THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Degradation of Railway Rails from a Materials Point of View

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Whether life is worth living depends on the liver[1]

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[1] Accredited to William James (1842-1910)

Preface

The research in this thesis was carried out at the Department of Material and Manufacturing Technology, Chalmers University of Technology, during the period October 2007 – March 2013. The project was part of the activities within the Centre of Excellence in Railway Mechanics (CHARMEC). Main collaboration partners were Trafikverket and voestalpine Schienen GmbH. The thesis is based on work contained in the following papers, which are being referred to in the thesis:

Paper I

M. Schilke, N. Larijani and C. Persson

Interaction between cracks and microstructure in three dimensions for rolling contact fatigue

To be submitted for international publication

Paper II

N. Larijani, J. Brouzoulis, M. Schilke and M. Ekh

The effect of anisotropy on crack propagation in pearlitic rail steel

Proceedings of Contact Mechanics and Wear of Rail/Wheel Systems conference 2012, Chengdu, People's Republic of China, August 27-30, 2012

Under review for publication in a special edition of Wear

Paper III

P.T. Torstensson and M. Schilke

Rail corrugation growth on small radius curves – Measurements and validation of a numerical prediction model

To be submitted for international publication

Paper IV

M. Schilke and C. Persson

White etching layers on the Stockholm local traffic network

Proceedings of Contact Mechanics and Wear of Rail/Wheel Systems conference 2012, Chengdu, People's Republic of China, August 27-30, 2012

Under review for publication in a special edition of Wear

Paper V

M. Schilke and C. Persson

Cyclic mechanical behaviour of pearlitic, bainitic and martensitic railway rail steels

Submitted to Journal of Rail and Rapid Transit

Paper VI

M. Schilke, J. Ahlström and B. Karlsson.

Low cycle fatigue and deformation behaviour of austentitic manganese steel in rolled and in as-cast conditions

Proceedings of the 10th International Fatigue Congress, Prague, Czech Republic, June 6-11, 2010

Contribution to papers:

All papers were prepared in collaboration with supervisors and co-authors. The following clarifies what the author has not performed with regard to the appended papers:

Paper I: Digital assembly of the cross section micrographs to three-dimensional models of the cracks was done by N. Larijani.

Paper II: Sample extraction and preparation as well as hardness measurements and some micrographs were done by the author. Writing was done by N. Larijani and modelling was done by N. Larijani and J. Brouzoulis.

Paper III: Coordinate machine measurements were done by the author assisted by B.G. Rosén. Sample preparation, microstructure evaluation and magnetic particle investigation as well as photographing thereof was done by the author. The rest was done by P.T. Torstensson.

Paper IV: Retained austenite determination was assisted by S.B. Hosseini. Evaluation of fracture surfaces was assisted by P. Sotkovszki.

Paper V & Paper VI were done by the author.

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Abstract

From time to time railway rails need to be replaced. In that case and when new track is built, a decision has to be made about which rail grade that is going to be installed. The intention of this work was to compare different rail steels concerning their suitability from a mechanical durability perspective. The most common steel types used for rails are presented as well as the most common damages that occur as part of the degradation process. The rail-wheel contact is the primary source for damages. Two types of damages were studied in detail, white etching layers (WEL) and rolling contact fatigue (RCF) cracks.

The WEL that was investigated originates from a metro rail with heavy traffic. It can be shown, that the WEL is more brittle than the pearlitic base material of the rail. Also, evidence can be provided for a type of crack that is exclusive to WEL in rails. This crack type is perpendicular to the surface of the rail and can initiate or be connected to other cracks in the base material. Retained austenite measurements in the WEL prove that the microstructure was produced under the influence of high temperatures and suggests that there is martensite present.

Rolling contact fatigue cracks from field samples and from test rig samples were investigated. Three-dimensional images were produced. Interaction between the plastically deformed microstructure and cracks could be shown as well as shielding of cracks by other cracks or their own branches.

When determining which rail grade is best suited, a holistic view must be adopted, including all relevant influencing factors, such as traffic, track geometry, maintenance regime and climate. The problem of rail degradation cannot be solved by material choice alone.

Keywords: Railway Rail, Rolling contact fatigue, Rail grade, White etching layer, Crack, Three dimensions, Plastically deformed layer, Anisotropy

Table of Contents

1 Introduction

In the world of perpetual growth that we desire to live in, improvement has to take place continuously. We expect our new phone to have more features and our new TV to be bigger as compared to the previous models. We have also come to be accustomed to a world where we can order products from all corners of the world and have them delivered fast. We also want to be able to travel fast. Railway is a means of convenient, safe and environmentally friendly transportation and as such, it has also developed to fit our current life style. This has increased the demand on the rails and the material used. Higher axle loads and train velocities increase the wear of rails. Tighter schedules also allow less time for in track maintenance. There are different strategies to cope with the increased demands on the rail materials.

1.1 Objective

The aim of this thesis is to explain some of the current challenges for rail materials and how they can be addressed.

2 Rail materials

This chapter will give an overview of steels used for railway rails, the chemical compositions for the rail grades investigated in this project can be found at the end of the chapter. One of each rail steel type presented here are investigated in more detail in papers V and VI.

2.1 Historically

First constructions of railways can be dated back to as early as the ancient Babylonian empire where grooves on roads were used for rail going wagons. The goal then, just as now, is to minimize resistance to rolling [1]. The concept was then not developed much until the history of what would become todays railway started, when miners rediscovered the concept in the 17th century. Järnväg, Eisenbahn, Ferrovia and Raah Aahan to name just a few leave little doubt that it was iron which was the main material used for construction of rail at the outset of the modern railway age. When Henry Bessemer discovered the process for producing steel on an industrial scale in the 1850's it soon became economically feasible to use steel for railway construction [2, 3]. Ever since, in principal all railway rail material has been steel, with the lion share in Europe historically and actually being pearlitic steel. However, other steels have been developed and used as well, albeit mostly in small niches such as switches and crossings where the stress states differ a great deal from straight track. Some steels were developed with the hope that they would be superior to the existing pearlitic steel in mechanical properties and also economically advantageous.

2.2 Pearlitic steels

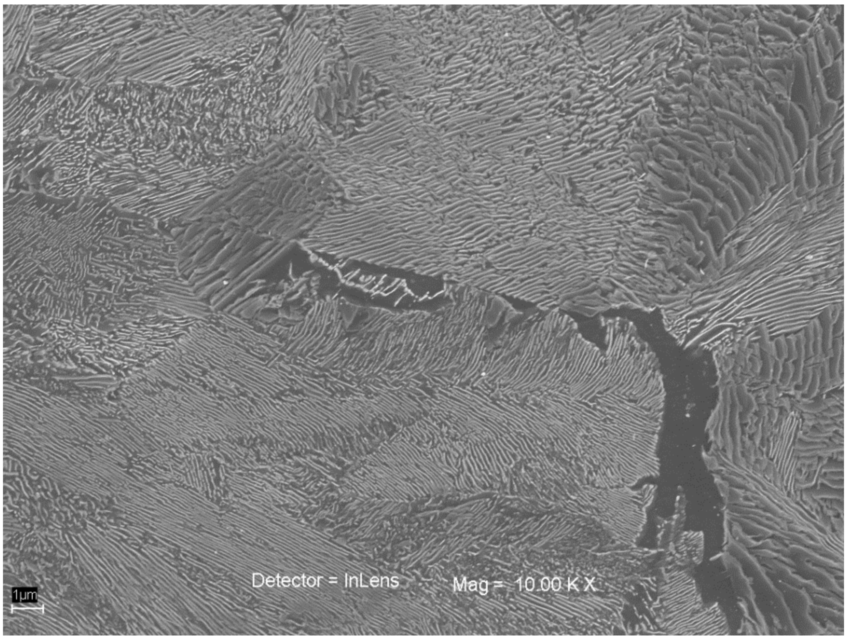

Figure 1 Microstructure of pearlitic steel.

Pearlitic steel has been and still is the major part of all railway rail steels used in Europe. It does not contain any major alloying elements and is very simple to produce with relatively good mechanical properties. There have been improvements taking place since pearlitic steels were first introduced. Unlike austenite and martensite, pearlite consists of two phases, ferrite and cementite. The initial structure when producing any type of steel is austenite, which is obtained when steel is heated above ~730°C. When austenitic steel is cooled its equilibrium reaction to cooling is to transform to ferrite. Since ferrite can solve only very small amounts of carbon, a second phase is created, cementite, which has high carbon content. Depending on the percentage of carbon, there will be either a surplus of ferrite, if the carbon content is lower than 0.8 wt% (cf. Figure 12) or a surplus of cementite, if the content is higher than 0.8 wt%. At 0.8 %, or more specific, at 0.78 wt%, the phases will be balanced to produce a microstructure consisting only of the lamellar structure constituting pearlite, cf. Figure 1. This means that there are alternating layers of the harder and more brittle cementite and the softer and more ductile ferrite. It is the qualities of these two constituents which give pearlitic steel its mechanical properties. When low alloy steels are being cooled at intermediate rates the result is some form of pearlite, depending on the cooling rate and the amount of carbon. The amount carbon used for railway steels is usually in the range of 0.5 to 0.8 wt%. In recent years, the amount of carbon in premium steels, that is steels with higher hardness and allegedly better resistance to rolling contact fatigue [4], has been set at 0.8 wt%. During production, there are two ways to manipulate the properties of steel. One is by alloying elements, which is not done to any large extent in pearlitic rail steels. Only in order to control the contamination to avoid unwanted carbides, sulphides and intermetallic particles, that can form weak points in the rail microstructure. The other way to influence mechanical properties is by controlling the production process, most importantly, the cooling rate [5]. Thereby the thickness of the cementite and ferrite layers in the pearlite can be controlled. This is usually measured as the average distance between two layers of the same kind and is called the inter-lamellar distance. As a rule of thumb, if the cooling rate is faster, the inter-lamellar distance becomes smaller and the steel harder. Also, pearlitic steels with smaller inter-lamellar spacing have been reported to be more resistant to wear [6]. The relations between alloying elements, hold time at high temperature and cooling rate on one side and mechanical properties of the resulting steel on the other side, are too intricate to be described fully in this thesis. The interested reader is referred to literature on the subject of metallurgy, e.g. Steels [7].

2.3 Austenitic steel with high manganese content

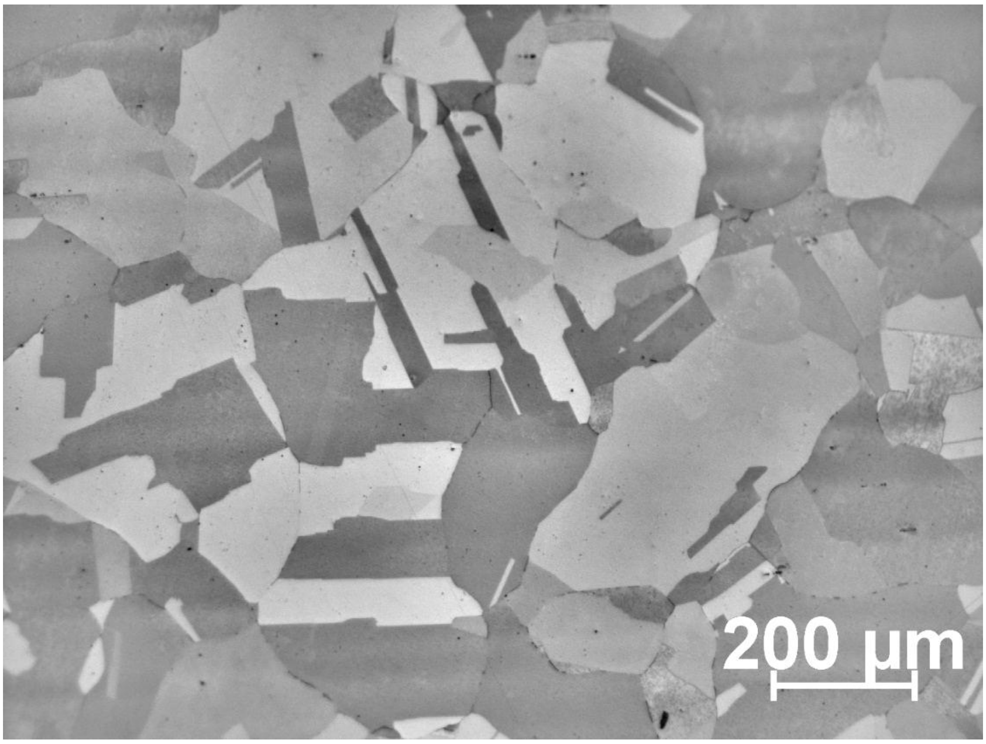

Figure 2 Microstructure of high manganese austenitic rail steel.

