Cape Peninsula University of Technology

ANALYSIS OF DEFECTS OCCURING ON RAIL TRACKS

By

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Thesis submitted in partial fulfilment of the requirements for the degree

Master of Engineering: Mechanical Engineering in the Faculty of Engineering

at the Cape Peninsula University of Technology

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Date submitted: 09 March 2018

DECLARATION

I, Conrad Charl Peter Basson, declare that the contents of this thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

South Africa's railway system is the most highly developed in Africa. There are different kinds of transport systems in South Africa but rail transport is considered as one of an important element of the country's transport infrastructure. In South Africa, over 2.4 million passengers make use of rail transport to get them to their destinations. However, evidence shows that train accidents have become a common occurrence across the country. Train-related accidents such as collision, derailments, platform change incidents and commuter accidents, cost South Africa over R400 million per year.

The analysis of derailments indicates that the most significant single contributor to derailments is rail breaks. This contrasts considerably with prescribed relevant local and international benchmarks, which show a much lower percentage of derailments due to rail break. The frequency of derailments due to rail breaks in South Africa seems to be higher in the northern than the southern region. Furthermore, the proportion of rail breaks that result in derailment is considerably higher than the set benchmarks and therefore, if there is a rail break, then the probability of this translating into a derailment is astonishingly high. Equally, the high incidence of derailments due to rail breaks is affected by the train length and axle load and further exacerbated by the absence of track circuitry. Since derailments are a direct function of the incidence of rail breaks, focus is required to characterize the factors causing defects on rail lines.

This study investigated steel rail material by characterising the piece of the damaged rail with the aim to gain a better understanding of the wear mechanism. Chemical composition analysis of steel rail sample was conducted with the use of a Scanning Electron microscopy. Hardness of steel rail was measured with a Vickers hardness tester. An Optical Microscopy was used to examine the microstructure features of the worn rail samples.

This study discovered that the worn out rail, which was produced from high carbon steel with pearlite and ferrite microstructure, undergoes decarburization and a plastic deformation process. The decarburization process happens when the rail track is heated to 700 ^{o}C and above when the carbon atoms at the surface interact with the atmospheric gases and are removed from the steel as a gaseous phase. Plastic deformation is created when the iron atoms are heated above the elastic point resulting in the permanent movement of iron atoms.

ACKNOWLEDGEMENTS

My profound gratitude to God the giver of life whose loving kindness endures forever and by whose mercies and benevolence I got this far.

I wish to thank:

- Gerda Koopman, for the support and encouragement.
- My supervisor Dr V Msomi, for his organisational and technical input into my research
- Laboratory assistants, for cooperation during analyses of specimen.

ABBREVIATIONS

HV	Hardness Value
RCF	Rolling Contact Value
SEM	Scanning Electron Microscope
SAR & H	South African Railways and Harbours
UTS	Ultimate Tensile Strength
YS	Yield Strength
ASTM	American Society for Testing and Materials
COF	Coefficient of Friction

GLOSSARY

Microstructure:	Structure of a prepared surface
Characterisation:	A description of a quality or peculiarity
Grain Size:	Diameter of individual grains of sediment
Failure:	Deviation from required action or result
Ferrites:	Iron or iron alloys with a body centred cubic crystal structure
Crack propagation:	Developments of cracks due to stress
Pearlite:	Two-phased, lamellar structure composed of alternating layers of alpha-ferrite (88wt. %) and cementite (12wt. %)
Resistance:	The ability not to be affected by something
Wear:	Erosion or sideways displacement of material
Phase Diagram:	Graphical representation of the physical states of a substance under different conditions of temperature and pressure

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CHAPTER ONE

Introduction

This chapter describes the background, problem statement, justification and the objectives of the study. It also outlines the importance of the study with regard to the impact that the problem under study has on rail transport in South Africa consequently contributing to the existing body of knowledge, mechanical engineering research in particular

1.1 Background to the Research Problem

There has been a strong upward trend in derailments over the last few years. The analysis of derailments indicates that the most significant single contributor to derailments is rail breaks. This contrasts considerably with relevant local and international benchmarks, which show a much lower percentage of derailments due to rail break. Likewise, density of derailments due to rail breaks is much higher and the sections northern side of South Africa have considerably higher probability of derailment compared to the southern side of South Africa. Furthermore, the proportion of rail breaks that result in derailment is considerably higher than the benchmarks and therefore, if there is a rail break, then the probability of this translating into a derailment is astonishingly high. The high incidence of derailments due to rail breaks is affected by the train length and axle load and this is further exacerbated by the absence of track circuitry. Since derailments are a direct function of the incidence of rail breaks, focus is required to characterize the factors causing defects on rail lines. The vast majority of derailments due to rail breaks occur in winter, naturally aligning with the higher incidence of rail breaks. However, April and May (the early winter plunge in temperatures) account for over half of derailments due to rail breaks. Two derailments have occurred in summer (both on welds), demonstrating that if the impact load is sufficiently high and the rail foot defect is large enough, the combined effect can be catastrophic even in the absence of tensile longitudinal stress.

This research is focusing on the analysis of defects on rail lines and come up with possible recommendations on how to mitigate these factors before they become uncontainable.

1.2 Problem Statement

The problem to be researched within the ambit of this proposal is to characterize the defects causing rail line failure that results into derailment.

1.3 Background Study

In mechanical engineering wear is a consequence of friction between wheel and rail. The wear of wheels and rails can be directly measured by the use of profilometers. Arguably wear is influenced by material response to a combination of tangential and normal stresses and slippage. Wear coefficients are also used in dynamic simulations of wheel and rail interaction. The interaction dynamics between train/track and wear may result in periodic wear patterns on the wheel tread and the railhead. The ‘bouncing’ motion of the train wheel on the rail causes some portions to wear more than others. Arguably, if this continues over a long period, it potentially leads to formation of rail corrugations and wheel polygonalisation. These in turn leads to increasing contact loads, and significant increase in noise emissions called ‘roaring rail’ [Ekberg et al., 2005]

Wear is inevitable on rail tracks due to daily operations between wheel and rail. However, excessive gauge face wear and plastic flow on curves of heavy haul railway track is a problem for rail life [O’Rourke, 1987]. This is evident on the metropolitan rail network of the public transport corporation [Mutton et al., 1992]. [Kalousek, 1987] gauge face wear on high rails in a curve is a dominating problem.

Rail lifespan is calculated by head loss limit, which is a comparative amount of the fraction of a worn rail head versus an area of a new rail head [Zhang, 2000]. Rolling and sliding wear occurs due to the wheel-rail connection. On straight tracks wheel treads are in connection with the rail head. However, in bends the wheel flange may be in connection with the gauge corner of the rail, which results in a large sliding motion in the contact. The wheel load is conveyed to the rail through a small connection area triggering high contact stresses. This results in repeated loading beyond the elastic limit causing plastic deformation [Nilsson, 2002]. Plastic deformation influence the hardness of the rail and the movement of the bends [Johnson, 1988, Jones, 1997] due to sliding in the connection area under poorly lubricated conditions. Wear occurs at wheel-rail connection. In addition to the connection pressure and size of the sliding component, lubrication, microstructure, hardness and temperature influence the wear rate [Garnham and Beynon 1992]

Plastic deformation of material effect damage of the surface layer, and eventually can affect the formation of cracks. A crack matures under the guidance of mechanical loading and trapped fluid [Ekberg et al., 2005]. The interface between wear and fatigue are directly proportional. Minor originated cracks may be worn off if the wear rate is adequately high. However, wear will also change the connection geometry, which may endorse a faster introduction of new cracks. Weak connection geometry results in high stresses under the surface [Ekberg et al., 2005].

Plastic deformation is always assumed to occur initially and then proceeds to an elastic reaction due to material hardening and the development of residual stresses in the wheel, called elastic shakedown. This theory is defensible under trilling conditions where recurring plastic deformation of the material initiate cracks after a short time suggest that cracks originate from ratchetting (head checks) grow perpendicular to the path of the resultant traction force. Rail strength has increased so much over the last decade to accommodate the increasing axle load. Rails with a tensile strength of 1300-1400 MPa are now being used on Northern and Southern side of South Africa’s railways. To achieve this 1300-1400 MPa tensile strength material, the spacing between the pearlite lamellae needs to be fine to control the growth of pearlite [Grassie and Kalousek 1997].

As the average wheel load increases above 39 ton axle load, rolling contact fatigue and rail wear becomes the main concerns within the rail industry according to [Grassie and Kalousek 1997]. Thus enhance movement density, axis loads, inappropriate lubrications and an increase in speed are contributing factors to rail line failure which leads to rail break. Below is a list of processes and elements that are very significant in controlling wheel wear.

1.3.1 Mechanical Properties

The mechanical properties of a material are those properties that involve a reaction to an applied load. The range of usefulness, service life, classification and identification of materials can be determined by the mechanical properties. The most common properties considered are strength, ductility, hardness, impact resistance, and fracture toughness.

Most structural materials are anisotropic, which means that their material properties vary with orientation. The variation in properties can be due to directionality in the microstructure texture from forming or cold working operation, the controlled alignment of fiber reinforcement and a variety of other causes [Nondestructive Testing, n.d]

1.3.2 Microstructure of Railway steel

Steel used for rails has a much altered microstructure from the low carbon mild steel used for railway sleepers. The microstructure of low carbon steel is made up of ferrite and pearlite structure whereas the microstructure of rail steel is solely made up of a pearlite structure. This theory are confirmed by using an optical microscope to analysing mild steel, you will find light coloured grains of soft ferrite with only a small amount of darker coloured pearlite compared to the rail steel with only pearlite apparent. By magnifying the microphotograph of the pearlite structure you will find that it consist of a two-phased alternating layers of ferrite and cementite which are called lamellar.

The hardness and tensile strength of steel are determined by the proportion of pearlite in its microstructure. They are also determined by the 'fineness' of the pearlite structure. The shorter the inter-lamellar spacing, the higher the hardness, wear resistance and tensile strength [Denby, 2003].

1.3.3 Railway Steel Tensile Strength

The tensile strength of steel is dignified in units of newtons per square millimeter with mild steel having a tensile strength of about 430 MPa. Thus a wire with a diameter of 1.4 mm can up hold load of a 70 kg man. High carbon rail steel, by contrast, may have a tensile strength from 900 MPa to above 1200 MPa [Denby, 2003].

1.3.4 Railway Steel Hardness

The hardness of steel is determined by Brindle Hardness Number (BHN). The typical hardness of high carbon rail steel is about 280 BHN [Denby, 2003].

1.3.5 Crack Resistance

Steel used for rails needs to be permitted from interior cracks which are initiated by the confined hydrogen in the liquefied metal as it cools. The hydrogen can be removed from the steel either by a process called vacuum degassing of liquefied steel before it is cast or by allowing hot rails to cool down very slowly [Denby, 2003].

1.3.6 Rail Steel Fatigue

Fatigue is the everlasting structural variation that transpires in a material subjected to recurring or unstable strains at nominal stresses that have maximum values less than the tensile strength of the material. Fatigue may end into cracks and cause fracture after an adequate number of fluctuations [Boardman, 1990].

