FAILURE ANALYSIS OF GEAR MATERIAL

Thesis Submitted in partial fulfillment of the requirement for the award of

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CERTIFICATE

This is to certify that the thesis entitled "**Strength and fracture studies of Steam Turbine blade**" submitted by **Mr. Rahul Kaushik** in the partial fulfillment of the requirement for the award of the degree of **M. Tech.** in **Materials Science and Engineering** from the **School of Physics and Materials Science, Thapar University, Patiala (Punjab),** is a record of candidate's own work carried out by him under my supervision and guidance. The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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ABSTRACT

Presently, there is great challenge in front of automotive industries to overcome failures existing in gears. In order to study failure analysis of gears in industries, the present work was planned. Gears have wide variety of applications. They form the most important component in a power transmission system. Their applications vary from watches to very large mechanical units like the lifting devices and automotives.

Gears generally fail when the working stress exceeds the maximum permissible stress. Advances in engineering technology in recent years have brought demands for gear teeth, which can operate at ever increasing load capacities and speeds. The gears generally fail when tooth stress exceeds the safe limit. Therefore, it is essential to determine the maximum stress that a gear tooth is subjected under a specified loading. Analysis of gears is carried out so that these can be prevented from failure.

In this study the technology of gears is presented along with the various types of failures that gears have. The causes of these failures are studied. The type of stress related failure due to (fatigue failure) of a gear tooth because of stress concentration is detailed in this thesis. Before testing the mechanical properties, it is essential to understand their structural features as structure is going to govern the properties. Considering this aspect the proposal was planned.

Detailed metallurgical analysis was conducted on the fractured gears and compared with the unfailed gears in service. Results showed that gears hardness values were higher than values stated in the literature.

The thesis describes about the different types of gears used in industry, their properties and limitations. In order to overcome these limitations, some ideas were planned and accordingly experiments were designed and performed. In this work different types of failures existing in gears have also been discussed. With the help of microstructures obtained from optical microscope and SEM, it was convenient to study the defects existing in failed gear and methods, to reduce the failure, has been suggested.

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CHAPTER 1

INTRODUCTION

1.1 Introduction of Gears

Gears are the most common means of transmitting motion and power in the modern mechanical engineering world. They form vital elements of mechanisms in many machines such as automobiles, metal cutting machine tools, rolling mills and transmitting machinery. Toothed gears are used to change the speed and power ratio as well as direction between an input and output shaft.

A gear is a component within a transmission device that transmits rotational force to another gear or device. A gear is different from a pulley in that a gear is a round wheel which has linkages ("teeth" or "cogs") that mesh with other gear teeth, allowing force to be fully transferred without slippage. Depending on their construction and arrangement, geared devices can transmit forces at different speeds, torques, or in a different direction, from the power source. Gears are a very useful simple machine. The most common situation is for a gear to mesh with another gear, but a gear can mesh with any device having compatible teeth, such as linear moving racks. A gear's most important feature is that gears of unequal sizes (diameters) can be combined to produce a mechanical advantage, so that the rotational speed and torque of the second gear are different from that of the first. In the context of a particular machine, the term "gear" also refers to one particular arrangement of gears among other arrangements (such as "first gear"). Such arrangements are often given as a ratio, using the number of teeth or gear diameter as units. The term "gear" is also used in non-geared devices which perform equivalent tasks.

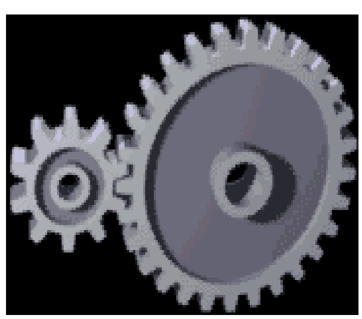


Fig: 1.1 Intermeshing gears in motion

The interlocking of the teeth in a pair of meshing gears means that their circumferences necessarily move at the same rate of linear motion (eg. metres per second, or feet per minute). Since rotational speed (eg. measured in revolutions per second, revolutions per minute, or radians per second) is proportional to a wheel's circumferential speed divided by its radius. Larger the radius of a gear, the slower will be its rotational speed, when meshed with a gear of given size and speed. The same conclusion can also be reached by a different analytical process: counting teeth. Since the teeth of two meshing gears are locked in one to one correspondence, when all of the teeth of the smaller gear have passed the point where the gears meet i.e., when the smaller gear has made one revolution, not all of the teeth of the larger gear will have passed that point, the larger gear will have made less than one revolution. The smaller gear makes more revolutions in a given period of time; it turns faster. The speed ratio is simply the reciprocal ratio of the numbers of teeth on the two gears.

