In the case of disk-braked wheels surface cracks may develop due to high traction forces, a phenomenon which is, however, largely restricted to high speed operation. In the contact zone plastic deformation developes combined with the generation of residual stresses and some strain hardening. At high load levels, no elastic shake-down occurs. Instead, each new load cycle increases the plasticity and eventually the accumulated deformation exceeds the ductility of the material, a phenomenon which is called ratcheting [13]. Subsurface cracks are initiated below the tread at certain material imperfections such as non-metallic inclusions or as shear cracking of the pearlitic microstructure usually between 3 and 5 mm below the running surface [14] which coincides with the region of the largest shear stress from an elastic analysis [13].

The initiation of subsurface cracks requires very high load levels, e.g., introduced by impact loads due to track irregularities or rail joints [15]. Like surface cracks, subsurface-induced cracks will also propagate parallel, or in an inclined angle to the wheel surface. At a certain point they may, however, branch towards the surface [14] and/or in radial direction [16]. The second alternative includes the danger of catastrophic failure. Subsurface-induced failures are potentially more dangerous than surface-induced because of a larger crack extension before spalling.

All forms of metal failure associated with repeated contact stress cycles are usually called rolling contact fatigue (RCF). A lot of work has been done on this subject, which mainly refers to the crack initiation phase as the dominant time interval for durability design. The application of fracture mechanics to RCF of wheels is faced with a number of problems in addition to a common damage tolerance assessment. Ekberg [17] provides a list of such problems. Among them are the following items:

- The loading causes a multiaxial stress state with the principal stress directions in a fixed material point rotating during the load cycle.
- The stress components are out-of-phase.
- Due to large confining stresses under the contact, patch cracks propagate mainly in a mode II/mode III state.
- Friction between the opposite crack faces is typical of mixed mode crack propagation and plays a major role in crack extension which is difficult to quantify.
- Crack extension occurs under predominantly compressive loading whereas the predictive methods based on the Paris law have been developed and validated mainly for tensile loading.
- Occasional overloads may accelerate crack extension.
- Because of the high crack initiation loads, larger plasticity effects at the crack tip cannot be disregarded which means that the application of the common stress intensity factor concept might be questionable.

With respect of fatigue crack growth there seems always to be an influence of lubricants, e.g., water [18]. In a rotating wheel the crack is opened just before the contact load reaches the crack mouth. The crack is filled with the fluid existing in the environment by capillary action. When the contact load moves further the fluid is trapped inside the crack because of crack mouth closure. It is not quite clear what is the effect behind the lubricant. One possible explanation is a "hydraulic pressure mechanism", i.e., the fluid hinders the crack to be closed over its complete length. Another point may be that the crack with fluid lubricated crack faces can propagate more easily in mode II because of reduced crack face friction. [19].

A brief overview on fracture mechanics applications to block-braked as well as disk-braked wheels is given in [20], an example is given in Fig. 4 where the effect of mixed mode loading on the residual lifetime of a wheel is illustrated [21].

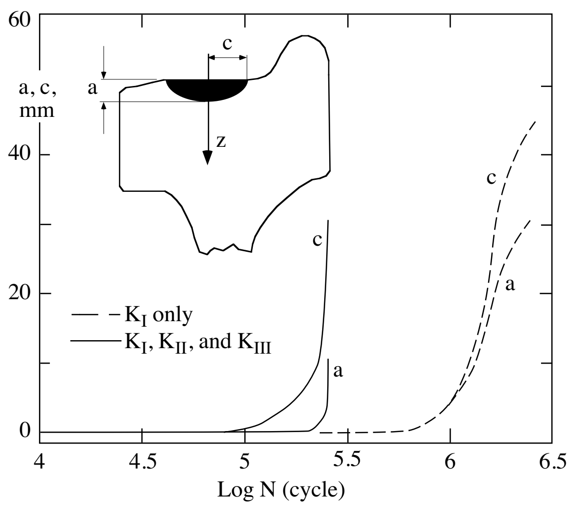

Fig. 4: Effect of mixed mode loading on the residual lifetime of a wheel [21].

4. RAILS

Fatigue and fracture of rails is a rather complex issue. It has to be distinguished between rails in straight and curved track sections, rails of tracks which are operated in one or in both directions, rail butt welds, switches, etc. Various aspects such as highly complex variable loading, secondary stresses and seasonal changes of the environmental conditions have to be taken into account.

