ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL & INDUSTRIAL ENGINEERING

(SMIE)

The Influence of Heat Treatment on Wheel and Rail Wear

A Thesis Submitted to the School of Mechanical and Industrial Engineering in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Railway Engineering

(Rolling Stock Stream)

By

Asmamaw Dagne

Advisor

Dr. Daniel Tilahun Redda (Phd)

March, 2015

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL and INDUSTRIAL ENGINEERING (SMIE)

(ROLLING STOCK)

The Influences of Heat Treatment on Wheel and Rail wear

By

Asmamaw Dagne

February, 2015

Approved by Board of Examining:

Dr.Daniel Tilahun	____________________	____________________
Advisor	**Signature**	**Date**
Mr.Habtamu Tkubet	____________________	____________________
Internal Evaluator	**Signature**	**Date**
Mr.Tsegaye Feleke	____________________	____________________
External Evaluator	**Signature**	**Date**
Dr. Birhanu Beshah	____________________	____________________
Railway Center head	**Signature**	**Date**

Acknowledgment

First of all, I would like to express my deep felt gratitude for my advisor, Dr. Daniel Tilahun Redda, for his interest in this thesis subject, for his helpful comments and suggestions and without whose advises, encouragement and patience, this work would not have been possible.

I would thanks to the School of Mechanical and Industrial Engineering work shop and laboratory head and staff members. Specially to Ato Endalkachew Mekonnen who help me to carry chemical composition test and makes the necessary facilitation to carry the other laboratory test. I thank Ato Ayalesew Dagnew who helps me in carrying the hardness test and the heat treatment process. I also would like to thank Ato Abiy Alemayehu who helps me to carry the roughness test.

I also thanks Ato kibru Agza staff member of School of Electrical and Computer Engineering who make all the necessary electrical set up of twin disc machine during rolling/sliding wear test of rollers.

I would like also to thanks Ato Habtamu Tikubat Instructor and staff member of School of Mechanical and Industrial Engineering who helps me to carry twin disc rolling/sliding wear test by making the necessary coordination between school of Mechanical and Industrial Engineering with that of school of Electrical and computer Engineering.

My special thanks also extends to senior rail way mechanical engineering graduates Ato Mesfin G/Tsadik and Gutanbar Debrie who manufacture twin disc machine and gives me the rollers for rolling/sliding wear test.

Finally, special thanks to my beloved and loyal wife W/ro Genete Fekrie for her patience, advice, support and motivation standing always on my side for the successful accomplishment of this research and for the success of my life at all.

Abstract

Wheel and rail is one of the most important material used to support and guide rail vehicle safely and smoothly. Since wheel and rail suffers from various interacting mechanical and thermal forces, friction modifiers, various contaminants and environmental atmosphere, wear poses large problem on wheel and rail.

Wheel and rail wear can be result in an extensive cost for truck owner, if it is not predicated and prevented in an efficient way. To limit these costs, one measure is to predicate and prevent wheel and rail wear through wear modeling.

The purpose of this research is to investigate the influence of heat treating both wheel and rail at the same time on rolling/sliding wear of wheel and rail.

The rolling/sliding wear of three pair of rollers used to model wheel and rail material is studied using twin disc rolling/sliding wear testing machine. The three pair of rollers used in this study is manufactured from carbon steel having similar hardness and chemical composition as that of standard wheel and rail. Then the two pair of rollers is heat treated in an electric furnace to improve their hardness. Heat treatment was done by heating the rollers to austenite temperature, holding at that temperature for 45minutes for uniform temperature distribution. Water or air plus oil are used as cooling median.

Hardness of the rollers is measured using Rockwell hardness C scale of indentation hardness testing machine. Spectrometry analysis is also carried on the rollers to know the chemical composition of rollers. Roughness of rollers is measured by using surface roughness testing machine.

Results from hardness test showed that the hardness of the roller can be increased by heat treatment. Result of spectrometry analysis shows that the chemical composition of the roller agrees with the chemical composition of wheel and rail. Twin disc wear test of the roller shows that rolling/sliding wear of wheel/rail can be improved by increasing the hardness of wheel and rail by heat treatment.

Keywords: - rolling/sliding, twin disc, spectrometer

Contents

List of tables

List of figures

Abbreviations

UIC	International union of railway
EN	European Union of railway
U	Untreated wheel
N	Normalized wheel
T	Rim chilled
E	Immersed quenched
AALRT	Addis Ababa Light Rail Transit
BS	British Standard
AREMA	American Rail Engineering and maintenance Association
DIN	Deutsches fur Normuag
Q	Force of Kinetic Friction
μ	Coefficient of friction
P	Normal Load
LCF	Low Coefficient of Friction
HCF	High Coefficient of Friction
VHCF	Very High Coefficient of Friction
Sh	Wheel flange height
Sd	Wheel flange thickness
qR	Wheel flange slope
FCC	Face Centered Cubic
BCC	Body centered Cubic
γ	Creepage
P_o	Maximum Contact pressure

R_1, R_2	Rollers radii
BHN	Brinell hardness number
D	Diameter of steel ball
d	diameter of indentation
RA, RB, RC	Rockwell hardness A, B, C, scales respectively
VHN	Vicker hardness number
Ra	Arithmetic average roughness height
Rp	Largest peak height of surface roughness
Ry	Maximum peak height of surface roughness
Rz	average distance between 5 peaks and valleys of surface roughness
ERC	Ethiopia Railway Corporation

CHAPTER ONE: INTRODUCTION

1.1) Background

Travel, in the opening years of the nineteenth century, was a very tedious and slow process. Travelling those days meant going mostly on foot or bullock carts, if and when available.

Fancy a horse with a long train behind it, going down a railway track! Well, that is exactly how the first trains worked. Except that they were known as wagons. When it was discovered that heavy loads could be carried along a smooth track more easily than on a rough road; some coal miners got together and laid wooden rails. On this they placed wagons carrying coal. But a push was not enough to keep the wagons going. So horses were brought in. These wagons are considerably faster than before, but wooden rails were not very strong. So the rail and wheel of the trucks (wagons) were made of iron instead [16].

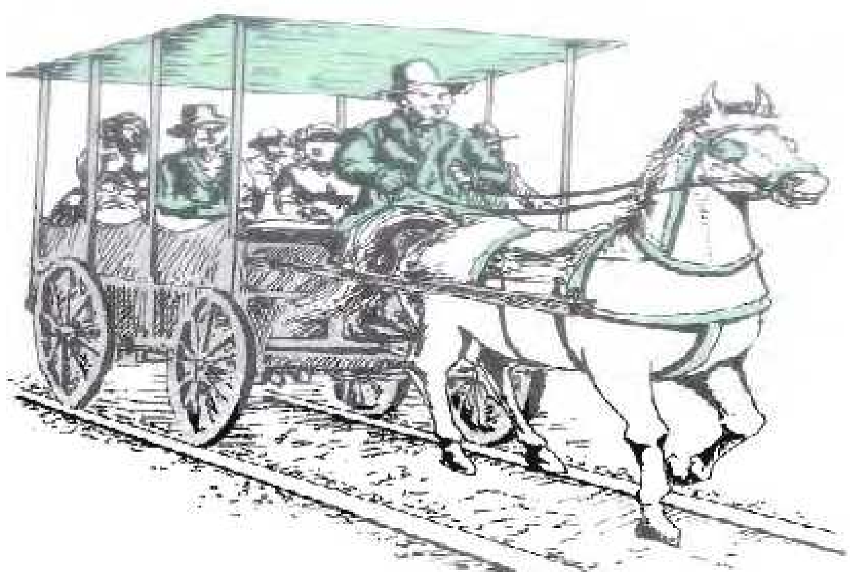


Figure 1.1 Traction by horse Power [42]

Richard Trevithick built the world's first steam locomotive in 1803. His second locomotive, called 'New Castle', was the first to be put to practical use when it began hauling iron a year later at the Peny-darren Iron Works in South Wales [43].

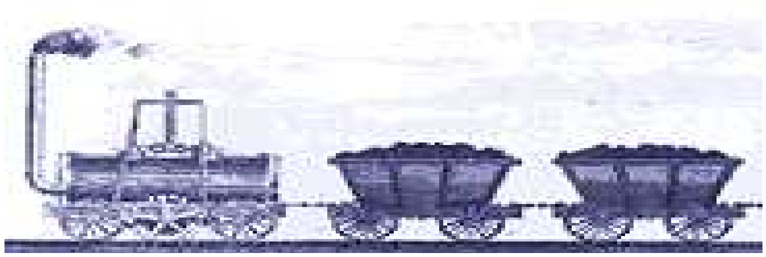


Figure1.2 World's first commercially successful steam locomotive [43]

On 27 September 1825 on the Stockton to Darlington line, the engine locomotion driven by George Stephenson became the world's first steam locomotive to haul passengers on a public railway. 500 passengers were carried mostly in open goods wagons, although a lucky few sat in a purpose built passenger coach called the Experiment. The first railway line to be built between two cities was constructed from Liverpool to Manchester a distance of 48km [43].

The first railway in Africa was built in Ethiopia. It was the brain-child of two French engineers who approached Ethiopian Emperor Menelik II in 1897 with the ambitious idea of constructing a railway to replace the six-week mule trek between Addis Ababa and the French port city of Djibouti [44].

Ethiopia covers a total area of 1.1 million, square kilo-meter. This area is vast and difficult to cover with road transport. Therefore, the country first phase plan is to construct 5000 kilo-meter of railway line. In addition to this the country plans to construct a light transit rail for the capital city of the country for the first time. The total length of this line is 34.25km and it is double track line with a standard gauge [17].

When the train runs on the track, always there is an interaction, between wheel and rail. This interaction is unique in nature, in the sense that rail should not only support the wheel but also guide it. The conicity of the wheel and the profile of railhead will play a great role in ensuring the above. But this lead to development of high contact stresses, which may cause the plastic deformation in the wheel and rail surface leading to increased wear and development of micro& macro cracks [10].

The life of wheel and rails is determined primarily by [41]:

Wear - This occurs primarily on the gauge corner, of the high rails in the sharper curves, due to the high wheel flanging forces. Some wear also occurs on the running surfaces of all rails due to wheel/rail interaction and also due to rail maintenance.

Plastic Flow - which can occur in both high and low rails, Plastic flow is due to the applied wheel/rail contact stresses exceeding the strength of the material.

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 profile change of rails on curves makes a large contribution to track maintenance cost. The profile change on wheels can also be significant. Damage mechanisms such as wear and plastic deformation are the main contributors to profile change [5].

1.2) Purpose

The purpose of this research is mainly to investigate the influence of heat treatment on wheel and rail wear. To carry this investigation; three pair of rollers were manufactured from carbon steel, which have the same mechanical properties and chemical composition as that of standard rail and wheel. Then the two pair of rollers was heat treated to obtain higher hardness of the roller, so that the other higher grade of rail and wheel is obtained.

The heat treatment of the two rollers is done in the following manner. One pair of roller is heat treated by cooling them in a quenchant called water to get the highest hardness of the three rollers, after heating the roller to austenite temperature and holding for certain period of time at austenite temperature. The second pair of roller is heat treated by cooling for ten seconds in air and then cooling in a quenchant called oil to obtain intermediate hardness between water quenched roller and standard roller, after heating the roller to austenite temperature and holding for certain period of time at austenite temperature. Improvement in hardness of heat treated rollers due to heat treatment process carried on the roller also is studied. Once the hardness of the roller is altered by heat treatment it is possible also to study rolling/sliding wear behavior of three different rollers.

Rolling/sliding wear of three pair of rollers is studied by running the rollers on twin disc machine. The mass of the rollers are measured before twin disc wear test and after running the rollers for half an hour on twin disc machine, the machine is switched off and rollers are taken away to measure their mass.

In addition to wear test supporting laboratory test are carried on the roller. These laboratory tests include chemical composition test, hardness test, roughness test and heat treatment.

1.3) Statement of problems

When two surfaces under load move relative to each other, wear will occur. Wear is often defined as damage to one or both surfaces, involving loss of material. The profile change of rails on curves makes a large contribution to track maintenance cost. The profile change on wheels can also be significant. Damage mechanisms such as wear and plastic deformation are the main contributors to profile change. Wheel and rail wear prediction is a current key-topic in the field of railway research. A number of different techniques have been used for studying wear of railway wheel and rail steel. Field measurements have been used in the past to study the causes of wheel and rail wear. Laboratory methods are also employed which includes full-scale laboratory experiments and twin disc set-up. In twin disc test pairs of roller prepare from wheel and rail or rollers having similar mechanical property as wheel and rail are used for rolling/sliding wear test. In addition to this software can be used to simulate wear of wheel and rail.

The rolling/sliding wear behavior of wheel or rail can be improved by heat treating wheel or rail, so that the hardness of rail or wheel is improved. But if the hardness of both wheel and rail increase in the same manner at the same time, what happened to wheel/rail rolling/sliding system wear and wheel and rail rolling/sliding wear? Such and other kinds of questions divert the interest of most researchers to direct their attentions to the area of studying the rolling/sliding wear behavior of three pair rollers having different hardness using twin disc rolling/sliding wear testing machine. Specially the role of increasing the hardness of both rollers at the same time by heat treatment as compared to that of standard roller.

1.4) Objective

1.4.1) General Objective

The main objective of this research is to investigate the influence of heat treatment on wheel and rail wear.

1.4.2) Specific Objectives

The specific objective of this research is

- To study chemical composition of test rollers
- To study the effect of heat treatment on the hardness of f rollers

- To investigate the relation between hardness and cooling rate during heat treatment
- To investigate the relation between hardness and wear
- To collect data obtained from laboratory test, plot mass lost graphically, draw conclusion about the obtained result for rolling/sliding wear test

1.5) General methodology

The methodology that will be applied by the study has been chosen in order to acquire information and deduce conclusions about influence of heat treatment on wheel and rail wear. Experimental investigations have been carried out using twin disc test machine. In order to investigate the influence of heat treatment on wheel and rail wear twin disc rolling/sliding wear test have been carried on three pair of rollers to simulate wheel/rail rolling sliding wear. Two pair of rollers has been heat treated to improve their hardness. Laboratory test such as hardness, chemical composition and roughness test were also carried on the rollers.

1.6) Scope and Limitations

The scope of this study is to carry twin disc rolling/sliding wear test of three pair of rollers. One pair of rollers was standard. The other two pair of rollers was prepared by heat treating standard rollers. In this research the effect of increasing hardness of two pair of rollers by heat treatment on rolling/sliding wear is studied. The limitations of the research are the following

- Lower motor power of twin disc rolling/sliding wear testing machine
- Difficult in assembling and disassembling of test roller
- Higher misalignment during assembling which cause mechanical problem
- Lack of mass measuring device to thousandth of a gram
- Lack of alloyed steel roller

1.7) Thesis Structure

This thesis paper composed of the following five chapters,

Chapter 1; deals with introductory part of the research work. It includes background, purpose, problem statement, objective, methodology and scope and limitation of the research.

In chapter 2; different types of literatures relevant to research topic is reviewed. In this part of the paper different standards of rail and wheel is also included.

Chapter 3; deals with experimental condition and method used. In this part of the paper the various experiments done in this research is discussed. Material required for the research, test roller dimension, test condition and test rig used for this research is also discussed. Various data obtained from experiment is also presented in tabulated form.

In Chapter 4; results obtained from experimental condition are presents and discussed.

Chapter 5; summarizes the findings in this thesis and draws conclusions, which lead to recommendation and suggestions for future work.

CHAPTER TWO: LITURATURE REVIEW

2.1) Wear

Wear is surface damage or the removal of the material from the surface of a solid body as a result of mechanical action of the counter body [5]. The mechanical action may be sliding, rolling, rolling/sliding or impact motion between worn bodies.

In general wear can be of five types

Adhesive wear: - occurs when the material fragments are pulled off one, initially smooth, surface and adhere to the other surface in sliding contact. Material is transferred rather than lost.

Abrasive wear: - occurs when rough surfaces slides over one another, displacing material which forms loss wear particle.

Fatigue wear: - is observed during repeated sliding or rolling, causing the formation cracks which eventually result in the breakup of surfaces.

Corrosive wear: - occurs when sliding wears break away the protective film formed, allowing further corrosion to take place.

Erosive wear: - occurred due to fluid action on mechanical elements.

In railway wear of wheel and rail occurs due to interaction between wheel and rail. Abrasive wear occurs as a small amount of material removal with every wheel passage. Ratcheting refers to wear mechanism that result of high stress exceeding the elastic limit of the material and leading to some form of plastic flow.

In the wheel-rail contact three wear regimes are usually identified; mild, sever and catastrophic [2, 37, 29]. Most types of wear mechanisms have mild and severe forms, and most materials can exhibit both types of behavior. Coarse features and high wear rates are characteristics of severe wear. Severe wear behavior usually cannot be tolerated. The wear regimes named catastrophic wear leads to an extremely large wear rate and this wear regime is often considered unacceptable for the wheel-rail contact [35].

