PREFACE

This literature survey is part of the joint research project *Prediction of Lifetime of Railway Wheels* between the wheelset manufacturer ABB Sura Traction AB, the train manufacturer ABB Traction AB (Mechanical Systems Division) and the Division of Solid Mechanics at Chalmers University of Technology.

The aim of the project is to find reasonably accurate and effective methods to predict the lifetime of railway wheels. As a first part of this project, fatigue is being studied for the wheels of high-speed trains. A preliminary lifetime model considering rolling contact fatigue was presented in the paper "*A Fatigue Life Model for General Rolling Contact with Application to Wheel/Rail Damage*" which is published in "*Fatigue & Fracture of Engineering Materials & Structures*" (*322*). It is also available as Report F177 at Chalmers University of Technology, Division of Solid Mechanics. In the continued project the present fatigue lifetime model will be improved and a comparison of numerical and in-field results will be made. Also an analysis of wear and thermal effects will be included.

GÖTEBORG IN NOVEMBER 1995

ANDERS EKBERG HANS BJARNEHED

SAMMANFATTNING

Denna litteraturstudie behandlar mekanisk rullkontaktutmattning med särskild tillämpning på kontakten hjul/räl. Basen för forskningen är ett antal avancerade teorier, vilket gör att en presentation av enbart litteratur inom huvudområdet förmodligen varit av begränsat värde. Därför presenteras litteratur även från angränsande områden.

Efter en kortfattad beskrivning av utmattning som ett generellt fenomen belyses ett antal delområden som var för sig har tillämpning inom rullkontaktutmattning av järnvägshjul. De delområden som behandlas är *experimentell teknik*, *residualspänningar*, *spricktillväxt*, *stokastisk last*, *skadeackumulering*, *fleraxlig utmattning*, *kontaktutmattning*, *kontaktmekanik* och *rullkontaktutmattning*. Teoridelen avslutas med en relativt detaljerad beskrivning av huvudområdet *rullkontaktutmattning av hjul och räl* där ett försök görs att definiera de mekanismer som styr initiering och tillväxt av utmattningssprickor. I anslutning till referenserna ges, för varje delområde, en kort beskrivande text. Omfånget hos dessa texter varierar beroende på den bedömda användbarheten inom huvudområdet.

Litteraturstudien avslutas med en litteraturlista som innehåller 358 referenser, samt en bilaga som innehåller definitioner av använda beteckningar och en engelsk–svensk ordlista med vanliga fackuttryck inom utmattningsområdet.

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ROLLING CONTACT FATIGUE OF WHEEL/RAIL SYSTEMS – A LITERATURE SURVEY

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SUMMARY

The literature on rolling contact fatigue (RCF) of railway wheels is the main objective of this survey. The subject involves several areas where there are no generally accepted theories. This complex problem is here divided into several reasonably separate areas. While there are no distinct borderlines between some of the areas (for example *cumulative damage* and *random loading*), some references could perhaps just as well have been presented in a different section.

The presentation starts with an overview of the general phenomenon of fatigue. It then takes a closer look at several areas related to the concept of fatigue. Finally, the main subject of rolling contact fatigue, especially in the case of wheel/rail contact, is treated in some depth.

1. METHOD OF SEARCH

Most of the 358 listed references were found using the CD-ROM facility at the main library of Chalmers University of Technology. The CD-ROM databases cover journal articles back to 1986.

The CD-ROM databases used were

- ☐ Compendex Plus (includes 4 500 journals)
- ☐ Science Citation Index (includes 3 300 journals)
- ☐ Dissertation Abstracts

In the first search, the following key word(s) were used single or in Boolean combinations:

- ☐ Fatigue
- ☐ Multiaxial
- ☐ Criterion
- ☐ Contact
- ☐ Damage
- ☐ Life prediction
- ☐ Railway wheel

A second search was made on the subject of cumulative damage. This second search was carried out by examining references in articles on cumulative damage found in the first search.

A third search was made especially for books. This was partly performed in the main library of Chalmers University of Technology, using the key-word “fatigue” in the “INCHANS” database, and partly in the local library at the Division of Solid Mechanics, Chalmers University of Technology.

Finally, a search has been made in the special railway engineering library at the Division of Solid Mechanics, resulting mainly in conference papers.

2. GENERAL FATIGUE

2.1 SOME HISTORICAL NOTES

The concept of fatigue has been known since the midst of the nineteenth century. A major literature survey which should contain all articles regarding fatigue published between 1838 and 1950 is presented by Mann (*24*).

In 1871, the first major systematic investigation of the phenomenon was made by Wöhler (*77*). This study was initiated by the fracture of locomotive wheel axles.

Since the discoveries by Wöhler, fatigue has been thoroughly studied. However, there are still several areas for which there are no satisfactory theories to explain the observed phenomena and to serve as a tool to predict fatigue behaviour. Some of these areas (e.g. multiaxial fatigue and cumulative damage) are crucial parts in the modelling of rolling contact fatigue in wheel/rail contacts.

A more comprehensive review of the historical development, regarding the understanding of fatigue, is presented by Suresh (*34*).

2.2 SOME NOTES ON THE CONCEPT OF FATIGUE

According to Lin (*61*), more than 90% of all catastrophic failures of structures are caused by fatigue of materials. Fatigue does, as indicated by the designation, include some sort of exhaustion of the material. This is manifested by material failure at fluctuating stress levels far below those leading to fracture at static loading. The provision is that the material is exposed to these fluctuating stress levels for a “long time”, or rather, for many cycles.

LOW AND HIGH CYCLE FATIGUE

The term "long time" is somewhat crucial in the definition of the two main types of fatigue. If the lifetime is limited to approximately 10^3 – 10^5 stress cycles, we are dealing with Low Cycle Fatigue (LCF). In this type of fatigue, the material is subjected to stress levels that produce macroscopic plastic strains. The standard engineering approach to solving LCF problems is to use the Coffin–Manson relationship to calculate the fatigue life as a function of the number of applied strain cycles, see Suresh (*34*), ch.4.5. Another possible approach is to calculate, cycle by cycle, the strain loops caused by the applied fluctuating loads. In order to quantify the fatigue in a certain volume of the material, a damage parameter is introduced. This approach is presented by, for instance, Lemaitre (*21*) and Runesson (*30*).

The other main type of fatigue, mainly dealt with in this survey, is designated High Cycle Fatigue (HCF). Here, the material is subjected only to microscopic plastic strains and the number of cycles to fracture can be many millions. Because of the immense number of cycles to failure, it is often not possible to use the same approach of modelling as in the case of low cycle fatigue. However, Ottosen and Stenström (*238*) have developed an approach that is similar to the LCF method mentioned above. It uses a moving "damage region" in the stress space to define the domain where damage is initiated. One advantage of this approach is the similarity to constitutive modelling. In addition, it is possible to check whether the damage criterion is admissible from a thermodynamical point of view (e.g. that energy is actually dissipating).

The micromechanics of crack initiation in HCF is more thoroughly treated by Lin (*61*). According to Lin, fatigue crack propagation predominates the fatigue life in LCF, while crack initiation predominates the life in HCF.