At temperatures above ~730°C, steel has an austenitic structure, cf. Figure 2. When the temperature drops, the structure will transform into one or several other structures, unless there is an alloying element present which can prevent phase transformation. Manganese is one of those elements. For switches and crossings when wheels have to pass from one rail to another, impact loads can become very high. For these situations manganese steel can be employed since it has properties better suited to handle repeated impacts. The particular type of manganese steel used for railway rails has around 13 wt% of manganese and is called Hadfield[1] steel. Austenitic rails are either in rolled condition, as-cast or as-cast and explosion hardened condition. Hadfield steel is extremely resistant to wear which is makes it suitable as material for bulldozer blade edges and in stonebreakers. The property that allows this steel to handle wear as good as it does is its extreme work hardening, investigated in detail in paper VI [8], which is caused by twinning in the microstructure [9]. Some rail network operators do not allow austenitic steels in their railway systems since it allows ultrasonic waves to penetrate much more easily than other steels. Therefore, cracks might be overlooked when routine ultrasonic testing of rails is performed. Austenitic steel is non-magnetic, which is why it is sometimes used for the hulls of navy minesweeper vessels.

[1] Named after its discoverer Sir Robert Hadfield, not to confuse with Hatfield, Hertfordshire, UK, which is the site of the tragic train accident of 2000.

2.4 Bainitic steels

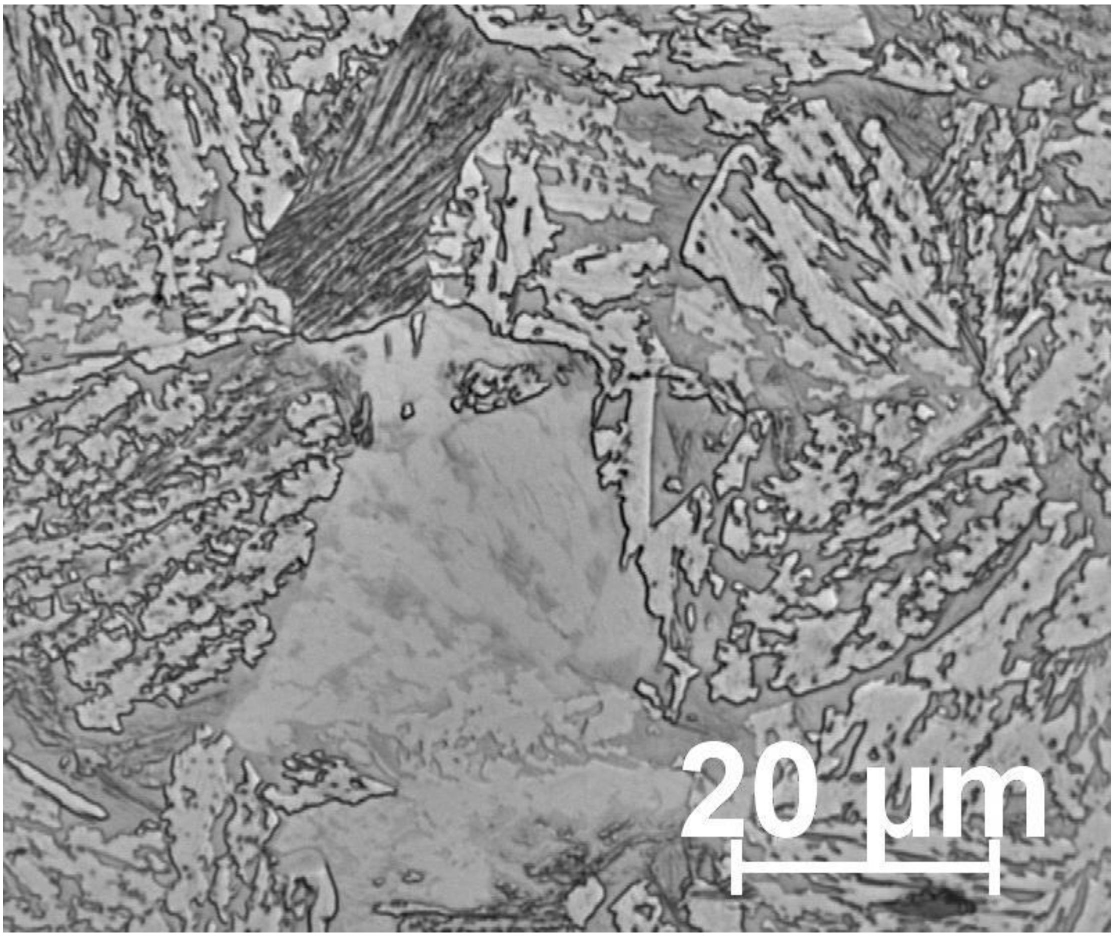

Figure 3 Microstructure of bainitic rail steel.

Bainitic steel is low alloyed steel that is produced when a slow cooling rate is forced upon steel cooling down from above 730°C. Bainite can be obtained in a variety of qualities depending on the exact cooling rate. The bainite used for railway rails is usually the carbide free type, which means that the ferrite within the bainite is carbide free, cf. Figure 3. Bainite rail grades are usually harder than the typical pearlitic grades. Hopes were high that bainitic rails could become a premium rail grade that can compete with the highest hardness pearlitic grades [10-12]. Development of bainitic rail grades started decades ago, but so far aspirations have been thwarted time after time. Wear properties of bainitic rail steel has been reported to be better than those of pearlitic steels of comparable hardness [13]. But there are also conflicting results where wear was unpredictable [14]. The problem of bainitic rail steel seems to be that it is hard to predict its performance beforehand [15], which seems to be due to its complicated and inhomogeneous microstructure which can allow cracks to nucleate premature [16]. Nevertheless bainitic steel is still being assessed and developed. The bainitic steel under investigation here (in paper V) is mostly used for switches and crossings.

2.5 Martensitic steels

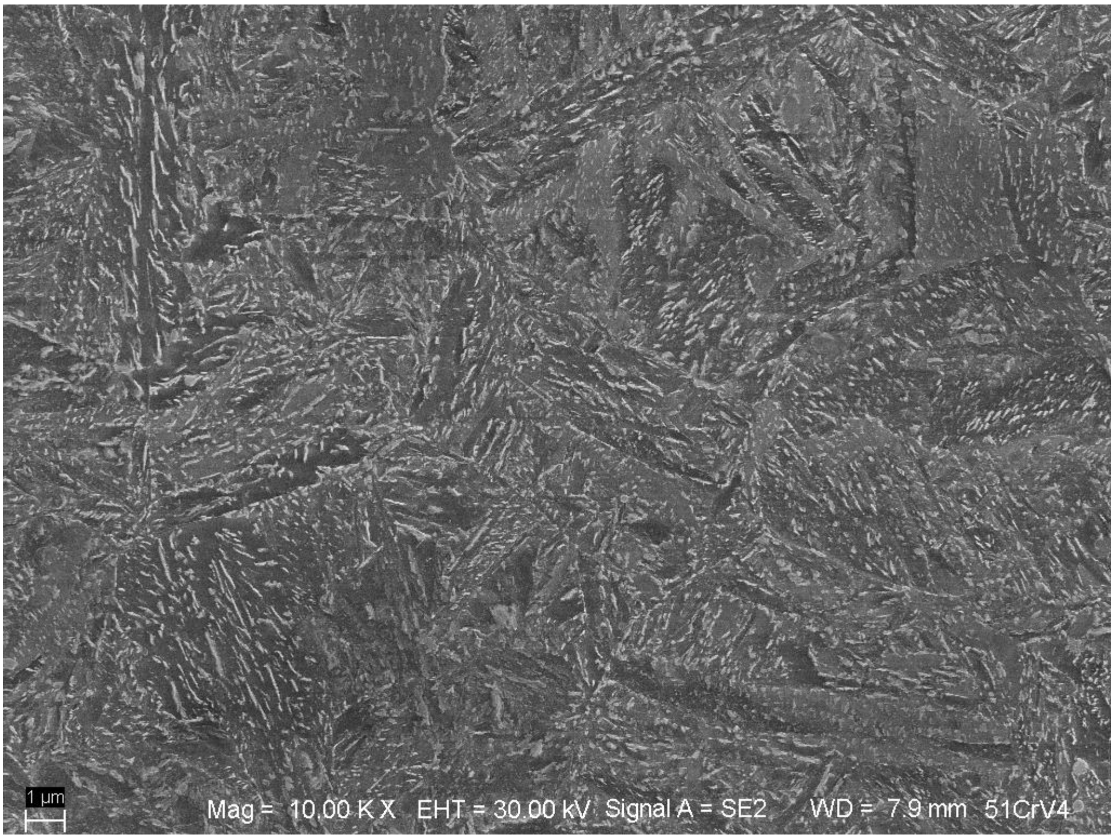

Figure 4 Microstructure of martensitic rail steel.

Martensitic steel is produced when low alloyed austenitic steel is cooled very fast from above 730°C to room temperature. Martensitic microstructure is shown in Figure 4. As explained in the pearlite steel section, the equilibrium reaction to cooling is transformation to ferrite and cementite. During this process, carbon diffuses out of ferrite domains in order to produce cementite. If the cooling rate is too fast to permit this diffusion process, the carbon gets locked into a matrix of iron atoms. This is not an equilibrium state, since the carbon atoms do not really fit into the locations they are locked into. The carbon atoms create tensions which result in a very hard and brittle material. Therefore martensitic steel is in virtually all cases heat treated before usage. This means that the temperature is increased enough to allow some of the carbon to diffuse and form carbides, but not enough to permit phase transformation. The result is steel that is softer than untreated martensitic steel, but harder than most other steels. Martensitic steels are not used to a large extent in railway rails, but they have found a niche as parts of crossings and switches.

2.6 Other Material Solutions

The different regions of a rail cross section are subjected to different types of requirements. The rail head is the part that is subjected to the most difficult loadings. This is where cracks usually start and material is worn off due to the rail wheel contact. Therefore, the material requirements at the rail head are different from the web and the foot of a rail. This kind of differences in requirements could be resolved by using a rail made of two steels. Experiments for doing so started over a hundred years ago. The Bochumer Verein für Gußstahlfabrikation in Germany reported a successful combination of two steels of different hardnesses from cast as early as 1908. By doing that they produced a rail with harder steel in the rail head and softer steel in the web and foot of the rail. A full test report with promising results including track tests was issued in 1933 by the materials testing institute at the Swiss Federal Institute of Technology in Zürich [17]. It then somehow fell into oblivion, perhaps assisted by political events in Europe. In later times, however, attempts have been made to revive the idea of a two steel rail. The latest idea was presented within the European project InfraStar [18, 19]. Instead of casting two steels together, harder steel is applied onto a more ductile one by means of laser cladding. The goal was not only to increase durability of the rail, but also to reduce noise pollution, by decreasing squealing noises. So far material testing and in track testing have been performed with the material, but it has not become a major break-through. There are mainly two reasons for this. One is that the bonding strength between the layer and the rail is not strong enough which can lead to delamination. The second reason is that network operators rely heavily on rail grinding and in the Netherlands, where in track tests were performed, the cladded layer was removed by grinding, when the other rail in the test curve developed corrugation. Also it was difficult to test the rails with laser cladded layers, since the layers had to be applied at a facility and then installed in track instead of being applied by a mobile laser cladding device [20].

	C	Cr	Si	Mn	V	S	P	Cu	Fe
Pearlite R350HT	0.79	0.08	0.44	1.19	<0.005	0.013	0.014	0.018	97.4
Pearlite 900A or B	0.6	0.09	0.25	1.08	0.004	0.031	0.026	0.22	97.56
Bainite B360	0.32	0.55	1.27	1.57	0.007	0.014	0.016	<0.010	96
Austenite Mn13	1.14	0.18	0.36	12.25	0.005	<0.001	0.008	0.047	85.8
Martensite SAE6150	0.51	1.1	0.23	0.9					97

Table 1 Chemical composition of the rail steels presented. Numbers are in weight percent.

3 Damages on rails

Railway rails are exposed to a wide range of loading situations, from light to heavy vehicles and low to very high velocities as well as arctic to tropic environments. Therefore, the possible damages and deterioration effects that can affect them are endless. The most important effects in Europe are cracks produced by rolling contact fatigue as well as simple plain wear of the rail.