This fatigue process consists mainly of three phases namely:

- First fatigue damage leading to crack commencement
- Crack propagation to some critical size
- Sudden fracture of the remaining cross section

Cyclic stress, plastic strain, and tensile stress act as the main contributors of fatigue damage. Fatigue cracks will not initiate and propagate if these three main contributors are not present. The plastic strain resulting from cyclic stress initiates the crack and tensile stresses promotes crack propagation. Careful measurement of strain shows that microscopic plastic strains can be present at low levels of stress where the strain might otherwise appear to be totally elastic. Although compressive stresses will not cause fatigue, compressive loads may result in local tensile stresses [Boardman,1990].

1.3.7 Chemical Structure

Chemical structure denotes to the arrangement, type, and fraction of atoms in molecules of chemical elements. Chemical structure differs when chemicals are added or deducted from the material, when the fractions of substances changes, or when other chemical deviations occur in chemicals.

The chemical structure of a material defines the properties of the material. Thus, the colour, density, strength, and other properties of the material are defined by the arrangements of the atoms.

The main types of structural steel are usually classified according to the following chemical structure types:

- Carbon-manganese steels
- High-strength, low-alloy (HSLA) steels
- High-strength quenched and tempered alloy steels

1.3.8 Carbon (C)

Carbon remains by far the greatest essential chemical element in steel. The strength of steel is direct proportional to carbon and indirect proportional to the ductility of it. Structural steels, therefore, have carbon contents between 0.15% to 0.30%; if the carbon content goes much higher, the ductility will be too low, and for magnitudes less than 0.15% the strength will not be satisfactory [Design of Steel Structures,1999].

1.3.9 Manganese (Mn)

Manganese appears in structural steel grades in amounts ranging from about 0.50% to 1.70%. It has effects similar to those of carbon, and the steel producer uses these two elements in combination to obtain a material with the desired properties.

Manganese is a necessity for the process of hot rolling of steel by its combination with oxygen and sulfur [Design of Steel Structure,1999].

1.3.10 Aluminium (Al)

Deoxidizers such as aluminium form a more fined-grained crystalline microstructure which is needed in a steel structure with pearlite microstructures. It is usually used in combination with silicon to obtain a semi- or fully killed steel [Design of Steel Structures, 1999].

1.3.11 Chromium (Cr)

Chromium is present in certain structural steels in small amounts. It is primarily used to increase the corrosion resistance of the material, and for that reason often occurs in combination with nickel and copper. Stainless steel will typically have significant amounts of chromium. Thus, the well-known “18-8” stainless steel contains 18% of nickel and 8% of chromium [Design of Steel Structures, 1999].

1.3.12 Columbium (Cb)

Columbium is a strength-enhancing element and is one of the important components in some of the High Strength Low Alloy (HSLA) steels. Its effects are similar to those of manganese and vanadium; it also has some corrosion resistance influence [Design of Steel Structures,1999].

1.3.13 Copper (Cu)

Copper is primarily corrosion resistance element. It is typically found in amounts not less than 0.20% and is the primary anti-corrosion component in steel grades like A242 and A441 [Design of Steel Structures, 1999].

1.3.15 Nickel (Ni)

In addition to its favourable effect on the corrosion resistance of steel, nickel enhances the low-temperature behaviour of the material by improving the fracture toughness. It is used in structural steels in varying amount; for example, certain grades of ASTM A514 have Ni contents between 0.30% and 1.50%; some types of A588 have nickel contents from 0.25% to 1.25% [Design of Steel Structures,1999].

1.3.16 Phosphorus (P) and Sulfur (S)

Both of these elements are generally undesirable in structural steel. Sulfur, in particular, promotes internal segregation in the steel matrix. Both act to reduce the ductility of the material. All steel grade specifications, therefore, place severe restrictions on the amounts of P and S that are allowed, basically holding them to less than about 0.04% to 0.05%. Their detrimental effect on weldability is significant. [Design of Steel Structures,1999].

1.3.17 Silicon (Si)

Along with aluminum, silicon is one of the principal deoxidizers for structural steel. It is the element that is most commonly used to produce semi- and fully killed steels, and normally appears in amounts less than 0.40% [Design of Steel Structures,1999].

1.3.18 Vanadium (V)

The effects of this chemical element are similar to those of Mn, Mo, and Cb. It helps the material develop a finer crystalline microstructure and gives increased fracture toughness. Vanadium contents of 0.02% to 0.15% are used in ASTM grades A572 and A588, and in amounts of 0.03% to 0.08% in A514 [Design of Steel Structures, 1999].

1.3.20 Pearlite Microstructure of Railway Steels

The transformation process that produces pearlite is the formation of nuclei of ferrite and cementite on a grain boundary in the austenite. Cementite nucleus mainly forms on the boundary grains which are rich in carbon obtained from its immediate surroundings. This reduction in the carbon content encourages the nucleation of ferrite next to the nucleus of cementite. If this occurs and the cooperative process continues, adjacent nuclei of alternating ferrite and cementite are formed. These can then grow by a relatively short range diffusion process in which carbon diffuses parallel to the reaction from the growing ferrite to the growing cementite and the diffusion distance does not increase with time as would be the case for a continuous precipitation process. This is a plausible process which leads to the lamellar product [Meyrick, 01].

Consider the steady state nucleation flux equation which relates the nucleation flux of particles of a new phase to the free energy of formation of a critically sized nucleus, the absolute temperature and Boltzmann's constant. There is no critically sized nucleus at the A_1 line because all three phases can coexist-exist in equilibrium at that temperature. The nucleation flux is zero because there is no chemical free energy available to provide the energy required to form an interface between a nucleus and the matrix. The chemical free energy of formation of ferrite and cementite from austenite becomes negative at temperatures below the A_1 line, and, as the temperature drops, nucleation becomes possible [Meyrick, 01].

1.4 Research Question

The research question within the field of this proposal reads as follow: factors causing defects on the pearlite microstructure of railway lines.

1.4.1 Investigative Sub-Questions

- What happens in the microstructure of railway line material when it is exposed to excessive axle loads and wear
- What happens in the microstructure of railway line material when it is exposed to high temperature

1.5 Objectives of the research

The main objective of this study is to analyse the defects occurring on the rail tracks and come up with a possible cause of the defects.

1.6 Organization of the dissertation

This dissertation is organized as follows:

Chapter 1 is looking at introduction of the study, research problem, background study and research objective.

Chapter 2 looks at the background related to this study.

Chapter 3 describes the methodology and the procedure used to prepare the specimen and do the analysis on the specimen.

Chapter 4 discusses the results obtained through the use of the procedure explained in chapter 3.

Chapter 5 concludes about the findings of the study.

CHAPTER TWO

2.0 Introduction

This chapter presents the theoretical framework. It discusses reviewed literature on the history of railway transportation in South African railway, types of defects on rail tracks, derailments due to broken rails and the major rail break contributors.

2.1 Rail transportation

The earliest common use of rail conveyance in Europe goes back as far as 1500 to 1800 period. During that time the wooden railed infrastructures were used for the movement of horse-drawn wagons and carts. The use of these infrastructures was to eliminate the motion discomfort which occurred on the dirt roads. The earlier or first reports on mechanised rail infrastructures appeared in 18th century in England. Those infrastructures used steam locomotive for industrial exports and imports, as a result, the introduction of these system brought a worldwide expansion of import and export economies. This mode of transportation remained the primary form of long distance transportation for many bulk materials such as coal, iron elements and agriculture liquids [Lewis, 2001].

Rail transportation still remains as extremely appropriate for the transportation of bulk, dense goods because of its low ton energy usage. This perception is the one which motivates and activates the continuous improvement of railway systems i.e. study on the possible factors that reduce the life span of the wheel and rails, minimizing friction which allows for greater speed of trains and wagons [Fling et al., 1868].

The first development and installation of flanged steel rails in England dates back to the late 18th century by Robert Forester Mushet [Walsh, 1990]. The flanged wheel rails were proven superiority over plate-ways because of their performance on bends. The combination of iron and wood rail was substituted by a metal rail which came with its strong stiffness and toughness. The introduction and the production of high superiority steel began through the method called Bessemer method [Fogel, 1964]. This steel was developed so as to replace and improve the railways which were then developed through cast and wrought iron. [Rosenberg et al., 1982]

2.2 Rail network in South Africa

Rail transport plays an important role in South Africa due to the fact that it connects main cities of the country. The initial rail track for steam-powered locomotives was about 3.6 km in length, which was connecting the town of Durban and the harbour point. In 1872, a Cape rail construction was formed and was owned by Cape government. This rail construction was formed so as to build the national network of rails to all provinces which was completed in 1910. The active use of this mode of transportation emerged such that the direct government agency ownership was changed to government owned corporation called Transnet. Currently, the rail infrastructure is being run by Transnet Freight Rail which is the division of Transnet [Burman, 1984].

2.3 Derailment and accidents records due to broken rails

Derailments are the most significant challenge faced by the railway industry globally. The derailments stem from track failures which are caused by rail breaks and geometry. [Mistry, 2015]. The one example about derailment is the incident occurred in Canada in 2003 where the derailment of 19 wagons was initiated by the breakage of segment on California Western Railroad. The analysis of this breakage revealed that the breakage was due to high wheel impact of the 15th wagon behind the main locomotive and this was due to the poor support of the rail joint [Dhanasekar, & Bayissa, 2011].

The daily average of 2.4 million of South African commuters depends on rail transportation to get to their destinations. These huge numbers of rail users suggest more rail cars should be made available. These huge numbers contribute to the frequent train accidents reports which are caused by different factors. Those accidents are costing the country about R400 million per year [DSC Attorneys, 2017].

2.4 Rails

Rails are defined as longitudinal steel members that accommodate wheel loads and dispense these loads over the sleepers or supports, controlling the train wheels evenly and continuously [Esveld, 2001]. The rails still remain as one of the greatest essential components of the track erection. In generally, the rail is divided into three parts as shown in figure 2.1. The development of rails profiles depends on the standard use in its development. Those profile development standards involve Union Internationale des Chemins de fer (UIC), American Society of Civil Engineers (ASCE) and American Railway Engineering Association (AREA). These standards differ country to country.

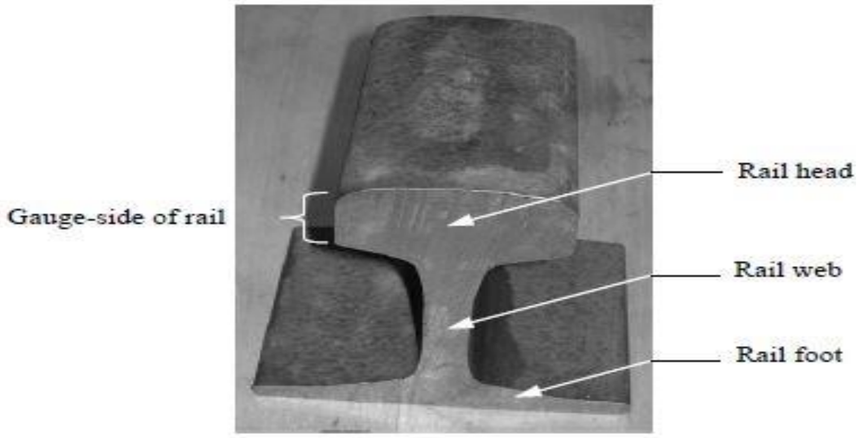


Figure 2.1: Flat bottom rail profile [Rhen and Larsson, LTU]

These standards contribute towards the determination of the maximum static axle loads in each profile [Saurabh, 2006]. All these axle loads are nominal values which are calculated based on the assumption that vehicles are uniformly laden. Any other assumption will follow a different calculation route [Canon et al., 2003].