CRACK INITIATION AND PROPAGATION

Two basically different ways of categorising fatigue are defined by looking at the physics behind the failure. After a fatigue crack is initiated at a microlevel, its initial shape and direction is defined and the crack will eventually start to propagate through the material. Depending on whether the initiation or the propagation is dominating the lifetime, one can use different approaches.

If, on one hand, the dominating part of the fatigue life is crack propagation, a fracture mechanics approach is normally used. The crack propagation is then studied by the use of stress intensity factors. As an example of an area for which crack propagation is dominating the fatigue life, one can mention welds, for which initial cracks always have to be assumed.

If, on the other hand, the initiation of cracks is dominating the fatigue life of the component, a different method has to be used. In the case of uniaxial stress with one stress level (i.e. a load spectrum consisting of a load with constant amplitude and mid value), a standard method can be used. From experimental data, a relationship between the stress level and the number of cycles to failure is established (a so-called Wöhler curve). Then, by using inter- or extrapolation, the number of cycles to failure corresponding to a specified stress level can be estimated.

An approach that, in some sense, combines the studies of initiation and propagation of cracks, is the concept of short fatigue cracks. Here, an initial small crack is assumed, and the propagation of this crack to failure is studied. This approach avoids the idealisation of a material free from defects and is therefore satisfactory from some physical point of view. However, the approach presumes that an initial size, shape and position of a "critical" crack (or defect) can be estimated. The concept of short cracks is briefly treated in the section "Fatigue Crack Growth", p.6.

SOME OTHER ASPECTS OF FATIGUE

If there are several levels of stress present, the case becomes more complicated. The question is then how to add damage corresponding to the different stress levels. This subject is treated in the section "*Cumulative Damage*", p.8.

Another complication is when the stresses are not uniaxial or, even worse, when the principal stresses are rotating. In these cases, one has to find a way to relate multiaxial stresses to uniaxial fatigue data. This case is more thoroughly treated in the section "*Multiaxial Fatigue*", p.9.

Since fatigue involves failure of the "weakest link" of the material, the fatigue strength is very closely coupled with the microstructural integrity and purity of the material. In fact, larger inclusions can be regarded as initiated cracks and the reduced fatigue life of the component has to be evaluated by the use of a crack propagation model. In some cases, as in fatigue of railway wheels for which the initiation stage is supposed to dominate the lifetime, the presence of large inclusions is obviously detrimental and can result in catastrophic failure.

LITERATURE

There are many books dealing with fatigue. However, the main subject of most books is failure and fracture in a wider perspective and fatigue is only briefly treated in a few chapters.

Fatigue of materials (*34*) by Suresh is a book, in which the main issue is the description of fatigue from a metallurgical point of view. This is supplemented by a description of theories concerning fatigue crack growth. It also deals with fatigue in brittle and noncrystalline solids. Since metallurgy is one of the main topics, the book contains several illustrative photographs, showing the formation and propagation of cracks.

Kompendium i utmattning (*1*) by Andersson, is an introduction (in Swedish) to the concept of fatigue. It gives a basic, but comprehensive, description of several of the main phenomena and theories in the area of fatigue.

Metal fatigue in engineering (*14*) by Fuchs and Stephens is another introduction to fatigue. It covers most areas and deals with the subject from an engineering point of view. The book is fairly easy to read and most chapters also contain a "dos and don'ts"-section.

Metal fatigue (*13*) by Frost, Marsh and Pook is an ambitious textbook on the concept of fatigue. Since it was written in 1974, recent advances in fatigue research can not be found here.

Fatigue design handbook (*29*) by Rice *et al* deals mainly with the practical engineering problems of fatigue and fracture mechanics. It is a widely spread work regarding the concept of design for fatigue.

Metal fatigue – past, current and future (*64*) by Miller is a review of developments in theories of fatigue. The emphasis is on understanding the behaviour of fatigue cracks.

Failure analysis in engineering applications (*25*) by Nishida gives a basic description of the observed material phenomena at failure.

There are also some journals dealing with fatigue, such as:

Fatigue & Fracture of Engineering Materials and Structures from the University of Sheffield, Sheffield, U.K.

International Journal of Fatigue from Butterworth–Heinemann, Oxford, U.K.

Engineering Fracture Mechanics from Pergamon Press, Oxford, U.K.

2.3 FATIGUE TESTING AND EVALUATION

In all mathematical modelling of physical processes, there is a need for experimental testing in order to develop, verify and calibrate the models. In the case of fatigue modelling, this need is especially high since the underlying physical phenomena are difficult to understand. Besides, several different phenomena are interacting, which often calls for an advanced statistical treatment of the collected test results. A description of advanced statistical models for treatment of test results can primarily be found in textbooks on statistical analysis.

Regarding experimental methods in general, Kobayashi (*84*) presents a widely spread work that covers most aspects of experimental mechanics. For rail/wheel systems, ERRI (*325*) gives a review of available techniques in the testing of resistance to rolling contact fatigue.

Another important feature in the analysis of rolling contact fatigue is the estimation of residual stresses. Orkisz and Skrzat (*85*) and Czarnek (*79*) deal with methods on estimating these stresses.

Papers dealing with experimental results, rather than methods, are here treated in a section relevant to the problem studied.

2.4 RESIDUAL STRESSES

Many components have inherent residual stresses due to the manufacturing process or the service loads. Flavenot and Skalli (*89*) define the residual stresses at three levels. The first order stresses are macroscopical residual stresses. The second order stresses act on the level of the metal grains, and the third order residual stresses act on the the level of the crystal structures. The second and third order stresses are of main interest from a research point of view. In an engineering perspective, the behaviour of a component under residual stresses has to be treated on a macroscopical level.

According to Flavenot and Skalli, the standard procedure is to add the residual stresses to the mean stress and use a standard fatigue criterion such as the Haigh or Goodman charts. However, this procedure neglects both the effect of cyclic stress relaxation and the multiaxial nature of the residual stresses. Flavenot and Skalli make a comparison between several criteria for multiaxial fatigue and experimental results. The conclusion is that criteria taking the hydrostatic stress into account (Sines, Crossland and Dang Van) give a satisfactory prediction of fatigue life in the case of residual stresses. In using these criteria, the residual stresses are simply added to the stress tensor. In cases where the magnitude of the residual stresses is exceeding the yield stress, as can be the case for welds, special techniques have to be used.

In the case of residual stresses in railway wheels, mainly compressive residual stresses are introduced in the wheel rim. Normally these have a beneficial effect on the fatigue behaviour of the wheel (see Lundén (*344*)). For a review of residual stresses, see for instance Giménez and Sobejano (*329*) regarding wheels and Farris (*88*) regarding rails. The subject of how to estimate residual stresses by use of experimental methods is treated in the section *"Fatigue Testing and Evaluation"*, p.5.

2.5 FATIGUE CRACK GROWTH

The concept of fatigue crack growth is somewhat beyond the scope of this literature survey, since it focuses on the initiation of fatigue cracks. Therefore, only an attempt will be made to highlight some important features of the subject and give examples of papers in the field.