Severe wear is predominant in curves and dry conditions. Mild wear is observed at the wheel tread and rail crown, and severe wear is observed at the wheel flange and gauge face. Wear debris in the size range of 300μm, 500μm and 1000μm are categorized into mild, severe and catastrophic wear respectively [11].

2.2) Rolling /Sliding Contacts

The contact area between surfaces that moves relative to each other is divided into zones with stick and slip. Stick is a situation when there is no relative motion between the opposing surfaces. Slip, on the contrary, occurs when the surfaces moves relative to each other. If only stick occurs in the entire contact area the whole contact is subjected to pure rolling. If only slip occurs in the whole contact area is subjected to sliding. If both stick and slip occurs in the contact area the contact is called rolling/sliding contact [9, 35].

Wheel/rail contact can be divided into stick and slip regions. Longitudinal creep and tangential tractive forces arise due to the slip that occurs in the trailing region of contact patch. With increasing tractive force, the slip region increases and the stick region decrease, resulting in rolling and sliding contact. When the tractive force reaches its saturation value, the stick region disappears, and the entire contact is in a state of pure sliding.

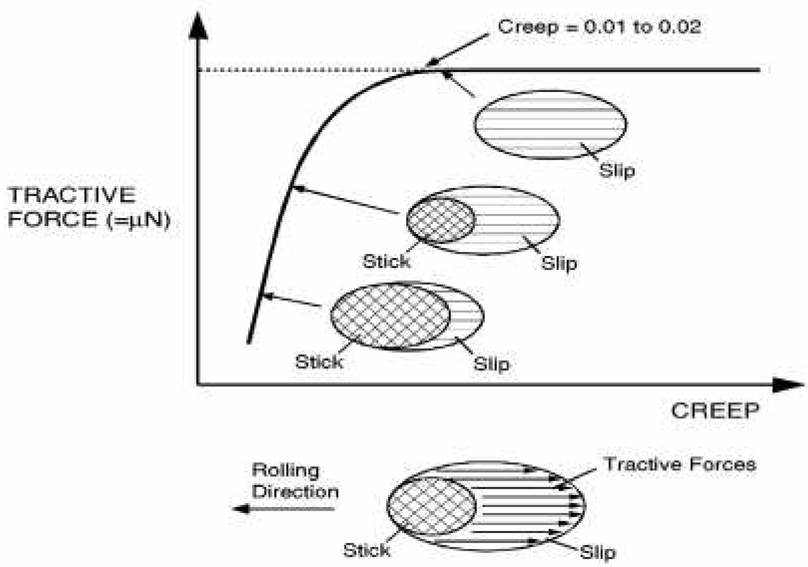


Figure 2.1 Relation between traction and creep in the wheel/rail contact [35]

In wheel/rail contact, both rolling and sliding also occur in the contact zone due to the geometrical fit between wheel and rail. On straight track, the wheel treads is in contact with the rail head, but in curves the wheel flange may be in contact with the gauge corner of the rail. Due to the conicity of the wheel profile, flanging result in large creep and also a large sliding motion in the contact.

2.3) Hardness

Hardness may indicate resistance to abrasion, scratching, cutting or shaping. Hardness is a measured quantity. For hardness testing, indentation hardness test methods are most commonly used type.

All the indentation hardness testing method are based on the principle of forcing a hard material, called an indenter, against a flat surface of the metal, whose hardness is to be measured, under a fixed load. Depending up on its hardness, the metal resist deformation, and finally an impression is made by the indenter on the surface of the metal. The diameter or the depth of impression determines the hardness of the material.

Hardness testers which have wide commercial application are Brinell, Rockwell and Vickers hardness testers. These devices of hardness measurements differ in the shape, size and type of indenter used, the load applied, and the method of measuring the diameter or depth of impression.

2.3.1) Brinell Hardness

The test consist of forcing a steel ball of diameter D under a load P into the test piece and measure the mean diameter d of the indentation left in the surface under test, after removing of the load. The Brinell hardness number BHN is obtained by dividing the test load P by the curved surface area of the indentation.

$$\text{BHN} = \frac{\text{Test Load}}{\text{Surface of indentation}} \qquad 2.1$$

2.3.2) Rockwell Hardness

This is the most widely used hardness test. Its wide-spread use is due to its speed, freedom from personal error, ability to distinguish small hardness difference in hardened steel and small size of the indentation; so that finished heat treated parts can be tested without damage.

The Rockwell hardness test is very similar to the Brinell test, but in this case the machine measures the depth of the impression rather than the diameter. The measurement is read on the dial of a micrometer depth gauge which is connected to the indenter. No microscope is used in Rockwell hardness test. The depth of impression is so calibrated as to read the Rockwell hardness number directly on the dial.

The indenter used in Rockwell hardness machine is either a hardened steel ball or carefully ground diamond cone. Two sizes of balls are used, 1.5 and 3.0mm. The diamond cone is grounded to an angle of 120^0.

In performing Rockwell test, perfectly flat specimen is supported by the anvil of the machine which is raised upward by a jack screw until the specimen come in contact with the indenter. A small load, called the minor load, of 10kg is applied by raising the anvil further up to a definite position on the dial gauge. The final or major load of 150kg is then applied by releasing a system of levers, which force the indenter down into the surface of the specimen. Before the reading of the gauge is taken, the major load is removed leaving the indenter in the new position but only under the minor load of 10kg.

In general three Rockwell scales are used for hardness measurement. Hardened steel is tested on the C scale and the hardness number obtained is written as RC. Softer materials are usually tested on the B scale and hardness values are written as RB. Rockwell A scale is generally used for hard materials, specially sintered carbides produced by powder metallurgy.

2.3.3) Vickers Hardness

In the Vickers machine the indenter is a diamond pyramid having four sides. The angle between the opposite sides is 136^0. This gives an indentation that appears as a square. The hardness number is the total load divided by this area.

$$VHN = \frac{\text{Load}}{\text{Area}} \qquad 2.2$$

In Vickers hardness testing machine, the load is automatically applied and released. The specimen is removed from under the indenter and the diagonal of the impression is measured using a microscope and illuminating lamp.

2.4) Wheel Material

Steel is relatively inexpensive and offers a very attractive combination of strength, ductility, and wear resistance. Almost all wheels worldwide are made from plain carbon-manganese pearlitic steel, which has a lamellar structure of iron and iron carbide. The UIC Leaflet 812-3 for wheels lists seven types of steel, which mainly differ in carbon content, EN 13262 contain only four types.

Table 2.1 Chemical composition and hardness wheels [26]

Grade of steel	Chemical Composition											Brinell Hardness Range
	C max	Si max.	Mn Max.	P max.	S max.	Cr max.	Cu Max.	Mo max.	Ni max.	V max.	Cr+Mo+Ni max.	
	%	%	%	%	%	%	%	%	%	%	%	
R1	-	0.50	1.20	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	179-217
R2	-	0.50	1.20	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	207-248
R3	0.70	0.50	0.90	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	235-277
R6	0.48	0.40	0.75	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	217-262
R7	0.52	0.40	0.80	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	229-277
R8	0.56	0.40	0.80	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	241-285
R9	0.60	0.40	0.80	0.04	0.04	0.30	0.30	0.30	0.08	0.05	0.60	255-311

Wheels are supplied in one of the following conditions [26]. Untreated, in the case of steels R1, R2 and R3, which shall be designated by the letter U. Normalized or normalized and tempered, in the case of steels R1, R2 and R3, which shall be designated by the letter N. Rim chilled, in the case of steels R6, R7, R8 and R9, which shall be designated by the letter T. Immersion quenched and tempered in the case of steels R6, R7, R8 and R9, which shall be designated by the letter E. Addis-Ababa light transit rail project plans to use **ER9** wheel for Addis-Ababa light transit rail vehicle.

2.5) Rail

2.5.1) Rail Nomenclatures and Profile

Before discussing about rail, it is necessary to have some understanding of the terminology that is commonly used with rails. Some of the rail terminologies are discussed as follows [38, 41].

Running Surface - zone on top of the rail head, which makes contact with wheel tread.

Gauge Corner Region - top corner on the gauge side of the rail, which makes contact with the wheel throat region.

Field Corner Region - top corner on the field side of the rail

Fishing Surface - the region at the bottom of the rail head, which makes contact with fish plates.

Rail Head - The region of the rail that is above the extensions of the fishing surfaces to the rail centre line

Rail Foot - the region of the rail that is below the extensions of the top of foot surfaces to the rail centre line.

Rail Web - the region of the rail that is between the rail head and the rail foot

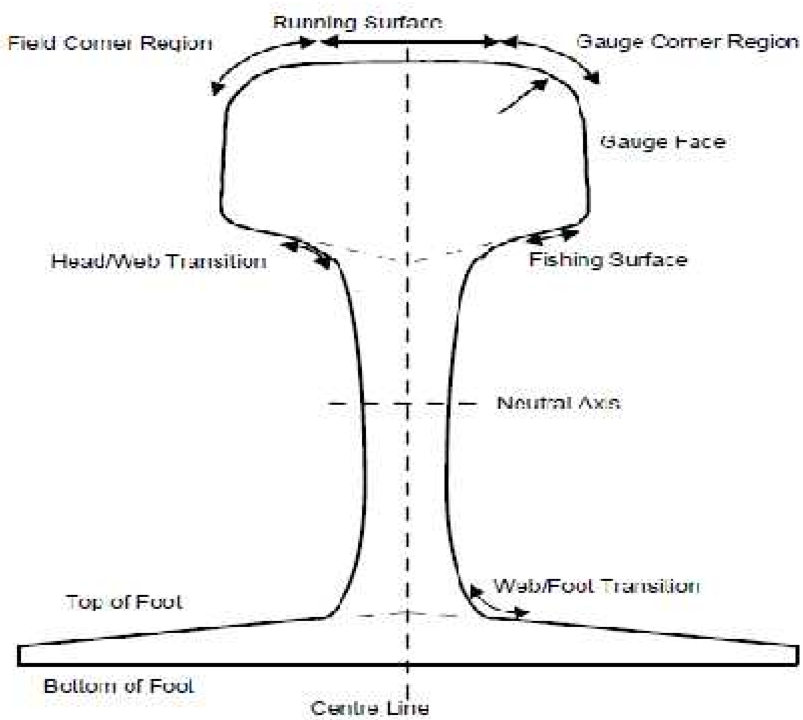


Figure 2.2 Terminologies used with rail [38]

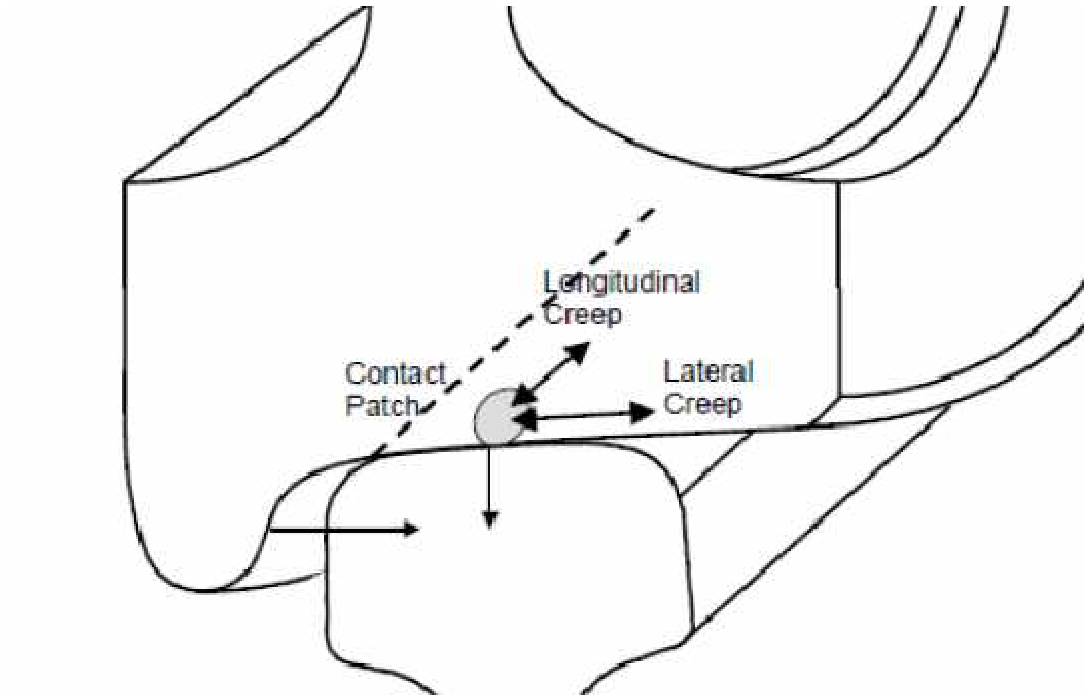


Figure 2.3 Terminologies used for wheel/rail loads [41]

Rail can be classified into two by considering its profile. These are simple wide foot rail and special groove rail. These two types of rails have similar foot, but different rail head. Rail type can be named according to its weight per meter length (kg/m) [39]. The higher the weight, the higher the load it can take, and thus adapts to heavier train. Rail types are specified in UIC, EN specifications [15].

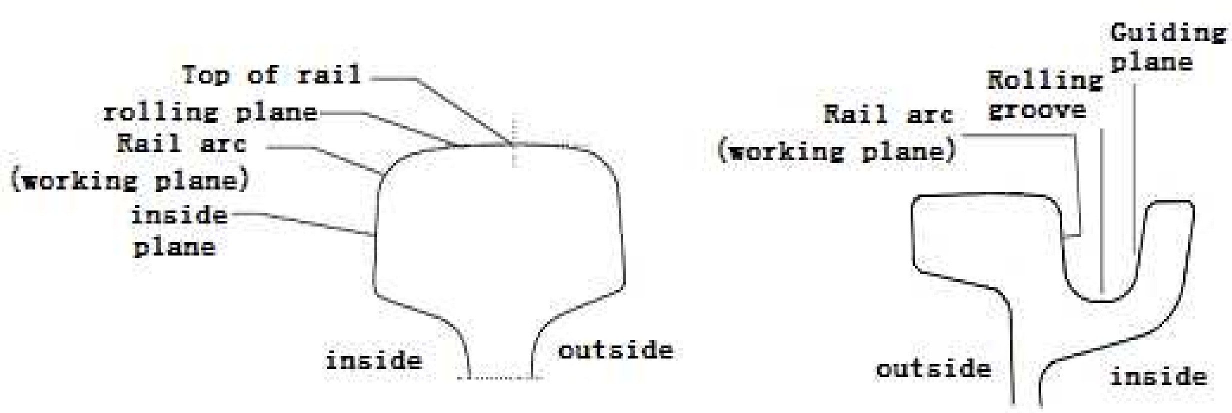


Figure 2.4 Rail head profile and its definition

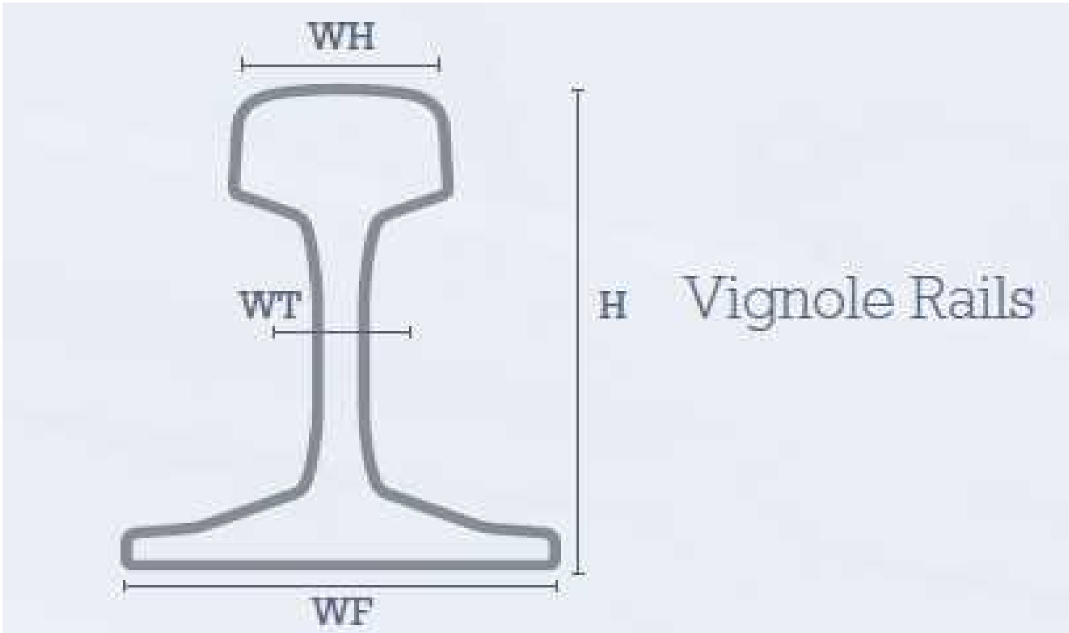


Figure 2.5 Rail dimensions and definitions [39]

Table 2.2 Rail profile and its dimensions [39]

Specification	Profile	Weight (Kg/m)	H	WF	WT	WH
UIC 860.0	60UIC	60.34	172.00	150.00	16.50	72.00
	54UIC	54.43	159.00	140.00	16.00	70.00
	54UIC E	53.81	161.00	125.00	16.00	67.00
EN 13467-1	60E1	60.21	172.00	150.00	16.50	72.00
	60E2	60.05	172.00	150.00	16.50	72.00
	56E1	56.30	158.75	140.00	20.00	69.85
	54E1	54.77	159.00	140.00	16.00	70.00
	54E2	53.82	161.00	125.00	16.00	67.01
	54E4	54.30	154.00	125.00	16.00	67.00
	50E5	49.90	148.00	14.00	14.00	67.00
	50E6	50.90	153.00	15.50	15.50	65.00
	49E1	49.39	125.00	14.00	14.00	67.00
	46E1	46.17	125.00	14.00	14.00	65.00
	46E2	46.27	134.00	15.00	15.00	62.00
	46E4	46.90	135.00	14.00	14.00	65.00
BS 11:85	BS113A	56.39	158.75	139.70	20.00	72.01
	BS 100A	50.18	152.40	139.70	20.00	73.01
	BS 90A	45.02	142.88	127.00	13.898	66.68
	BS 80A	39.76	133.35	117.47	13.10	63.43
	BS 80R	39.67	133.65	127.00	13.49	63.50
	BS 70A	34.81	110.33	123.82	12.30	62.19
	Bs 60R	29.82	114.30	109.54	11.11	57.15
AREMA	141RE	69.83	188.91	152.40	17.48	77.79
	136RE	67.44	185.74	152.40	17.46	74.61
DIN 5902	S49	49.43	149.00	125.00	14.00	67.00
	S49A	49.05	148.00	125.00	14.00	67.00
	S40	36.54	128.00	115.00	13.00	58.27
	S33	31.18	126.00	105.00	11.00	58.00

2.5.2) Rail material

Rails as an important part of the railway infrastructure have exactly level of quality. Quality of rails is prescribed by international union Railway UIC 860, European Union of Railways EN13674 and Chinese standard. The characteristic quality tracks are prescribed standards of the International Union Railway published UIC860 and European Union of Railways published EN13674 [27].