The rails are expected to have good stiffness so that they can transmit the resolute wheel loads to the placed sleeper supports without extreme deflection among supports [Ernest and John, 1994]. Rails are normally made from high carbon steel (up to 0.82% of carbon), which offers high fatigue durability. Higher quality steels are recently produced, which lead to a substantial enhancement in rail fatigue performance and a considerable reduction in residual stress development [IHHA, 2001].

2.5 Rail defects

The global demand coming from commercial sector calls for the continuous improvement on axle loads, movement density and speed to reduce the operational budget and increase the effectiveness of railways. Axial loads coming from rail cars have increased from 22.5 to 32.5 tonnes in the last ten years. This leads to an increased rate of defect creation in rails [Allen, 1999]. Deficiencies which emerge due to rolling contact fatigue (RCF) can be distributed into subsurface created and surface-created cracks. Subsurface cracks often get initiated by metallurgical deficiencies. On the other hand, surface- created cracks are formed generally due to upsurge in movement density and axis loads [Olofsson and Nilsson, 2002]. Deficiencies are classified into different categories like acute deficiency and non-critical deficiency. An acute deficiency is a rail defect that will disturb the safety of train processes. Non-critical deficiencies are the defects that arise in the rail but do not affect the structural reliability of the rail or the safety on the trains operating over the defect [US Railroad Track Standards, 1991]. Some of the common deficiencies are described in next subsections.

2.5.1 Shelling

Shelling defect is a direct cause by material loss created by subsurface fatigue, which normally takes place at the gauge corner of high rails in bends [Nielsen and Stensson,1999]. An elliptical shell-like crack spreads in the subsurface comparable to the rail surface. When these cracks occur on the surface, they cause the metal to arise from the crack area. These cracks move in downward direction which might possibly lead to a transverse fracture of rail [Kumar, 2006]. As this is subsurface created deficiency, steel metallurgy plays a significant role in its creation. Traces of oxide inclusion and residual stress development during manufacturing donate in shelling [Esveld, 2001]. Figure 2.2 shows gauge corner shelling which is usually removed by grating.

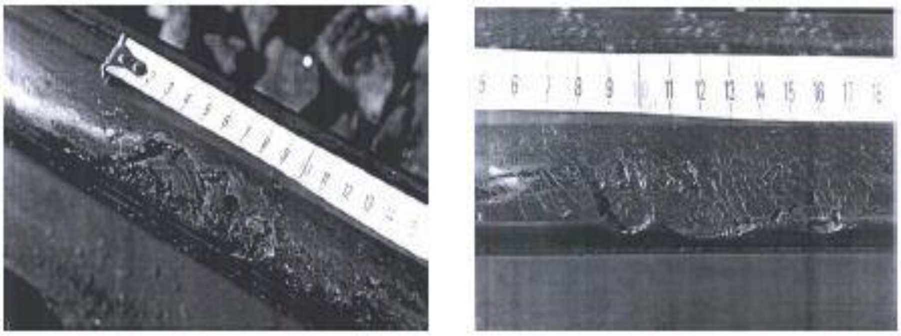


Figure 2.2: Gauge corner shelling in rails [Rhen and Larsson, LTU]

2.5.2 Head cracks

Due to the large profile radius in the crown area, contact stresses are generally low compare to the gauge side of the rail. High contact stresses are created on the gauge corner of the high rail bend with radius which range from 1000 to 1500 m. Head checks might also arise in tighter which have a radius smaller than 1000 m bend near the gauge corner of the high rail [IHHA, 2001]. Welded profiles which have minor profile differences with real rail contours have a big effect on connection stresses and head checks. Head checks are surface created deficiencies which usually occur at an angle of 30-60 degrees to the longitudinal axis of the rail (Figure 2.3). If head checks are not controlled, they might cause a rail break. Grating is the most common exercise to eliminate head checks where severe head checks need rail section replacement.

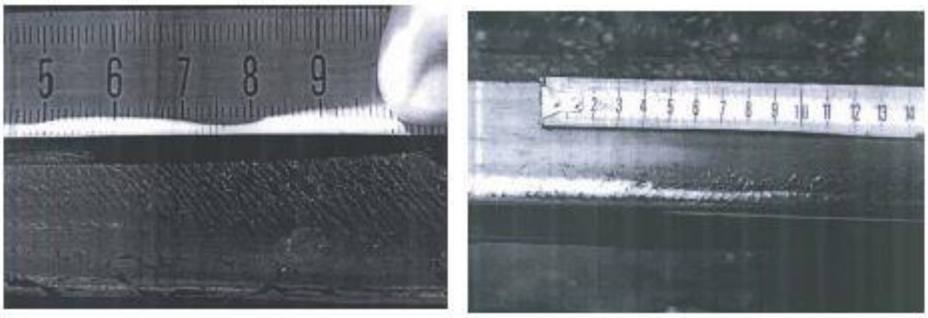


Figure 2.3: Head Checks in rails [Rhen and Larsson, LTU]

2.5.3 Spalling

Spalling is defined as shallow chip of rail material which falls out when the surface-created crack development path is traversed by other comparable surface cracks on the rail head area (see figure 2.4). Uninspected spalling occurs at a much later stage of crack propagation phase. Spalling is occurring mostly on cold climates due to an increased in material stiffness [Nielsen and Stensson, 1999].

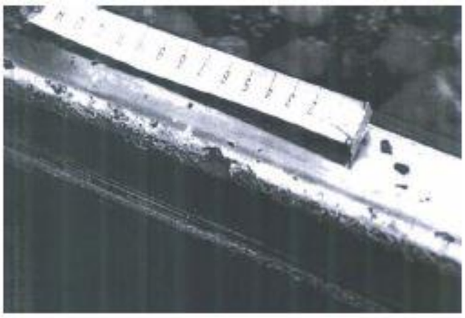


Figure 2.4: Spalling in rails [Rhen and Larsson, LTU]

2.5.4 Squats

A squat is formed by two cracks, a leading crack and a trailing crack which propagate in opposite directions. The leading crack ensues in moving direction, but the trailing crack spreads faster than the leading one. Squats appear similar to a depression in the crown area. The depression is a consequence of crack which grows gradually and branches out horizontally just below the running surface, detaching it from the rail body. These deficiencies could be prevented by grating. Literature has shown that rail grating has an important role in decreasing rail degradation, which can lessen rail brakes, early rail replacements and derailments [Kalousek and Magel, 1997].

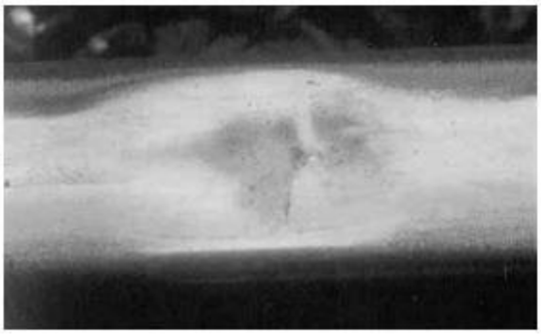


Figure 2.5: Squats in rails [Rhen and Larsson, LTU]

2.5.5 Tache ovale

Tache Ovale is a subsurface deficiency formed around 10-15 mm below the rail head surface (see Figure 2.6). This subsurface deficiency is initiated by hydrogen accumulation during the development of rail or when sub-standard welding is done on rails. Thermal and residual stresses also contribute to this form deficiency.

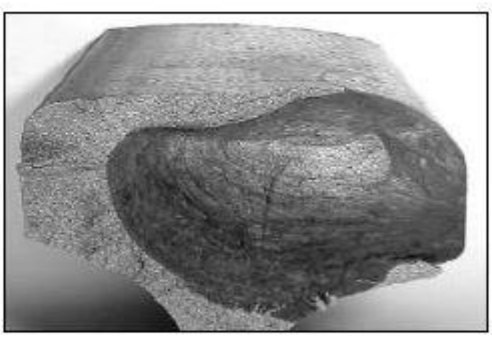


Figure 2.6: Tache Ovale [Queensland Rail, Australia, 2005]

2.5.6 Plastic flow and torque lipping

Plastic flow happens on the field side of the low rail due to overloading and this occur at the head area. Plastic flow might also happen in low rail on the bends due to overloading. Tongue lipping is also a form of plastic deformation which is created by surface cracks. These cracks partly separate a layer of material from the bulk of rail. Under high axis loads, these separated protrusions distort plastically. Tongue lipping gives a hint of the presence of cracks. This deficiency could be reduced by grating which would also bring back the original rail profile [IHHA, 2001].

2.5.7 Bolt hole crack

Bolt holes cracks appear in the rail web often starting from fishplates fastening points. This becomes weak sockets and is left exposed to resist crack creation, as they face very high stress concentrations, and web shear stress. Generally, these cracks spread radially along the web plane at an angle of 45 degrees to the vertical plane and are very likely to cause rail breaks and require urgent rail section replacement [Esveld, 2001].

2.5.8 Longitudinal vertical crack

This is an engineering deficiency, which generally acts in the rail web and may spread into the rail head. If interconnected by some additional crack, it might lead to a premature fracture or rail break. The danger of sudden breakage due to this type of crack is elevated in cold climates. Figure 2.7 shows a longitudinal vertical crack.

Figure 2.7: Longitudinal vertical crack [Granstrom, LTU]

2.5.9 Transverse crack

Transverse crack is generally established in the cross-sectional area of sub-standard weld joints. A welding deficiency may be due to sub-standard weld in the material or rail manufacturing flaw. Transverse cracks in weld joints have their deficiency origin from the welding processes such as pores, inclusions, misalignment, etc., Figure 2.8(a). Transverse cracks might be generated by tache ovale which develops from the centre of the rail head or the rail foot as shown in Figure 2.8(b). This crack cultivates in the subsurface and by the time it touches the rail head surface, rail break becomes certain. To escape its realization clean steel and deeper hardening of rail head need be accomplished.