In the analysis of fatigue crack growth, the fracture mechanics approach is commonly used. A basic treatment on the concept of fracture mechanics and crack growth can be found in textbooks on fracture mechanics, such as Dowling (*10*), Broek (*7*) and Carlsson (*8*).

The stress field in front of a crack is defined by a *stress intensity factor* under the assumption of linearly elastic conditions. In studying this stress intensity factor under fluctuating stresses, a *threshold value* can be identified (compare with the occurrence of a fatigue limit in crack initiation). For a range of the stress intensity factor below this value, the crack is not propagating, see Kitagawa and Takahashi (*99*). Finding the threshold value is therefore of major interest for components subjected to high frequency loads, where fatigue cracks are propagating so fast that they form a severe security risk. The concept of fatigue thresholds is treated by, among others, Bäcklund, Blom and Beavers (*4*, *5*) and ElHaddad, Topper and Smith (*97*).

For stress intensity factors exceeding the threshold value, a region with "stable" crack growth can be identified. In this region, the rate of fatigue crack growth can be expressed by Paris' law (by Paris, Gomez and Andersson, 1961)

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m \tag{1}$$

Here $\mathrm{d}a/\mathrm{d}N$ is the crack growth per stress cycle, ΔK is the range of the stress intensity factor, and C and m are scaling constants, see Suresh (*34*), ch.6. The growth of a crack from an initial size to a critical size can, in principle, be analysed by integrating Paris' law.

Eventually, the crack will propagate to a critical length, where the maximum value of the stress intensity factor in a stress cycle approaches the fracture toughness of the material. This results in a significant increase of the crack propagation rate, compared to the regime governed by Paris' law, and finally in a total fracture of the component, see for instance Smith (*105*).

An expansion of Paris' law using micromechanical parameters is given by Khen and Altus (*100*). Their paper also proposes a physical interpretation of Paris' law.

The description above covers the basic treatment of fatigue crack growth. However, there are often several complicating factors involved which call for expanded models. Some examples are given below.

- ❑ If the cracks are "small", see Suresh (*34*), ch.9.1, special techniques have to be used to correct the basic fracture mechanics model. An overview of the concept of short fatigue cracks from a broad point of view is given by Miller and de los Rios (*103*).

- ❑ The case of fatigue crack retardation and arrest has been given a comprehensive treatment by Suresh (*34*), ch.7.

- ❑ In the case of non-linear conditions, the J-integral is often used. Since this method is developed for non-linear elasticity it is generally not valid in the case of plastic loading followed by elastic unloading (as for cyclic elastic-plastic loading) without modifications, see Suresh (*34*), ch.5.7. and Dowling (*10*), ch.8.8.3.

- ❑ In the analysis of multiaxial fatigue crack growth, a superposition of modes is often used. However, this demands linear conditions. Also, the consideration of crack friction is very difficult. The subject is treated by Suresh (*34*), ch.11.

- ❑ In many engineering problems, as for instance wheel/rail applications, the direction of fatigue crack growth is of major interest. Kinked and forked cracks have been studied by Suresh (*34*), ch.5 and 7, and Lundén (*344*) among others.

- ❑ Hanson and Keer (*98*) give a thorough description of the propagation of fatigue cracks under the influence of a lubricant. The paper also contains a comprehensive description of prior work with pertinent references.

There are some works dealing with crack propagation in railway wheels and rails. These papers are treated in the section "*Rolling Contact Fatigue of Wheel*", p.17.

2.6 RANDOM LOADING

When dealing with (more or less) random loads, there are two major problems. One is how to identify complete stress cycles as induced by the load spectra. The other problem is how to sum up partial damages resulting from these different stress cycles. The latter problem is dealt with more thoroughly in the section "*Cumulative Damage*", p.8.

A load spectrum can be defined by use of a statistical approach. A basic description of this technique is presented by Andersson (*1*). The statistical approach assumes that the loads can be quantified as a statistical distribution (e.g. normal distribution). From this distribution, a level crossing distribution can be evaluated. However, in using this level crossing distribution, one loses some of the information regarding the stress cycles.

There are methods that preserve this information while quantifying a load spectrum, such as the Range-Pair-Count and the Rain-Flow-Count methods. Fuchs and Stephens (14) present an introduction to different such methods. Murakami (*117*) has edited a book dealing entirely with the Rain-Flow-Count method.

Sobczyk has written several books (*120*, *121*, *122*) and papers on random fatigue and its treatment from a stochastical point of view. An engineering treatment of random loads, with application to the car industry, is presented by Olsson (*118*) (in Swedish).

When dealing with multiaxial fatigue, the concept of random loading becomes extremely complicated. Not only should the methods identify load cycles from a random load spectrum, but they should also identify the multiaxial characteristics of these loadcycles, i.e. for which shear plane damage is induced. Standard methods can not be used in this case.

2.7 CUMULATIVE DAMAGE

The problem of how to add damage stemming from different load cycles was first raised by Palmgren in 1924 (*164*). His approach was later adopted by Miner in 1945 (*162*). Although this linear addition of damage, known as the Palmgren–Miner rule, many times gives an incorrect estimation of the fatigue life, it has been widely used. To achieve better results, different theories of how to adjust the criterion for different load spectra, have been proposed. An example is the approach presented by Kogaev and Gadolina (*149*).

A different approach is the description of the Wöhler-curve with a knee-point presented by Subramanyan (*171*) and Zhaofeng, Dejun and Hao (*179*). However, these methods are primarily used when the structure is subjected to a load spectrum consisting of two load levels.

Another approach is to describe the fatigue life by two different criteria forming an upper and a lower fatigue life limit. Ben-Amoz (*125*) presented such a method using the Palmgren-Miner and Subramanyan theories, respectively. Also this method is developed for load spectra consisting of two load levels.

Kutt and Bienek (*154*) give a review of aspects concerning damage accumulation rules and especially the case of statistical treatment of fatigue damage and damage accumulation.

A review of experimental work concerning cumulative damage is presented by Manson and Halford (*159*). The main content of the paper is a description of the development of a double-linear damage rule setting out from the description of damage accumulation using damage curves.

SOME CRITERIA OF CUMULATIVE DAMAGE

Kujawski and Ellyin (*151*) introduce a criterion based on an arbitrary scalar damage function $f(\psi, p)$, where ψ is the "controlling damage variable" (i.e. some sort of equivalent stress) and p is a material parameter (i.e. some threshold value). The Kujawski–Ellyin criterion can be expressed as:

$$D_i = \left\{ \left[\left(\frac{n_1}{N_1} \right)^{\frac{f(\psi_1,p)}{f(\psi_2,p)}} + \frac{n_2}{N_2} \right]^{\frac{f(\psi_2,p)}{f(\psi_3,p)}} + \ldots + \frac{n_{i-1}}{N_{(i-1)}} \right\}^{\frac{f(\psi_{(i-1)},p)}{f(\psi_i,p)}} + \frac{n_i}{N_i} \qquad (2)$$

where n_i is the number of applied load cycles at a specified load level and N_i is the number of load cycles to failure at the same load level, see also "*Nomenclature*" in Appendix 1.