3.1 The rail-wheel contact

The vast majority of all rail damages are initiated and advanced by the rail-wheel contact. Crack initiation is preceded by plastic deformation of the patch of the rail that is in contact with the wheel. The strains in the material at and close to the rail-wheel contact exceed the elastic limit. There are normal loads caused by the axle loads and shear loads caused by traction, braking or flange contact. The normal loads cause slight to medium work hardening which, depending on the rail grade, can reach as deep as several millimeter. The shear loads cause severe deformation of the microstructure down to a depth of around 50 µm. The deformation caused by shear loads does not reach as deep as the normal load caused deformation [21], but the shear load deformation leads to much higher strains in the material. The rail steel becomes heavily plastically deformed and the microstructure becomes aligned in the shear strain direction, cf. Figure 5. Large amounts of material can be moved which can lead to the phenomenon of tongue lipping. This means that material on the flank of a rail flows downwards along the flank, where the flange contact of the wheel is most severe, to end up at a point just under the flange contact, creating a bulge of the rail profile that actually exceeds the original cross section of the rail, seen in Figure 6.

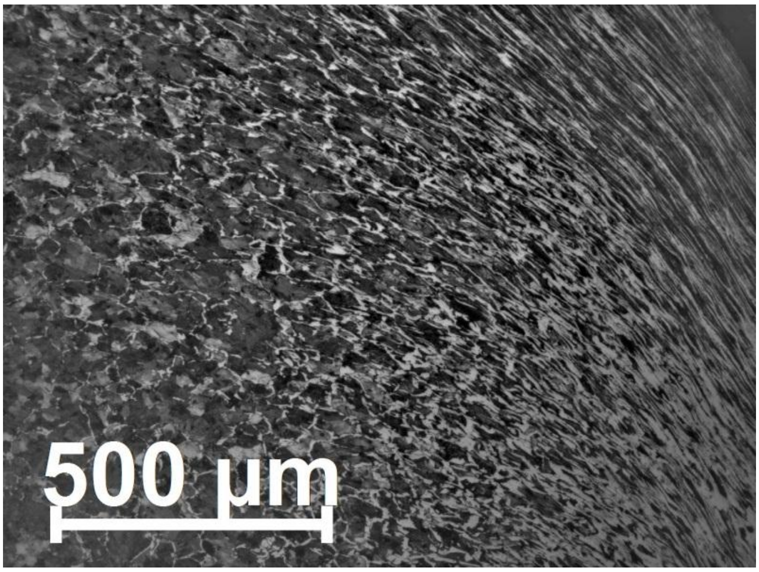

Figure 5 Deformation of the rail microstructure from the surface (top right corner) to the bulk (lower left corner).

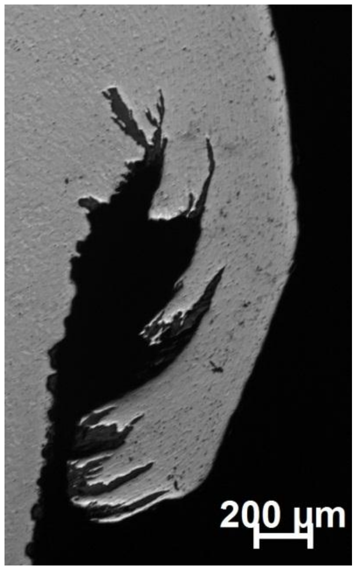

Figure 6 Effect of wear on the rail profile, dashed line indicates the original geometry (left). Close up of the material overflow of the tongue lipping (right).

3.2 Rolling contact fatigue

The shortest description of rolling contact fatigue (RCF) is that cracks are initiated and subsequently advanced by the repeated passing of a rolling contact. By looking closer it becomes more complicated [22]. Cracks are initiated differently, which means with different angles relative to the surface and different orientations relative to the rolling direction, on different locations of the rail. Also, there are different mechanisms for crack initiation. Exhaustion of plasticity is probably the most common initiation reason for large clusters of cracks. Inclusions in the rail or damages on the rail, like indentations from gravel can also serve as initiation points. Also the number of cracks initiated differs, depending on the material and the loading situation. Harder material usually allows for more cracks to be initiated and therefore show closer crack spacing [23, 24]. The initiated cracks then grow into the rail at angles depending on the loading and on the plastic deformation of the material which the cracks tend to follow [25]. These cracks can lead to rail break if they develop into deep cracks. Cracks have also been reported to grow back to the surface, creating loss of small pieces of material so called spalling. Problems with RCF increased in the second half of the 19^{th} century because of, among other reasons, harder rail steels, which wear slower. Initiated cracks are not as likely to be worn away as for softer rails [26]. RCF can be decreased by preventive grinding [27, 28], or by applying friction modifier [24, 29, 30].

3.3 Wear

Wear is in principle the loss of material due to grinding between the rail and the wheel. Figure 6 shows the cross section of a rail that has been in service for around 35 years on a 20 MGT/year track and the material loss caused by the passing wheels. Loss of material can be accelerated by flaking or spalling. Wear can be decreased by either increasing the hardness of the rail steel [25] or by decreasing the friction between the rail and the wheel by applying of a friction modifier [29-31]. Also regularly reversing the rolling direction would decrease wear [32], even though that would probably be difficult to execute on modern railway networks. The main problem with softer rail steels is that rails are worn down faster. Therefore harder rails were introduced, moving the major problem from being wear to being rolling contact fatigue instead.

3.4 White etching layers, squats and other damages

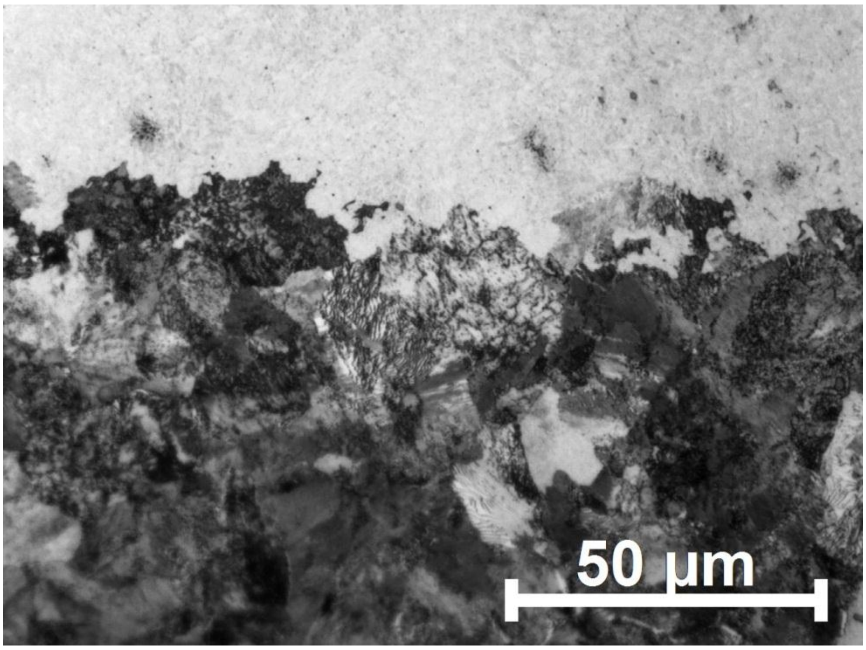

Figure 7 White etching layer, unaffected by etching (top 1/3 of the picture) and clearly etched pearlitic base structure (lower 2/3 of the picture).

Besides from the two big problems, i.e. wear and fatigue, there are numerous problems that do occur, albeit they imply a lot less severe problems. One problem that can occur is the so called white etching layer (WEL) which was studied in paper IV. When metallic pieces are ground and polished, they receive a mirror-like surface. In order to make the microstructure visible, that surface has to be etched. A corrosive blend is applied to the surface for some time and then washed away. The disposition of the constituents in a microstructure to corrode is normally different. A topography is produced, which in a light optical microscope produces an image of the microstructure. If one of the constituents is much more resistant to etching than the others, it will remain mirror like while the other constituents are already heavily etched. If this resistant constituent has a considerable area, it will appear white in the light optical microscope, therefore the name, white etching layer, cf. Figure 7. Denomination layer is due to the fact that it appears on surfaces that are heavily worked and that they usually are broad rather than thick. Another feature that almost all WELs have in common is that they are much harder than the original microstructure. On railway rails and in other applications these layers have been known for a very long time [33]. However, what phase they are and how they are produced is disputed. That is probably due to the fact that WELs are different and can be produced in different ways and constitute different microstructures with only one thing for sure in common, their white appearance in the microscope after etching. There are two principal ways reported in literature to produce a WEL. One way is that friction through accelerating and braking raises the temperature enough to transform the steel to austenite and subsequently cooled fast enough to result in martensite [34]. The other possibility is that repeated contact breaks down the microstructure [35-38] to a level where the grains are so small that the surface topography cannot be resolved in an optical microscope, because the wave length of light is too long. In that case it does not really matter whether or not it is etched or not. In reality, it is likely that WELs are produced by a combination of both effects, both high temperature and mechanical crushing of the microstructure. There are also studies that conclude that the WEL on a rail most likely is martensite even though the temperature for its creation was not high enough [39]. However, martensite and retained austenite have been proven to be present by X-ray techniques [34, 40-43].

Once the WEL is produced it constitutes a hard and brittle layer on top of the running surface of the rail. Because of the higher hardness and higher resistance to wear and corrosion, hopes were that WEL could be beneficial [33]. The problem however, is cracks that are initiated in the WEL which go straight down into the rail [44]. Most of those cracks end at the interface between the WEL and the base material of the rail. Some of the cracks however are connected to cracks that run perpendicular to the surface and can lead to breaking out of pieces of WEL. It is not possible to say which crack came first, the crack under the WEL or the crack through the WEL. At the edge of a WEL, cracks can be found which extend themselves parallel to the white etching layer. These cracks can lead to crack growth into the bulk material or to delamination of parts of the WEL [34]. Both of these effects are undesirable.

Squats are defects visible on the surface of the rail. They are roundish to oval in shape and usually the running surface has a deepening at the squat. There are many opinions on squats. Where they appear and how they are initiated as well as how to classify them is all disputed. It has been written that squats appear on straight track [45]. However, Figure 8 shows a squat on a 300 m radius curve. Squats can occur as singles or in groups.

Figure 8 Squat on the surface of a rail (Scale is in millimeters).

Corrugation of rails is an undesirable phenomenon that occurs predominantly in curves and was studied in paper III. By different effects, regular waviness of the rail running surface is introduced which can have longer or shorter wavelength and larger or smaller amplitudes, cf. Figure 9. One of the causes for corrugation is that boogies have to negotiate through too tight curve radii, which leads to one wheel set of the boogie sliding through the curve rather than rolling. This causes material flow perpendicular to the rolling direction. The result of corrugation is vibrations upon wheel passage, which can damage the rolling stock and further damage the track. Also, there can be considerable noise pollution which can disturb people living nearby [46].

The list of problems that can occur is endless and some problems can be very local. Corrosion of rails is a problem in India [47] but not in Europe, with the exception of very corrosive environments like the Öresund bridge connecting Sweden and Denmark, where salt water constitutes a corrosive environment.

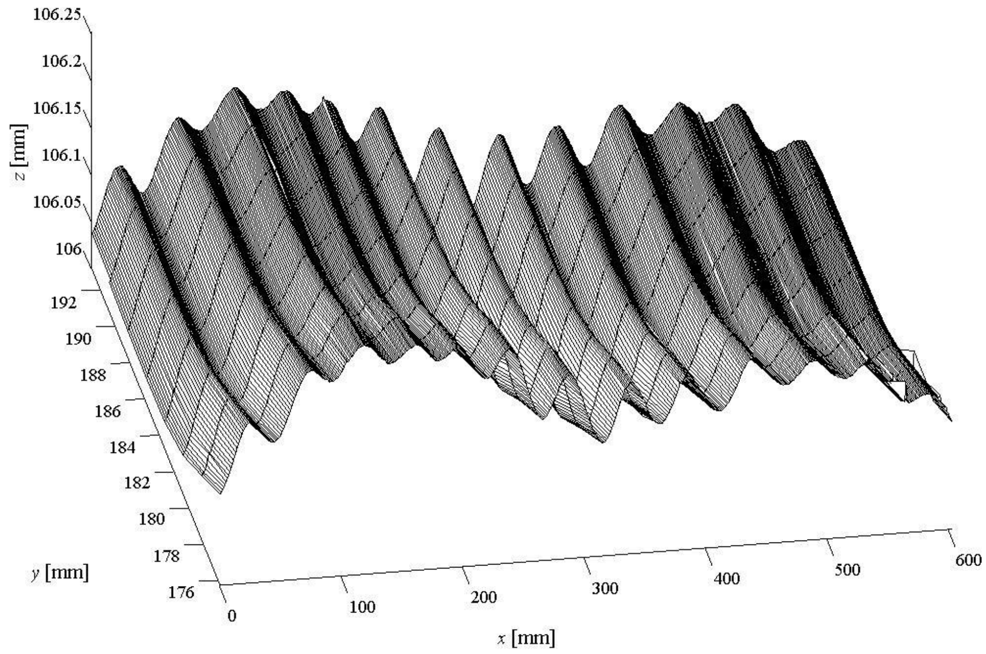

Figure 9 Corrugation pattern on the rolling surface of a tight curve.