Requirements of UIC 860

Standard of UIC 860 prescribe four types pearlite steel rails. For a selection of different types of rails, the corresponding chemical composition and mechanical property requirements are presented in Table 2.3 according to standard UlC 860

The increase in wear resistance is based on a theory of the mutual influence of certain elements. Carbon influences the mechanical properties through the volume fraction of cementite and the content of pearlite. Manganese influences the temperature decrease of the eutectoidal reaction and the fineness of pearlite lamellae, that is, the reduction in the inter-lamellar distance [27].

Table2.3 Rail classification according to UIC 860 [27]

Steel grade	Chemical composition by %						Tensile strength N/mm2
	C	Si	Mn	Cr	P max.	S max.	
700	0.40-0.60	0.05-0.35	0.80-1.25	-	0.05	0.05	680-830
900 A	0.60-0.80	0.10-0.50	0.80-1.30	-	0.04	0.04	min.880
900 B	0.55-0.75	0.10-0.50	1.30-1.70	-	0.04	0.04	800-1030
1100	0.60-0.82	0.30-0.90	0.90-1.30	0.80-1.30	0.04	0.03	Min. 1080

Requirements of EN 13674

The European standard EN13674-1:2008-1 is the comprehensive specification generally accepted by all major Infrastructure Managers for the supply of rail sections and rail steels [7]. A basic grade of steel used for the production of rails and sections for railroad switches is carbon-manganese steel with a pearlitic structure [18]. The European Rail Standard PN-EN 13674-1:2008-1 distinguishes seven pearlitic steel grades, the hardness of which varies in a wide range from 200 to 390 HB [28].

Table2.4 Steel grades and branding lines according to prEN13674-1:2008 [28, 7]

Steel Grade	% by mass			Hardness BHN
	C	Si	Mn	
R200	0.38/0.62	0.13/0.6	0.65/1.25	200-240
R220	0.50/0.60	0.20/0.60	1.00/1.25	220-260
R260	0.6/0.82	0.13/0.60	0.65/1.25	260-300
R260Mn	0.53/0.77	0.13/0.62	1.25/1.75	260-300
R320Mn	0.58/0.82	0.48/1.12	0.75/1.25	320-360
R350HT	0.7/0.82	0.13/0.60	0.65/1.25	350-390
R350LTH	0.70/0.82	0.13/0.60	0.65/1.25	350-390

The steel grades mentioned in the leaflet are the grades R260 and R260Mn “standard grades” and the grades R320Cr, R350HT and R350LHT “hard grades”.

Requirements of China

China rail standard distinguishes five steel grades, the hardness of which varies in a wide range from 260 to 360 HB. For a selection of different types of rails, the corresponding chemical composition and mechanical property requirements are presented in Table 2.5and 2.6 according to Chinese standard respectively.

Table 2.5 Chemical composition rail as Chinese standards

Rail Grade	Chemical composition by %							
	C	Si	Mn	P	S	Cr	V	Al
U71Mn	0.65-0.76	0.15-0.58	0.70-1.20	≤0.030	≤0.025	—	—	≤0.010
U75V	0.71-0.80	0.50-0.80	0.75-1.05	≤0.030	≤0.025	—	0.04-0.12	≤0.010
U77MnCr	0.72-0.82	0.10-0.50	0.80-1.10	≤0.025	≤0.025	0.25-0.40	—	≤0.010
U78CrV	0.72-0.82	0.50-0.80	0.70-1.05	≤0.025	≤0.025	0.30-0.50	0.04-0.12	≤0.010
U76CrRE	0.71-0.81	0.50-0.80	0.80-1.10	≤0.025	≤0.025	0.25-0.35	0.04-0.08	≤0.010

Table 2.6 Mechanical properties of rail as per chinese standard

Rail Grade	Tensile Strength in MPa	Percent Elongation	Brinell hardness number
U71Mn	≥880	≥10	260-300
U75V	≥980	≥10	280-320
U77MnCr	≥980	≥9	290-330
U78CrV	≥1080	≥9	310-360
U76CrRE	≥1080	≥9	310-360

The rail used for Addis-Ababa light rail transit was **U71Mn**.

2.6) Wheel on the Rail

The wheel is coned and the rail head slightly curved as shown in Figure 2.6. The degree of coning is set by the railway company and it varies from place to place [40].

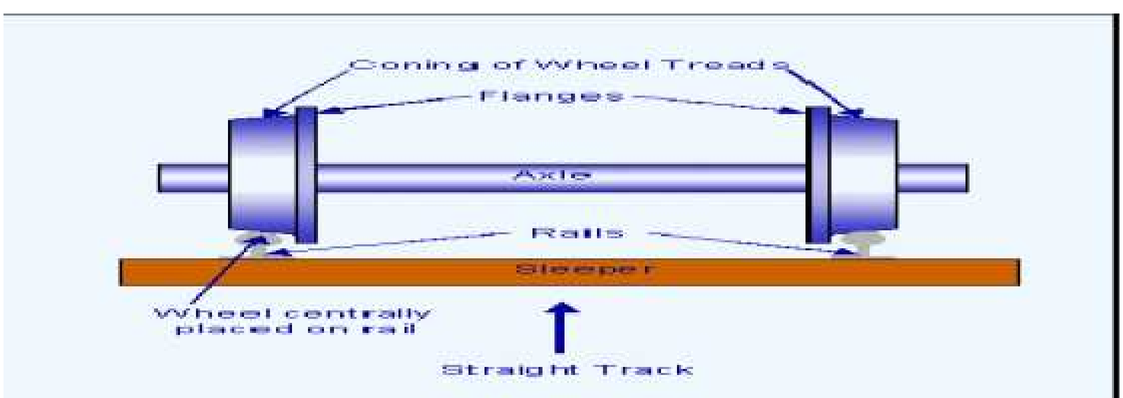


Figure 2.6 Shape and location of wheels and rails on straight track [40]

Note that the flanges do not normally touch the rails. On curved track, the outer wheel has a greater distance to travel than the inner wheel. To compensate for this, the wheel-set moves sideways in relation to the track so that the larger wheel radius on the inner edge of the wheel is used on the outer rail of the curve, as shown in Figure 2.7.

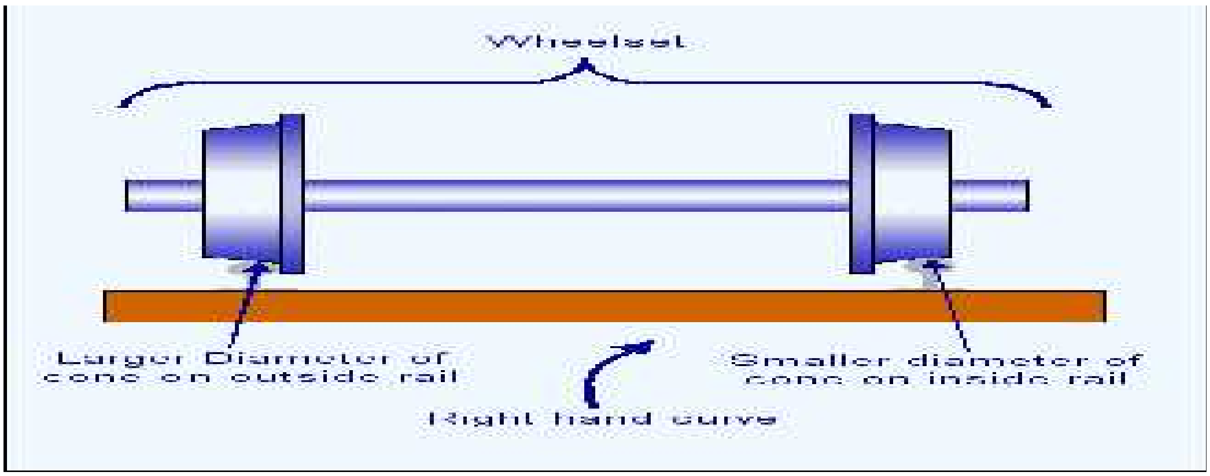


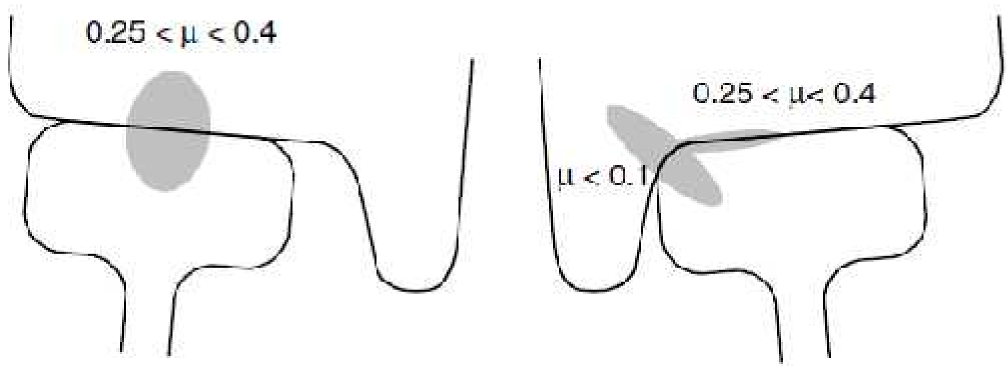
Figure 2.7 Location of the wheels in relation to the rails on curved track [40]

The inner wheel uses the outer edge of its tread to reduce the travelled distance during the passage round the curve. The flange of the outer wheel will only touch the movement of the train round the curved rail is not in exact symmetry with the geometry of the track. This can occur due to incorrect speed or poor mechanical condition of the track or train. It naturally causes wear [40].

Many operators use flange or rail greasing to ease the passage of wheels on curves. It is important to ensure that the amount of lubricant applied is exactly right. Too much will cause the tread to become contaminated and will lead to skidding and flatted wheels. There will always be some slippage between the wheel and rail on curves.

2.6.1) Wheel/Rail Friction

If a force is applied to two bodies so as to generate a pressure for one to slid against the other, this is opposed by a tangential force of friction Q. If the force is increased until sliding across the complete contact just occurs, then that is the point of limiting friction from where Amonton's Law applies, that is Q represent the force of Kinetic friction such that $Q=\mu P$, where μ is the coefficient of kinetic friction and P is applied normal load. If the force is insufficient to cause complete sliding, as in tractive propulsion of a locomotive, the average value of Q for the complete contact patch is available and it is less than μP, which is a force of static friction. Q/P for rolling/sliding is termed as the Coefficient of traction.



Low rail High rail

Figure 2.8 Ideal friction coefficients in the wheel/rail contact [5, 19]

Friction Management is the ability to control friction at the rail/wheel interface at levels between 0.06 and up to 0.60. Friction modifiers can be applied to the wheel/rail contact to generate the required coefficients of friction. Friction modifiers are classified according to their influence after full slip conditions have been reached in the wheel/rail contact. If friction increases after the saturation point, the modifiers have positive friction properties, if friction reduces, the modifier has negative friction properties [4].

Friction modifiers can be divided into three categories [5, 19]. Low coefficient friction modifiers called lubricants are used to give friction coefficients less than 0.1 at the wheel flange/gauge corner interface. High friction modifiers with intermediate friction coefficients of 0.17 − 0.35 are used in wheel tread-rail top applications. Very high friction modifiers called friction enhancers are used to increase adhesion for both traction and braking.

Figure 2.9 illustrates the frictional characteristics of three different friction management products compared to steel on steel dashed line under different creep conditions. LCF is a dry solid stick lubricant that maintains the coefficient of friction below 0.1 over a wide range of creep conditions. It is applied to the wheel flange, and because of its dry solid nature does not migrate to the wheel tread or the top of the rail. HPF is a friction modifier with positive friction characteristics that maintains coefficient of friction from 0.17 to 0.35 depending on creep conditions, and is applied to the wheel tread. VHPF provides very high positive friction up to 0.6 that can effectively increase traction and increase brake performance [20].

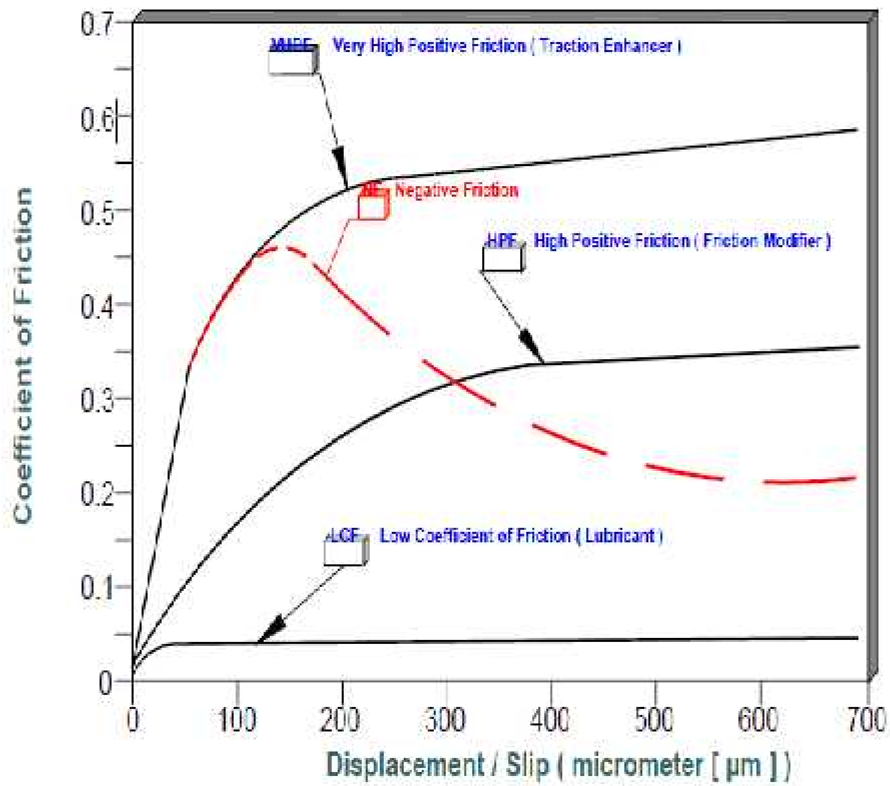


Figure 2.9 Friction characteristics of different friction management products [20]

When rail vehicles are in motion the friction between the wheel and rail leads to high wear and tear on wheel flanges and rail faces, undesirable screeching above all in curves and considerable energy losses during acceleration. Selective, precision application of lubricant to the flange faces of the locomotive or motor car wheels lubricates not only these wheels and rail face but also all the following wheels.

The lubricant sprayed on the first wheel flange in the direction of travel is transferred to the rail face, thus lubricating the following wheel flanges. A large number of motor cars with wheel flange lubrication assure requisite lubrication of the rail network, the basis on which wheel flange lubrication systems achieve the desired effect.