Golos (*143*) introduces the damage parameter κ pertinent to the current load level and a material parameter b. The cumulative damage becomes

$$D_i = \left\{ \left[\left(\frac{n_1}{N_1} \right)^{\left(\frac{\kappa_2}{\kappa_1}\right)^b} + \frac{n_2}{N_2} \right]^{\left(\frac{\kappa_3}{\kappa_2}\right)^b} + \ldots + \frac{n_{i-1}}{N_{(i-1)}} \right\}^{\left(\frac{\kappa_i}{\kappa_{i-1}}\right)^b} + \frac{n_i}{N_i} \qquad (3)$$

which is the Kujawski and Ellyin criterion with $f(\psi, p) = \kappa$ provided that $b=-1$.

Introducing

$$f(\psi, p) = \frac{1}{\sigma_a - \sigma_e} \qquad (4)$$

where σ_a is the stress amplitude (in some equivalent stress) and σ_e is the pertinent fatigue limit, results in the Subramanyan criterion (*171*)

$$D_i = \left\{ \left[\left(\frac{n_1}{N_1} \right)^{\frac{\sigma_{a2}-\sigma_e}{\sigma_{a1}-\sigma_e}} + \frac{n_2}{N_2} \right]^{\frac{\sigma_{a3}-\sigma_e}{\sigma_{a2}-\sigma_e}} + \ldots + \frac{n_{i-1}}{N_{(i-1)}} \right\}^{\frac{\sigma_{ai}-\sigma_e}{\sigma_{a(i-1)}-\sigma_e}} + \frac{n_i}{N_i} \qquad (5)$$

Several other damage accumulation criteria can be deduced from the Kujawski and Ellyin criterion, see (*151*). For example, assuming $f(\psi, p) = 1$ yields the Palmgren–Miner rule

$$D_i = \sum_{j=1}^{i} \frac{n_j}{N_j} \qquad \textbf{(6)}$$

Manson and Halford (*159*) use a slightly different approach and develop an empirical double damage curve approach for two load levels

$$D_i = \left(\frac{n}{N}\right)\left(q_1^5 + \left(1 - q_1^5\right)\left(\frac{n}{N}\right)^{5(q_2 - 1)}\right)^{\frac{1}{5}} \qquad \textbf{(7)}$$

where

$$q_1 = \frac{0{,}35\left(\frac{N_{\mathrm{ref}}}{N}\right)^{0{,}25}}{1 - 0{,}65\left(\frac{N_{\mathrm{ref}}}{N}\right)^{0{,}25}} \quad \text{and} \quad q_2 = \left(\frac{N}{N_{\mathrm{ref}}}\right)^{0{,}4} \qquad \textbf{(8)}$$

and N_{ref} is the number of load cycles to failure at a “reference” load level.

Manson and Halford then apply a double linear damage curve, that approximates the double damage curves. In the case of multilevel loading, Manson and Halford consider this by adjusting additional load levels to the two most “important” levels.

Several authors (including Manson and Halford) suggest the existence of a, more or less pronounced, knee point on the damage accumulation curve. This could suggest that the first part of the curve is describing the fatigue crack initiation and the second part of the curve the propagation of fatigue cracks. However, according to Manson and Halford this is not the case.

For propagating cracks, it is possible to use a fracture mechanics approach and evaluate the propagating crack length cycle by cycle. In order to get an accurate model, one has to deal with effects such as crack closure (Elber (*96*), Newman and Elber (*104*), Suresh (*34*), ch.7), crack friction etc.

2.8 MULTIAXIAL FATIGUE

When dealing with multiaxial fatigue, one of the main objectives is to define a criterion that compares different states of stress in a quantitative way. The methods currently employed for the studies of crack propagating and of crack initiation differ considerably.

In the case of crack propagation, the propagation of the cracks is analysed by the use of stress intensity factors corresponding to different modes (I, II and III). Here, the major problem is how to interpret the resulting stress intensity factor and to account for effects such as crack closure. The case of fatigue crack propagation is briefly presented in the section “*Fatigue Crack Growth*”, p.6.

In the case of crack initiation, the problem is how to compare a multiaxial stress field with the uniaxial stress field for which the fatigue material parameters were evaluated. This is most often done by the use of an *equivalent stress*. This equivalent stress describes the entire stress field in a material point by a scalar (or by a scalar and a plane of application as in the case of a shear stress criterion), which then should be comparable to pertinent fatigue data from uniaxial tests.

Two papers giving a good review of different equivalent stress criteria are presented by Nøkleby (*190*) and Renault (*191*), respectively. Nøkleby focuses on the issue of high cycle fatigue of ductile materials. The paper also presents a qualitative analysis of the limitations of the different criteria. In the Renault report, a brief presentation is made of several different criteria of fatigue, involving both high and low cycle fatigue. The criteria are compared with results from tests. Both papers contain comprehensive lists of references.

A special case of multiaxial fatigue involves rotating principal stress directions. Also in this case, which for instance occurs in rolling contact, a scalar equivalent stress can be calculated. A problem occurs when the equivalent stress is not a stress invariant. In these cases, the equivalent stress is calculated for different planes of action at different instants of time. This is because the principal stresses are not acting in the same direction throughout an entire stress cycle. Thus, fatigue damage can be initiated in different directions for different stress cycles or parts of stress cycles. There are three ways of dealing with this problem.

The first approach is to find the direction in which most damage is inflicted. This plane is called a "critical plane" (also denoted "critical shear plane" if a shear stress criterion, e.g. Tresca, is used). This approach is probably the most favourable method provided that a critical plane can actually be identified.

A second approach is to use an equivalent stress that is based on a stress invariant and thus has the same magnitude for all directions (e.g. Sines and Crossland). The result should be a criterion that is very easy to use. However, such a model would ignore the fact that a distinct direction of fatigue damage can be identified. Thus, the approach is not satisfactory from a physical point of view.

A third approach is to evaluate equivalent stresses for all shear planes of interest (Ekberg, Bjarnehed and Lundén (*322*)). In this approach, stresses have to be evaluated and damage has to be accumulated for a large number of possible critical planes and material points. This will obviously result in a significant increase in computational efforts.

A brief summary of some of the criteria of equivalent stress available for the analysis of multiaxial fatigue, is given below. For explanation of used notation, see section "*Nomenclature*" in Appendix 1.

PRINCIPAL STRESS CRITERION (Nøkleby (*190*))

$$\begin{gathered}\sigma_{\mathrm{eq,a}} = \max \sigma_{i,\mathrm{a}} \\ i = 1,2,3\end{gathered} \tag{9}$$

- ❑ Mainly used for brittle materials.
- ❑ No consideration of rotating principal stresses.

- Predicts the same fatigue damage for pure hydrostatic loading as for uniaxial loading with the same σ_1. This is not in agreement with empirical data.

SHEAR STRESS CRITERION (TRESCA CRITERION) (Nøkleby (*190*))

a) Time independent

$$\sigma_{\text{eq,a}} = \max \tau_{\text{a}} = \max(\sigma_i - \sigma_j)/2 \tag{10}$$

- No consideration of rotating principal axes and out-of-phase loading.

b) Time dependent

$$\sigma_{\text{eq,a}} = \max \tau(t) = \max(\sigma_i(t) - \sigma_j(t))/2 \\ i, j = 1,2,3 \tag{11}$$

- No consideration of rotating principal axes.