3.5 Singular events

In order to understand and prevent damages, they are classified into categories depending on types, revereness and other features that will help understanding. Since rails are in an uncontrolled outside environment, there is always the possibility that events occur that cannot be explained in retrospect. From children placing coins on rails in order to have them flattened by a passing tram or train to the unlikely yet not impossible event of a small meteor hitting a rail surface and initiating a defect, there are endless possibilities that can occur, some of them so unlikely that they cannot even be imagined. It is not worthwhile to try and track down the source of every damage found, but instead the goal should be to understand general mechanism of the phenomena responsible for the large majority of defects and prevent them in future.

3.6 The influence of maintenance and development in rolling stock

Most of the European rail network is directly or indirectly state-owned. While large resources were spent on maintenance historically, the economization and rationalization that swept through private companies in the new economy of the 1980's eventually reached the railroads. According to people at the Swedish transport administration (Trafikverket), people working at maintenance contractors and people working in academia, the consequence is a maintenance organization that has been subjected to economization which has sometimes been beyond reason. It is common for maintenance to be assigned to contractors. In Sweden, however, these contracts are problematic in two ways.

They are only short term. As a consequence contractors do not have an incentive to fix problems that are visible and easily fixed if the consequences are not likely to occur during their current contract time. Damages will grow and become more expensive to repair later maybe entailing additional costs due to temporary track closing. Second, the contracts are usually for function, which means that only damages are repaired and no concern is given to preventive maintenance. This not only increases the total cost for maintenance, which eventually has to be paid by the train operators and in last consequence their customers alternatively the tax payers, it also diminishes the total life of the tracks.

Desire to travel faster and development in the rolling stock led to introduction of higher velocity trains, called X2, in Sweden about 20 years ago. The X2 was designed to travel on the existing rail network in Sweden with a velocity of 200 km/h while the maximum velocity for most tracks in Sweden used to be 130 km/h (160 km/h for some lines from the mid 1980's). As a consequence, the track was worn much faster and more damages were reported as a consequence of cant deficiency and subsequent flange contact and higher dynamic loads in general. In order to manage these velocities an active tilting technology and softer bogies to enhance passenger comfort were installed on the X2. Compared to bullet trains in France and Germany, these X2 trains have poor travel comfort, even though velocities are much lower, due to the poor condition of the Swedish railway tracks. Another development that has taken place in the rolling stock is the increase of power output on driven axles. This increases the shear forces and has increased the occurrence of surface related problems like white etching layers and squats, especially but not only on metro lines where fast accelerating and braking are the keys to a fast transportation system.

4 Discussion

The choice of rail grade is of major importance for the endurance of a rail. There are several factors to be weighted in when choosing rail grade. Most important to network operators is the price, not only the purchasing price but the whole life cycle cost, including repair and maintenance. Investing in a new rail grade, which has been on the market only a few years, when life expectancy is in the range of decades is difficult. It might therefore be the sensible decision to install well known grades of apparent lower quality but with well-known behaviour. This chapter will deal with a few effects that rail grade has on damage initiation and development which was studied in paper I.

4.1 Plastic deformation and its consequences

A structure that is loaded will deform. If it is loaded to a degree which does not excess the elastic limit of the material, it will return to its original shape upon unloading. If the load exceeds the elastic limit, permanent, so-called plastic deformation will remain even after unloading. Plastic deformation affects the properties of steel in various ways [48]. Most relevant for the railway application is that the hardness and brittleness increase which affects the resistance to crack growth. A plastically deformed layer will be formed where the rail comes into contact with the wheels [49, 50], that is at the running surface. It can also happen on the flank, if the wheel flange comes in contact with the rail, which mostly happens in curves. The increase of hardness due to plastic deformation is normally not more than 50% as compared to the original hardness. Special steels like the austenitic manganese steel can harden considerably more [8]. This hardening is beneficial for the load bearing capacity of the rail [51]. There are two types of loads responsible for the formation of the plastically deformed layer, depending on which, the plastically deformed layer will look different. If the load is only in the normal direction, that is only the weight together with dynamic forces of the axle acting vertically on the rail, then the plastically deformed layer will be thicker, but with a smaller hardness gradient [52]. This takes place everywhere on top of the rail where no exception of gravity makes rolling stock lose its mass acceleration. The other load that produces a plastically deformed layer is shear loads. Shear loads cause plastically deformed layers that are thinner with a much higher hardness gradient. Also it can lead to extensive material flow and lead to tongue lipping [52]. Shear loads arise when traction is applied to wheels, or when wheel flanges come in contact with rail flanks, for instance when a vehicle with too stiff boogies negotiates through a curve [53].

On the atomic scale, steel consists of grains of highly organized patterns of atoms. The orientation of these crystal structures is random. Since the grains are many and small, normally in the range of tens of micrometers, on a global scale, steel is isotropic [54]. This means that the properties are the same in every direction[1]. Once the rail steel is loaded and plastically deformed, it ceases to be isotropic. Since load is applied repeatedly in the same or at least in similar directions, the plastic deformation follows this direction. Now the top plastically deformed layer of the rail is anisotropic and has different resistance to crack growth in different directions. While it is difficult to determine in detail exactly how the anisotropy changes the properties like crack resistance in all directions, it is fairly easy to determine the range of the plastically deformed layer by hardness measurements. Figure 10 shows the cross section hardness contour of a R350HT rail grade tested in a full scale test rig at the facility of voestalpine Schienen GmbH. The test conditions were 10^5 cycles with 23 t vertical and 4 t horizontal load. As a comparison, Figure 11 shows the cross section hardness contour of a 900A or 900B[2] grade rail, which was produced at Domnarvet in 1977, and which was in service in southern Sweden for 35 years with a yearly traffic of round about 20 MGT. The plastically deformed layer is much thicker for the softer rail grade which is an effect that is known from literature [55]. The hardness figures only show the extension of the change in the material properties. How they are changed in detail must be determined by other methods. Understanding of these changes has been called the missing link to fully understand the degradation process [56]. While investigating the plastically deformed layers, one must keep in mind however, that the rail grade is only one component that determines the thickness of the deformed layer, the other is the loading magnitude and geometry. Higher normal loads cause thicker deformed layers. If the loads are applied in a shearing manner however, the result is usually more material flow and more deformed microstructure close to the surface (~50 µm). In the present case, cf. Figure 10 and Figure 11, the contact point for the softer rail was further up on the rail head, leading to higher normal forces and less shear forces as compared to the harder grade rail. Since there was only one contact point for the harder grade rail, and the normal loads must be present, it can be concluded that the deformation does not reach as deep in the harder grade rail.

[1] The perfect example of an anisotropic material is wood. Try to cleave wood perpendicular to the direction of its fibers as compared to parallel to it and you will understand anisotropy.

[2] Unfortunately there are no records to be found about the rail grade, but the composition suggests that it is either 900A or 900B.

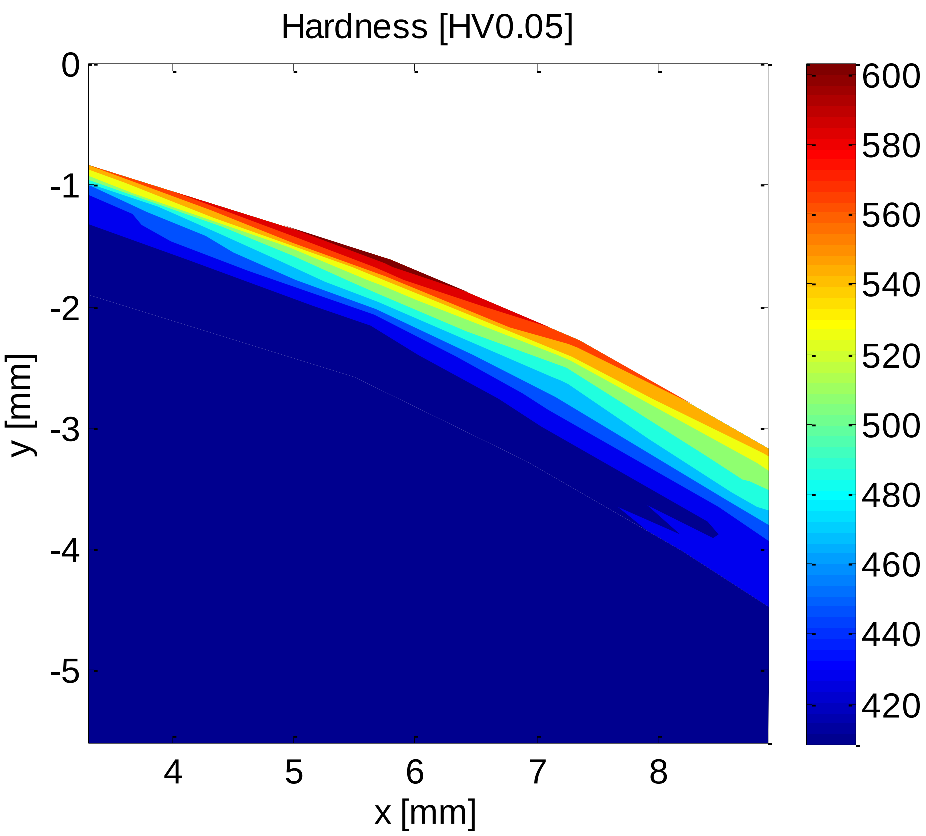

Figure 10 Hardness contour at the contact point of a R350HT rail that was tested in a full scale test rig.

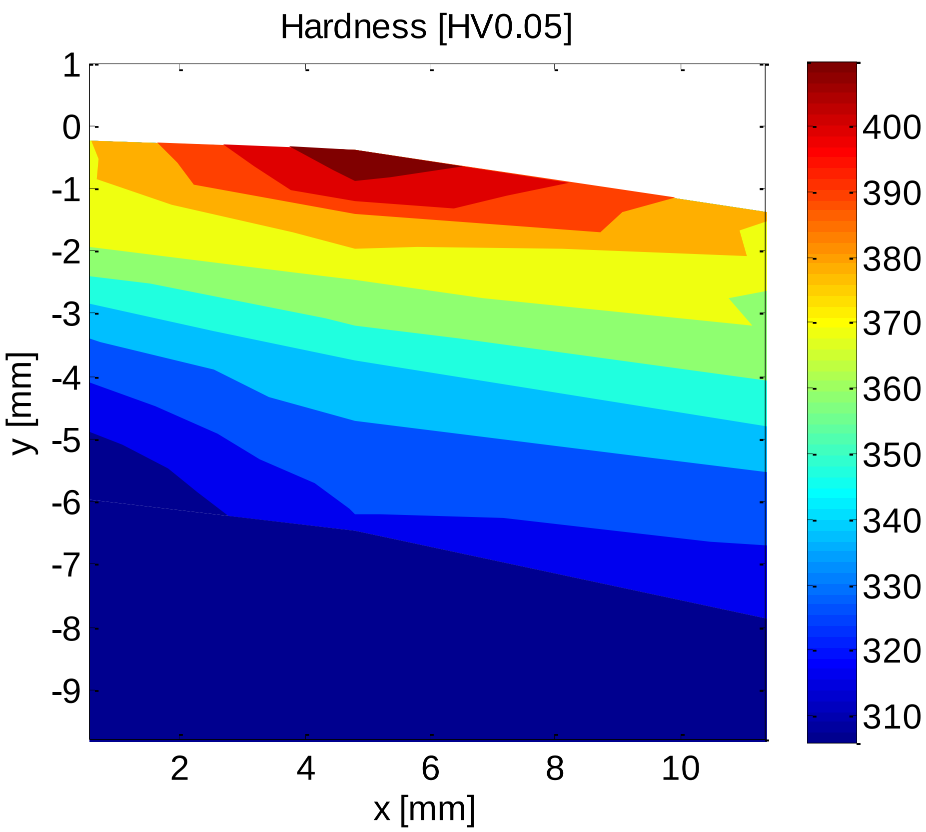

Figure 11 Hardness contour plot of a contact point of a 900A or 900B rail that was in service in Sweden for 35 years.