1.1.1 Law of Gearing

A primary requirement of gears is the constancy of angular velocities or proportionality of position transmission. Precision instruments require positioning fidelity. High-speed and/or high-power gear trains also require transmission at constant angular velocities in order to avoid severe dynamic problems. Constant velocity (i.e., constant ratio) motion transmission is defined as "conjugate action" of the gear tooth profiles. A geometric relationship can be derived for the form of the tooth profiles to provide conjugate action, which is summarized as the Law of Gearing as follows:

"A common normal to the tooth profiles at their point of contact must, in all positions of the contacting teeth, pass through a fixed point on the line-of-centers called the pitch point."

Any two curves or profiles engaging each other and satisfying the law of gearing are conjugate curves.

Fig 1.1 shows two mating gear teeth, in which

- Tooth profile 1 drives tooth profile 2 by acting at the instantaneous contact point K.
- N_1N_2 is the common normal of the two profiles.

• N_1 is the foot of the perpendicular from O_1 to N_1N_2

• N_2 is the foot of the perpendicular from O_2 to N_1N_2.

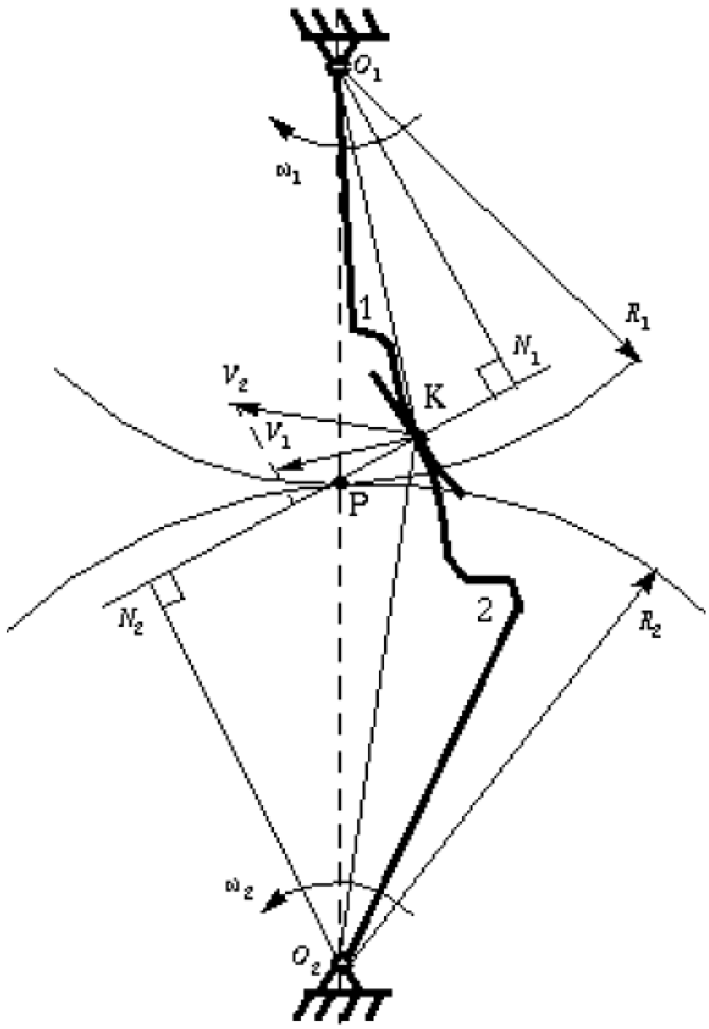


Fig 1.2 Law of Gearing

Although the two profiles have different velocities V_1 and V_2 at point K, their velocities along N_1N_2 are equal in both magnitude and direction. Otherwise the two tooth profiles would separate from each other. Therefore,

$$O_1N_1 . \omega_1 = O_2N_2 . \omega_2$$

Or

$$\frac{\omega_1}{\omega_2} = \frac{O_1 N_1}{O_2 N_2}$$

It is noticed that the intersection of the tangency N1N2 and the line of center O1O2 is at point P, and thus, the relationship between the angular velocities of the driving gear to the driven gear, or velocity ratio, of a pair of mating teeth is Point P is very important to the velocity ratio, and it is called the pitch point. Pitch point divides the line between the line of centers and its position decides the velocity ratio of the two teeth. The above expression is the fundamental law of gear-tooth action.