For both a) and b)

- There is no consideration of the influence of the mean stress σ_{m}. This is not in agreement with empirical data.
- The shear stress criterion is mainly used in the case of ductile materials.

VON MISES EQUIVALENT STRESS CRITERION (Nøkleby (*190*))

a) Time independent

in terms of principal stresses

$$\sigma_{\text{eq,a}} = \frac{1}{\sqrt{2}} \sqrt{\left(\sigma_{1,\text{a}} - \sigma_{2,\text{a}}\right)^2 + \left(\sigma_{2,\text{a}} - \sigma_{3,\text{a}}\right)^2 + \left(\sigma_{3,\text{a}} - \sigma_{1,\text{a}}\right)^2} \tag{12}$$

- Does not consider the effect of rotating principal stresses and out-of-phase loading.

b) Time dependent

in terms of deviatoric stresses

$$\sigma_{\text{eq,a}} = \sqrt{\frac{3}{2}\sigma_{ij}^{\text{d}}\sigma_{ij}^{\text{d}}} \quad \text{where} \quad \sigma_{ij}^{\text{d}} = \sigma_{ij} - \frac{\sigma_{kk}}{3} \\ i, j = 1,2,3 \tag{13}$$

in terms of engineering stresses

$$\sigma_{\text{eq,a}} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)} \tag{14}$$

in terms of the second invariant of the stress deviation tensor

$$\sigma_{\text{eq,a}} = \sqrt{-3J_2} \quad \text{where} \quad J_2 = \frac{1}{2}\left(\sigma_{ii}^{\text{d}}\sigma_{jj}^{\text{d}} - \sigma_{ij}^{\text{d}}\sigma_{ji}^{\text{d}}\right) = -\frac{1}{2}\sigma_{ij}^{\text{d}}\sigma_{ji}^{\text{d}} \\ i, j = 1,2,3 \tag{15}$$

- Does not consider the effect of rotating principal stresses.

For both a) and b)

☐ There is no consideration of the influence of σ_m.

☐ The von Mises equivalent stress is proportional to the square root of the second invariant of the stress deviation tensor J_2 (i.e. the stress tensor minus the hydrostatic stress tensor). Thus, it does not consider rotating principal stresses since the magnitude is the same for all shear planes.

☐ The von Mises criterion is mainly used for ductile materials.

OCTAHEDRAL STRESS CRITERION

(Nøkleby (*190*); Miller, Ohji and Marin (*233*))

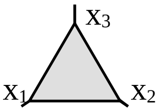
$$\sigma_{eq,a} = \tau_{oct}(t) = \left(\sqrt{\frac{1}{3}\sigma^{d}_{ij}\sigma^{d}_{ij}}\right)_{a}$$

$$\sigma_{oct}(t) = \frac{1}{3}(\sigma_{ii}) \qquad \textbf{(16)}$$

$$i, j = 1,2,3$$

☐ The octahedral stress criterion is mainly used in the case of ductile materials.

☐ According to Nøkleby better than the shear stress criterion.



The octahedral plane. The axes x_1, x_2, x_3 coincide with the direction of the principal stresses in the current state of stress. The plane is defined by $x_1 + x_2 + x_3 = \text{constant}$. There are eight such planes in the stress space, forming an octahedron, which explains the name.

The stress space of a cycle is transformed to components in an octahedral plane. The range of the shear stress (and in some cases the normal stress) acting on the octahedral plane is considered. Note that the normal stress acting on the plane is the hydrostatic stress (i.e. one third of the first stress invariant and thus independent of the co-ordinate system). Note also that $\tau_{oct} = 3/\sqrt{2}\ \sigma_{eq,vM}$, where $\sigma_{eq,vM}$ is the equivalent stress according to von Mises. The difference, compared to the von Mises criterion, is that the stresses are projected on a plane. Thus, the stress can be considered as a vector, which expands the scope of problems that can be treated, see Nøkleby (*190*).

SINES CRITERION

(Renault (*191*), Sines (*32*))

$$\sigma_{eq,a} = \tau_a + 3\ \alpha\sigma_{h,m} \qquad \textbf{(17)}$$

☐ τ_m has no influence on the fatigue behaviour, which is in accordance with experimental results.

☐ The influence of σ_m (and thus σ_h) is considered.

☐ Either the octahedral shear stress or the von Mises equivalent stress can be used as shear stress in the criterion.

☐ Only positive values (>τ_e) can induce damage.

- Since Sines criterion is based on the first stress invariant (the hydrostatic stress) and the second invariant of the stress deviation tensor (octahedral shear stress or von Mises equivalent stress), the criterion does not consider rotating principal stresses.

CROSSLAND CRITERION (Renault (*191*))

$$\sigma_{\mathrm{eq,a}} = \tau_{\mathrm{a}} + 3\,\alpha\sigma_{\mathrm{h,max}} \tag{18}$$

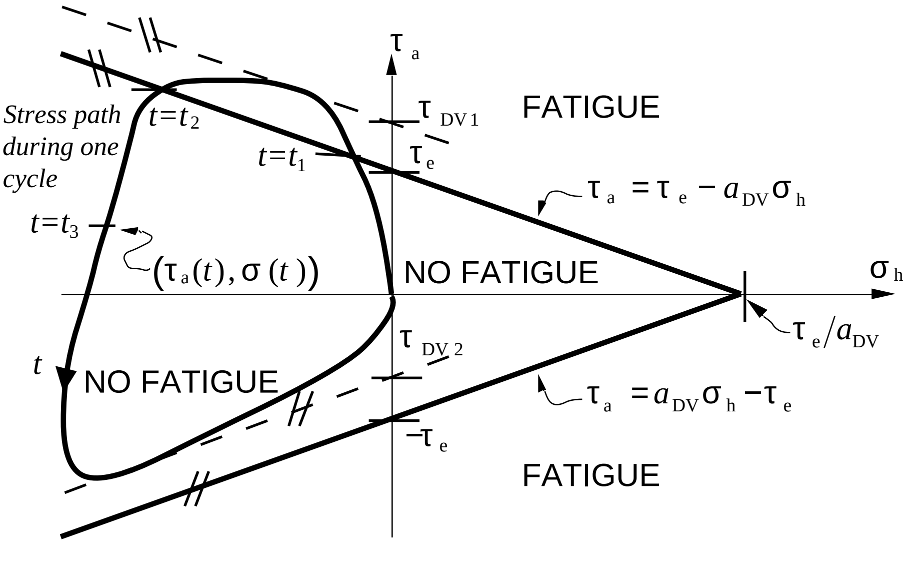
- Good in the case of high hydrostatic pressure (σ_{h}).

The Crossland criterion is essentially the same as the Sines criterion with the only difference that the maximum hydrostatic stress during a stress cycle is used instead of the mid value. Thus, the aspects mentioned above for the Sines criterion are valid for the Crossland criterion.