4.2 Crack shape and plastic deformation – some real examples

This section is divided into two parts, one with focus on the cracks in relation to the plastic deformation in two dimensions and the other with focus on crack shapes in three dimensions. It would be desirable to describe all these effects in three dimensions. However, since it is very difficult to extract the direction of the plastic flow in three dimensions out of two-dimensional pictures that is not done here. Also it would be very difficult to include all that information in two-dimensional pictures.

4.2.1 Cracks and plastic deformation in two dimensions

Depending on the rail grade and loading situation a crack will have a certain shape. Two examples of cracks are shown here. The first is a crack in a 900A or 900B material. The microstructure is mostly pearlitic with some pro-eutectoid ferrites. Undeformed microstructure taken from the core of the rail head is shown in Figure 12. The pro-eutectoid ferrites can be seen as straight white lines. When the rail is loaded and deformed, these ferrites become distorted and aligned towards the strain direction, cf. Figure 13. Cracks preferably follow these ferrites, which are weaker than the pearlite part of the microstructure [49, 57], hence the wavy path of the crack. What can be noted about this crack is that its opening does not have a radius, rather it goes straight into the rail head, cf. Figure 14. This crack is initiated almost at the top of the rail, where normal forces are dominant. Therefore the shear plastic deformation is not as severe as it would be on a rail flank. The plastically deformed layer is thick and the hardness gradient is mild. The direction of the plastic deformation can be seen on ferrites, which are the softest part of the rail microstructure, cf. Figure 13. Because of the distribution of the ferrites in the pearlite which the crack follows, there are a lot of asperities in the crack surface. The longest extension of the crack into the rail head is about 10 mm. Since it has an angle to the surface rather than being perpendicular to it, the crack is still well within the plastically deformed layer. As long as the crack is in this plastic zone, its path will be guided by it. If there are slags that are weak points in the microstructure, like the ones shown in Figure 15, then a crack can change direction or branch into several cracks.

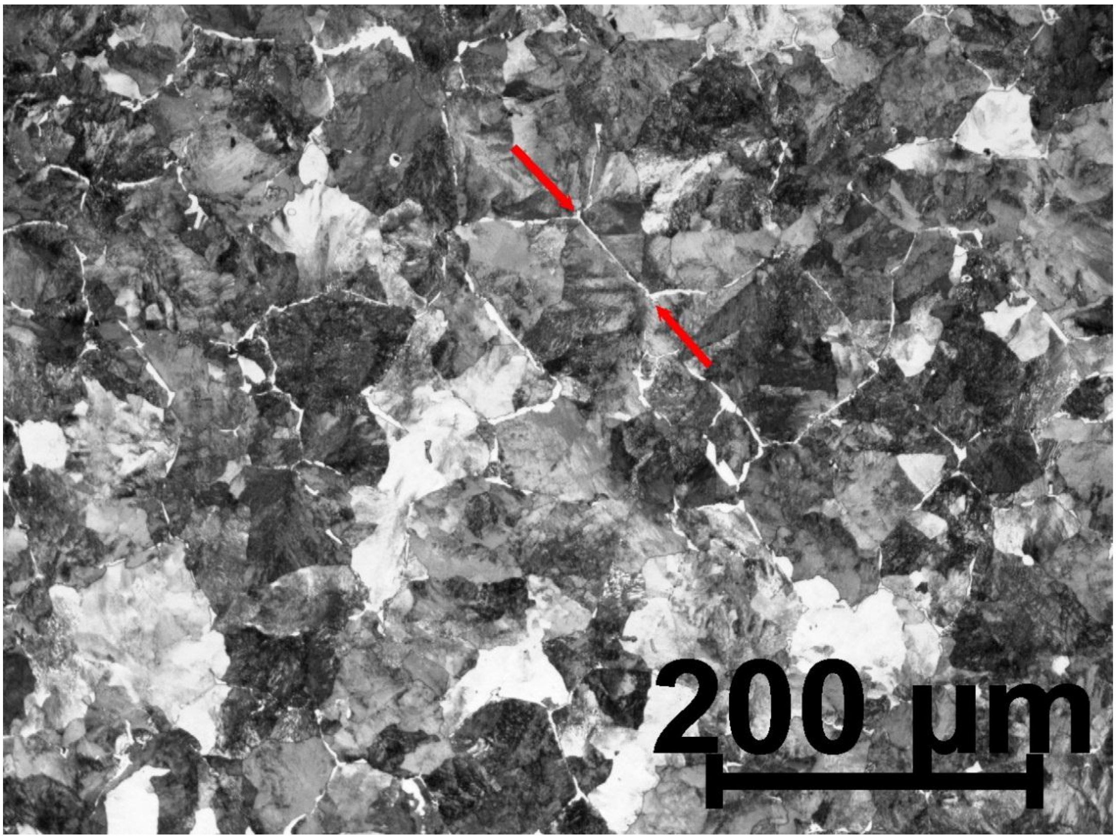

Figure 12 Undeformed microstructure of a 900A or 900B rail. White lines like the one indicated by the arrows are pro-eutectoid ferrites.

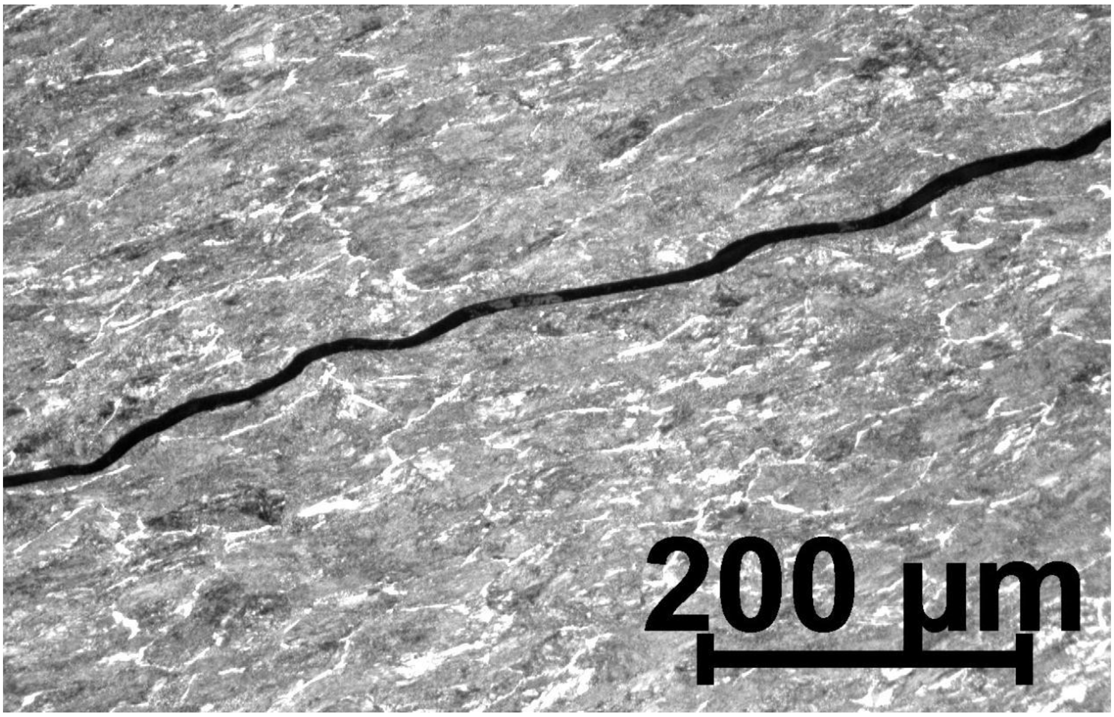

Figure 13 Deformed microstructure of 900A/B material with deformed pro-eutectoid ferrites and a rolling contact fatigue crack.

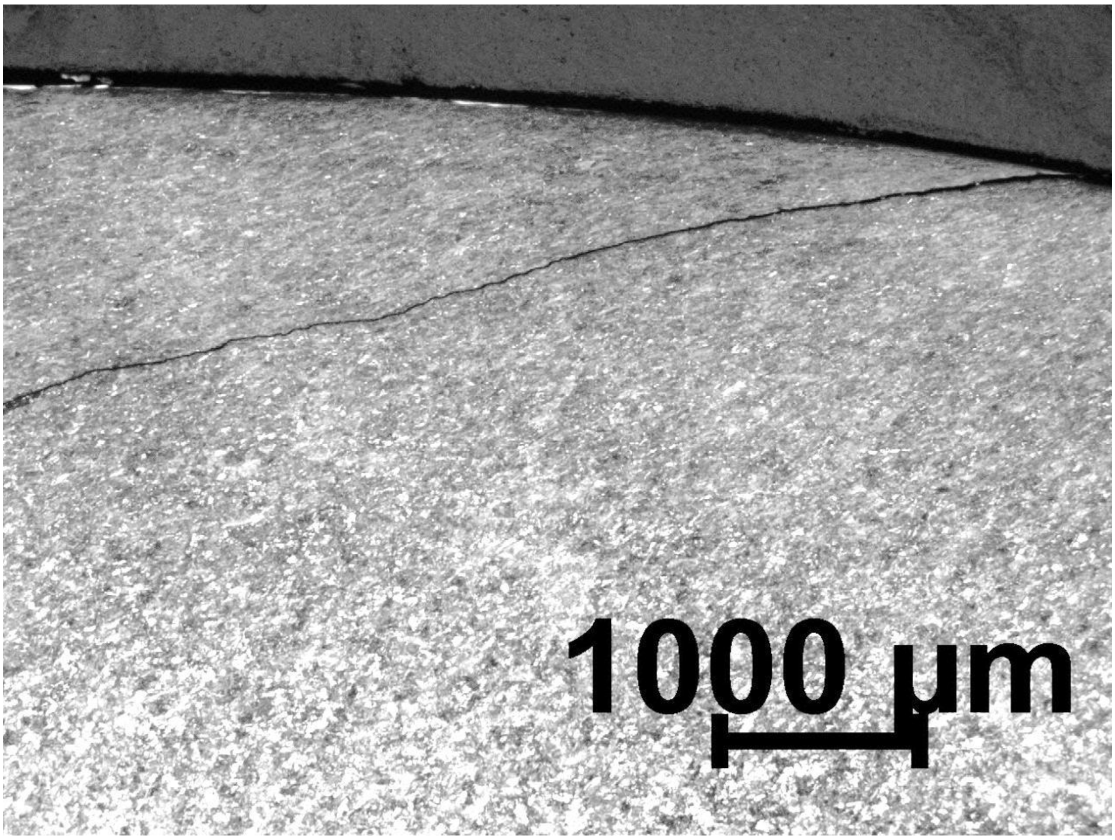

Figure 14 Crack path in the 900A/B rail.

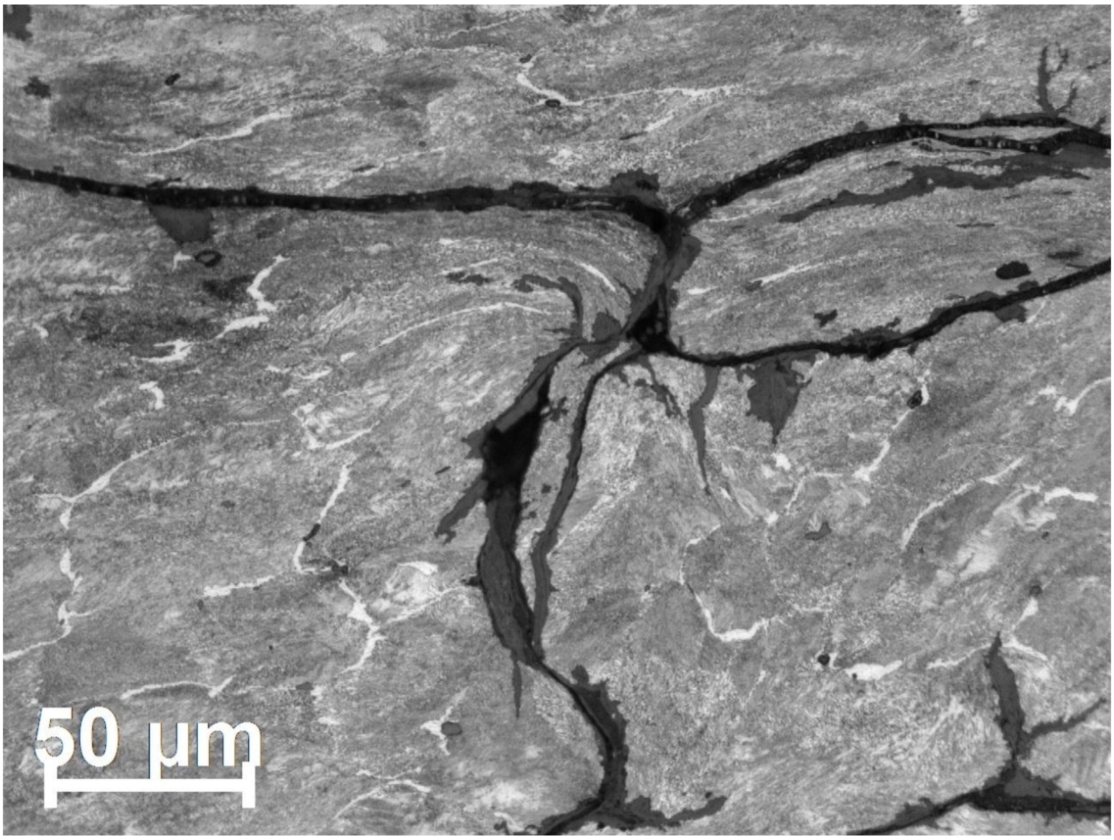

Figure 15 Cracks through Slags in the 900A/B rail.