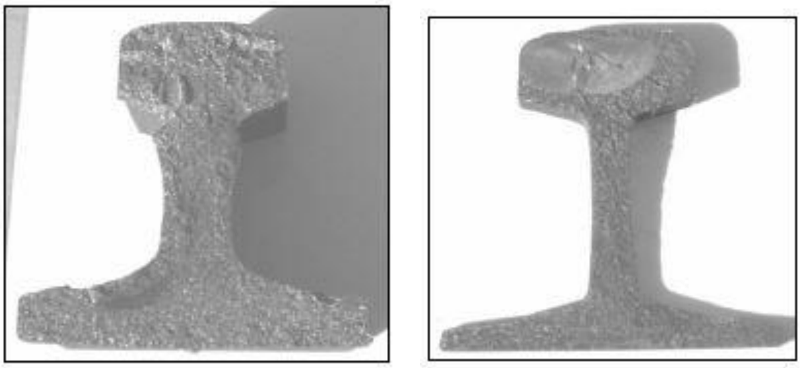


Figure 2.8 (a) and (b): Transverse crack [Granstrom, LTU]

2.5.10 Buckling

Expansion of sideways buckling in rails is a very common deficiency in which the rail bulges out on both sides as the temperature rises, longitudinal expansion in rail takes place [Zarembski *et al*., 2005]. Non-stop Welded Rails (NWR) and non-welded rails have their own benefits and shortcomings. Non-welded rails are connected by joints to provide them some room for longitudinal extension. It is used in places where heat may exist beyond 25 ^{o}C to avoid this sideways buckling in rails. Nonetheless, the build-up of high stress concentration at joints befits even higher in high speed rails which donate to the shortcomings of these rails. NWR do not have these drawbacks, fewer maintenance is necessary leading to decline in life cycle cost due to the stress distribution are more even. However, their use of (NWR) is restricted to temperatures under which negligible longitudinal extension takes place. Continuous welded rails (NWR) do not have any control to accommodate the extension in rails, henceforth rail bulges out. This poses stern derailment risks. There is a need for risk based analysis of track buckling considering most of the vital factors affecting track buckling. The risk approach can provide economic options for track maintenance to achieve the desirable buckling strength to avoid serious derailment risks [Kish and Samavedam, 1999].

2.5.11 Corrugation

Corrugation remains a rail flaw in a wave-like form wearing displaying a periodic unevenness of the rail surface [IHHA, 2001], see Figure 2.9. Rail corrugation exists as the result of a damage mechanism, such as wear, fatigue or plastic flow functioning at about characteristic frequency which does not pose any instantaneous derailment risks but they might be accountable for loosening of rail fasteners, ballast worsening, upsurge in noise and vibration level leading to customer anxiety. [Magel and Kalousek,2002]. Numerous reasons may be the reason for corrugations but it is challenging to connect these causes of corrugation at diverse rail sections.

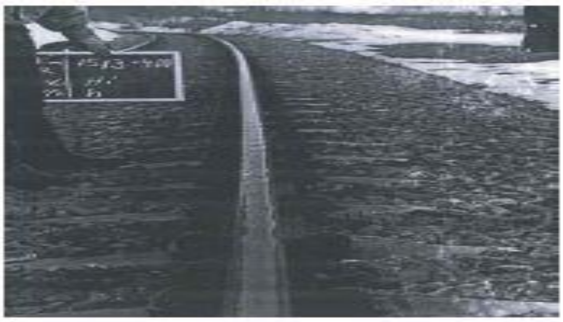


Figure 2.9: Corrugation in rails [Rhen and Larsson, LTU]

2.6 Rail breaks major contributors

The industries are experiencing difficulties with wear and fatigue from a mitigation point of view. The main contributing factors include train speed, axis load, rail-wheel material kind, dimension and shape, track structure, appearances of bogie type, Million Gross Tonnes (MGT), bend, transportation type, weather and environment contribute to rail deterioration depending on operational conditions [Chattopadhyay *et al*., 2006]. Rails are so intended that they fit with the profile of the wheel forming a combination, which lessens connection stresses. They cause longitudinal compressive and tensile stresses, which remain mainly resolute in the head and foot of the rail whilst the shear forces yield shear stresses which transpire mainly in the web. It is imperative to offer acceptable resistance against the bending moment which defines the areas of the head and foot of the rail [Cope, 1993]. The rail head gets worn out by wheels on its surface and deteriorated by abrasive contact with the base plate or sleeper below. Corrosion results in loss of rail section and the surface crack itself decreases the fatigue resistance of the rail. Rail wear, rolling contact fatigue and plastic flow are mounting problems for current railways. Amplified speeds, higher axis loads, amplified movement and freight leads to the surface created cracks on the rail [Reddy, 2004].

Rail break remains the last stage of crack development process. As the crack goes on growing in length as well as depth, stress concentration also goes on increasing and lastly rail break transpires, but this does not occur in all circumstances. Occasionally spalling takes place and a portion of rail material comes out as crack develops. The end result of a crack is directed by its expansion path. It is very hard to forecast the crack expansion path as it hinges on several factors. Some of the cracks are removed by wear process through early stages of crack development while most of them are removed in grating operations. Not all cracks inflict derailment risk, but they are the main contributors to rail degradation [Reddy, 2004].

Some of the sorts of rail break is known as detailed fracture. A detail fracture is a progressive fracture starting from a longitudinal separation close to the running surface of the rail head, then turning downward to form a transverse separation substantially at right angles to the running surface. Detail breakages account for about 75% of the rail deficiency population in continuous welded rail track in North America [Jeong, 2001].

2.7 Wear

Wear is a result of friction among wheel and rail. Wear of wheel and rails can be directly dignified by the use of profilometers. Wear is subjective by material response to combined tangential and normal stresses and slippage. Wear coefficients are used in dynamic simulations of vehicle/track interaction [Ekberg et el., 2005].

The interface of train/track dynamics and wear may end in interrupted wear patterns on the wheel tread and the rail head. The ‘bouncing’ motion of the wheel on the rail affects about portions to wear more than others. If this remains over a long period then it can lead to construction of rail corrugations and wheel polygonalisation. These lead to increasing contact loads, and significant increase in noise emissions called ‘roaring rail’ [Ekberg et al., 2005].

Wear is inevitable on rail tracks. However, excessive gauge face wear and plastic flow on curves of heavy haul railway track is a problem for rail life [O’Rourke, 1987]. This is evident on the metropolitan rail network of the public transport corporation, Victoria [*Mutton* et al., *1992*]. [Kalousek. 1987] also indicated that gauge face wear of high rails in a curve is a dominating problem.

The rail life is determined by head loss limit, which is a relative measure of the ratio of a worn rail head of the area of a new rail head [Zhang, 2000]. In the wheel-rail contact both rolling and sliding occur. On straight track the wheel tread is in contact with the rail head. However, in curves the wheel flange may be in contact with the gauge corner of the rail, which results in a large sliding motion in the contact. The wheel load is transmitted to the rail through a tiny contact area causing high contact stresses. This results in repeated loading beyond the elastic limit causing plastic deformation [Nilsson, 2002]. Plastic flow depends on the hardness of the rail and the severity of the traffic and the curves [Johnson, 1988 & Jones, 1997] due to sliding in the contact area under poorly lubricated conditions. Wear occurs at wheel-rail contacts. In addition to the contact pressure and size of the sliding component, lubrication, microstructure, hardness and temperature influence the wear rate [Garnham and Beynon 1992].

2.8 Rail contact fatigue

Rolling contact fatigue (RCF) is a group of rail damages which manifest themselves on the surface or close to surface inside the rails due to overstressing of the rail material. The defects may first appear on the rail surface in the form of shelling, squats and gauge corner cracks or within the subsurface in the form of deep seated shells. All these defects appear as a result of repeated overstressing of the surface or subsurface rail material by the millions of repeated wheel-rail contact cycles. Two main physical processes that govern the development of RCF defects are crack initiation and crack propagation in the rails. These are, in turn, governed by the factors like rail and wheel profiles, track curvatures, grades, lubrication practices, rail metallurgy, vehicle characteristics, track geometry errors, environmental conditions, and many others. All these factors play an important role in the formation and development of RCF and, therefore, could be optimized to control and minimize RCF defects [Singh, 2011].

2.9 Steel

Steel with very high carbon content is used to produce railway tracks. Steel is essentially an alloy of iron and carbon which also contains manganese and a variety of residual elements. These residual elements were either present within the raw materials used in the production process e.g. iron ore and scrap steel additions, or they were added in the production process for a specific purpose, e.g. deoxidization by means of silicon or aluminium. Hence they are called residual elements to distinguish them from alloying elements that are deliberately added according to specified minimum amounts. The American Iron and Steel Institute (AISI) has defined a plain carbon steel to be an alloy of iron and carbon which contains specified amounts of Mn below a maximum amount of 1.65 wt.%, less than 0.6 wt.% Si, less than 0.6 wt.% Cu and which does not have any specified minimum content of any other deliberately added alloying element. It is usual for maximum amounts (e.g. 0.05 wt.%) of S and P to be specified. We should be aware that various manufacturing practices can affect the oxygen, nitrogen and sulphur content and hence the cleanliness of the product. The term cleanliness usually refers to the amounts of various phases such as oxides, sulphides and silicates that can be present in steel. The smaller the amount of these phases, the cleaner is the steel. [Satyendra, 2015]

Carbon is a hardening agent, avoiding displacements in the iron atom crystal framework from slipping past one another. Changing the quantities of alloying elements in steel controls qualities such as the hardness, ductility and tensile strength of the resultant steel. By increasing the carbon content in the steel it also becomes less ductile than iron [Ashby et al., 1986].

2.10 Heat treatment

This is a metalworking process used to alter the physical and chemical properties of a material. There are many types of heat treating processes available to steel, which are annealing, quenching and tempering.

Annealing is a heat treatment that alters the physical and sometimes chemical structure of a material to upturn its ductility and reduce its hardness, making it more workable. It involves heating a material to above its recrystallization temperature, maintaining a suitable temperature and then cooling [Smith et al., 2006].

Quenching is the rapid cooling of a workplace in water, oil or air to obtain certain material structure. Quenching prevents undesired low-temperature processes, such as phase transformation, from occurring. It does this by reducing the window time during which these undesired reactions are both thermodynamically favourable, and kinetically accessible; for instance, quenching can reduce the crystal grain size of both metallic and plastic materials, increasing the hardness [Smith et al., 2006].

2.11 Steel phase diagram

Steel can be heat treated to create a different range of micro structures and properties. Generally, heat treatment uses phase transformation during heating and cooling to change the microstructure in a solid state. The heat treatment of steel in the Fe-C phase diagram consists of two illustrations, namely steady iron-graphite illustration and meta-stable Fe-Fe_3C illustration [Shashank. 2008].