2.6.2) Wheel and Rail Wear

The wear that inevitably occurs between the wheel and the rail while the vehicle is moving depends on a large number of factors, among which sliding phenomena inside the contact patch, the normal force transmitted, the friction coefficient, lubrication conditions, size and shape of the contact patch etc. Wear on wheels and rails makes it necessary for equipment to be replaced when the upper safety limits have been reached and, as a general rule, the vehicle also sustains losses in terms of dynamic performance. Worn profiles tend to be less stable and show lower performance levels when negotiating curved tracks, and this makes reducing the wear index a major factor in the design of railway vehicles [25].

During service, the steel wheels of railway vehicles are subjected to wear. These changes in the profile geometry affect the dynamic behavior of the whole transit and, consequently, their evolution has to be assessed. A common method for wheel wear geometric analysis is provided in the UIC 510-2 leaflet [31]. According to this standard, a good and pragmatic approach for the geometric characterization of the wheels wear is based on the measurement of the profile parameters Sh, Sd and qR. These parameters are represented in Figure 2.10, where Sh is the flange height, Sd represents the flange thickness, qR is the flange slope quota, D is the wheel diameter, ΔD represents the deviation of roundness and d is the wheel-set external gauge. The quantities L_1, L_2 and L_3 are the reference quotas for the measurement of the wheel wear parameters [30].

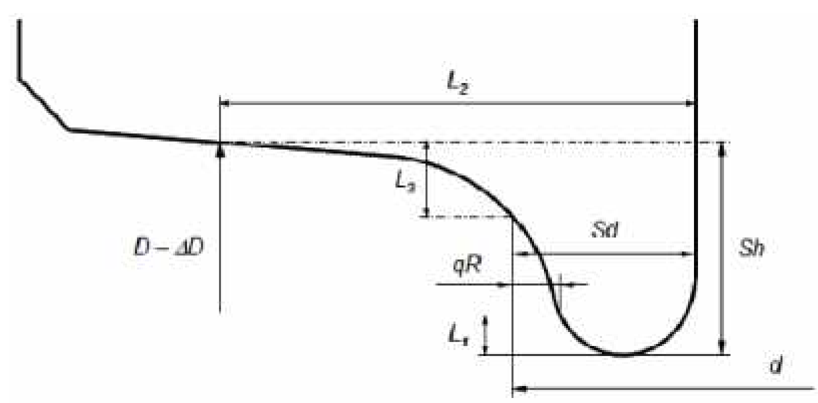


Figure 2.10 Wear parameters for railway steel wheels [21]

The wheel wear characterization based on programmed measurements of the geometrical parameters Sh, Sd and qR is widely used by the railway industry. Such assessment is a relevant criterion to evaluate the wear state of the wheels. This approach consists of monitoring periodically the geometrical parameters of the wheel profiles in order to check if they have reached the safety limit values defined by the technical specifications. When that happens, it means that the wheels have to be re-profiled [30]. According to the UIC 510-2 [31], the admissible values for parameters Sh, Sd and qR are defined in Table 2.7.

Table 2.7 Admissible values for wheel wear parameters [30]

Wheel Profile	Wear parameters (mm)			Reference Quota (mm)			Flange Angle
	Sh	Sd	qR	L_1	L_2	L_3	
New profile (mm) (760<D<1000)	28	32.5	10.8	2	70	10	70^0
Allowable (mm) (840<D<1000)	≤36	≥22	>6.5				-

The measurement of the wear parameters Sd and qR allows predicting the influence of the wear state of the wheel profiles on the dynamic behavior of the railway vehicles. For example, the flange thickness Sd is very important as it limits the lateral clearance of wheel-set with respect to the track, which influences the vehicle stability. The flange slope quota qR is also an important parameter. If it is too small, the wheel flange will be almost vertical, which implies that the transitions such as switches and crossing, flange contacts will occur abruptly. Such a situation originates very high contact forces that damage both vehicle and infrastructure. From Table 2.7 it is also noticeable that the difference between the new and the allowable values for the flange height Sh reveals that the maximum wear depth admissible in the wheel tread is 8 mm.

Different types of Wheel wear can be summarized as follows [22]

Thin Flange- when the flange thickness reduces to less than 16 mm, the flange is called a thin flange. It should be measured at the distance of 13mm below the flange tip. A thin flange increases lateral play between the wheel set and track and increases. Lateral oscillations and Angularity of wheel set on run.

Worn Out Flange- when radius at the root of the flange becomes less than 13 mm, it is called worn out flange. A worn out flange increases the value of μ [22].

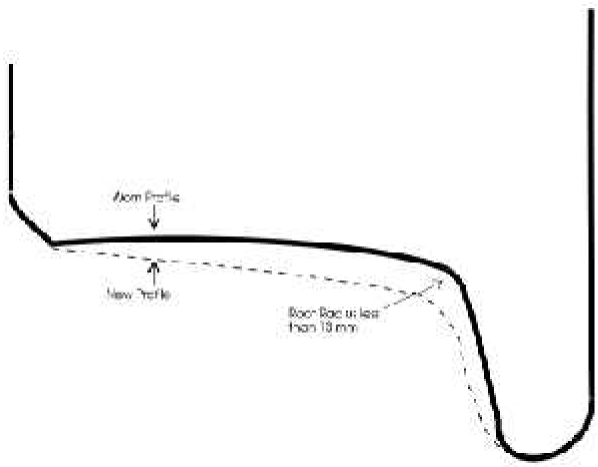


Figure 2.11 Worn out flange [22]

Deep Flange: - When the depth of flange, measured from the flange top to a point on the wheel tread, becomes greater than 35 mm, it is called a deep flange.

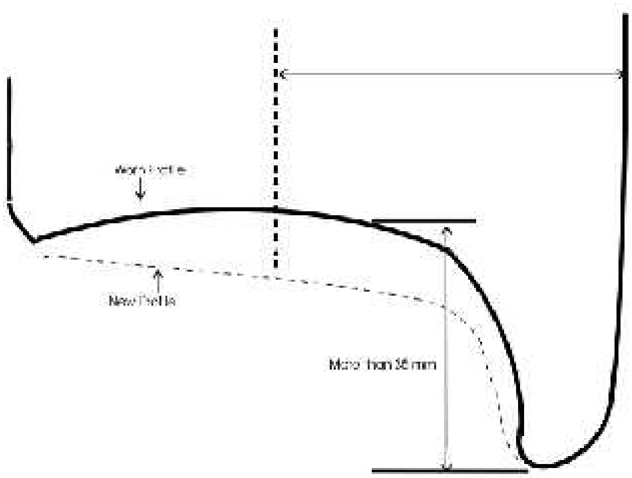
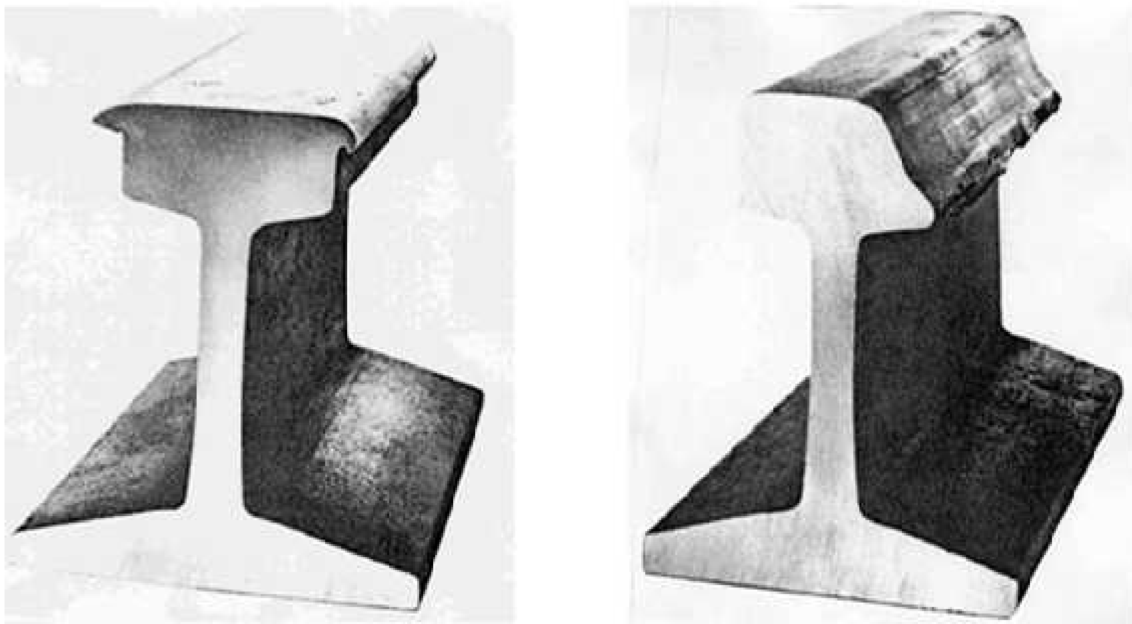


Figure 2.12 Deep Flange wear [22]

Wear occurs in rail with increasing operation time. Rail wear is much more serious in sharp curve than in straight track and large curves. Wear occurs in longitudinal direction which causes high vibration and thus leads to poor ride comfort and quick track damage. Wave with a length greater than 8cm called corrugation, with length between 3cm to 8cm called ripple [11].



a) b)

Figure 2.13 Wear of rail in operation a) Inner rail b) Outer rail

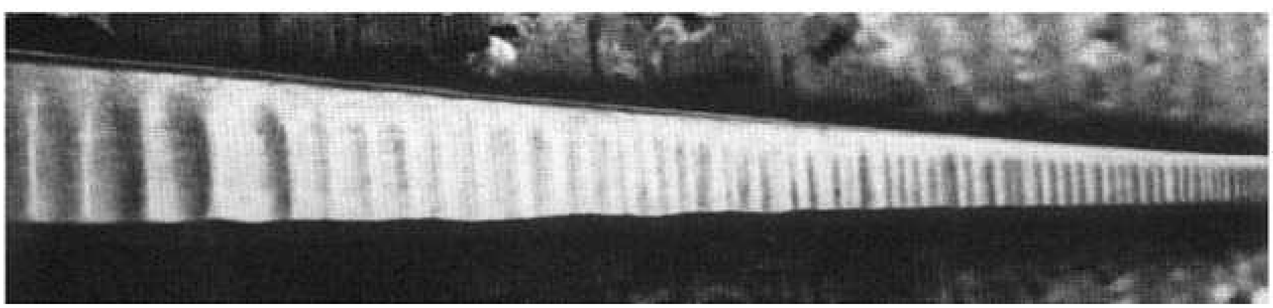


Figure 2.14 Rail corrugation

According to material prepared by CAMTEH/M/3, by Ministry of India railway called A Technical Guide on Derailments [2], rail wear can be one of the following Vertical, Lateral and Angular.

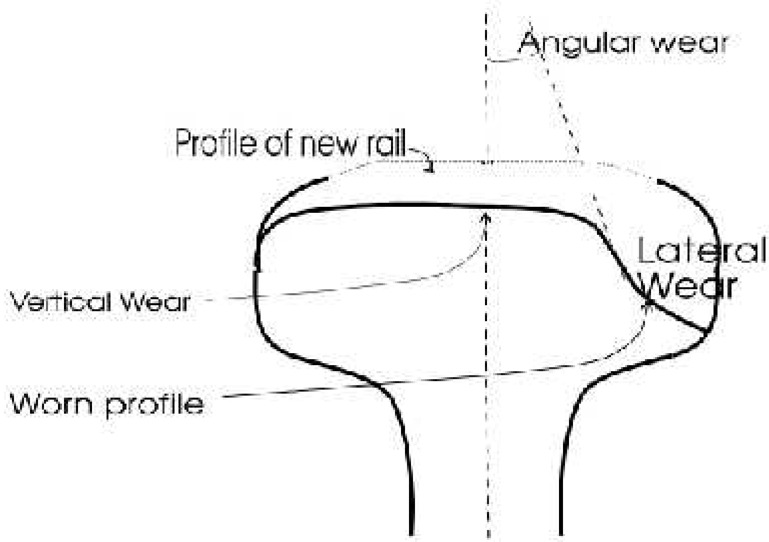


Figure 2.15 Different types of rail Wear [2]

If vertical wear is excessive, a deep flange may ride over the fish plate and may damage the track components. Excessive lateral wear increases the play between the wheel set and the track which would contribute to increased oscillations and greater angularity of the flange during run. The angular wear is most critical. Angular wear is invariably encountered on the outer rails on sharp curves as well as on turn outs. If angular wear is excessive, the rail presents an inclined plain to the wheel on which the flange may slide upwards.

2.7) Fundamentals of Heat Treatment

Fundamentals of heat treating steel according to ASM reference called practical heat treating is summarized as follows [32].

Steel an important material because of its tremendous flexibility in metal working and heat treating to produce a wide variety of mechanical, physical, and chemical properties. From metallurgical point of view broad possibilities provided by the use of steel are attributed mainly to two all-important metallurgical phenomena: iron is an allotropic element; that is, it can exist in more than one crystalline form; and the carbon atom is only 1/30 the size of the iron atom. These phenomena are thus the underlying principles that permit the achievements that are possible through heat treatment [32].

The constitutional phase diagram for commercially pure iron is presented in Figure 2.16. As pure iron, in this case, cools, it changes from one phase to another at constant temperature.

Pure iron solidifies from the liquid at 1538^0C or 2800^0c. A crystalline structure, known as ferrite, or delta iron, is formed at point a. As cooling proceeds further to point b to temperature 1395^0C crystalline structure known as gamma iron formed. As cooling further proceeds to temperature of 910^0C or 1675^0F point c crystalline structure known as alpha iron is formed. The entire field below 910^0C or 1675^0F is composed of alpha ferrite, which continues on down to room temperature and below.

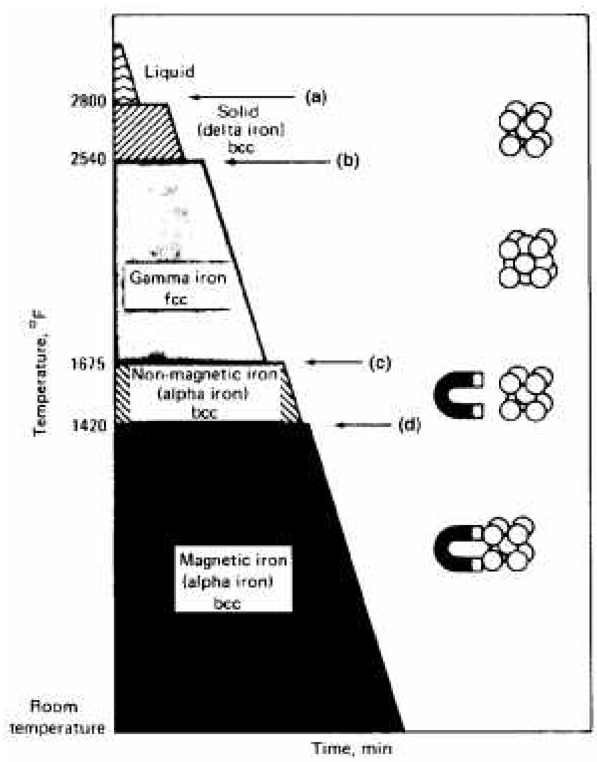


Figure 2.16 Phase diagram of pure iron [32]

Metal alloys are usually formed by mixing together two or more metals in their molten state. The two most common methods of alloying are by atom exchange and by the interstitial mechanism. The exchange mechanism simply involves trading of atoms from one lattice system to another. Interstitial alloying requires that there be a large variation in atom sizes between the elements involved. Because the small carbon atom is 1/30 the size of the iron atom, interstitial alloying is easily facilitated. Under certain conditions, the tiny carbon atoms enter the lattice the interstices of the iron crystal [32].

When carbon atoms are present in iron, two changes occur. First, transformation temperatures are lowered, and second, transformation takes place over a range of temperatures rather than at a single temperature. These data are shown in the well-known iron-cementite phase daigram.

The area denoted as austenite is actually an area within which iron can retain much dissolved carbon. Austenite is the term applied to the solid solution of carbon in gamma iron, and, like other constituents in the diagram, austenite has a certain definite solubility for carbon, which depends on the temperature bounded by AGFED. As indicated by the austenite area, the carbon content of austenite can range from 0 to 2%. Under normal conditions, austenite cannot exist at room temperature in plain carbon steels; it can exist only at elevated temperatures bounded by the lines AGFED. Although austenite does not ordinarily exist at room temperature in carbon steels, the rate at which steels are cooled from the austenitic range has a profound influence on the room temperature microstructure and properties of carbon steels. Thus, the phase known as austenite is FCC iron; capable of containing up to 2% dissolved carbon.