Loading: Rails are subjected to primary and secondary loading components. Fig. 5 shows a typical primary loading configuration [22]. The loading by the wheel is applied to the rail as bending stresses, σ_b, axial stresses, σ_m, and Hertzian pressure, p, from rolling contact. The bending stresses arise from the static axle load and its dynamic magnification by a moving train. The overall magnitude also depends on the quality of the grounding of the track. Usually, quite different types of vehicles with different axle loads are operated on one track. Defects in the running surface of the rails such as joints, dips and twists and irregularities in the wheel such as flats and out-of roundness may play a role. Axial stresses arise from structural irregularities of the track and from the acceleration and deceleration of the train during train start and stop. The loading due to rolling contact is similar to what has been discussed for wheels and plays a major role in the early crack extension phase. Note, that there is additional loading in lateral direction especially in curved track sections and at switches and crossovers. These forces are also dynamically magnified with increasing speed. For trains equipped with tilting technology local track irregularities in particular in small-radius curves seem to play a major role with respect of lateral load increase in track and boggy as well [23]. The main load case for rails in switches is horizontal lateral bending.

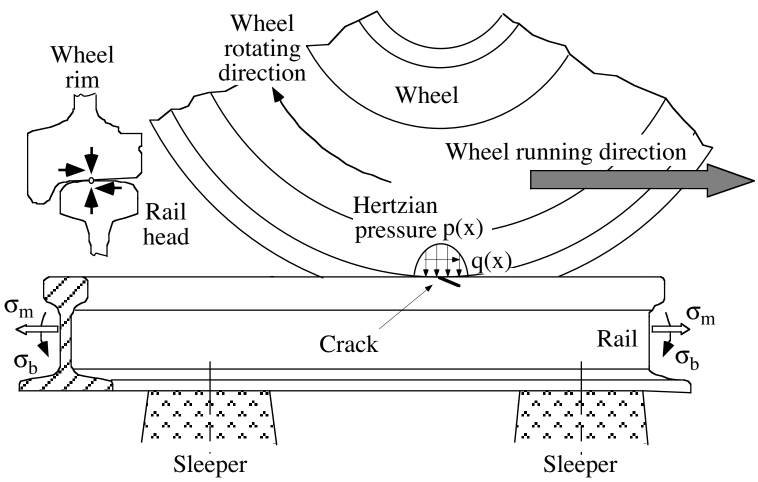

Fig. 5: Primary loading configuration of a rail [22]

The primary loads are superimposed by secondary loads, which, by their nature, are thermal and residual stresses. A rail track is installed at a certain ambient temperature, e.g. in springtime or autumn. Because built-in rails cannot elongate and shrink with increasing and decreasing temperatures, seasonal differences in the temperature will produce axial thermal stresses. These are tensile stresses at lower and compressive stresses at higher temperatures. Residual stresses in rails are introduced by different mechanisms. Primarily they stem from the manufacturing process, namely from heat treatment and roller straightening. Maximum axial tensile residual stresses of about 200 MPa have been measured in the vertical centre line of the rail below the running surface and in the rail foot whereas the other regions of the rail section are characterised by compressive residual stresses. The residual stress distribution in a rail head is illustrated in Fig. 6 [24].

In service, the wheel-rail contact causes local yielding in a thin layer in the running surface. Microhardness measurements show that the rail head is work hardened to a depth of about 2.5 mm [25]. By this mechanism the residual stresses are redistributed. The original peak tensile stresses close to the running surface are significantly lowered and even replaced by compressive residual stresses at the surface itself. A special case of residual stresses is welding residual stresses at rail joints. Note, that the residual stress profiles from the manufacturing processes mentioned above will be totally altered within and close to the weld. Welding residual stresses reach peak values up to yield strength if, as in the case of rails, no post weld heat treatment is carried out.

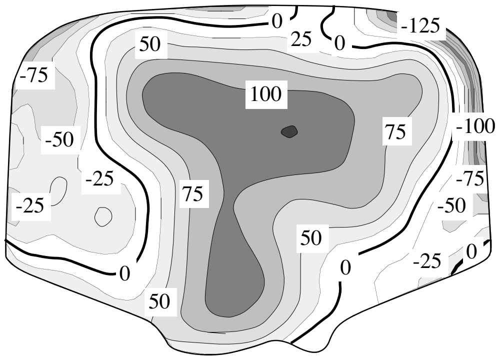

Fig. 6: Residual stress field in a rail head [24] (Stresses in MPa).