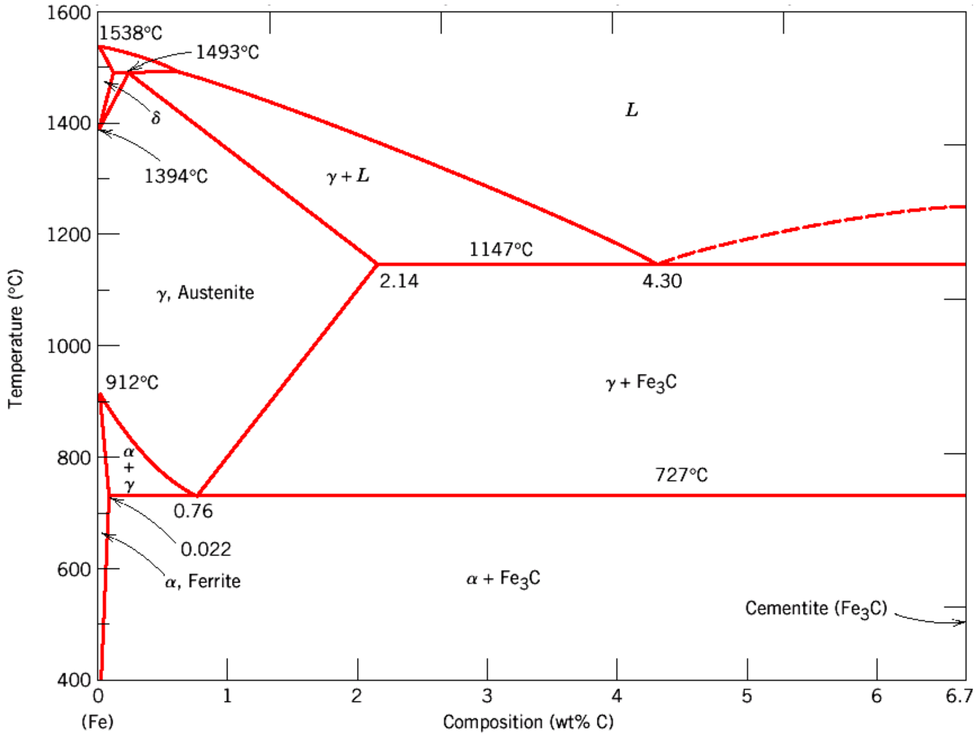


Figure 2.10: Fe-Fe_3C Phase Diagram [Shashank, 2008]

Figure 2.10 presents the meta-stable Fe-Fe_3C phase diagram. The microstructure of iron and steels is complex and diverse which is influenced by composition, homogeneity, heat treatment, and processing. The microstructural phase for these materials could be varied from one phase to another through temperature variation. The mostly useful phase in steel for rail tracks is the pearlite phase. Pearlite is defined as a fine mixture of ferrite and cementite arranged in lamellar form which is formed due to eutectoid reaction. The eutectoid transformation is an isothermal, reversible reaction in which austenite is converted into two intimately fixed solid phases namely ferrite and cementite. Pearlite has an advantage of increasing the strength of carbon steels. It is stable at all temperatures below 723 ^{o}C [Satyendra, 2014].

2.12 Summary

The literature regarding the history of railway, rails, rail break major contributors, steel rail phase diagrams and its heat treatments were discussed in this chapter. There is a need for characterisation of the factors causing defects to these rail tracks so that we can minimize the damage it may cause during operations.

CHAPTER THREE

3 Sample preparation and characterization techniques

3.0 Introduction

A water-jet cutter was used to cut the damage rail track into 10mm pieces of which four pieces was chosen to be analysed. These four pieces were labelled as specimen 1, 2, 3 and 4 (see figure 3.1). The four 10mm pieces were than hot mounted into a conventional hot mounting press. Lastly, the specimens were grinded, polished and etched to finally get these specimens ready for characterization. These test samples analysis and preparation were done at the Mechanical Engineering laboratory of Cape Peninsula University of Technology, Bellville Campus. Details on the processing with the apparatus that were followed during the experimental procedure are discussed below.

Figure 3.1: Damage Rail Track

3.1 Experimental Procedure

3.1.1 Water-jet cutter

This is an industrial tool capable of cutting a wide range of materials by means of a very high-pressure jet of water or a combination of water and an abrasive material. Due to the minimum heat transfer to the microstructure during the cutting process, using a water jet cutter was best suited to preserve the microstructure of the rail track during the cutting process.

Figure 3.2: Steel rail sample cut into four 10mm pieces

3.1.2 Grinding and Polishing

Grinding is to remove damage because cutting, planarize the specimens and to eliminate material potentially interest the area. The greatest communal metallographic abrasive das been used, namely Silicon Carbide. It remains a supreme abrasive for grinding because of its hardness and sharp edges.

Polishing is the utmost important step in preparing a specimen for microstructural analysis. It is the step which is required to eliminate previous damage. To eliminate distortion from fine grinding and obtain a surface that is extremely reflective, the specimens were refined before the can be inspected beneath the microscope.

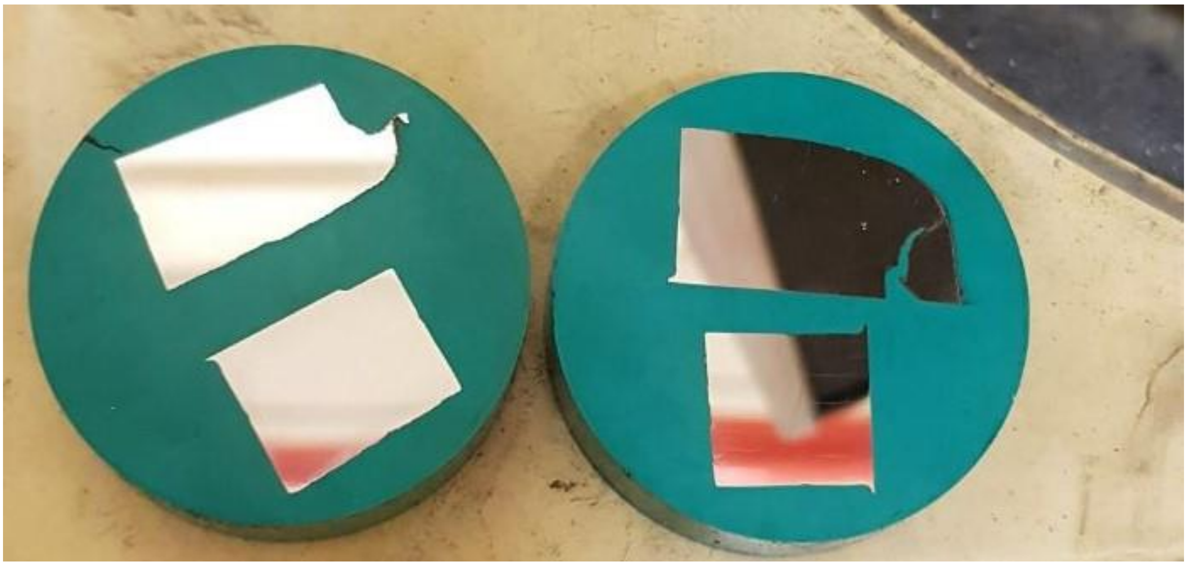


Figure 3.3 Steel rail samples obtained after grinding and polishing process

3.1.3 Etching

Metallographic etching is a chemical method to highpoint types of metals at microscopic stages. Analysing and studying the character, quantity and distribution of these diverse structures, metallurgists can forecast and clarify physical structures and performance failures of a given model of metal [Wojes ,2017].

To reveal the crystalline structure (grains and grain boundaries) of the specimens, the polished surface was etched by a proper etchant. For steels Nitol (3% HNO_3-ethyl alcohol) was used. This represented by differential chemical attack depending upon chemical composition, energy content, and grain orientation. Thus, the grain boundaries are attacked at a greater rate than the proper grain due to higher energy content of the grain boundaries. The result is a compression of the grain boundaries. In addition, the presence of chemically different phases results in variations in the rate of chemical attack. These changes in the rate of chemical attack produce deviations both in angle and depth of certain portions of the surface. Thus, the light is reflected in varying amounts depending on manner the crystalline microstructure of the specimen is revealed. [Wojes, 2017].

Etching is performed by immersion and swabbing the etchant on the specimen. The mount is then removed from the solution when a bloom appears. A bloom is a slight haze that appears and is evidence of the first appearance of the microstructure. If necessary, further etching may be performed after examination under a microscope to strengthen any details. After etching, the mount is thoroughly rinsed in running water. Then alcohol is sprayed over the surface and the mount is finally dried in a stream of hot air.

3.2 Sample Characterization

3.2.0 Introduction

Detailed investigation on microstructural and mechanical properties of the 10mm wear out pieces of steel rail specimens were conducted using various characterization tools including Q4 Tasman scanning electron microscope (SEM) coupled with electron dispersion X-ray spectroscopy (EDX), optical microscope as well as Vickers hardness machine.

3.2.1 SEM-EDX

The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens at a nanoscale. The main types of signals that are detected are the backscattered (BSE) and secondary electrons (SE), which generate a grayscale image of the sample at very high magnification. These signals that derive from the electron-sample interactions reveal information about the sample including external morphology, chemical composition and crystalline structure and the orientation of materials making up the sample. In this case data were collected over a selected area of the surface of the sample, and a 2-dimentional image is generated that displays spatial variations in these properties.

These backscattered electrons produce images with contrast that carries information on the differences in atomic number whereas the secondary electrons give topographic information. See below the working technique of a SEM.

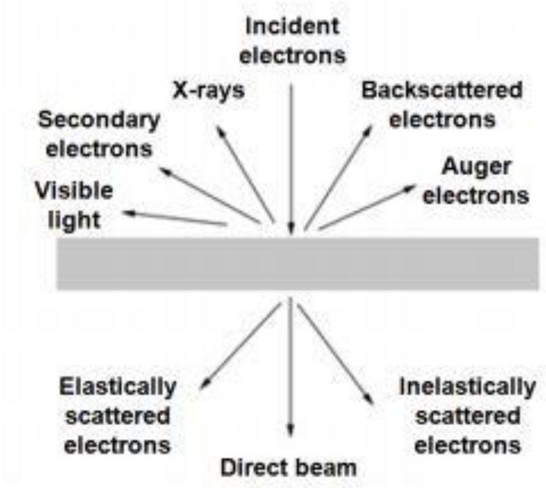


Figure 3.4: High energy electrons that strike a material will generate different types of signals. These signals can be used for imaging and chemical analysis [Ingemarrson & Halvarsson, 2001]

The other signal that is widely used in SEM's is X-rays. The generation of the X-rays in a SEM is a two-step process. In the first step, the electron beam hits the sample and transfer part of its energy to the atoms of the sample. This energy can be used by the electrons of the atoms to jump to an energy shell with higher energy or be knock-off from the atom. If such a transition occurs, the electron leaves a hole behind. Holes have a positive charge and, in the second step of the process, attract the negatively-charged electrons from higher-energy shells. When an electron from such a higher-energy fills the hole of the lower-energy shell, the energy difference of this transition can be released in the form of an X-ray.

This X-ray has the energy which is characteristic of the energy difference between these two shells. It depends on the atomic number, which is a unique property of every element. In this way, X-rays identify the type of each element that exists in this sample.

Figure 3.5: Q4 Tasman scanning electron microscope (SEM) coupled with electron dispersion X-ray spectroscopy (EDX)

3.2.2 Optical Microscope

Optical microscope is a technique which is generally used for analysing the microstructural arrangement of the material. This incorporates the grain sizes, grain arrangement, and apparent phases namely; ferrite, cementite, austenite and pearlite.