The solubility limit for carbon in the BCC structure of iron-carbon alloys is shown by the line ABC. This area of the diagram is labeled alpha, and the phase is called ferrite. The maximum solubility of carbon in alpha iron called ferrite is 0.025% and occurs at 725^0C or 1340^0F. At room temperature, ferrite can dissolve only 0.008% C. The large area extending vertically from zero to the line BGH temperature 725^0C or 1340^0F and horizontally to 2% C is denoted as a two-phase area ferrite plus cementite. The line BGH is known as the lower transformation temperature A1. The line AGF is the upper transformation temperature A3. The triangular area ABG is also a two-phase area, but the phases are alpha and gamma, or ferrite plus austenite. As carbon content increases, the A3 temperature decreases until the eutectoid is reached at 725^0C or 1340^0F and 0.80% C point G. This is considered a saturation point; it indicates the amount of carbon that can be dissolved at 725^0C 1340^0F. A1 and A3 intersect at G and remain as one line to point H as indicated. The area above 725^0C or 1340^0F and to the right of the austenite region is another two-phase field austenite plus carbide.

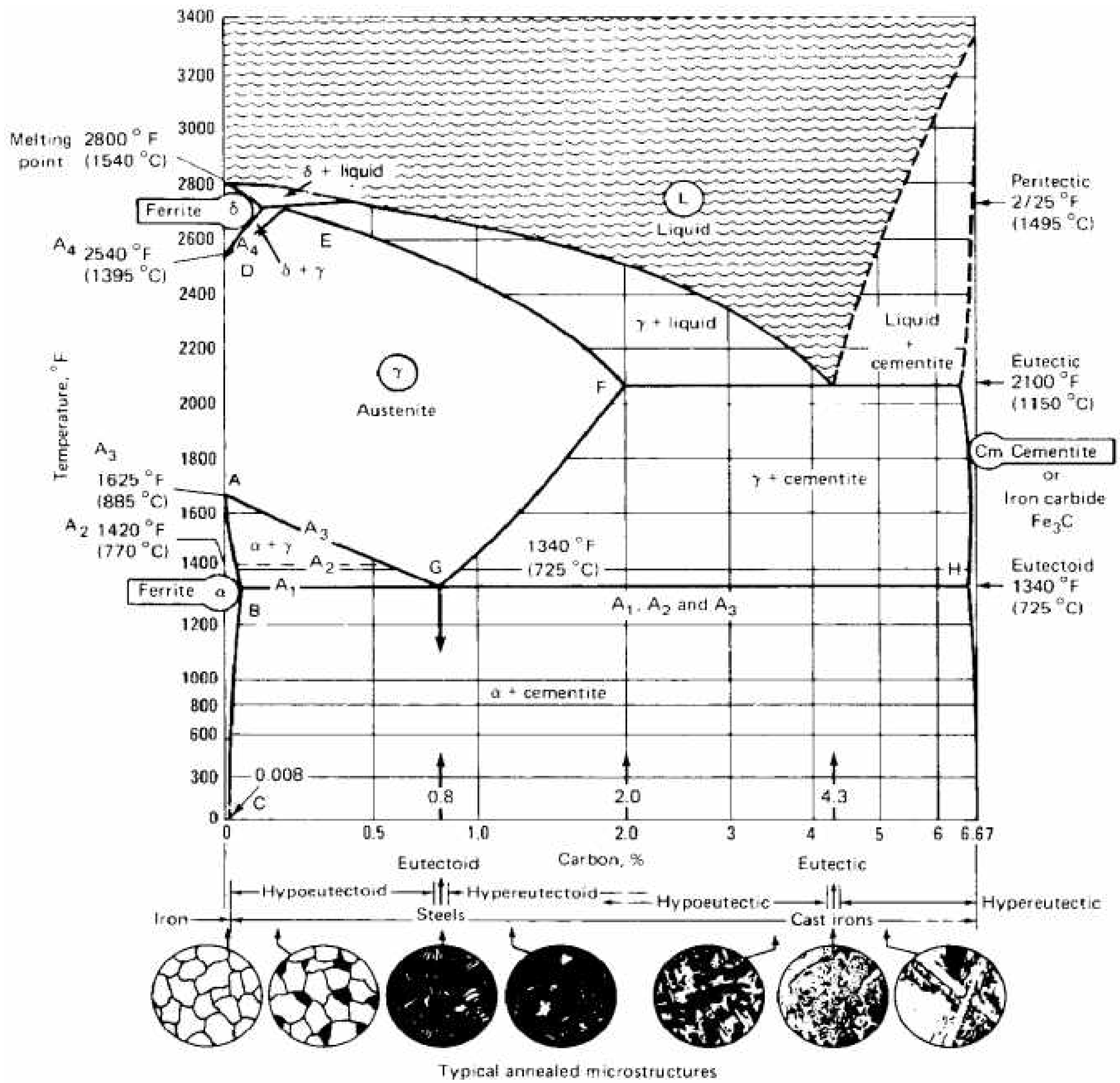


Figure 2.17 Iron-cementite phase diagrams [32]

Now as an example, when 0.40% carbon steel is heated to 725^{0}C or 1340^{0}F, its crystalline structure begins to transform to austenite; transformation is not complete however until a temperature of approximately 815^{0}C or 1500^{0}F is reached. In contrast steel containing 0.80% C transforms completely to austenite when heated to 725^{0}C or 1340^{0}F. Now assume that a steel containing 1.0% C is heated to 725^{0}C or 1340^{0}F or just above. At this temperature, austenite is formed, but because only 0.80% C can be completely dissolved in the austenite, 0.20% C remains as cementite, unless the temperature is increased. However, if the temperature of 1.0% carbon steel is increased above about 790^0C 1450^0F, the line GF is intersected, and all of the carbon is thus dissolved. Increasing temperature gradually increases the amount of carbon that can be taken into solid solution. For instance, at 1040^0C or 1900^0F, approximately 1.6% C can be dissolved [32].

2.7.1) Transformation of Austenite

When a steel containing 0.50% C is heated to 815^0C or 1500^0F, all of the carbon will be dissolved. Under these conditions, all of the carbon atoms will dissolve in the interstices of the FCC crystal. If the alloy is cooled slowly, transformation to the BCC or alpha phase begins when the temperature drops below approximately 790^0C 1450^0F. As the temperature continues to decrease, the transformation is essentially complete at 725^0C or 1340^0F. During this transformation, the carbon atoms escape from the lattice because they are essentially insoluble in the alpha crystal BCC. Thus, in slow cooling, the alloy for all practical purposes returns to the same state in terms of phase that it was before heating to form austenite. The same mechanism occurs with higher carbon steels. In addition to the entry and exit of the carbon atoms through the interstices of the iron atoms, other changes occur that affect the practical aspects of heat treating. First, a magnetic change occurs at 770^0C or 1420^0F. When an iron-carbon alloy is converted to austenite by heat, a large absorption of heat occurs at the transformation temperature. Likewise, when the alloy changes from gamma to alpha that is austenite to ferrite, heat evolves. What happens when the alloy is cooled rapidly? When the alloy is cooled suddenly, the carbon atoms cannot make an orderly escape from the iron lattice, causing distortion of the lattice, which manifests itself in the form of hardness and/or strength. If cooling is fast enough, a new structure known as martensite is formed, although this new structure an aggregate of iron and cementite is in the alpha phase.

2.7.2) Effect of Time on Transformation

TTT curve is presented for 0.77% eutectoid carbon steel. In analyzing TTT curve begin with line Ae_1 725^0C or 1340^0F. Above this temperature, austenite exists only for eutectoid steel. When the steel is cooled and held at a temperature just below Ae_1 705^0C or 1300^0F, transformation begins following line Ps Bs, and the transformation product is coarse pearlite called spheroidite. Now assume a lower temperature 650^0C or 1200^0F on line Ps Bs line of beginning transformation;

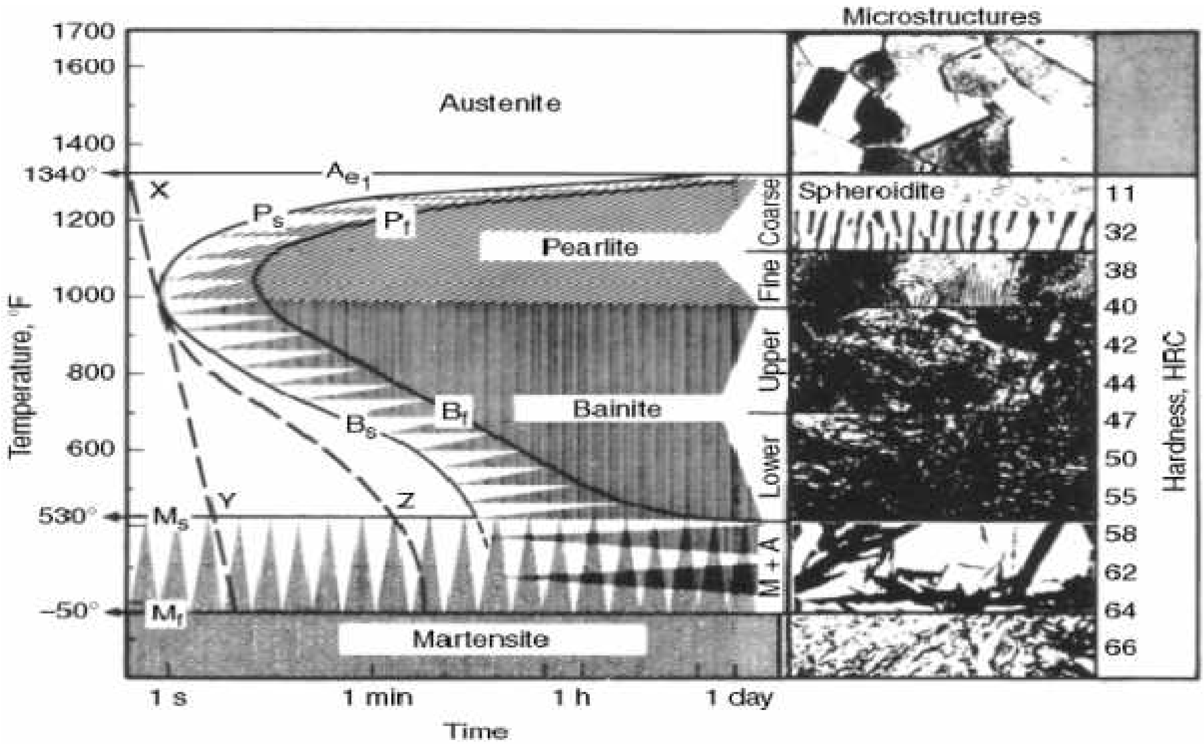


Figure 2.18 TTT diagram

transformation product is coarse pearlite. Next, assume a temperature of 540^0C or 1000^0F; product of transformation is fine pearlite. The line Pf Bf represents the completion of transformation and is generally parallel with Ps Bs.

When transformation takes place isothermally within the temperature range of approximately 290 to 425^0C (550 to 800^0F), the transformation product is a microstructure called bainite upper or lower. If steel is cooled so rapidly that no transformation takes place in the 540^0C or 1000^0F region and rapid cooling is continued below 275^0C or 530^0F or Ms. Under these conditions, martensite is formed. Point Ms is the temperature at which martensite begins to form, and Mf indicates the complete finish of transformation. It must be remembered that martensite is not a phase but is a specific microstructure in the ferritic phase. Thus, martensite can be considered as an aggregate of iron and cementite.

CHAPTER THREE: EXPERIMENTAL CONDITIONS AND METHODS

Rolling/sliding wear tests were carried on three pairs of rollers three times on each pair of rollers. The test were carried by running each pair of rollers on twin disc test rig for half an hour to study rolling/sliding wear of the rollers. During wear test, a pair of steel rollers were loaded together mechanically and driven independently by two electric motors. In twin disc test the rotating speed of the rollers and diameters of the roller; have been used to define creepage percentage in the test.

The tests have been interrupted after half an hour and the rollers are removed from the rolling/sliding wear testing machine and mass of rollers are measured which is used to analyze the rolling/sliding wear of the rollers. In addition to rolling/sliding wear test, laboratory test such as chemical composition test, hardness test, roughness test and heat treatment was carried on the rollers.

3.1) Material

Three pair of rollers is used to carry twin disc rolling/sliding wear test with this research. The rollers are machined from steel sections having similar mechanical properties and chemical compositions to that of standard wheel and rail. Chemical compositions of rollers are tested by spark light spectrometer. The data for chemical composition test is presented in section 3.8. Hardness of the rollers is measured on Rockwell C scale. The data for hardness test is presented in section 3.7. The first pair of rollers left without heat treatment and this pair of rollers are considered as standard roller. The second pair of rollers is cooled by air for ten second and then cooled with oil, after heating to austenite temperature and hold at that temperature until the phase is homogenized, to obtain intermediate hardness between quenched and not treated roller. The third pair of rollers is water quenched, after heating to austenite temperature and hold at that temperature, to obtain the highest hardness of the three rollers. In general the rolling/sliding wear of three different pair of rollers; two pair of rollers hardness is altered by heat treatment and one pair of rollers left without treatment is going to be studied in this research.

3.2) Test Rollers Dimension

The rollers for rolling/sliding twin disc wear test should be manufactured in such a manner that, the rollers outer diameter should not be small that creates difficulty to apply the necessary pressure and also should not be larger than the center distance of the electric motors shaft that drives both rollers.

Figure 3.1 shows the rollers prepared for rolling/sliding twin disc wear test. The outer diameter of wheel rollers is 98mm and the width of the rollers is 10mm.

Figure 3.1 Specimen of roller for rolling/sliding wear test [6]

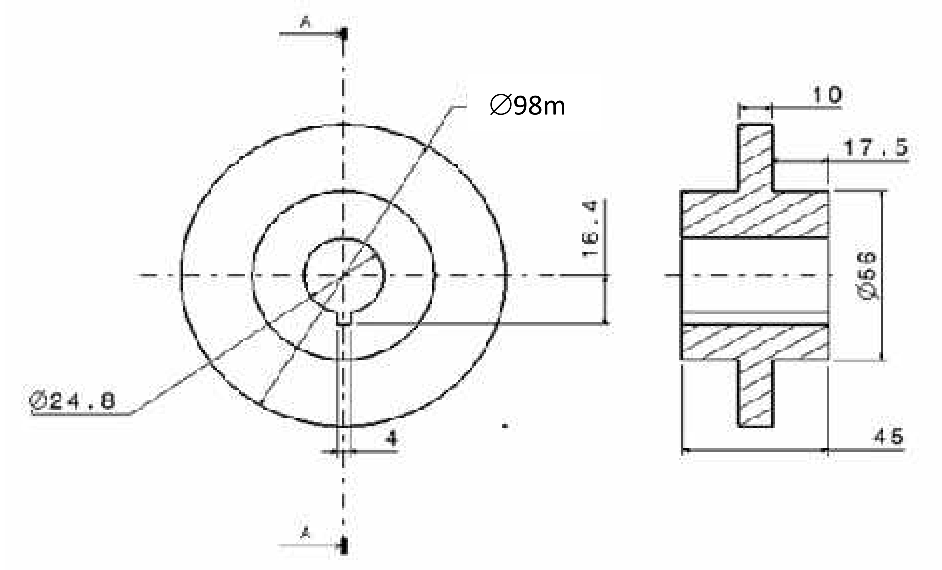


Figure 3.2 Roller dimensions for twin disc rolling/sliding wear test

3.3) Methods

A twin disc rolling/sliding wear testing machine was used to carry out the rolling/sliding wear experiments. The machine was designed to investigate wheel and rail rolling/sliding wear. A pair of steel disks were loaded together mechanically and driven independently by two electric motors. The inputs are the applied normal contact load and the slip between the two rollers (creep), while the outputs are the resulting tangential force and the quantity of wear.

The rail roller is driven at a fixed speed by the motor, and the wheel roller is driven by an A/C motor; the speed of the wheel roller, and thus the relative (longitudinal) slip, can therefore by controlled precisely [13].

The following rules should be obtained at twin disk testing. Rolling/sliding wear test is carried for three pairs of rollers three times, the pressure forces between the two disks are applied mechanically, twin disc test rig is stopped after running for half an hour, rollers are taken from the test rig and rolling/sliding wear test was conducted by measuring the rollers mass.

3.4) Test condition

Rolling/sliding Wear tests for three different pairs of rollers were conducted on the twin disc test rig under the following condition. The test rollers have been mounted on independent electric motor shafts. By means of spring and threaded element a controlled load of a 400N was applied on the rollers. Since cylindrical disks with 10mm width are used in the experiments, a line contact of 10mm is present. In the tests, the wheel roller was adjusted to rotate faster than the rail roller to realize the slip; the rotational speed of rail motor was maintained at 400rpm, while the rotational speed of wheel motor is 420rpm and creepagr of 6%. The tests were carried under dry condition.

During the test twin disc is stopped and the mass of both rollers are measured to know the amount of rolling/sliding wear [1, 29].

3.5) Test Rig

The twin disc test arrangement can be studied as two cylinders with parallel axes in rolling-sliding contact as shown in Figure 3.3 [24].