The second example of cracks is taken from a rail that was tested in a full scale test rig at voestalpins Schienen GmbH. It was subjected to 100,000 wheel passes with 23 t vertical and 4 t horizontal load. The rail grade is R350HT, which is a head hardened, fully pearlitic grade. There are cracks that have a radius at the opening, subsequently they change direction and go into the rail in an almost normal direction to the surface, cf. Figure 16. That radius is due to the direction of the plastic deformation close to the surface which is very thin where these cracks appear. Cracks that grow in an area where the plastic deformation is thicker have a more continuous roundness, cf. Figure 17. The absolute depth of the cracks in this R350HT test rig tested sample is less than the cracks in the 900A/B sample taken out of the field described above. However, the cracks length relative to the plastically deformed layer is deeper. In this case, only the cracks in the lower end of the plastically deformed layer grow into un-deformed microstructure. There are also cases reported from literature where cracks have outgrown the plastically deformed layer and connected to neighboring cracks with break out of material as a consequence [58].

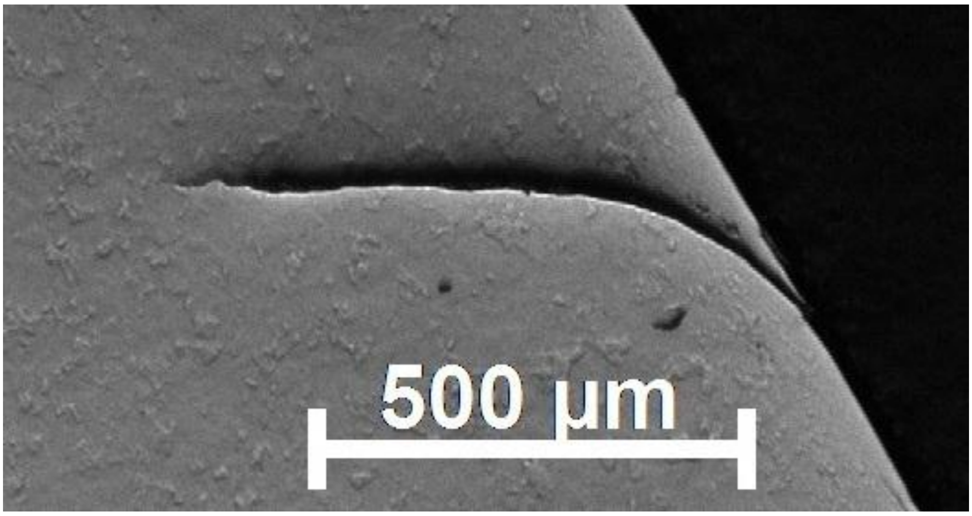

Figure 16 Crack shape in an area with thin plastically deformed layer.

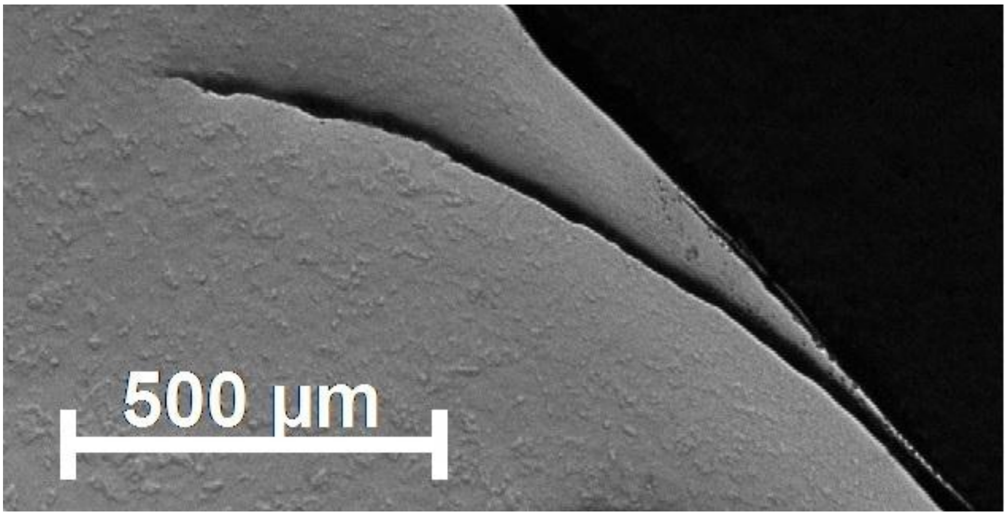

Figure 17 Crack shape for a crack confined to the plastically deformed layer.

4.2.2 Crack shapes in three dimensions

In addition to the two examples of cracks shown in the previous section, here also the crack shape of a crack taken from the corrugated rail sample investigated in paper I and paper III is shown. The crack shapes were determined as described in paper I [52].

The crack shape of a crack in the 900A/B rail grade is shown in Figure 18. The crack shape resembles a half penny shape and the surface of it is somewhat wavy. The crack, however, is still in the plastically deformed layer and its direction follows the direction of the deformed microstructure and the pro-eutectoid ferrites. Branches at the lower end of the crack can be explained by a slag field in that part of the rail, cf. Figure 15. Slags like those are very uncommon in newly produced rails [3]. It is impossible to tell whether the crack started in the slag field, or if it grew into it.

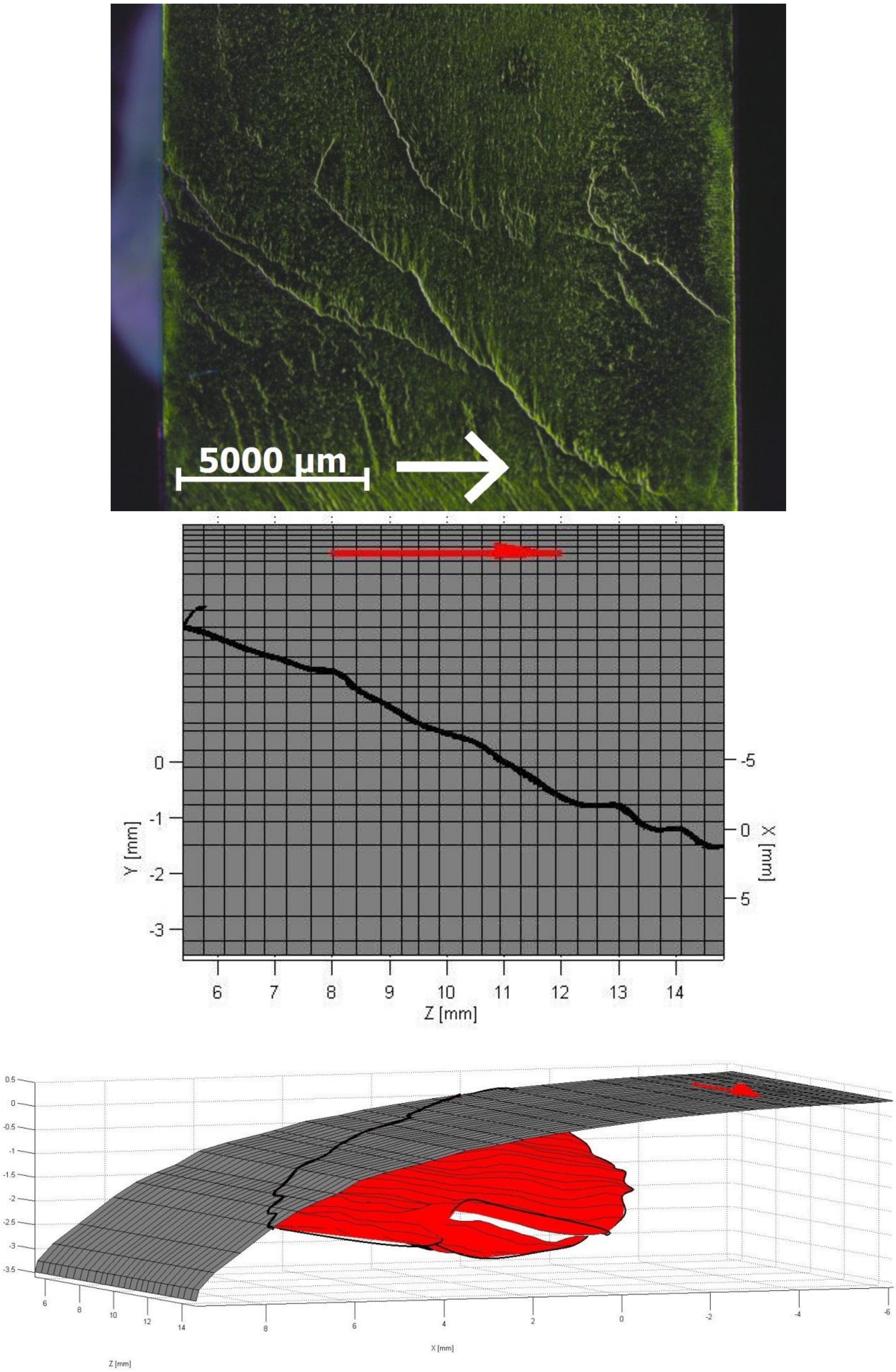

Figure 18 Cracks on the surface of the 900A/B sample made visible by magnetic particles (upper figure), digitalized on the surface (middle) and under the surface (lower figure). Arrows indicate rolling direction.

Figure 19 shows three cracks in the sample taken from a rail tested in a full-scale rail-wheel test rig. Two of the cracks also have branches. Since the test rig only employs one wheel that is rolled over the same rail repeatedly, it can be assumed, that the contact is as uniform over time as can be. The cracks are initiated and advanced under the influence of the same, or very similar loading, with only the plastically deformed layer being formed and some wear taking place. If only the loading was responsible for the crack shape, then the cracks would all have the same shape. The blue crack in Figure 19 is fairly straight on the surface and has an inclination of round about 45°. This orientation is likely to be due to the loading situation, and if there was no influence of the material, all cracks would look like this. The other two cracks however are not straight, or rather, they have branches which deviate from the 45° inclination. The problem with the branches is that it is difficult to establish which part of the crack grew first. Looking under the surface, there are some hints. For the green crack there is a visible dent in the crack going in the main direction close to one of the branching points, cf. Figure 20. This suggests that the branching came first and then the crack also continued in the main direction, but not to the same depth, since the already existing crack branch shielded the main crack. The reason why cracks deviate from the main direction is most likely that there are weaknesses in the material which allow a crack to grow in another direction than the most favored one if only looking at the loading and plastic deformation. The plastically deformed layer and the loading, however, still drive the crack in the main direction, hence it branches. Looking under the surface again, it can be seen, that the blue crack does not reach the same depth as the other two cracks at the lower quarter of the blue crack. This is an area where the blue crack is close to the red crack. Most likely, the red crack grew first, leaving the growth of the blue crack in a shielded, less loaded area. Shielding has been studied theoretically in two dimensions by Tillberg et al. [59]. Here it can be seen in reality in three dimensions.

Looking at the crack surface, there are few asperities as compared to the crack in the field sample. This is due to the fact that the cracks follow the aligned pearlite lamellae for the fully pearlitic H350HT rail grade rather than skipping from pro-eutectoid ferrite to pro-eutectoid ferrite.