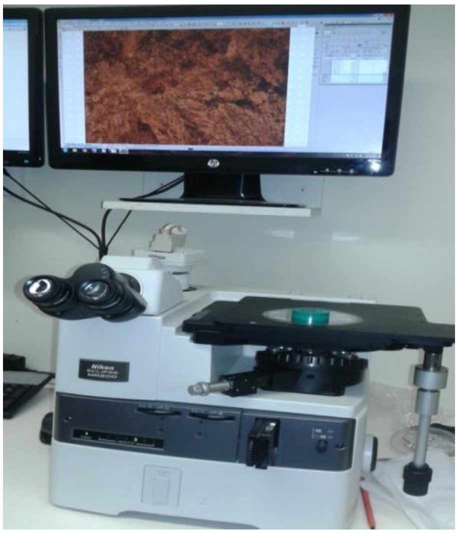


Figure 3.6: Optical Microscope

3.2.3 Macro Vickers harness machine

Hardness tests were carried out on the Macro Vickers hardness machine. The Macro Vickers micro-hardness profiles were measured using the Zwick Roel indenter, according to the ASTM 384 standard. This was conducted on rail samples to determine assured conformance to rail specifications.

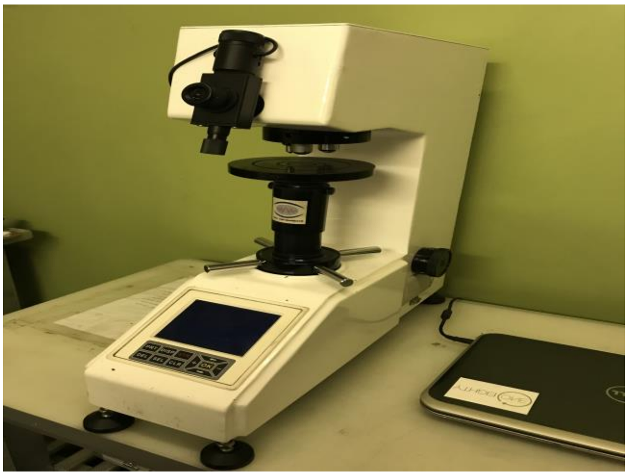


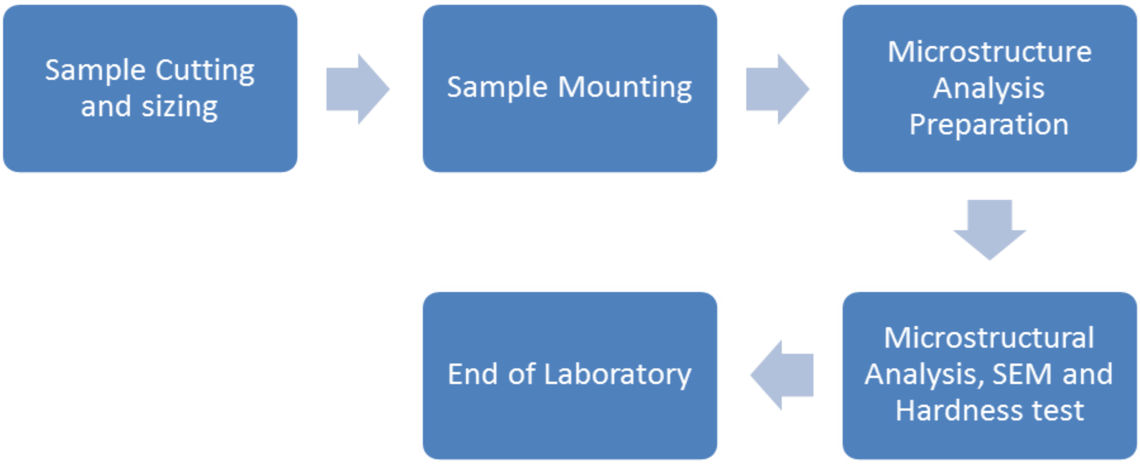
Figure 3.7: Macro Vickers Hardness Tester TH720

This machine determines the material resistance to indentation at a constant load 80kg from the indenter. Its basic principle is to get the material resistance depth to plastic deformation; that is, the smaller the indentation depth, the harder the material, the larger the indentation, the softer the material.

The etched rail piece samples were placed for indentation by the indenter at constant load at both the surface edge and the sub-surface of the steel rail sample. The indentation depths and their hardness results were calculated and are discussed in Chapter 4.

3.2.4 Project Flow Sheet

This flow sheet summarises the different stages of the experimental procedure as presented below



CHAPTER FOUR

4 Results and Discussions

4.0 Introduction

In this chapter, the results of the findings obtained during the analysis are presented and discussed. These findings are the chemical analysis of the rail, characterization of the rail hardness, steel rail microstructure analysis through the use of the microscope, and the grain sizes by using a Scanning Electron Microscope (SEM).

4.1 Sample chemical identification

The EDX was used to conduct some chemical analysis of the samples. This technique is attached to the scanning electron microscope (SEM) to quantify the chemical composition of the samples. The chemical component results of this steel rail are presented below in Table 4.1

Table 4.1: Chemical Composition results

CHEMICAL COMPOSITION OF SUPPLIED SAMPLES											
Sample No	Symbol:	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al
	Unit:	%	%	%	%	%	%	%	%	%	%
1		0,52	0,185	0,71	0,0098	0,014	0,005	0,001	0,0015	0,0049	0,0034
2		0,513	0,173	0,705	0,0094	0,025	0,005	0,001	0,0015	0,0043	0,0015
3		0,513	0,171	0,705	0,0094	0,015	0,0047	0,001	0,0015	0,0041	0,0011
4		0,516	0,169	0,7	0,0087	0,019	0,0051	0,001	0,0015	0,0041	0,001
Average		**0,516**	**0,175**	**0,705**	**0,009**	**0,018**	**0,005**	**0,001**	**0,002**	**0,004**	**0,002**

Looking at the chemical compositions presented above in Table 4.1, the only elements that are prominent are carbon, silicon and magnesium. The contribution of the other elements was very minimal such that they were ignored during the analysis.

The focus for this study was on the prominent elements like carbon, silicon and manganese.

4.1.1 Carbon

This prominent element brings certain properties to this plain carbon steel that creates desired microstructures. We found that this steel contains 51.7% carbon which improves the hardness and strength and improves hardenability. But carbon also increases brittleness and reduces weldability because of its tendency to form martensite. This means carbon content can be both a blessing and a curse when it comes to commercial steel.

Hardness, brittleness and ductility are very important properties as they determine mainly the way these different carbon content steels are used. Microstructures of slowly cooled steel; for mild steel with 0.2% carbon consist of about 75% proeutectoid ferrite that forms above the eutectoid temperature and about 25% of pearlite. As the carbon content in the steel increases, the amount of pearlite also increases until we get a fully pearlitic structure of a composition of 0.8% carbon. Beyond 0.8%, high carbon steel contains protectoid cementide in addition to pearlite. The overall hardness and ductility of slowly cooled carbon steels are determined by the relative proportions of the soft, ductile ferrite and the hard-brittle cementite. Increased carbon content enhances the increase of cementite which results in an increase of hardness and a decrease of ductility, as we go from low carbon to high carbon steels.

Therefore, the presence of carbon is imperative because carbon is the hardening element of steel that can be attained by quenching.

4.1.2 Manganese

Manganese is normally used to improve the strength properties of steel, while marginally impairing its elasticity. In addition, manganese has favourable influence on forging, welding and grain refining properties in steel castings. A higher content of manganese in the presence of carbon substantially increases the wear resistance. With up to 3% of manganese, tensile strength of steels increases by 10 kg/mm^2 for every added percentage of manganese. With addition of manganese in contents above 3% to 8% the increase rises more slowly and at content more than 8% of manganese, it drops off again. The yield point behaves in a similar manner. Manganese enhances the depth of hardening of steels.

4.1.3 Silicon

Silicon is one of the principal deoxidizers of steel. Silicon helps to remove bubbles of oxygen from the molten steel. It is the element that is most commonly used to produce semi- and fully killed steels, and normally appears in amounts less than 0.4 %, usually only small amounts are present in rolled steel when it is used as a deoxidizer. However, in steel castings 0.35% to 1% is commonly present. Silicon dissolves in iron and tend to crease strength and hardness but to a lesser extent than manganese. Table 4.2 below summarise the different effects of the different alloying elements on steel

Table 4.2: Alloying Elements

Alloying Elements	**Cr**	**Co**	**Mn**	**Mo**	**Ni**	**Ti**	**W**	**V**
Hardenability	++	…	++	++	+	++	++	+++
High Temperature strength	+	+	….	++	…	+	++	++
Ductility and toughness	…	…	+	…	++	…	…	…
Abrasion resistance	+	…	…	+	…	+	++	+
Fine austenite grain size	…	…	…	+	…	++	+	+++
Corrosion resistance	++	…	…	++	+	…	…	…

4.1.4 Classification of this Steel

Generally, steel is classified according to the alloying element it contains, whereas these alloying elements are in turn classified according to their readiness to form carbides, austenites and ferrires. Carbon is the main alloying element in steel hence it is used as the reference in classifying the steel grades.

Alloy steels have standards which facilitate their analysis and their classifications. One of these standards is the one established by the Society of Automotive Engineering (SAE) which uses a four digits numeration system to classify steel. The first digit indicates whether the steel is a plain carbon type, whereas the second number gives an idea about the type of modification to which the steel has been subjected to. The last two digits indicate the composition of carbon in the steel. In this study the steel that is being analysed is a SAE1057 which is a plain carbon steel. Table 4.3 below shows the (SAE-AISI) classification of carbon steels

Table 4.3: Classification of Carbon Steels

Classification	**Number**	**Range of Numbers**
A. Carbon Steel SAE-AISI	1xxx	
Plain Carbon	10xx	1006-1095
Free Machining (Resulphurized)	11xx	1108-1151
Resulphurized Rephoshorized	12xx	1211-1214

4.2 Microstructural Analysis

During the microscopic analysis the following will be discussed below;

- Decarburization
- Plastic Deformation
- Hardness

4.2.1 Decarburization

Decarburization is the process opposite to carburization, namely the reduction of carbon content in steel. Decarburization occurs when metal is heated to temperatures of 700 ^{o}C and above when carbon atoms at the steel surface interact with the atmosphere and are removed from the steel as a gaseous phase. Carbon from the interior diffusion towards the surface, moving from high to low concentration and continues until above the upper critical temperature. The removal of carbon removes hard carbide phases resulting in a softening of the metal, primarily at the surface which is in contact with the decarburizing gas (Wieland.and Rudzki, 1979).