Since the loading conditions at the tread of a wheel and at the running surface of a rail have a number of features in common the appearance of cracks is also similar. Cracks may be induced at or below the surface. Surface cracks are initiated due to high traction forces at high speed rails and they will propagate under the influence of a lubricant in an inclined angle in the direction of the motion of the applied load for rails operated in one direction. Transverse branching may then lead to the complete fracture of the rail. Subsurface cracks are reported to initiate beneath the gauge corner 10 to 15 mm below the running surface [26]. It was shown [27] that lubricants such as water are also necessary for rolling contact crack propagation in rails. The effect is similar to that described for inclined surface cracks in wheels

Defect types: Important flaw types are shellings, squats, head checks and transverse cracks. Surface and sub-surface flaws such as squats, head checks and shellings usually result in the detachment of small material fragments at the rail surface. They may, however, also develop into transverse cracks which when propagating cause complete fracture of the rail. Transverse cracks in rails of switches have their origin also in surface cracks but not at the rail head but at the corner of the rail foot. Initial points are corrosion pits or ground flanges. Note, that cracks close to or at the surface are a rather new problem connected with high speed operating. In former times rails experienced enough wear to permanently remove the surface layer containing the new emerging cracks. In order to fulfil the increasing demands for higher axial and dynamic loads modern rail steels tend to exhibit much higher resistance to wearing with the disadvantage that the surface layer removed is not any more large enough to prevent small cracks from extending into the rail.

Modelling of shallow surface cracks is a very complex issue due to factors such as mixed mode loading under rolling contact fatigue conditions, crack face friction, fluid entrapment, multiaxial loading and others. An up-to-date review on this issue is given in [28]. Very short cracks can be modelled only by elastic-plastic fracture mechanics and/or damage mechanics. But also with respect to longer cracks a number of problems remain. One of these is that the loading conditions of a rail are non-proportional and out-of-phase. The stationary stress state resulting from the thermal and residual stresses is superimposed by transient stresses at the consecutive passage of the wheels of a train. As a consequence the crack tip of a head check or squat experiences a moderate initial mode I cycle followed by a mode II shear cycle when the wheel passes over the crack tip region and, at the end of the cycle, additional mode III loading. Such a sequence is illustrated in Fig. 7 [29]. Note, that the mode I loading is too small to be responsible for any crack propagation. In contrast, the mode II stress intensity factor shows a significant magnitude, therefore controlling the fatigue process at this stage.

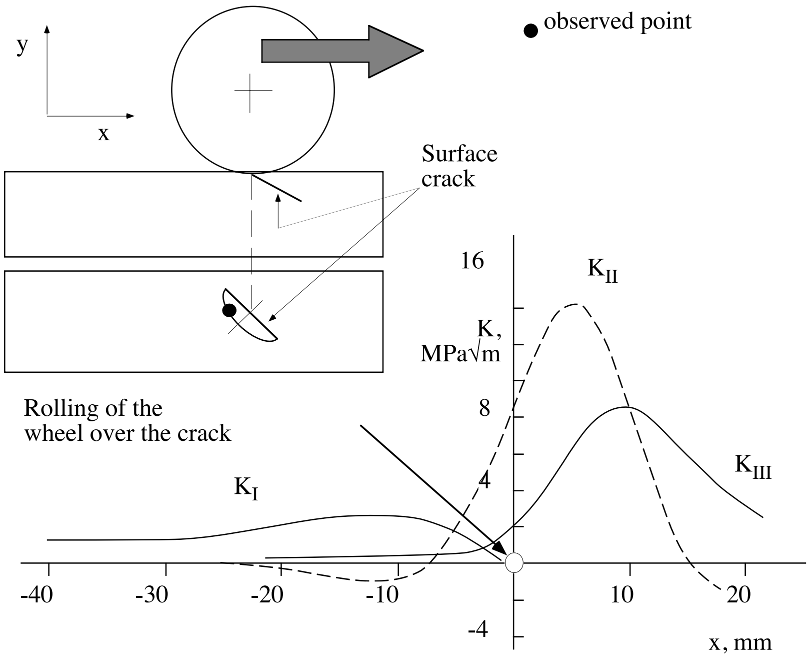

Fig. 7: Mixed mode loading sequence a rail is subjected to during wheel pass over [29].

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