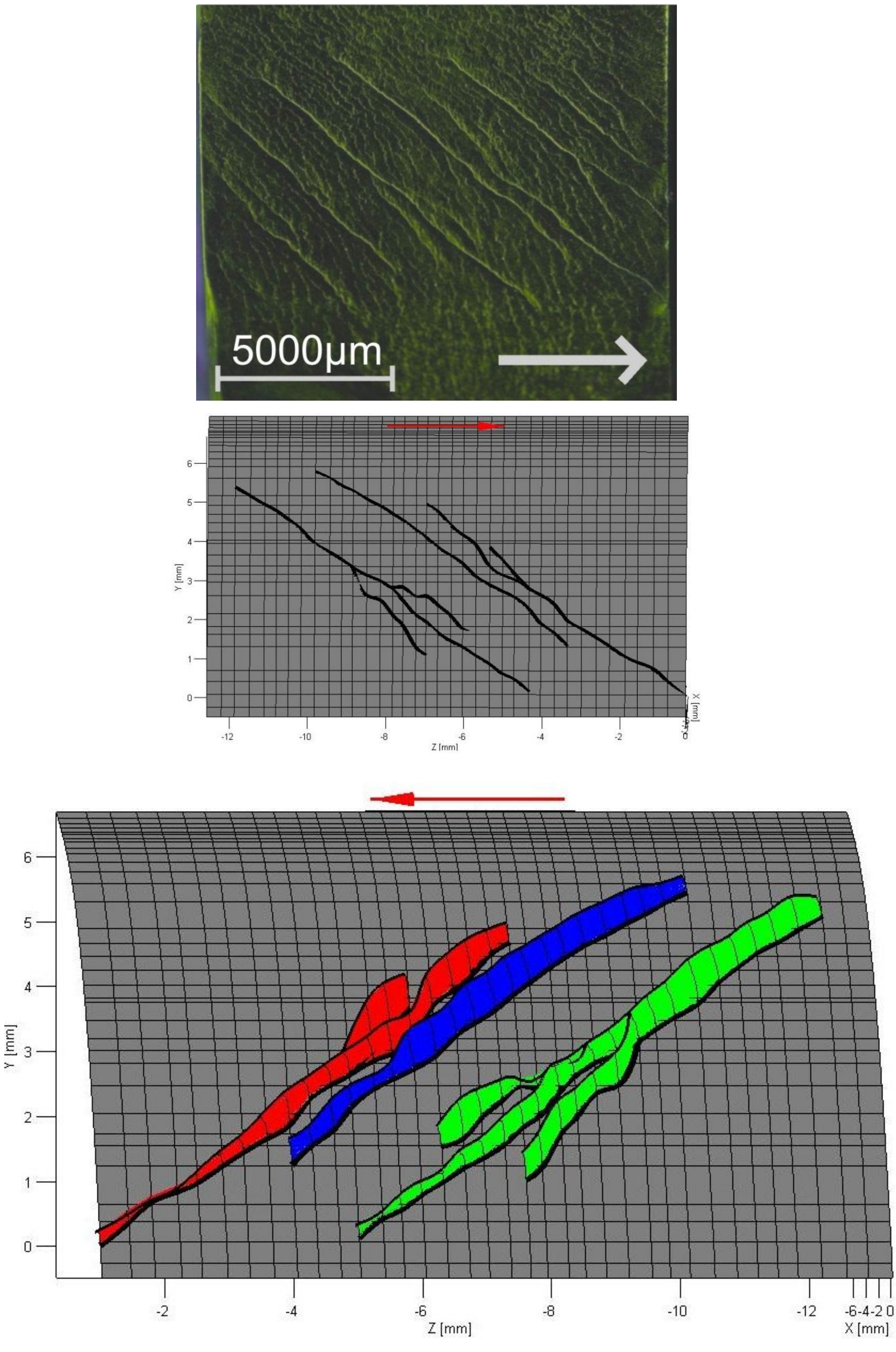

Figure 19 Cracks on the surface of the test rig sample made visible with magnetic particle visualisation (upper figure), digitalized on the surface (middle) and under the surface (lower figure). Arrows indicate rolling direction. Colours in the lowest figure from left to right: red, blue and green.

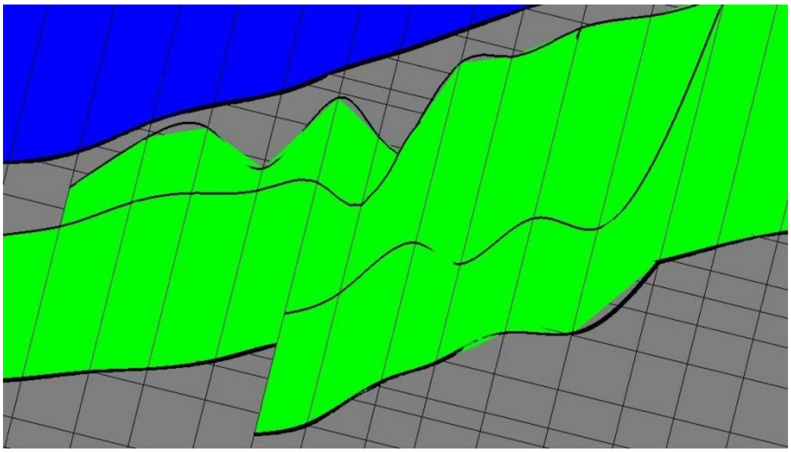

Figure 20 Crack depth variation close to a branching point in the test rig sample.

The last example of cracks is taken from a corrugated rail sample taken from the curve investigated in paper III [60]. This type of crack is different from the other two shown before. It is less deep. Also the crack opening is towards the field side of the rail. This is due to the fact that axles slide rather than roll through this tight curve. Therefore, there is plastic deformation in the direction of the field side. Even though the cracks in this sample look very different from the cracks shown from the field and the test rig sample, they still follow the plastic deformation as the cracks in the other two examples do. These cracks are taken from a rolling surface, where crack patterns with numerous cracks can be seen cf. Figure 21. The cracks however are all very shallow and few of them reach more than 100 μm in depth.

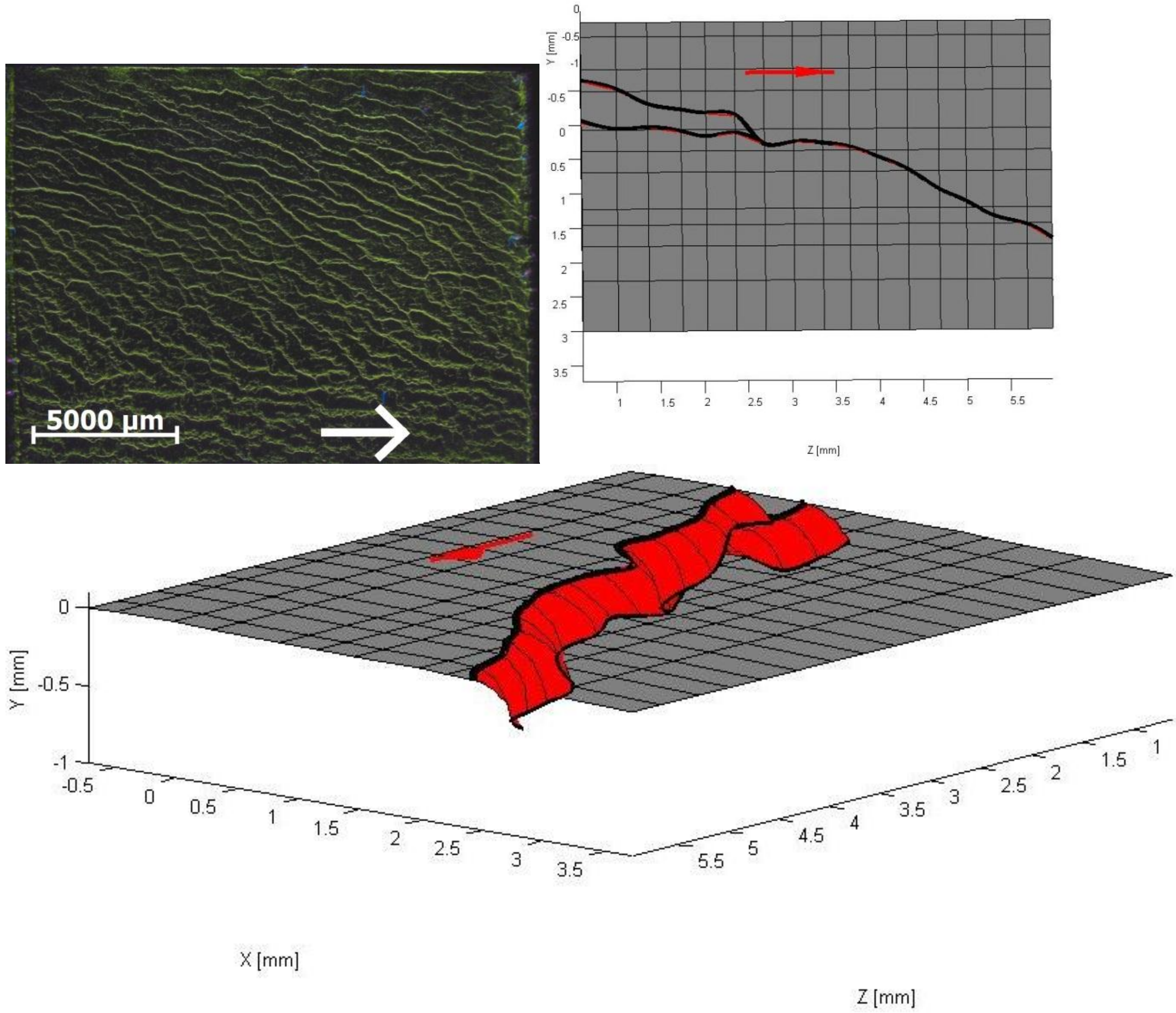

Figure 21 Cracks on the surface of the corrugated sample (upper figure) and under the surface (lower figure). Arrows indicate rolling direction.

4.3 Prediction of rolling contact fatigue

Cracks are the predominant reason for rails to fail. Therefore, detailed understanding and prediction tools would be valuable. There are many models that have been developed in order to predict crack growth during fatigue in metals. The problem with cracks in rolling contact fatigue, and that includes railway rails, is that the conditions are different from most other fatigue situations. In normal push-pull fatigue, crack initiation occurs at the surface and the starting crack has an angle of around 45° relative to the surface, where there is a favourably oriented plane in the crystallographic microstructure [61, 62]. What happens first for fatigue in rails is that the layer close to the surface deforms plastically and becomes aligned in the direction of the shear forces. The top layer of the rail is now anisotropic and has weaknesses that favour crack growth in certain directions. The important part is that different rail steels harden to different magnitudes. This has to be taken into account when modelling the crack growth process. The rail steel in service consists of two regions, one heavily deformed at the running surface, and the virgin material in the centre of the rail head, where no plastic deformation has taken place. In between there is a transition zone. That has to be understood in order to determine which rail steel is to be favoured over the other. How rail steels perform in tests performed on virgin material is far from enough since e.g. their resistance to cracks can have diminished by the plastic deformation. The data from low cycle fatigue tests like the ones performed in paper V [63] can, however, be used to calibrate material models even though some extrapolation has to be done in order to account for the much higher strains occurring in the rail-wheel contact.

A model that successfully predicts rolling contact fatigue, i.e. crack growth in railway rails, will have to include the anisotropy of the material. One way to do this is visualized in Figure 22 (paper II, [64]). A fracture surface is defined for the pearlitic material which predicts the resistance at each material point against propagation of the crack in any hypothetical direction. The intersections of $G_{th,1}$ and $G_{th,2}$ are hypothetical positions for crack tips. The resistance to crack growth is proportional to the distance to the red line. Close to the surface there is a clear preferred direction. The material is anisotropic within the surface layer and there is a favourable orientation for the crack to follow depending on the degree of deformation and anisotropy. Therefore, the fracture surface is tilted in this layer by an angle called as average orientation angle. This angle is represents the orientation with the lowest resistance against crack propagation in the model and is calculated by predicting the average reorientation of the grains in a representative volume element over the microstructure. Figure 22 shows the adapted development for the employed fracture surface over the anisotropic surface layer.

Far from the surface, there is no anisotropy and there is no direction given from the material. Of course there is still the crack growth rate that has to be determined.