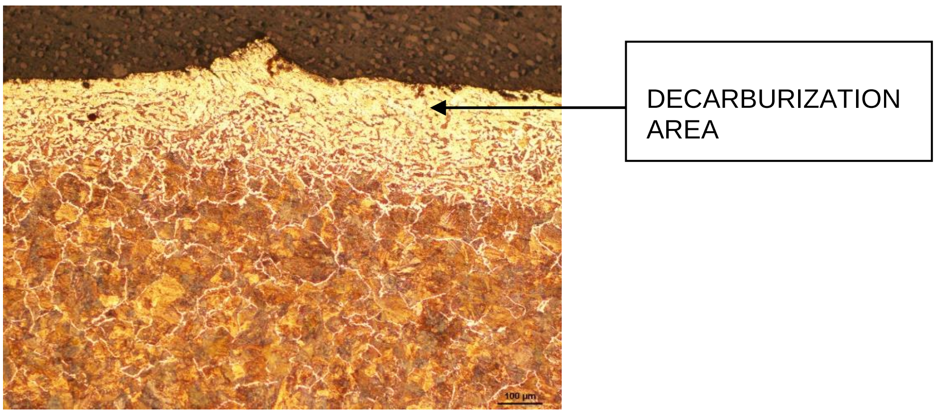


Figure 4.1 The microstructure of the decarburized steel

4.2.2 Plastic Deformation

Plastic deformation is a process in which permanent deformation is caused by a sufficient load. It produces a permanent change in the shape or size of a solid body without fracture, resulting from the application of sustained stress beyond the elastic limit. Plastic deformation can be applied in the creation of a variety of items constructed with metal or plastic and can be conducted under controlled circumstances or may occur unintentionally

4.2.3 Hardness

Hardness is a measure of the resistance to localised plastic deformation induced by either mechanical indentation or abrasion.

4.3 Optical Microscopy Analyses

4.3.1 Derailed steel rail specimen 1

A steel specimen was examined under an optical microscope as presented below.