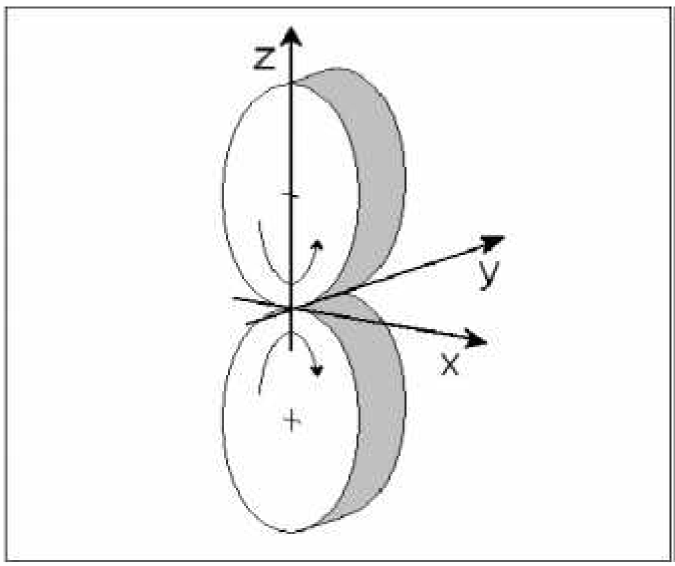


Figure3.3 Schematic diagram of twin disc test rig [24]

Twin disc machine has been designed to simulate a wheel in rolling/sliding contact with a rail. It is used to carry out the rolling/sliding wear taste. The shaft of twin disc on which rail roller is mounted rotates at a speed of 400rmp. The shaft of twin disc on which wheel roller is mounted rotates 1.05 times faster; hence Creepage is defined as the difference in velocities of the contacting surfaces with respect to their mean velocity, and for the twin disc machine is given by [12]:

$$\gamma = \frac{2(1.05D2-D1)}{D1+1.05D2} \qquad 3.1$$

Where, D_1 and D_2 are the diameter of rail and wheel roller respectively. Throughout the test rail steel roller 97mm in diameter were mounted on the top shaft and wheel steel roller of 98mm diameter were mounted on the bottom shaft.

The steel rollers were loaded together mechanically and driven independently by two electric motors. The top shaft is mounted in a swinging bracket, to which load is applied by means of a compressed spring.

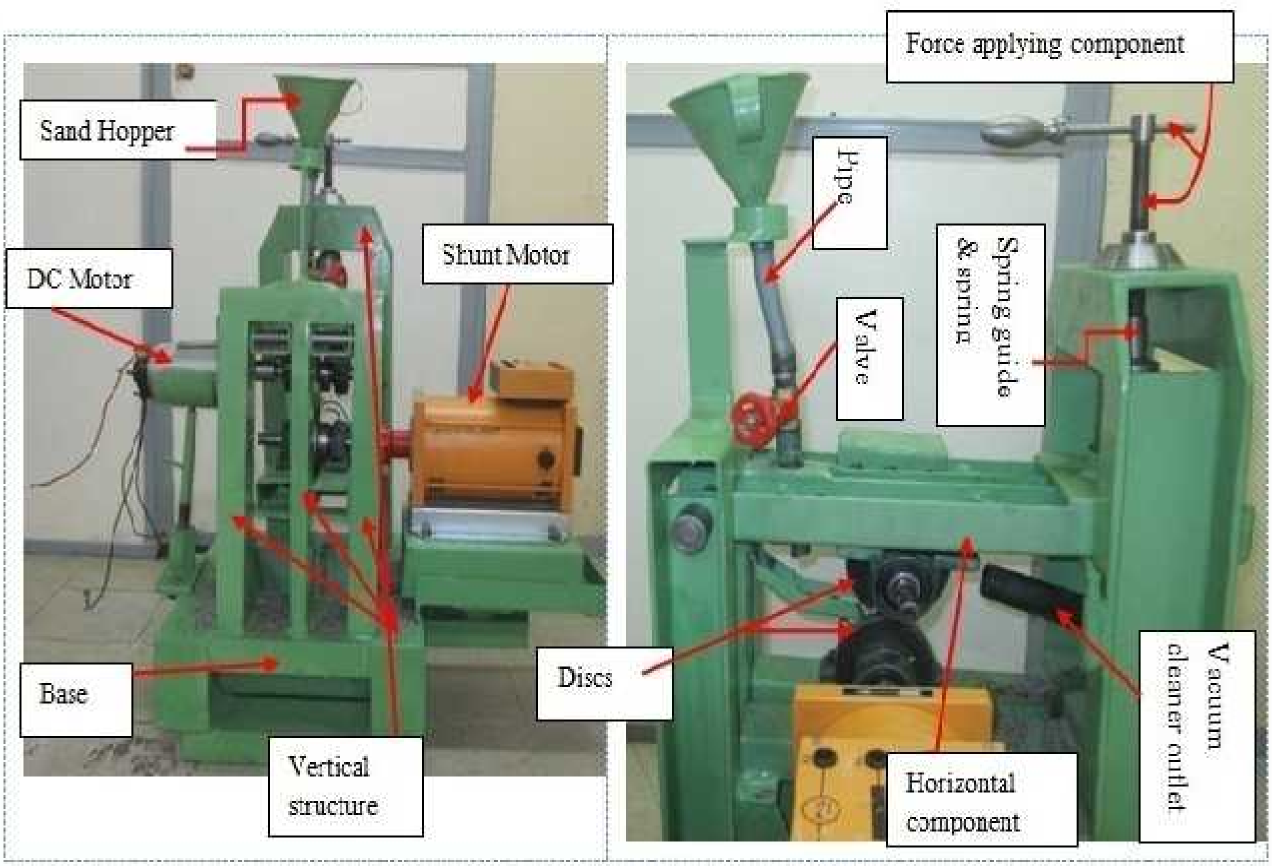


Figure 3.4 Twin disc test rig used for rolling sliding wear test [8]

The load is applied by a coil spring, from which the nominal maximum contact pressure can be calculated, assuming Hertzian contact theory, according to the following formula:

$P_o=0.418\left(\frac{LE}{R}\right)^{1/2}$ 3.2

Where P_O is the maximum contact pressure, E is Young's modulus, $l/R = l/R_1 + 1/R_2$, where R_1 and R_2, are the roller radii, and L is the load per unit contact width. In all cases, the roller contact width was 10mm.

3.6) Heat Treatment

Heat treatment is defined as a sequence of heating and cooling designed to get the desired combination of properties in rollers. The changes in property of rollers after heat treatment are due to phase transformation and structural changes that occur during heat treatment. The factors which determine and control these structural changes are called principles of heat treatment. The important principles of heat treatment are as follows:

- Phase transformation
- Effect of cooling rate
- Effect of carbon content and alloying elements

The heat treatment consists of; heating of the rollers up to austenite temperature which is 900ºC for this research, soaking at a temperature of 900ºC for a period 45 minutes for identical temperature distribution and cooling of the rollers back to room temperature, according to hardness required.

For the purpose of this research one pair of rollers was cooled by immersing into water after heating to austenite temperature. These fast cooling of rollers from austenite phase result in the formation of a meta-stable phase called martensite, which results in increased hardness. The second pair of rollers is cooled in air for ten seconds and then oil cooled in order to obtain pair rollers with intermediate hardness in between the hardened roller and standard roller which is not heat treated.

Figure 3.5 Furnace used for heat treatment of the rollers

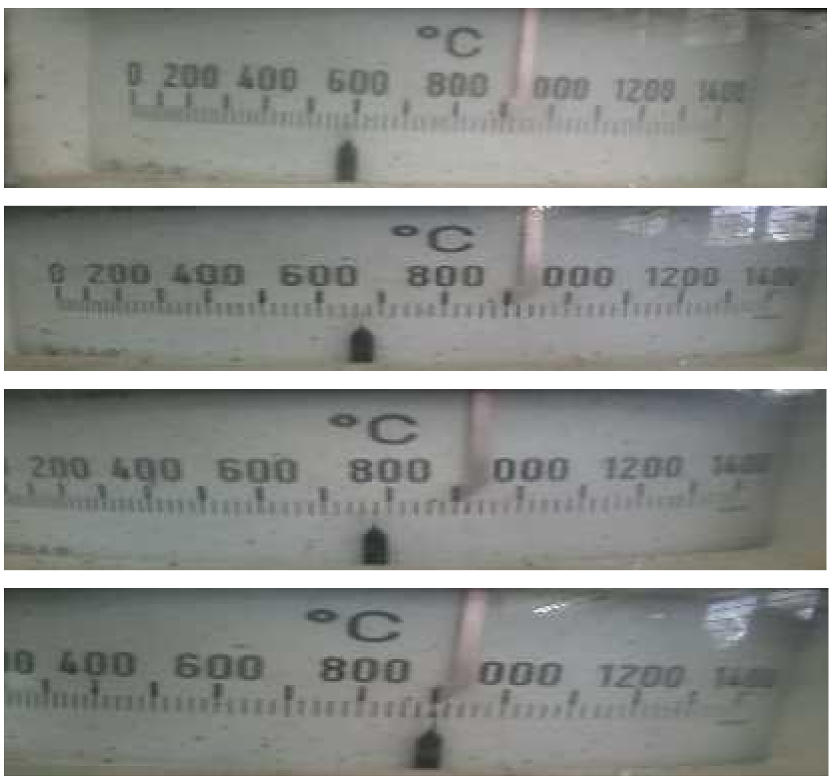


Figure 3.6 Gauge of heat treatment furnace at different temperature during heating of rollers

Figure 3.7 pair of rollers quenched in water

3.7) Hardness Test

Hardness of the rollers for this research is tested using Rockwell C Scale indentation hardness tester. Diamond cone indenter is used with this test. The diamond cone is grounded to an angle of 120^0. During the test a minor load of 10kg and a major load of 150kg are used. The data obtained from the test are shown in the table 3.1.

Table 3.1 Data obtained from hardness measurement

Roller Type	Hardness Testes					Heat Treatment Condition
	1	2	3	4	5	
Wheel-A	29.00	29.50	31.00	32.00	30.00	Air cooled and then oil quenched
Wheel-B	45.00	44.00	46.00	46.00	45.00	Water Quenched
Wheel-C	26.00	26.00	24.00	28.00	28.00	Standard not treated
Rail-A	34.00	32.00	33.00	35.00	36.00	Air cooled and then oil quenched
Rail-B	47.00	47.00	48.00	46.00	46.00	Water Quenched
Rail-C	27.00	25.00	25.00	28.00	29.00	Standard not Treated

Figure 3.8 Hardness testing on Rockwell C scale of rollers

3.8) Chemical Composition Test

The chemical composition of all three pairs of rollers used for this research were tested at AAiT School of Mechanical and Industrial Engineering laboratory on December 23/2014 by the researcher in collaboration with mechanical work shop head. The test rig used for the chemical composition test is called spark light emission spectrometer.

Spark light emission spectrometer detects the light, particular for their wave length and transform the detected amount into electrical charge. This amount of electricity is related to the amount of the element in the metal. The computer part will calculate, show, print and file result according to the wish of the spectrometer operator.

During the test metals must be classified in groups with similar chemical compositions. Un-alloyed, low alloyed steel, high alloyed steel. Chemical composition measurement is only valid for the range between the lowest and highest value, per element.

Test piece are prepared by polished with grinding to remove scale, oxides, oil and other residues on belt grinder. Grinding the test piece also provides flat surface. Before the test the operator must check the surface for smoothness, flatness and clear of any oxides or other surface contaminates.

Figure 3.9 Roller preparations on belt sander for chemical composition test

During the test, the operator must work according to the instructions, which include:

- Check if the equipment is properly calibrated
- Check that Argon properly supplied
- Check that flatness and quality of the sample
- Check the burn-spot in homogeneity
- Burn at least 2, preferred 3 times
- Never burn overlapping

Figure 3.10 burnt test roller after chemical composition test

Table 3.2 Data obtained from chemical composition test of rollers

Type of Roller	No. Tests	Chemical composition of rollers by weight percent									
		C	Si	Mn	P	S	Cu	Cr	Mo	Ni	V
Rail-A	1	0.427	0.178	0.64	0.002	0.020	0.090	0.054	0.001	0.024	0.00
	2	0.398	0.190	0.66	0.004	0.018	0.096	0.057	0.003	0.026	0.00
	3	0.402	0.179	0.65	0.00	0.020	0.095	0.054	0.001	0.023	0.128
Rail-B	1	0.407	0.223	0.680	0.008	0.019	0.089	0.089	0.003	0.030	0.094
	2	0.482	0.224	0.690	0.006	0.019	0.089	0.090	0.004	0.030	0.095
	3	0.335	0.219	0.670	0.007	0.017	0.087	0.090	0.004	0.030	0.000
Rail-C	1	0.498	0.151	0.730	0.000	0.025	0.208	0.165	0.041	0.066	0.000
	2	0.485	0.150	0.740	0.000	0.260	0.213	0.168	0.043	0.067	0.000
	3	0.498	0.149	0.720	0.00	0.025	0.204	0.164	0.040	0.066	0.084
Wheel-A	1	0.304	0.232	0.700	0.006	0.007	0.086	0.092	0.005	0.032	0.000
	2	0.247	0.230	0.670	0.004	0.012	0.083	0.089	0.001	0.029	0.029
	3	0.256	0.235	0.680	0.005	0.008	0.087	0.090	0.001	0.029	0.000
Wheel-B	1	0.440	0.277	0.680	0.007	0.022	0.096	0.091	0.003	0.038	0.032
	2	0.450	0.277	0.670	0.006	0.020	0.088	0.089	0.003	0.029	0.006
	3	0.317	0.234	0.690	0.006	0.015	0.085	0.090	0.003	0.030	0.367
Wheel-C	1	0.454	0.224	0.690	0.007	0.024	0.085	0.091	0.003	0.030	0.000
	2	0.454	0.219	0.680	0.008	0.026	0.084	0.089	0.003	0.030	0.000
	3	0.461	0.222	0.670	0.007	0/025	0.087	0.091	0.004	0.040	0.000

3.9) Roughness measurement

The nominal surfaces of objects appear as absolutely straight lines, ideal circles, round holes, and other edges and surfaces that are geometrically perfect. But actual surfaces of a part are determined by the manufacturing processes used to make it. Different manufacturing processes results in wide variety in surface characteristics [36].

Roughness with its typical roughness height and roughness spacing represents the more closely spaced peaks and valleys. Roughness is usually produced by basic surface forming process. These may be cutting tool marks or may be produced by the grit of grinding wheel. The waviness consists of the more widely spaced irregularities and is often produced by vibration in machine.

Error of form consists of long period or non-cyclic deviation in the surface profile. Flaws are discrete and infrequent irregularities; these might include cracks, pits and scratches. Lay is the term used to indicate the direction of the dominant pattern of texture on the surface.

Surface roughness is studied in this research to know whether the surface roughness of rollers is close to each other or far apart from each other. In addition to this the surface roughness is of roller is studied to know that the surface roughness of the roller confirm to surface roughness of manufactured method used to produce the rollers. In the case of this research the manufacturing method of the roller is turning operation on lathe machine.

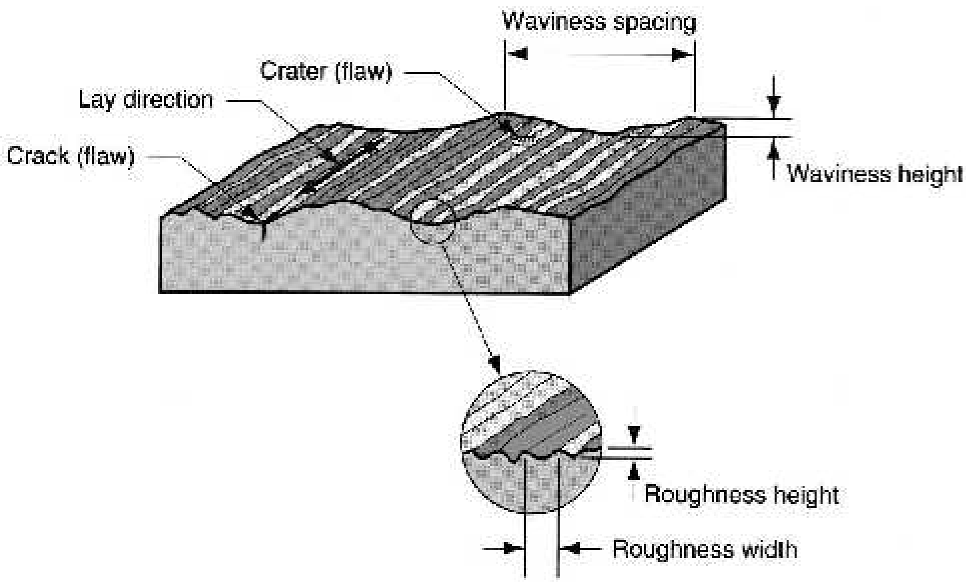


Figure3.11 Terminologies of Surface Texture

The most commonly used terminologies used to define surface roughness are

Ra - Arithmetic average roughness, or Ra, is the arithmetic average height of roughness-component irregularities peak heights and valleys from the mean line [32].