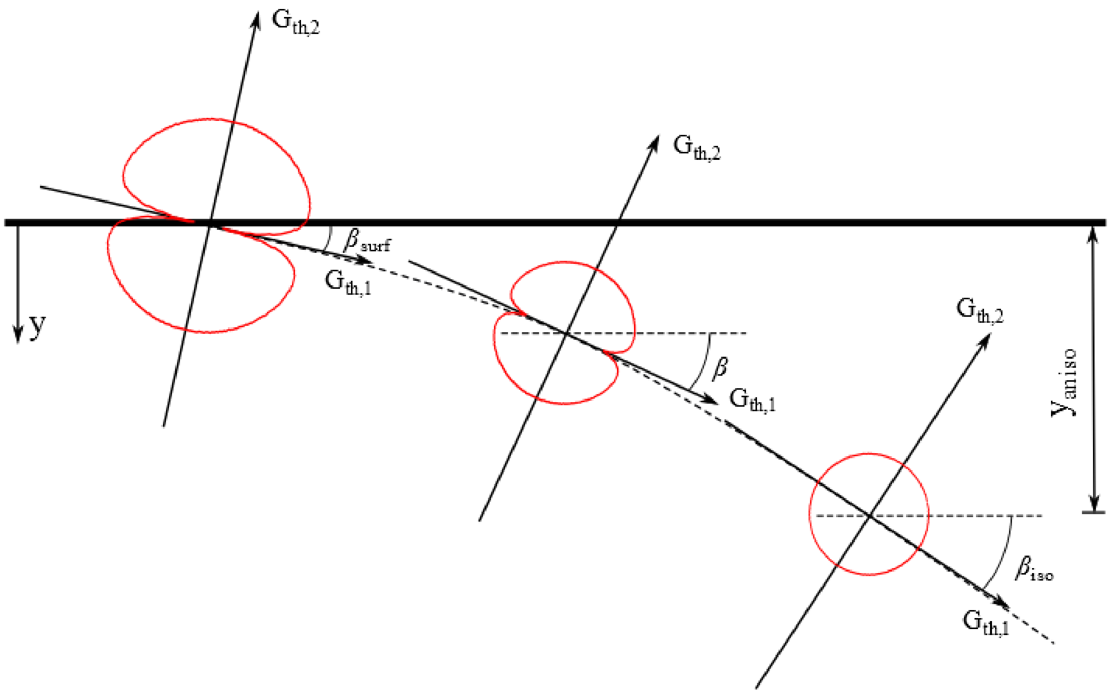

Figure 22 The effect of anisotropy on the direction of crack growth as a function of distance from surface.

4.4 The usefulness of materials testing

In the late 18th and early 19th century, the scholar Thomas Robert Malthus set out to explain the causes of famines in the British colonies. His core finding was that if a population grows too big, the land that it occupies cannot support it with enough food and hence famine spreads. In cases when famines start in one of the colonies, the British government should not take any measures to stop the famine, rather people should starve to death to adjust the demand to the supply. Since Malthus had never been to India, a place for occurring famines at the time, he did not know the real cause for famines. In India at that time many people were day laborers. If there was a slump in the economy then poor people could not afford to buy food. So even though there was food available, people died of starvation. Nevertheless, Malthus theories were translated into how to respond to famines, which was not to respond at all. As a consequence, millions of people died in vain and still today many people believe that the cause for all famines is food shortage [65]. What can be learned from this episode is that in an applied field of research it is imperative to investigate the reality before drawing any conclusions.

It is very difficult to conceive a material testing method for rail steel that imitates the situation in track satisfactorily. There are a few full scale test rigs at different research facilities around the world. In these test rigs, rail steels can be tested and the results from these tests can be applied to reality with some limitations. However, there is the problem with uniformity. It is only one wheel that passes over and over again and the climate is a steady indoor one. Besides the test rigs, there are few tests that yield good results for virgin rail material. The reason is that the altered layer on top of the rail cannot easily be reproduced in a small scale. There is some work being done that can achieve parts of it. A high pressure torsion experiment for creation of deformed pearlite is a good exception. The way to further understanding of rail material degradation must go through a careful examination of rails worn in service. Only after understanding how the material properties in different parts of a worn rail are different as compared to a new one, can one can attempt to make experiments to reproduce those. Otherwise there is no result to compare the experiments to. Once the degraded rail is sufficiently mapped property wise, small scale lab tests can be conceived. Chances are that those are then not necessary any more. The human mind likes familiarity. As a consequence, we prefer to do what we already know [66]. The relevance of doing tests just because we are good at them might not be given. In the same way it can lead to complete irrelevance to try and simulate something if the knowledge of the real thing is not large enough. We have to frequently ask ourselves whether our work is relevant and our assumptions are realistic, otherwise we might end up doing a similar mistake as Malthus.

4.5 Decisive properties for railway rail steels and their determination

The ideal rail would not wear nor crack. Wear can be decreased by increasing the hardness of a rail. At the same time, the crack resistance should be high. Pearlitic rail grades with more pro-eutectoid ferrite have a shorter time to RCF crack initiation [67]. However, since those steels also tend to be softer, many of those initiated cracks might be worn away before they reach any considerable depth. The only way to be sure about how a rail grade will perform in a given track situation is to put it in that track. There are a large number of tests that can be performed, more or less elaborate, time consuming and costly.

Determining the hardness of a rail is one of the cheapest and fastest measurements to make. The correlation between higher hardness and better wear resistance is quite good, with an exception for steels that show considerable work hardening such as the high manganese austenitic steel. Hardness tests can also determine the dimensions of a plastically deformed layer of a used rail but not its direction.

Standard material properties such as tensile and yield strength, fracture toughness, resilience and elongation to rupture are all determined on virgin material. That ensures the comparability of the results. However, since these properties are all changed to larger or lesser extent by the rail-wheel contact, these properties cannot be used to predict how well one type of rail steel will perform compared to any other type of rail steel. That could only be done, if the tests were performed on rail steel that has been in track. Doing that, however, poses the question of comparability of the results since the samples would be taken from different positions in track and hence have different loading histories.

Uni-axial push-pull fatigue tests are fairly simple to conduct. The loading situation, however, is very far from the rail-wheel contact loading in track. Number of cycles to failure for a rail is in the range of high cycle fatigue. However, this is due to the fact that the loading in RCF is compression-shear, while in push-pull tests it is compressive and tensile with the implications that has on crack growth through crack opening. The plastic deformation caused by shear forces in the rail-wheel contact exceeds the plastic deformation seen in low cycle fatigue situations for push-pull. The crack initiation in high cycle fatigue has nothing and the crack initiation in low cycle fatigue has next to nothing in common with crack initiation in rolling contact fatigue. There are few things that can be used from low cycle fatigue tests. One is the crack propagation and the crack sensitivity, in a qualitatively manner [63]. However, there are tests that are specialized for that purpose and are better employed if one wishes to determine these properties. Crack propagation in high cycle fatigue could be compared to crack propagation for cracks in rails that have outgrown the plastically deformed layer. Network operators, however, try to grind cracks away before they reach such a depth and therefore this knowledge seems only modestly relevant.

A test frequently carried out with railway rail and wheel steels is twin disc testing. A disc is produced from rail material and another one from wheel material and then these two discs are run against each other. Twin disc tests were not performed in this project, only studied in literature. Therefore, the knowledge on the author's part is not good enough to give a conclusive assessment. Of all tests presented, it is the one which resembles the field loading situation most (if full-scale test rigs are disregarded). There might be problems arising from the scale effect. Nevertheless there should be valid conclusions that can be drawn from this kind of test.

A promising test is high pressure torsion as done by Wetscher et al. [68]. In these tests, a test piece is compressed and the then twisted under compression. The result is a sheared microstructure that can be studied regarding crack propagation characteristics in relation to the direction of the shear deformation. This is a way of mimicking the plastically deformed layer that is generated in track.

4.6 Which material is best suited as a railway rail steel?

The problem with railway tracks is that there are so many factors that influence the exact loading of the rail. Therefore, it is difficult to find fully comparable lines of track. If there is a problem, e.g. excessive wear in a curve, then one is tempted to look to a similar case that had the same problem and got solved.

Assume the solution was to change to a harder rail grade. That does not mean that the same procedure will be a successful solution for the problem at hand. The traffic might be different, and sure enough the harder rail would wear slower, but instead maybe corrugation would appear. Therefore the question of which material is best suited as rail steel must always be followed up by another question and that is which situation the rail will be facing. As trivial as this sounds, the following will elaborate on the difficulties that have to be faced.

The question which steel is best suited for a railway rail can be answered differently depending on the perspective. The only perspective that is relevant for the network operators however, should be the total cost for one rail grade as compared to another over the whole life cycle of the rail. The following discussion is not claimed to be complete in any way. It is just an attempt to explain the difficulties faced when assessing the suitability of a rail grade.

The factors that determine the life cycle cost of a railway rail are the purchasing cost, the installation cost and the maintenance cost. Maintenance can be divided in emergency repair costs and planned preventive maintenance. Both of these can include costs for temporary track closure. If the planned preventive maintenance is not done properly then the need for emergency repairs are likely to increase. There are a number of other uncertainties which cannot be determined at the time of purchase. The traffic situation will most likely change over the life of a rail, not only in frequency but also in velocity of the rolling stock and geometry of the boogies used. If the track quality is low from a geometrical point of view, more dynamic loads will act on the rolling stock and the track. Some rail grades are more forgiving towards these dynamic loads than others. Many of these factors are not monitored or even considered much in practice. The influence of them is undeniable and the solution to the problems they cause cannot be solved by material science alone. What material science can do is to investigate problems in track and find explanations for their occurrence and find solutions, which do not always have to be a material change.

For a well-known track situation rail can, of course, be improved in a metallurgical way as proposed by Ordonez et al. [69]. However, those findings and improvements cannot automatically be translated to other tracks, where traffic, maintenance, climate and/or other factors are different.

5 Conclusions

The main general conclusion is that material science alone cannot solve the problems that occur on railway tracks. A holistic view must be embraced, considering all effects that play a major role in the degradation of rails. Material science can contribute a great deal in explaining and describing the processes that occur in the microstructure of the rail. The applicability of laboratory tests performed on virgin rail material however, is limited. In order to gain more understanding for the rail degradation in Sweden, more in track data is needed. The development of cheap measuring systems that can be placed on numerous trains in order to monitor the state of the rails, not only regarding defects, but also determining geometry faults, would greatly enhance the understanding. In addition, stationary measuring systems which monitor the state of the passing wheels could give the foundation to determine and improve the standard of rail and rolling stock.

The most important material conclusion in connection to crack growth in rails is the interaction between plastically deformed layer and cracks. The crack path is determined by the loading, the anisotropy of the plastically deformed layer and singular weaknesses in the material. Cracks interact with their neighbouring cracks and their branches insofar as they shield each other to some extent.

When it comes to white etching layers, the conclusions are that they can be created by heat pulses that transform pearlitic microstructure to martensite. However, other possible ways to form WELs are known from literature. Nevertheless, from this work and literature it can be concluded that WELs are harder and more crack sensitive than the original microstructure of the rail.

6 Future work

The work presented in this thesis has led up to a number of questions and opportunities for further research.

For further enhancing simulation tools, it would be very valuable to know more about anisotropy in rails subjected to rolling contact and the direction of preferred crack growth that arises from this anisotropy. There are only basic methods to determine the direction of the deformation today [70, 71]. Also, further understanding of anisotropy and cracks could explain why some steels both wear faster and have deeper cracks than others [23].

Little has been done on determining three-dimensional crack shapes in rails, exceptions are the works of Garnham et al. [72] and Nicholson et al. [73]. There is a usefulness for continuing that work. Since it is very labour-intensive the goal should be to find better methods to determine the exact shape of a crack. Rail pieces containing cracks from a variety of loading situations and rail grades should be chosen. The pieces should be examined with eddie current, ultrasonic testing and X-ray tomography. Only then should the pieces be cut, ground, etched and photographed repeatedly in the way described by Schilke et al. [52]. In that way hopefully a method for three-dimensional crack investigation can be developed that requires less work and time.

In order to understand the interaction between microstructure and crack propagation better, shorter step sizes in the grinding process should be used: only a few µm instead of 300-400 µm. The sample should be etched before photographing it. This can make the crack path visible in relationship to the microstructure. Of course this should only be done for a limited distance (not a 10 mm crack) otherwise the work will take too much time.

In order to gain further information about crack branching it would be a good idea to document crack growth on the surface under controlled conditions. In that way it can be determined which crack branch appeared first. The rail piece can then be cut up to determine whether or not the later crack branch was shielded or not. This is preferably done in a full scale test rig, where the environment is as controlled as possible and surface changes can be easily documented.

Initiation and growth of squats are very interesting subjects in railway research these days. To gain further understanding about them it would be a good idea to make a three-dimensional presentation of some of them in the same way as it was done with cracks in this thesis.

An attempt to gather all the influencing factors which determine the life cycle cost of one rail grade as compared to another would be a valuable tool to have for rail network operators. It would also be a complicated tool containing a lot of uncertain factors concerning future development of track usage. Even if it cannot be made to work quantitatively in a short time, even qualitatively such a tool would be beneficial for the knowledge it would provide.

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