DANG VAN CRITERION (Ekberg, Bjarnehed and Lundén (*322*))

$$\sigma_{\mathrm{eq,a}} = \tau_{\mathrm{DV1}} = \tau_{\mathrm{a}}(t) + a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) \tag{19}$$

$$\sigma_{\mathrm{eq,a}} = \tau_{\mathrm{DV2}} = \tau_{\mathrm{a}}(t) - a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) \tag{20}$$



*The Dang Van criterion, see Ekberg, Bjarnehed and Lundén (*322*). Damage is induced in the area where* $\tau_{\mathrm{a}}(t) + a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) < \tau_{\mathrm{e}}$ or $\tau_{\mathrm{a}}(t) - a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) > \tau_{\mathrm{e}}$ *(in this case between* $t = t_1$ *and* $t = t_2$*).*

- Considers the case of rotating principal stresses.
- Considers hydrostatic stresses.
- Evaluates an equivalent stress in any specified shear plane.
- Uses the current values of shear stress and hydrostatic stress.

- ☐ Only positive values of τ_{DV1} ($>\tau_e$) and negative values of τ_{DV2} ($<-\tau_e$) can induce damage.
- ☐ τ_m has no influence on the fatigue behaviour.

The strength of the Dang Van criterion is that it is based on the **current** values of the stress components acting on a specified "shear plane" in a material point, see Ekberg, Bjarnehed and Lundén (*322*). Thus the actual history of stress throughout a stress cycle can be evaluated and compared to the fatigue threshold limits. This is an advantage, from a physical point of view, compared to the Sines or Crossland criteria even if a critical plane has been identified. This is because the Sines or Crossland criteria are using the mean or maximum value of the hydrostatic stress, respectively, during a **complete** stress cycle. The improvement achieved by the Dang Van criterion has its drawback in the increase of calculation effort. This is because the complete state of stress has to be evaluated for all material points, time co-ordinates, and "shear planes" of interest.

The Dang van criterion is treated more thoroughly by Dang Van (*203, 207*), Dang Van, Douaron and Lieurade (*204*), Dang Van, Maitournam and Prasil (*320*), Dang Van, Griveau and Message (*206*), Dang Van *et al.* (*205*), ERRI (*212, 213*) and Ballard *et al.* (*193*).

An approach to decrease the calculation effort for the Dang Van criterion is to use the maximum shear stress (i.e. the Tresca criterion) instead of the shear stress in a specified plane, see Dang Van (*207*). Since the Tresca criterion only gives positive values of the shear stress, the equivalent stress can be expressed as

$$\sigma_{\mathrm{eq,a}} = \tau_{\mathrm{DV,mod}} = \tau_{\mathrm{a,Tresca}}(t) + a_{\mathrm{DV}}\sigma_{\mathrm{h}}(t) \qquad \textbf{(21)}$$

Values of $\tau_{\mathrm{DV,mod}}$ greater than τ_e are considered to cause fatigue damage. With this criterion, the plane for which the equivalent stress is calculated is not chosen a priori. Also, only the damage for the plane with the largest shear stress is evaluated for each loading cycle. This is a drawback since the plane of maximum damage for one cycle is not necessarily the only plane where damage is induced during a load cycle. However, one can overcome this drawback by evaluating the Dang Van stresses in all interesting shear planes for the material points where the modified criterion has identified damage. The calculation of the mid value of the shear stress for this simplified criterion can also cause some problems. As an example, the criterion will predict no damage for a rotating shear stress with constant magnitude, if special considerations are not made. The reason is that only the maximum shear stress, regardless of direction, is considered in this criterion.

There are several criteria similar to the Dang Van criterion. These criteria often use the shear stress and the corresponding **normal** stress of the shear plane to define an equivalent stress. Also, some measure of "strain energy density" can be used. Some of these criteria, using a critical plane approach, are discussed by Glinka, Wang and Plumtree (*219*).

3. CONTACT FATIGUE

Structural components subjected to fluctuating contact stresses may fail due to contact fatigue. This failure is due to cracks initiated either at the surface or below the surface, depending on the nature of loading.

In the case of surface initiation, the environment can be of crucial influence. The formation of corrosion pits leads to stress concentrations from which cracks can initiate and propagate. There is also a reciprocal action between chemical and mechanical loading at the crack tip. This can be of influence, especially for short cracks, see Andersson (*1*). For a more comprehensive description, see for instance Suresh (*34*), ch.12.

In (*256*) Tallian presents a review of 11 different models to predict contact fatigue life. With this review as a basis, he presents a new life prediction model (*257*). Attached to the latter paper is also a discussion on Tallian's first paper, where the SKF (*305*, *297*) and the FAG models for lifetime prediction of rolling bearings are discussed by the developers of these models. Tallian has also compiled a comprehensive atlas of failures due to contact fatigue (*258*). The failures are presented by photographs and explanatory texts.

A good introduction to the concept of contact fatigue is given by Hanson and Keer (*98*). The presentation has its emphasis on the description of fatigue crack growth.

3.1 CONTACT MECHANICS

The subject of analysing contact between two bodies can be divided into two separate areas. The first problem concerns the extension and magnitude of the contact stresses acting between the two bodies in contact. The second problem is to analyse the stress field in the material due to the contact.

The first satisfactory analysis of the contact stresses between two elastic solids was made by Hertz in 1882 (*268*). His theory is based on the assumptions of parabolic profiles, frictionless surfaces and elastic half-space theory. This means that the contact area must be small compared to the dimensions and radii of curvature of the bodies in contact. A more thorough description of the assumptions in the Hertzian theory and especially the demand for antiformal geometry (i.e. a large difference in radii of curvature for components in contacts resulting in a small contact area) is presented by Paul (*280*). The paper deals with the wheel/rail contact with a special view on conformal contact (the case when the two bodies in contact have similar radii of curvature) that arises, for instance, when the contact stresses are acting between the wheel flange and the rail corner.

When the contact stresses have been evaluated, the stress field in the components can be analysed. A fast and reliable way to do this, is to use the analytical point load solutions to the Boussinesq problem (vertical point load) and the Cerruti problem (lateral point load), see for instance Westergaard (*287*) and Kannel (*275*) for further details. The complete state of stress is then evaluated using a numerical integration of point loads approximating to the distributed load. This procedure and the resulting stresses are further discussed by Lundén

(*344*). This method has the advantage of being applicable to a general contact stress distribution as long as the conditions can be assumed to be linearly elastic.

In more complex cases, e.g. for complicated geometries, a finite element calculation can be used. There are several commercial codes that have contact elements implemented.

A comprehensive description of contact mechanics regarding both Hertzian and non-Hertzian contacts is given by Johnson (*271*) and Kalker (*273*).

3.2 ROLLING CONTACT FATIGUE

The problem of rolling contact fatigue is, as mentioned before, rather complicated since it always involves rotating principal stresses. In addition, there are several other mechanisms (such as wear, corrosion and corrugation) involved in rolling contacts. The influence of each one of these mechanisms on the fatigue life has to be evaluated.

In (*301*), Johnson gives a review of the concept of rolling contact. The review consists of several applications where rolling contact is involved, such as wheels, rolling bearings, cams, etc. A brief description of different types of failure modes is made and the concepts of plastic deformations and fatigue failure in the rolling contact are treated to some extent.