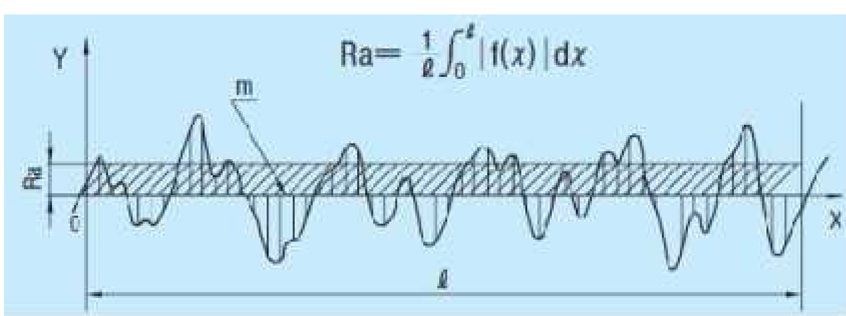


Figure 3.12 Arithmetic mean Ra of surface roughness [33]

Rp-The largest peak height of a surface finish profile within the sample length measurement from the mean line [34].

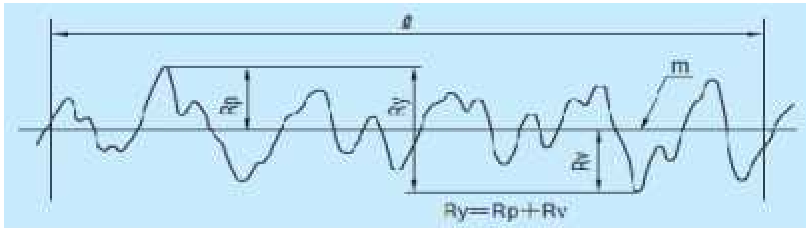


Figure 3.13 show the largest peak height Rp and maximum peak Ry [33]

Maximum peak Ry- The distance between the peaks and valleys of the sampled line is measured in the y direction [33].

Ten-point mean roughness Rz- The distance between the peaks and valleys of the sampled line is measured in the y direction. Then, the average peak is obtained among 5 tallest peaks Yp, as is the average valley between 5 lowest valleys Yv [33].

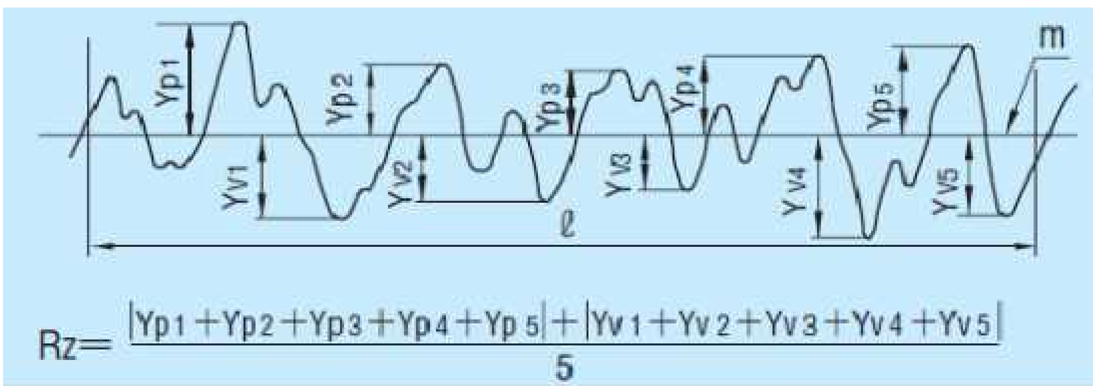


Figure 3.14 ten point mean roughness Rz [33]

The data obtained from surface measurement of the rollers is given in table 3.3.

Table 3.3 Data obtained from surface roughness measurement

Rollers	Roughness Parameter	Roughness measurements			
		1	2	3	4
Wheel-A	Ra	0.906	1.026	1.044	0.942
	Rz	2.502	2.901	2.952	2.664
Wheel-B	Ra	0.741	1.266	0.753	0.753
	Rz	2.095	3.580	2.129	2.129
Wheel-C	Ra	2.201	2.873	2.825	5.153
	Rz	10.360	12.260	10.120	10.230
Rail-A	Ra	1.385	1.241	1.241	0.808
	Rz	8.050	6.970	7.650	7.820
Rail-B	Ra	4.152	4.224	3.768	5.664
	Rz	11.740	11.940	10.650	10.650
Rail-C	Ra	3.744	3.624	3.792	3.384
	Rz	10.59	10.25	10.72	9.572

CHAPTER FOUR: RESULTS AND DISCUSSIONS

In chapter three it was shown that different types of laboratory tests were carried and data obtained from laboratory was collected. The results of these laboratory data are going to present hereafter. Next to laboratory results presentation, discussion of the result follows.

The laboratory test carried, for the purpose of investigate the influence of heat treatment on rolling/sliding wear behavior of three pairs of rollers labeled as A, B, and C; was twin disc wear test, chemical composition test, roughness test and hardness test. In addition to this heat treatment and reconditioning of the work piece is part of this research.

4.1) Results

4.1.1) Twin Disc Wear

Table 4.1 and Table 4.2 summarize the rolling/sliding wear result obtained for rail and wheel rollers during rolling/sliding wear test. Three rolling/sliding wear test is carried on each of the three rollers. The material removed as a function of roller revolution from the rollers is given as follows

Table 4.1 wheel and rail wear rate in gram, as a function of wheel and rail rotation

Rollers	Lost mass in grams		
	Firs rolling/sliding wear test after 12000rev	Second rolling/sliding wear test after 24000rev	Third rolling/sliding wear test after 36000rev
Rail-A	0.80	0.30	0.20
Wheel-A	1.10	0.20	0.20
Rail-B	0.20	0.20	0.10
Wheel-B	0.30	0.20	0.20
Rail-C	1.10	0.40	0.20
Wheel-C	1.00	0.50	0.30

Table 4.2 wear rate of rollers in gram, as a function of roller rotation

Rollers	Lost mass in grams		
	Firs rolling/sliding wear test after 12000rev	Second rolling/sliding wear test after 24000rev	Third rolling/sliding wear test after 36000rev
Roller-A	1.90	0.50	0.40
Roller-B	0.50	0.40	0.30
Roller-C	2.10	0.90	0.50

4.1.2) Chemical Composition

The chemical composition of rollers obtained from spectrometer test is presented in table 4.3.

Table 4.3 Chemical composition of the rollers

Types of Rollers	% of chemical composition by mass								
	C	Si	Mn	P	S	Cu	Cr	V	Ti
Rail-A	0.409	0.182	0.650	0.002	0.019	0.094	0.055	0.043	0.038
Rail-B	0.408	0.223	0.680	0.007	0.018	0.088	0.090	0.107	0.023
Rail-C	0.492	0.150	0.730	0.001	0.025	0.208	0.166	0.021	0.001
Wheel-A	0.300	0.232	0.680	0.006	0.005	0.082	0.090	0.002	0.030
Wheel-B	0.403	0.263	0.680	0.006	0.019	0.089	0.090	0.003	0.032
Wheel-C	0.456	0.222	0.690	0.008	0.025	0.085	0.090	0.003	0.030

4.1.3) Hardness

Hardness measurement results of standard rollers, rollers which were cooled in air for ten seconds and then oil quenched and rollers quenched in water are given in table 4.4. Hardness of standard rollers has been altered after heating the roller to austenite temperature and cooling by appropriate cooling media.

Table 4.4 Hardness values of standard, water quenched and air plus oil cooled rollers

Roller Type	Rockwell RC
Wheel-A	30.30
Wheel-B	45.20
Wheel-C	26.50
Rail-A	34.00
Rail-B	46.80
Rail-C	26.60

4.1.4) Roughness

The result of roughness of the rollers, as measured with surface roughness is shown in table 4.5

Table 4.5 Roughness value Ra and Rz of the rollers after reconditioned on lathe machine

Rollers	Roughness Parameter	Roughness measurements in µm
Wheel-A	Ra	0.9795
	Rz	2.755
Wheel-B	Ra	0.8783
	Rz	2.483
Wheel-C	Ra	3.262
	Rz	10.74
Rail-A	Ra	1.169
	Rz	7.6225
Rail-B	Ra	4.452
	Rz	11.245
Rail-C	Ra	3.636
	Rz	10.283

4.2) Discussions

In section 4.1 various laboratory results are presented. In this section the discussion of result obtained from laboratory is going to be presented. The discussion of the result begins with chemical composition test result, followed by roughness test result, next hardness test result and finally twin disc rolling/sliding wear test result.

Result of chemical composition test of the rollers is as shown in figure 4.1.

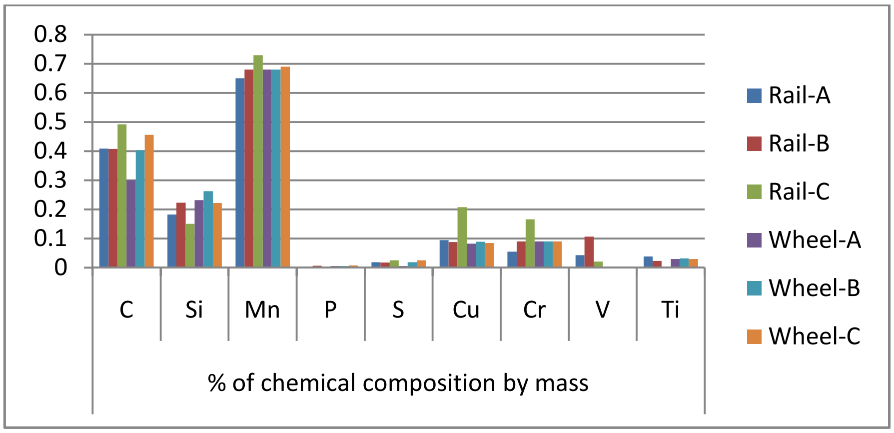


Figure 4.1 Graphical representation of chemical composition of rollers

In the case of rail, referring to standard values of rail the chemical composition by weight percent varies as follows

- The minimum percent of carbon is found to be 0.38 with R200 and the maximum percent of carbon is found to be 0.82 with R350HT according to EN standard. The minimum percent of carbon is found to be 0.65 with U71Mn and the maximum percent of carbon is found to be 0.82 with U78CrV according to Chinese standard.
- Chemical composition of rail roller by weight percent of carbon varies between 0.408 to 0.492 as tested by spark light spectrometer
- The minimum percent of silicon is found to be 0.13 with R200 and the maximum percent of silicon is found to be 1.12 with R320Mn according to EN standard. The minimum percent of silicon is found to be 0.1 with U77MnCr and the maximum percent of silicon is found to be 0.80 with U76CrRE according to Chinese standard.
- Chemical composition of rail by weight percent of silicon varies between 0.150 to 0.223 as tested by spark light spectrometer
- The minimum percent of manganese is found to be 0.65 with R200 and the maximum percent of manganese is found to be 1.75 with R260Mn according to EN standard. The

minimum percent of manganese is found to be 0.70 with U71Mn and the maximum percent of manganese is found to be 1.20 with U71Mn according to Chinese standard

- Chemical composition of rail by weight percent of manganese varies between 0.65 to 0.73 as tested by spark light spectrometer

In the case of wheel, referring to standard values of wheel the chemical composition by weight percent varies as follows

- The minimum percent of carbon is found to be 0.48 with R6 and the maximum percent of carbon is found to be 0.60 with R9.
- Chemical composition of wheel by weight percent of carbon varies between 0.30 to 0.456 as tested by spark light spectrometer
- The amount of silicon is found to be 0.40 to 0.50 for all wheels
- Chemical composition of wheel by weight percent of silicon varies between 0.222 to 0.263 as tested by spark light spectrometer
- The minimum percent of manganese is found to be 0.75 with R6 and the maximum percent of manganese is found to be 1.20 with R1.
- Chemical composition of wheel by weight percent of manganese varies between 0.68 to 0.69 as tested by spark light spectrometer

The result from roughness test of the rollers is shown by figure 4.2

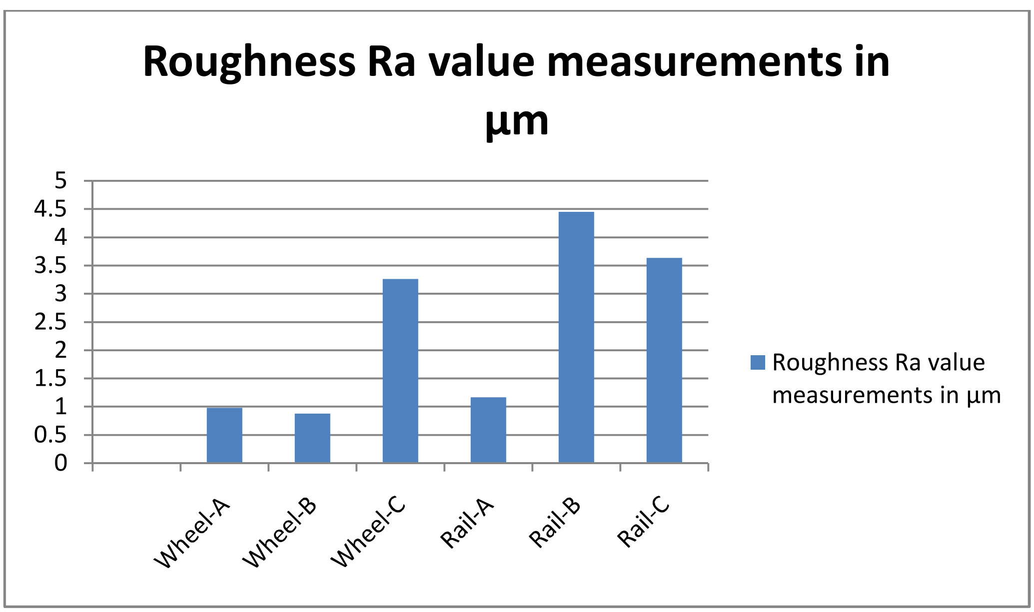


Figure 4.2 Roughness values of rollers shown graphically

Surface roughness Ra expected from turning process varies between 0.32 to 32µm [36]. Surface roughness Ra value of the rollers, which is reconditioned on lath machine in AAiT mechanical work, varies between 0.8783µm and 4.452µm.

The result of hardness test of the rollers is shown by figure 4.3.

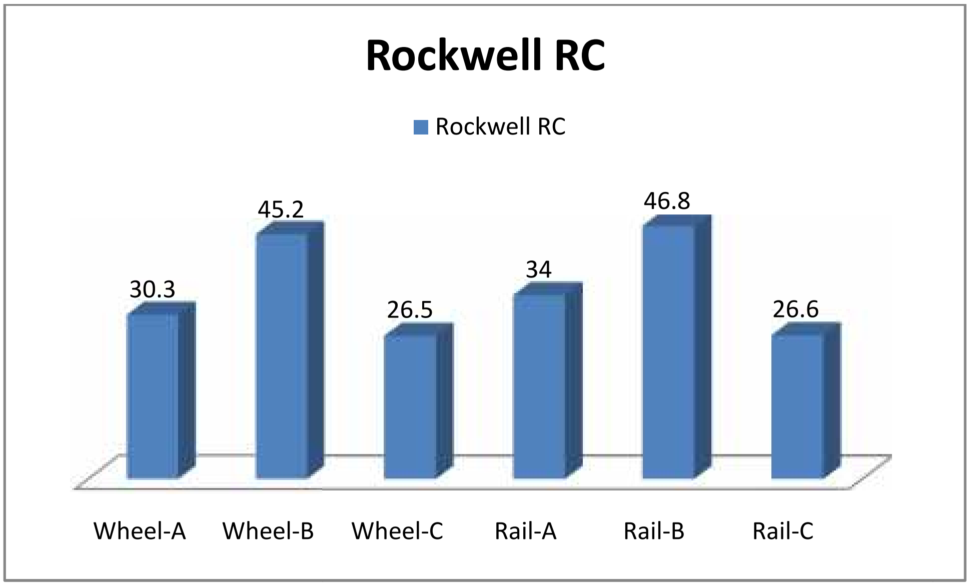


Figure 4.3 Hardness values of rollers shown graphically

In the case of rail,

- The minimum hardness value is found to be 200HB with R200 and the maximum hardness value is found to be 390HB with R350HT according to EN standard rail hardness values
- The minimum hardness value is found to be 260HB with U71Mn and the maximum hardness value is found to be 360HB with U76CrRE according to Chinese standard rail hardness values
- The result from hardness test for rail rollers varies between 26.60RC to 46.80RC

The hardness value of rail, used as of standard rail in this research, is 26.6RC. But due to the heat treatment process hardness value of rail-A is increased to 34RC and the hardness value of rail-B also increases to 46.8RC.

In the case of wheel,

- The minimum hardness value is found to be 179HB with R1 and the maximum hardness value is found to be 311HB with R9 according to EN standard hardness values of wheel
- The result from hardness test for wheel rollers varies between 26.50RC to 45.20RC

The hardness value of wheel, used as of standard wheel in this research, is 26.50RC. But due to the heat treatment process hardness value of wheel-A is increased to 30.30RC and the hardness value of wheel-B also increases to 45.20RC.

Result of twin disc Rolling/sliding wear test of three rails is shown by figure 4.4. From the figure we can observe that standard rail has the highest wear rate. Rail which is air cooled for ten second and then oil cooled during heat treatment has intermediate wear rate. Water quenched rail show the smallest wear rate.