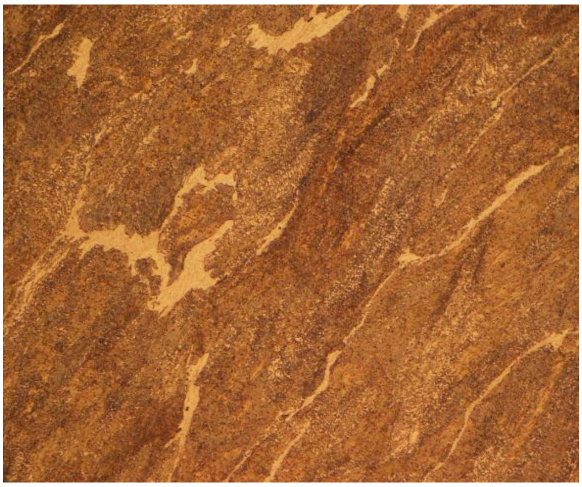


Figure 4.2: Top High Magnification

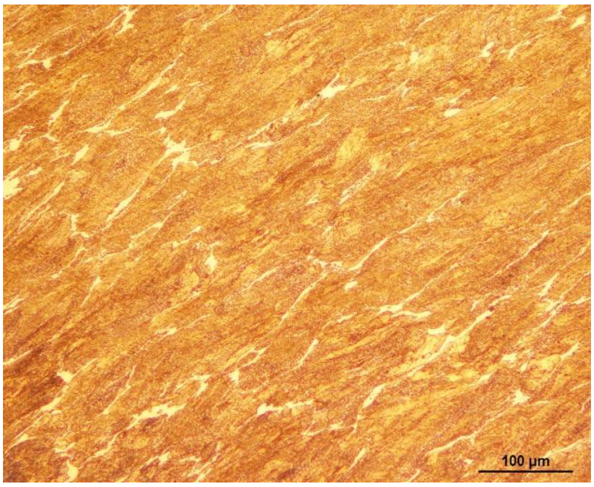


Figure 4.3: Top High Magnification

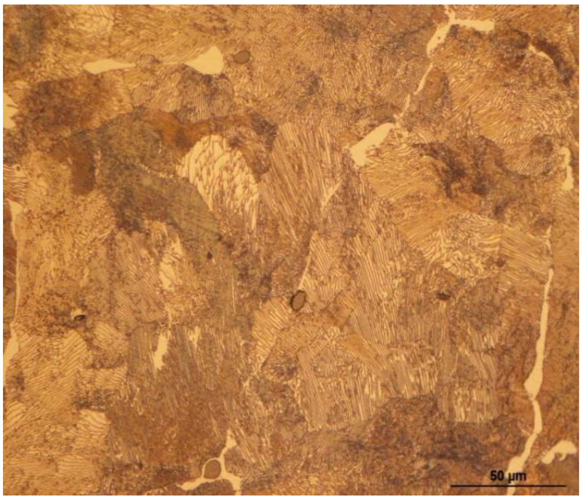


Figure 4.4: Middle High Magnification

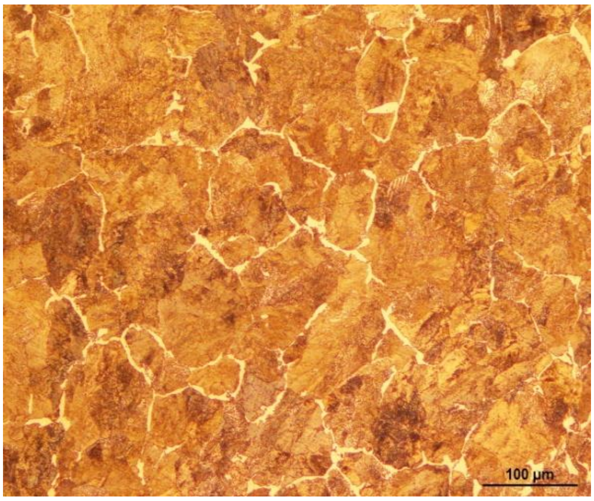


Figure 4.5: Middle Low Magnification

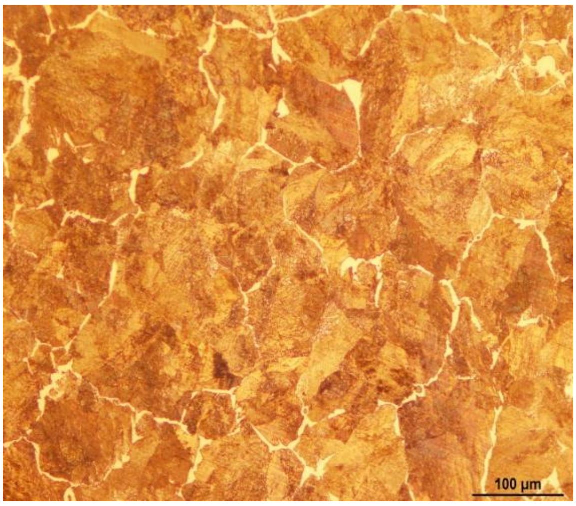


Figure 4.6: Bottom Low Magnification

Figure 4.7: Specimen 1

Derailed steel rail specimen 2

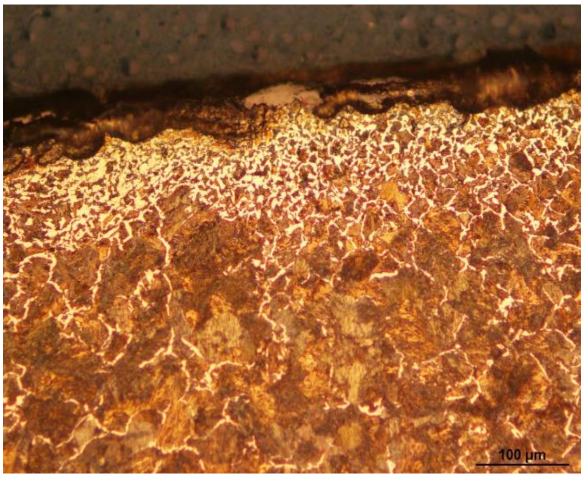


Figure 4.8: Low High Magnification

Figure 4.9: Specimen 2

Figure 4.10: Middle Low Magnification

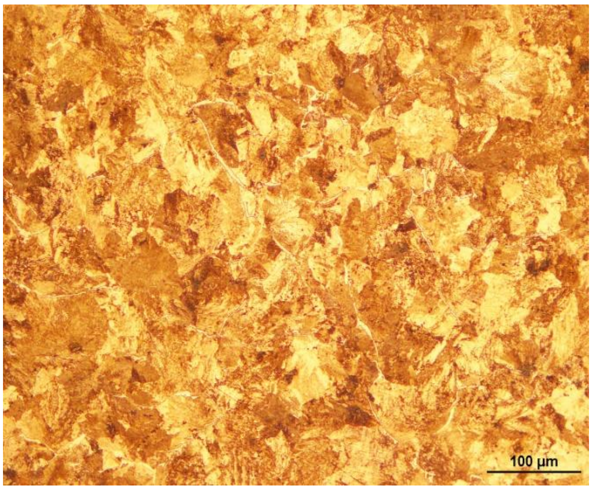


Figure 4.11: Middle Low Magnification

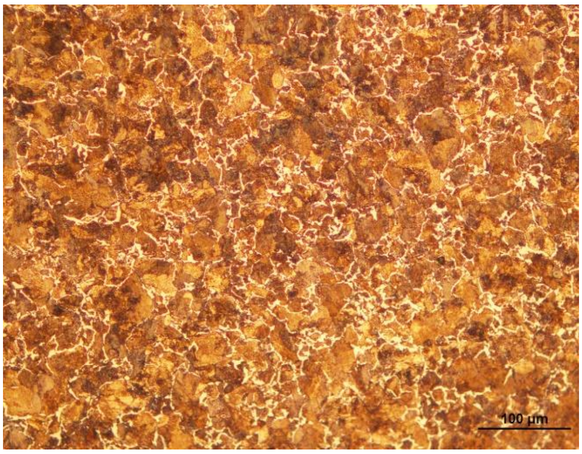


Figure 4.12: Bottom Low Magnification

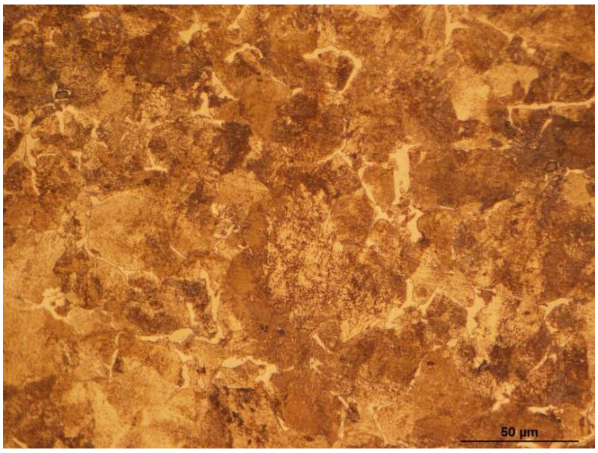


Figure 4.13: Bottom Low Magnification

Derailed steel rail specimen 3

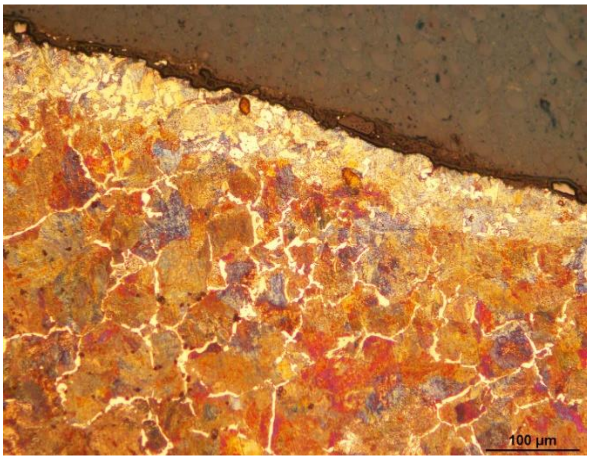


Figure 4.14: Top Low Magnification

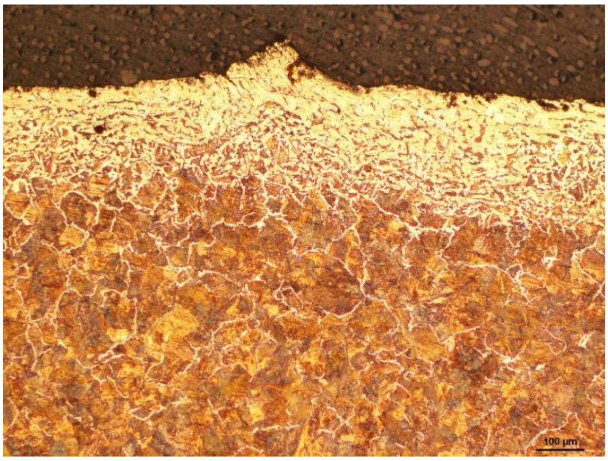


Figure 4.15: Top Low Magnification

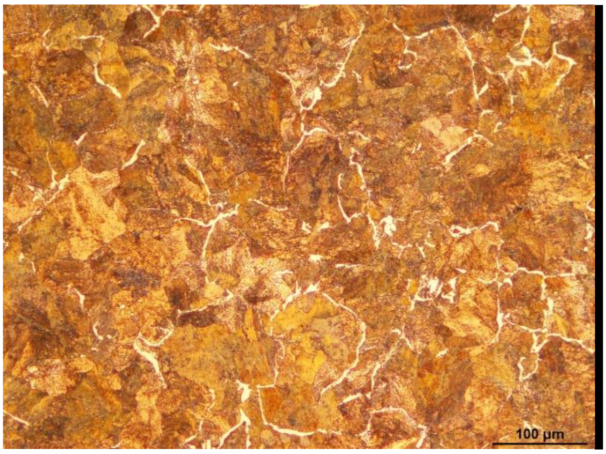


Figure 4.16: Middle Low Magnification

Figure 4.17: Specimen 3

Figure 4.18: Bottom Low Magnification

Figure 4.19: Bottom Low Magnification

Derailed steel rail specimen 4

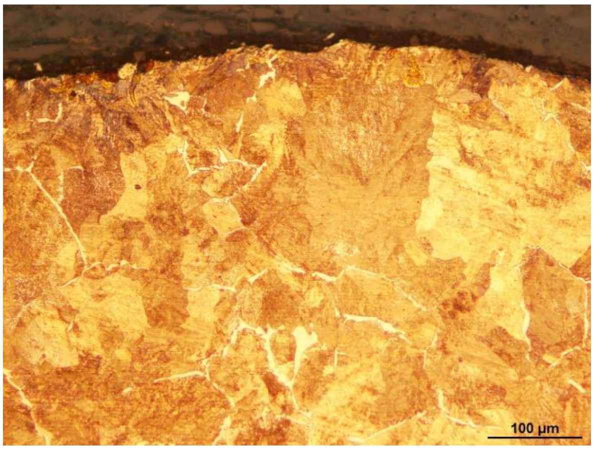


Figure 4.20: Top Low Magnification

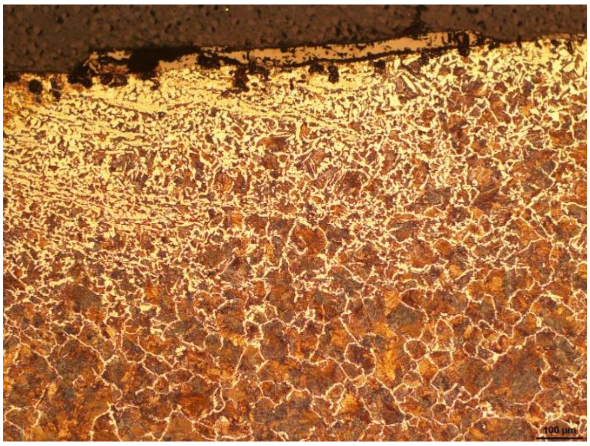


Figure 4.21: Top Low Magnification

Figure 4.22: Middle Low Magnification

Figure 4.23: Specimen 4

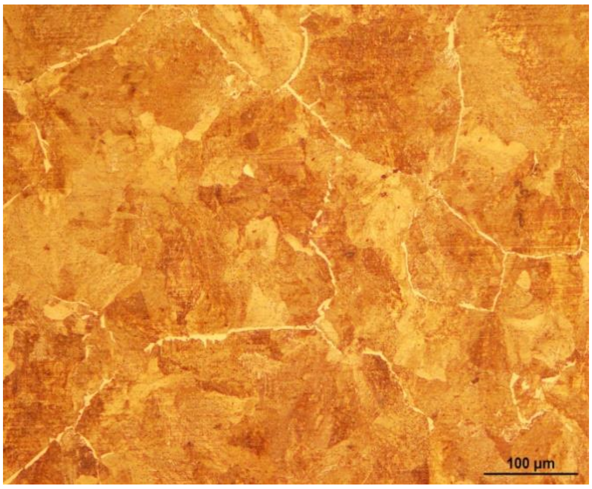


Figure 4.24: Bottom Low Magnification

Figure 4.25: Bottom Low Magnification

Looking at the top surface of specimens, it is evident that decarburization occurs to a certain depth per specimen. Decarburization is the process opposite to carburization, namely the reduction of carbon content. Decarburization occurs when carbon atoms at the steel surface interact with the atmosphere and are removed from the steel as a gaseous phase. Carbon from the interior diffusion towards the surface, moving from high to low concentration and continues until above the upper critical temperature, $AC_{3.}$ From temperatures in the two-phase region, between lower critical temperature, $AC_{1,}$ and, upper critical temperature, $AC_{3,}$ the process is more complex. Carbon diffusion rates in ferrite and austenite are different and are influenced by both temperature and composition.

Decarburization is a serious problem because surface properties are inferior to core properties, resulting in poor wear resistance and low fatigue life. To understand the extent of the problem, two characteristics that may be present at decarburized steel's surface can be measured: Free ferrite layer depth and the partial decarburization depth. The removal of carbon removes hard carbide phases resulting in a softening of the metal, primarily at the surfaces which are in contact with decarburizing gas. Decarburization can be either advantageous or detrimental, depending on the application for which the metal will be used. In the railway industry this is detrimental because this decarburization compromises the durability and longevity of the rail track.

The figures presented above reveal the micrograph of the rail, which is pearlite with mixtures of ferrite and cementite phases. This pearlite structure is relatively strong and can withstand the direct and wear stresses. The top surfaces of the specimens of the rail track grain boundaries are stretched in the direction of motion due to the excessive high temperatures induced to the rail track through the locomotive wheels. These excessive high temperatures are higher than 700 ^{o}C which indirectly are high enough to change the microstructure of the material. Rail track material is polycrystalline, grain boundaries are therefore an important feature of the microstructure. A reduced grain size which forms a grain boundary is directly related to the strength of the microstructures which give the material the desired chemical compositions. Grain boundaries are defects, forming easy diffusion paths. Thus, at high temperatures they weaken the material by permitting the easy diffusion of atoms in a way which leads permanent strain. Thus, for elevated temperature applications it is necessary to minimise the amount of grain boundary area per unit volume.

Thus, due to the stretch grain boundaries at the top surface of the rail track the wear resistance ability are compromised. Grain boundaries at the middle and bottom surfaces of all the specimens, the grain sizes are average with apparent ferrite and cementite forming the pearlite microstructure. Looking at the bottom surface we find small spots within the ferrite grains are inclusions or impurities such as oxides and sulphides. The dark regions are the pearlite. The light-coloured region of the micro structure is the ferrite. The grain boundaries between the ferrite grains can be seen quite clearly. This shows that the heat that was transferred into the material did not affect the microstructure of the specimen discussed above. The material has also experienced a plastic deformation due to the displacement of atoms. This permanent deformation is called slip. Slip occurs when planes of densely packed atoms slide over one another.

Hardness of the surface is also compromised due to the reduction of the carbon content within the material. This is the case because the temperature reaches above 700 ^{o}C, according to the Fe-Fe_3C diagram; there are two phases of ferrite and austenite which have their own microstructure with different properties.

4.4 Hardness Test Results

A Vickers hardness test was conducted with indentation on a polished steel rail sample. The material hardness of the specimen one degreases from the top surface to the bottom surfaces. This is directly related to the grain sizes as shown in table 4.4 below.

Table 4.4: Specimen 1 Hardness results

Vickers Hardness Results (HV10)						
Specimen 1						
Position from Top	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Average
2mm	259	257,5	262,5	266,5	266,5	262,4
4mm	239	239	237	241,5	255,5	242,4
6mm	219,5	233,5	232,5	241	246,5	234,6

The material hardness of specimen 4 increases from the top surface to the bottom surface. This is due to decarburization which leads to the reduction of carbon within the steel. See table 4.5 below.

Table 4.5: Specimen 4 Hardness Results

Vickers Hardness Results (HV10)						
Specimen 4						
Position from Top	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Average
2mm	218,5	219	221	230,5	227,5	223,3
4mm	246	235,4	231,5	234	230,5	235,48
6mm	244,5	240,5	239,5	240	239	240,75

CHAPTER FIVE

5.1 Conclusion

The damaged rail tracks were microstructurally analysed using the microstructural analysis equipment. The steel rail material characterisation revealed the defects occurring at the rail tracks are caused by the decarburization. Decarburization obviously contributes towards the weakening of steel which then reduces wear resistance, reduces strength, enabling fatigue failures to occur more easily and increased rate of crack growth which affect their service life. All these factors are directly related to the hardness of the material.

Looking at what is happening in railway industry, one can easily see that there is high possibility of the occurrence of adhesive wear. Adhesive wear is known as sliding wear, which is due to two surfaces sliding over each other under some applied load. The rate of material loss is due to sliding speed, applied load and ambient temperature. Decarburization occurs in between the sliding metals and some thin films on the rail surface. At high speed of a moving train wheel axle, high temperature is generated causing decarburization.

The microstructural results show that the defects occurring in rail tracks are caused by the process of decarburization. The temperature leading to this process is suggested to be coming the train wheel spin. The train wheel spin may be caused by irregularities occurring at the rail track network. It is obvious that the environmental temperature has no contribution to this problem but the contact surfaces.

5.2 Recommendations

The following recommendations are proposed to prevent decarburization in the railway industry

- Locomotive drivers should use sufficient steel grit when locomotive pulls away from an inclined or still standing position. By ensuring this you prevent wheel spin that can generate excessive temperature which can reach more than 700 ^{o}C.
- Rail grinding needs to be done timeously as per maintenance plan to prevent plastic deformation which is directly proportional to wear
- Axle loads needs to be ensured to be within the design specifications

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