Ioannides and Harris (*297*) present a lifetime model, mainly adopted for rolling bearings. This model is based on the model proposed by Lundberg and Palmgren (*304*) and is used as a standard model for SKF-bearings. The model is very efficient in dealing with different parameters and is easy to use, but it presumes that several material (and environmental) parameters are known. To establish these parameters, a very large number of tests in a controlled environment must be performed.

3.3 ROLLING CONTACT FATIGUE OF WHEEL/RAIL SYSTEMS

As axle loads and speeds in railway operations are increasing, and methods in preventing wear are becoming more effective, rolling contact fatigue (RCF) of rail and wheel has become a crucial problem, see for instance Tournay and Mulder (*355*). Clayton (*317*) gives a comprehensive review of current research concerning this problem. The subject is very complicated and several areas are still not fully understood. Therefore, the following description of different forms of RCF of wheel and rail is performed in order to summarize recent research and discoveries. Hopefully, the future will show whether this interpretation of current research is correct or not.

ROLLING CONTACT FATIGUE OF WHEELS

It appears that fatigue cracks can be initiated both at the surface and below the surface (Galliera *et al.* (*327*)). It also seems as if the mechanics behind these different phenomena are very different.

Initiation of Surface Cracks

The initiation of surface cracks seems to be highly influenced by the presence of thermal loads due to block braking.

Moyar and Stone (*346*) use a multiaxial fatigue criterion developed by Fatemi and Socie (*214*) to quantify fatigue damage induced at the running surface. According to Moyar and Stone, no fatigue damage is induced at the surface during free running of a cold wheel. When the brakes are applied and the temperature rises, the fatigue strength of the material drops. Also, the induced shear stress range and maximum normal stress are increased. This will increase the fatigue damage.

Giménez and Sobejano (*329*) analyse the propagation of a surface crack by the use of a fracture mechanics approach. According to them, the thermal cycles play a fundamental role in crack nucleation and in the growth of the crack until the threshold value of the equivalent stress intensity factor is reached. Also, thermal cycles play an important role in the generation of residual stress fields.

The hypothesis of a strong thermal influence on surface crack initiation is strengthened by the observation reported by Bartley (*313*) of martensite formation near fatigue cracks. This indicates a previous history of high temperatures and fast cooling.

According to experimental work by Marais and Pistorius (*345*), the thermal fatigue is due to the development of a tensile cyclic stress near the running surface of the wheel.

Residual stresses have a very strong influence on the propagation of surface cracks as shown by Giménez and Sobejano (*329*) and Lundén (*344*).

Propagation of Surface Cracks

Once the threshold value of the equivalent stress intensity factor is exceeded, the main cause of continued crack growth is the influence of mechanical loads, see Giménez and Sobejano (*329*). This propagation due to mechanical loads is very fast, see also Hirakawa, Toyama and Yamamoto (*332*). The fracture toughness seems to have only a slight influence on the total fatigue life (Giménez and Sobejano (*329*)).

In the paper by Hirakawa, Toyama and Yamamoto (*332*), lubrication is considered as the main parameter influencing the propagation of cracks. In fact, there seems to be no crack propagation in the absence of lubricants. This observation differs strongly from other results presented above. However, it shows good agreement with results obtained in the study of crack propagation in **rails** (see below). Further information on the test configuration used by Hirakawa, Toyama and Yamamoto may explain this fact.

Subsurface Initiated Cracks

For cracks initiated below the surface, the depth of crack initiation is reported to be at about 4 mm (Mutton, Epp and Dudek, (*347*)) or perhaps slightly more. Lundén (*344*) defines a critical region from the surface to a depth of approximately 6 mm. The initiation of cracks seems to presume very high load levels according to Ekberg, Bjarnehed and Lundén (*322*) stemming, for instance, from impact loads due to rail irregularities or joints.

As in the case of surface initiated cracks, the major part of the lifetime should be spent in initiating the crack. The presence of defects or inclusions in the steel will decrease this time of initiation. According to Lundén (*344*), the admissible size of a defect is strongly dependent on the crack friction coefficient. If a rather high crack friction coefficient is used, a defect length of 1–2 mm would be “safe” (i.e. the influence of the defect is negligible).

According to Lundén (*344*) and Mutton, Epp and Dudek (*347*), the cracks propagate towards the surface and therefore the probability of wheel failure would be small. However, Galliera *et al*. (*327*) show cracks propagating in a radial direction, which can lead to catastrophic failures. According to Giménez and Sobejano (*328*) the crack preferably grows in a radial direction under the influence of thermal loads, whereas the mechanical loads make the crack grow preferably in an axial direction. Also, a crack nucleated outside the running tread tends to grow in a direction that will position itself under the running tread.

ROLLING CONTACT FATIGUE OF RAILS

Initiation of Surface Cracks

According to ERRI (*325*), a major contributor to the initiation of surface cracks is plastic flow in the material due to large traction on high speed rails. Johnson (*301*) identifies spin, due to conicity of the wheels, as another contributing factor. The phenomenon of surface initiated cracks in rails does not seem to appear on heavy haul rails (ERRI (*325*)).

Propagation of Surface Cracks

There seems to be strong evidence that the presence of some lubricant is necessary for surface crack propagation to occur (Johnson (*301*)). The mechanisms behind the influence of the lubricant are not fully clarified. It has been suggested that the lubricants are “smoothing” the cracks, and thus decreasing the crack friction. Another suggestion is that the lubricants are “exploding” the cracks under the influence of fluid pressure which is built up by the presence of an external load. According to Hanson and Keer (*98*) the latter phenomenon is needed in order to propagate the crack. Bower (*293*) presents another treatment of the influence of lubricants.

According to Johnson (*301*) the cracks seem to propagate in an inclined angle of about 30°. The cracks are also propagating in the direction of the motion of the applied load. A transverse branching leading to a tensile fracture of the whole rail section can occur if the cracks are not detected and measured.

Sugino, Kageyama and Sato (*353*) reported that the shortest fatigue life, in laboratory tests, was found for a case of dry running, causing initiation of cracks, followed by a period of wet running, causing propagation. Thus, one could expect an increasing amount of fatigue cracks in the case of a dry summer followed by a rainy autumn.

The different mechanisms of crack propagation in rails and wheels are, according to Johnson (*301*) the fact that propagation influenced by lubricants was confined to the slower moving surface (i.e. the rail in the case of wheel/rail contact).

Subsurface Initiated Cracks

In the case of subsurface initiated cracks in rails, Clayton (*317*) reports that the cracks are initiated beneath the gauge corner 10–15 mm below the running surface and 6–10 mm from the gauge face. The critical depth of subsurface crack initiation is larger for rails than for wheels. Hellier, Corderoy and McGirr (*329*) found the largest shear stress range at a depth of approximately 3 mm below the surface evaluated for a plane 60° to the vertical. The difference between this depth and the depth to occurring cracks should be due to the influence of hydrostatic pressure (compare with the Dang Van criterion). Another finding, highlighted by Farris (*88*), is that large tensile stresses are developed at the depth of occurring cracks.