Figure 4.5 shows that the wear rate of three wheels. From the figure it has been seen that wheel which is cooled in air for ten second and then oil cooled show the highest wear rate up to 16000rev. After 16000rev standard wheel shows the highest wear rate then followed by wheel which is cooled in air for ten seconds and then cooled in oil. Water quenched wheel shows the smallest wear rate.

Figure 4.6 shows the system wear of wheel and rail. From the figure it has been seen that the wear rate of standard roller is the highest. Roller which is air cooled for ten seconds and then oil cooled show intermediate wear rate. Rollers cooled in water show the smallest wear rate.

From twin disc wear test carried on three pair of rollers indicate that the wear resistance of rail, wheel and wheel/rail system wear is directly related to hardness of rail and wheel rollers.

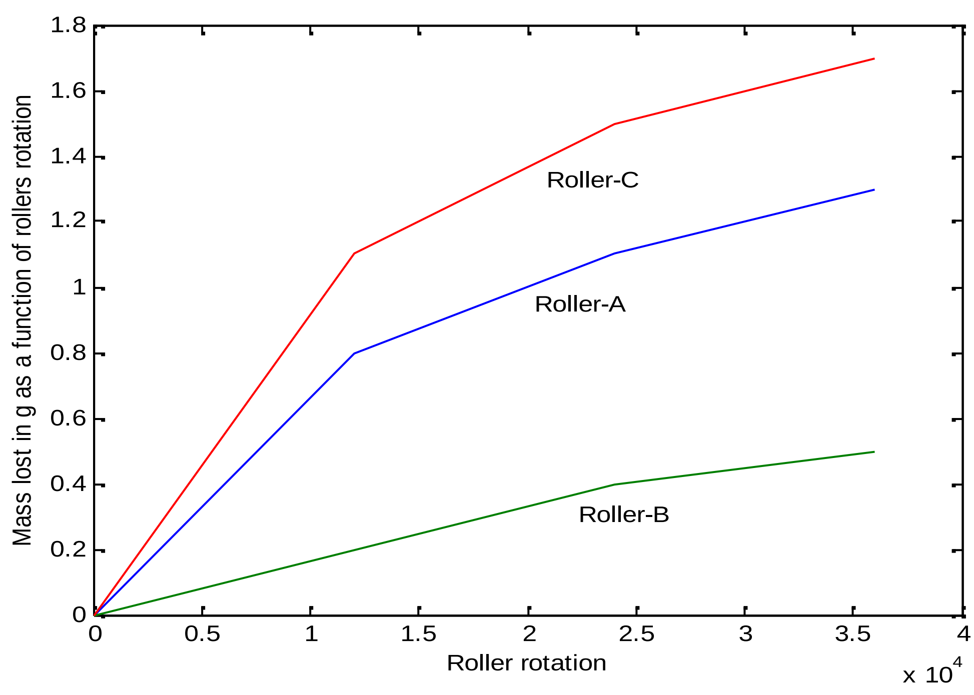


Figure 4.4 Mass loss of rail during twin disc wear test as a function of rollers rotation

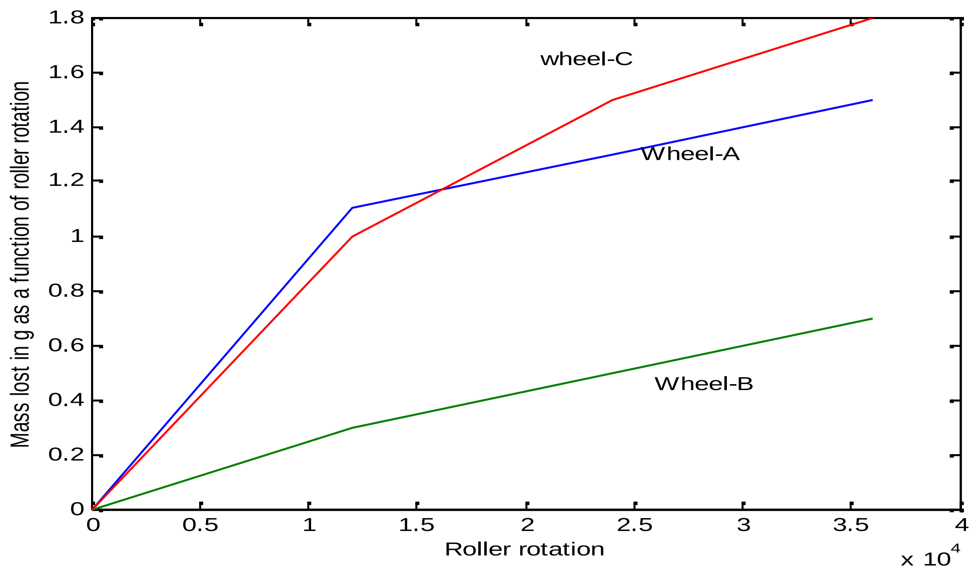


Figure 4.5 Mass loss of wheel during twin disc wear test as a function of rollers rotation

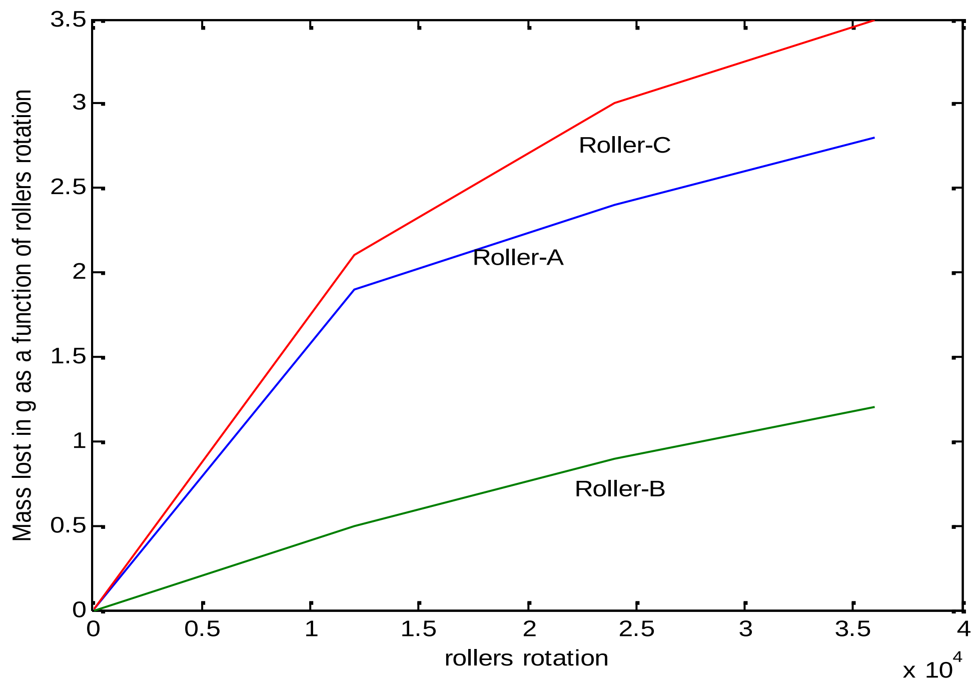


Figure 4.6 mass loss of rollers during twin disc wear test as a function of rollers rotation

CHATER FIVE: CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1) Conclusions

Rolling/sliding wear test of three different types of wheel and rail rollers was carried on twin disc rolling/sliding wear testing machine. Supporting laboratory tests such as hardness test, roughness test and chemical composition test were also conducted on the rollers. The rollers are also heat treated by heating them to austenite temperature and cooling back to lower temperature in appropriate cooling media to improve their hardness. According to the experimental and laboratory test result the following conclusions were drawn

- Heating steel roller to austenite temperature and then cooling back to lower temperature in water or air plus oil increase the hardness of the roller. Therefore; standard wheel and rail steel can be made high strength wheel and rail by heating wheel and rail to austenite temperature and cooling rapidly back to lower temperature.
- Using higher hardness steels for both wheels and rails has favorably impact on wear in the system as a whole in that it ensures more sustained profile stability.
- Wear resistance of wheel/rail is directly related to the hardness of the rollers; the higher their hardness the higher it can resist wear.
- Water quenched rollers shows more wear resistance than air plus oil cooled rollers.
- The quenching media or the rate of cooling affects the hardness of steel during heat treatment.

5.2) Recommendations

First, from hardness test result of both wheel and rail rollers on page 48 table 4.4, an increase in hardness of both wheel and rail is clearly shown. Wheel roller show an increase in hardness of 70 percent when water cooled after heating to austenite temperature. Rail roller show an increase in hardness of 75 percent when water cooled after heating to austenite temperature. Wheel roller also shows an increase in hardness of 14.4 percent when cooled in air for ten seconds and then oil cooled. Rail roller also shows an increase in hardness of 27 percent when cooled in air for ten seconds and then oil cooled. Increasing in hardness of wheel and rail roller is advantageous in reducing rolling/sliding wear of rail; wheel and system rolling/sliding wear of wheel/rail.

Therefore; I would like to recommend that ERC or other concerned government body can make the necessary facilitation for the production of high strength wheel and rail through heat treatment process in the country from standard wheel and rail.

Second, from the data obtained from Addis Ababa light transit project office the rail used for Addis Ababa light transit is U71Mn of Chinese standards, which have hardness value of 260HB to 300HB. This type of rail is equivalent to R260Mn rail of EN standards. It is a standard rail used for the construction of rail track. But in case of track exposed to high rolling/sliding wear the standard rail will be exposed to higher wear. Compared to standard rail grades heat treated rails show a superior rolling/sliding wear resistance.

Therefore; ERC can utilize heat treated rail which has higher wear resistance, at a place where higher wear can occurred, such as high rail of curved track, on a place where there is frequent stopping and starting and for heavy hauled trains.

5.3) Future Works

There are some further works that can be done in order to support the experimental results obtained by this research. The future work of this research includes

- Investigation of the rolling/sliding wear of alloyed rollers
- Investigation of effect of lubrication on rolling/sliding wear of high strength rollers
- Investigation of the effect of slip on rolling/sliding wear behavior of high strength rollers
- Investigation of the effect of various friction coefficient on rolling/sliding wear behavior of high strength rollers
- Study the influence of microstructure of rollers on rolling/sliding wear
- Improvement twin disc machine so that it is possible to carry rolling contact fatigue test on the twin disc machine

References

1. *Jung Won Seo, Seok Jin Kwon, Dong Hyeong Lee, Sung Tae Kwon and Ha Yong Choi, Fatigue Crack Growth and Fracture behavior of Rail Steels, IJR International Journal of Railway,2012, Vol. 5, pp. 129-134*
2. *Jo˜ao Pombo, Jorge Ambrósio, Manuel Pereira, A RAILWAY WHEEL WEAR PREDICTION TOOL BASED ON A MULTIBODY SOFTWARE, JOURNAL OF THEORETICAL AND APPLIED MECHANICS, 201, pp. 751-770, 2010*
3. *Bagus Budiwantoro, I.Made Parwata, Optimum Lateral Railway Wheel Flange Radius with minimum wear rate : Twin disc simulation, Journal of Solid Mechanics and Material Engineering, 2013, Vol.7,No.4*
4. *Gallardo-Hernandez E.A, R. Lewis, 2008, Twin Disc Assessment of Wheel/Rail Adhesion, 2008, pp. 1309-1316.*
5. *Ulf Olofsson and Roger Lewis, Tribology of the Wheel–Rail Contact, KTH in Stockholm Sweden,2006*
6. *Mesfin G/Tsadik, Extent of Adhesion Loss in Wheel-Rail Contact Under Contaminated Condition, Master Thesis,2014*
7. *Peter Pointner, 2012, Definitive guidelines on the use of different rail grades, 2012*
8. *Gutanbar Debere, Effect of Friction Modifiers (sand-Based) In Wheel/Rail Contact, Master Thesis, 2014*
9. *Vasic G., F.J. Franklin and Kapoor, New Rail Materials and Coating, Rail Research UK, 2003*
10. *Eric E.Magel, Rolling Contact Fatigue: A Comprehensive Review, U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Washington, 2012*
11. *Saurabh Kumar, Study of Rail Breaks Associated Risks and Maintenance Strategies, Techinical report, 2006*
12. *Xiaonong Qiu, Rolling Contact Fatigue Behavior of Three Eutectoid Rail Steels, Beijing University of Iron and Steel Technology,1987*
13. *INNOTRACK, INNOVATIVE LABORATORY TESTS FOR RAIL STEELS, Deliverable report D4.3.8*

14. *Schilke M., N.Larijani, and C.Persson, Interaction between cracks and microstructure in three dimensions for rolling contact fatigue in railway rails, Chalmers University of Technology, Gothenburg, Sweden, 2013*
15. *Xiangyuan Xu, Estimation of Stress Intensity Factor Ranges for Slant Crack under Cyclic Rolling Contact Fatigue, Sungkyunkwan University, 2010*
16. *NAVKALA ROY, The Rail Train, how it works, New Delhi, 2006*
17. *Yehualaeshet Jemere, Addis Ababa Light Rail Transit Project, Ethiopian Railways Corporation (ERC), 2012*
18. *Alison Chard, Deformation of inclusions in rail steel due to rolling contact, 2011*
19. *Yi Zhu, Adhesion in wheel rail contact, Doctoral thesis, KTH Industrial Engineering and Management, 2013*
20. *Kelvin S. Chiddick and Donald T.Eadie, Wheel/Rail Friction Management Solution, Presented at 14th Int. Conference on Current Problems in Rail Vehicles, 1999*
21. *Joao, Application of computational tools to study the influence of worn wheel on railway vechicle dynamics, 2012, pp.51-61*
22. *CAMTECH/M/3, A Technical Guide on Derailments, Government of India Ministry of Railway, 1998*
23. *JohnThnna, A Review of Wheel Wear and Rolling Contact Fatigue, UK Proprietary 05-009 TTCI (UK), Ltd. Research report, 2006*
24. *Tassini, N., Quost, X., Lewis, R., Dwyer-Joyce, R., Ariaudo, C., Kuka, N., A numerical model of twin disc test arrangement for the evaluation of railway wheel wear prediction methods,2010, pp. 660-667*
25. *Santamaria, J., Vadillo, E.G., Oyarzabal, Wheel-rail wear index prediction considering multiple contacts patches. 2009, Vol. 267, pp. 1100-1104*
26. *Stephen Tidmarsh, Railway rolling stock materials, Specification for monobloc wheels for traction and trailing stock, 2006*
27. *Branislav Sladojević, Miloš Jelić, 2010, Milica Puzić, NEW REQUIREMENTS FOR THE QUALITY OF STEEL RAILS, Scientific paper, 2011 p. 213-219*
28. *Herian J., K. Aniołek, Abrasive wear of railway sections of steel with a different pearlite morphology in railroad switches, Journal of Achievements in Materials and Manufacturing Engineering, 2010, pp. 236-243*

29. Lewis R., F. Braghin, INTEGRATING DYNAMICS AND WEAR MODELLING TO PREDICT RAILWAY WHEEL PROFILE EVOLUTION, 6th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, in Gothenburg, Sweden, 2003
30. Pombo, J., Ambrosio, J., Pereira, M., Lewis, R., Dwyer-Joyce, R., Ariaudo, C., Kuka, N. A study on wear evaluation of railway wheels based on multibody dynamics and wear computation, Multibody System Dynamics,2010, pp. 347-366
31. UIC CODE 5, Trailing stock: wheels and wheel-sets, 4th edition, 2004
32. ASM International, Practical Heat Treating: Second Edition, 2006
33. EXCERPT FROM JIS, SURFACE ROUGHNESS, TECHNICAL DATA, 1994
34. Greene Tweed, Surface finish guidelines/ product data, 2007
35. Rickard Nilsson, On Wear in Rolling/Sliding Contacts, Doctoral thesis, Department of Machine Designe, Royal Institute of Technology, 2011
36. Narayana K.L, P.Lannaiah and K.Venkata Reddy, Machine Drawing second edition, New age international Ltd, 2004
37. Lewis,R. Dwyer-Joyce,R.S., olofsson,U. and Hallam,R.I., Wheel Material wear mechanism and transitions. In:14th International wheel set congress , Orlando, USA, 2004
38. ARTC, Rail Defects Handbook, Some Rail Defects their Characteristics Causes and Control, Engineering Practices Manual, 2006
39. Rail and rolled product for railway application, Lucchini S.P.A., Headquarters, Berecia Italy, www.lucchini.com
40. Railway system, Technologies and operation Across the World, Railway Techinicals
41. Malcolm kerr, Rail Defect hand Book, Railcorp Engineering manual-track, 2012
42. Website, The Rail trans-how it works, www.arvindguptatoys.com.arvindugupta/cbt35, Accessed date 01/22/2015
43. Website, A brief history of British railway, www.teachingzone.org/railway/pdf, Accessed date 02/03/2015
44. Website, Railway History in Ethiopia, www.en.wikiupedia.org/wiki/railtransport, Accessed date 02/03/2015