The subsurface induced fatigue cracks seem to propagate towards the surface of the rail (ERRI (*325*)). When penetrating the surface, they are subjected to the influence of water and lubricants, and should therefore behave in a manner similar to surface induced cracks.

The crack propagation rate in rails is of great interest in order to define inspection intervals. An approach to this subject is given by Bogdanski, Olzak, and Stupnicki (*94*), who use stress intensity factors in order to evaluate the crack growth rate. In general, the rate of propagation of cracks in rails should be slower than the crack propagation rate in wheels (at least when considering the lower frequency of the load cycles). Therefore it is more suitable to use a maintenance criterion setting out from the rate of the crack propagation (fail safe criterion) instead of a criterion based on the avoidance of crack initiation (safe life criterion).

EPITOME AND TERMINOLOGY

It seems as if rolling contact fatigue of wheels and rails could be summarised as follows:

- ☐ Surface induced cracks in wheels are initiated due to the influence of cyclic thermal loads. The thermal loads are also needed for the crack to grow beyond a threshold length. Once the threshold is exceeded, the cracks grow very rapidly, mainly under the influence of mechanical loads.

- ☐ For subsurface cracks to initiate in a wheel, very high load levels are required. The cracks will initiate at a depth of approximately 4 mm below the surface. The final crack growth will be very fast under the influence of cyclic mechanical loads.

- ☐ In both cases mentioned above, the cracks will primarily propagate towards or parallel to the wheel surface.

- ☐ Surface induced cracks in rails are due to high traction forces combined with high speeds. They seem to appear only on high speed rails. The plastic flow in the surface will produce cracks that will propagate under the influence of a lubricant. Transversal propagation, leading to complete failure of the rail, is common.

- Subsurface cracks in rails are developed due to high stress levels stemming from a combination of high axle loads (or increased loads due to curves) and a point of contact close to the rail gauge. The cracks are initiated due to the influence of mechanical loads. The propagation is usually directed towards the surface. Once it has penetrated the surface, the subsurface crack will, in principle, act as a surface crack.

The terminology concerning fatigue of rails and wheels is rather confusing. Some of the main terms, see ERRI (*325*), UIC (*356*), ERRI (*323*), Cannon and Pradier (*316*), are given below:

- *Shelling* is used for all subsurface induced cracks.
- *Squats*, *Flakes* or *Pits* are used to describe small surface cracks leading to detachment of small metal fragments.
- *Transverse fissures* or *tache ovales* are the name of subsurface cracks mainly stemming from manufacturing defects.
- *Head checks* are fine surface cracks resulting from cold working of the metal.
- *Spalling* is surface cracks joining to produce loss of small pieces of tread material.

The ERRI report (*323*) uses a terminology and a description of probable causes that is somewhat archaic. The UIC catalogue of rail defects (*356*) is currently being revised.

4. ACKNOWLEDGEMENTS

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5. LIST OF LITERATURE

The references have been collected from several sources and the information about them can vary somewhat. All of the articles are not discussed in the text of this literature survey. However, such references are listed in relevant sections in order to give a picture, as good as possible, of available recent literature on the different subjects.

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APPENDIX I

NOMENCLATURE

VARIABLES

a_{DV}	material parameter in Dang Van criterion	[-]
D_i	accumulated damage after i applied load levels	[-]
J_2	second invariant of deviator stress	[Pa]
K	stress intensity factor	$[\mathrm{N/m}^{3/2}]$
ΔK	range of stress intensity factor	$[\mathrm{N/m}^{3/2}]$
n	number of applied load cycles at a specified load level	[-]
N	number of load cycles to failure at a specified load level	[-]
N_{ref}	number of load cycles to failure at a “reference” load level	[-]
t	time coordinate	[s]
α	material parameter	[-]
σ	normal stress	[Pa]
$\sigma_1, \sigma_2, \sigma_3$	principal stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$)	[Pa]
σ_{eq}	equivalent stress	[Pa]
σ_{h}	hydrostatic stress (positive when tensile)	[Pa]
τ_{a}	current value of shear stress minus mid value during a stress cycle	[Pa]
τ_{DV}	Dang Van equivalent stress	[Pa]
τ_{DV}	maximum Dang Van equivalent stress in one stress cycle	[Pa]
τ_{e}	endurance limit in pure torsion	[Pa]
τ_{m}	mid value of shear stress during one stress cycle	[Pa]
τ_{sp}	shear stress in a specified shear plane	[Pa]

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a	referring to current value minus the mid value during a stress cycle
d	referring to deviatoric
e	referring to endurance limit
eq	referring to equivalent
m	referring to mid value during a stress cycle
oct	referring to octahedral plane
sp	referring to a specified “shear plane”
x,y,z	referring to axes in a Cartesian coordinate system

ENGLISH–SWEDISH GLOSSARY

branched crack	förgrenad spricka
brittle	spröd (material som ej plasticeras före brott)
cam	kamaxel
compressive stress	tryckspänning
conicity	konicitet
contact fatigue	kontaktutmattning
corrosion pits	frätgropar
corrugation	korrugering, räffelbildning
crack initiation	sprickinitiering
criterion	kriterium
cumulative damage	ackumulerad skada
damage	skada
damage parameter	skadeparameter
ductile	seg (material som plasticeras före brott)
equivalent stress	effektivspänning
excessive stress distribution	överskridandefördelning för spänningar
fatigue	utmattning
fatigue crack	utmattningsspricka
fatigue threshold	utmattningsgräns
forked crack	spricka som förgrenat sig symmetriskt (tillväxt i två riktningar)
fracture mechanics	brottmekanik
fracture toughness	brottseghet
gauge corner	rälshörn
gauge face	rälssida
grain	korn
heavy haul rail	järnvägsspår för höga axellaster
Hertzian stress	Hertzspänning (kontaktspänning)
high cycle fatigue	högcykelutmattning
high speed rail	järnvägsspår för höghastighetståg
hydrostatic pressure	hydrostatiskt tryck
impact load	impulslast
inclusion	inneslutning
kinked crack	spricka med böj (tillväxt i ny riktning)
low cycle fatigue	lågcykelutmattning
lubrication	smörjning
maintenance	underhåll
martensite	martensit
mechanical load	mekanisk last
multiaxial fatigue	fleraxlig utmattning
octahedral stress	oktaederspänning
principal stress	huvudspänning
propagation	propagering, utbredning
radius of curvature	krökningsradie

random loading	stokastisk last
reciprocal action	växelverkan
residual stress	residualspänning (kvarvarande spänning efter avlastning)
rolling bearings	rullningslager
rolling contact fatigue	rullkontaktutmattning
rotating principal stress axes	roterande huvudspänningsriktningar
running surface	löpyta
shear plane	skjuvplan
shear stress	skjuvspänning
spin	slirning
strain	töjning
stress	spänning
stress concentration	spänningskoncentration
stress intensity factor	spänningsintensitetsfaktor
stress invariant	spänningsinvariant
tensile stress	dragspänning
thermal load	termisk last
threshold value	tröskelvärde
uniaxial	enaxlig
wear	nötning
weld	svets