1.1.2Conjugate Action

Mating gear teeth acting against each other to produce rotary motion are similar to cams. When the tooth profiles, or cams, are designed so as to produce a constant angular-velocity ratio during meshing, these are said to have conjugate action. In theory, at least, it is possible arbitrarily to select any profile for one tooth and then to find a profile for the meshing tooth which will give conjugate action. One of these solutions is the involute profile, which, with few exceptions, is in universal use for gear teeth.

There are two forms of tooth profile commonly used:-

a) Cycloidal teeth

b) Involute teeth

An advantage of the cycloidal teeth over the involute one is that wear of cycloidal tooth is not as fast as with involute tooth. For this reason, gears transmitting very large amount of power are sometimes cut with cycloidal teeth. On the other hand, involute teeth are very easy to manufacture and the actual distance between the centers may deviate slightly from the theoretical distance without affecting the velocity ratio or general performance. Because of this distinct advantage, gears with involute cut teeth are used much more than those with cycloidal teeth.

1.2 Gear Nomenclature:

ADDENDUM (a) is the height by which a tooth projects beyond the pitch circle or pitch line.

BASE DIAMETER (D_b) is the diameter of the base cylinder from which the involute portion of a tooth profile is generated

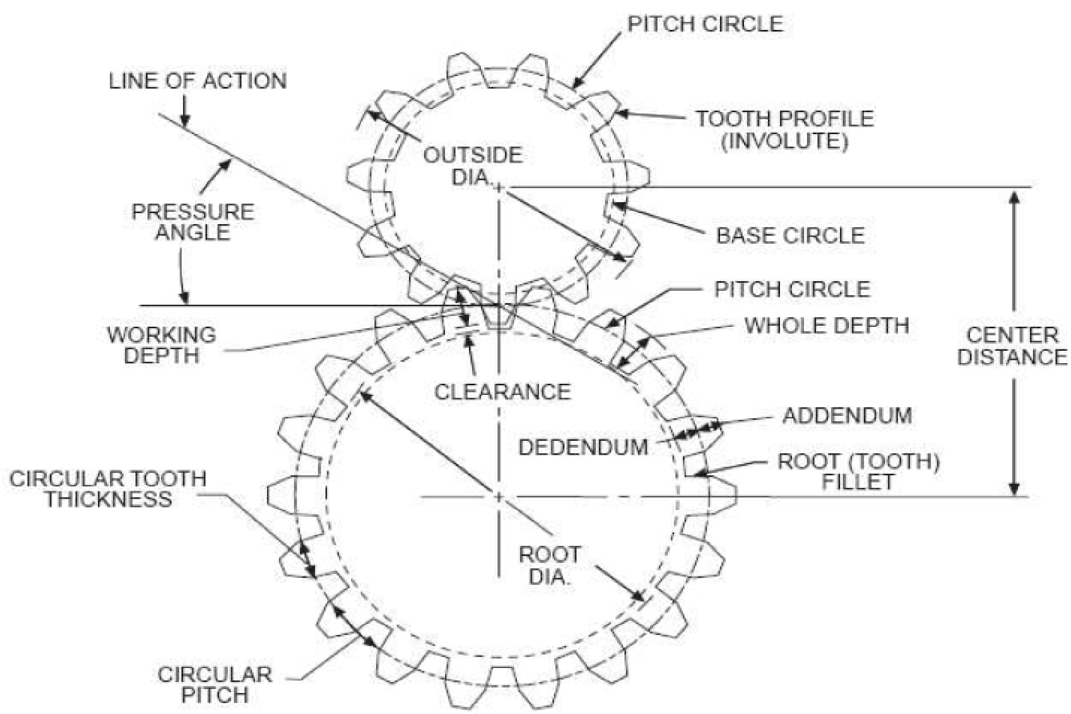


Fig.1.3 Gear Nomenclature

BACKLASH (B) is the amount by which the width of a tooth space exceeds the thickness of the engaging tooth on the pitch circles. As actually indicated by measuring devices, backlash may be determined variously in the transverse, normal, or axial-planes, and either in the direction of the pitch circles or on the line of action. Such measurements should be corrected to corresponding values on transverse pitch circles for general comparisons.

BORE LENGTH is the total length through a gear, sprocket or coupling bore.

CIRCULAR PITCH (p) is the distance along the pitch circle or pitch line between corresponding profiles of adjacent teeth.

CIRCULAR THICKNESS (t) is the length of arc between the two sides of a gear tooth on the pitch circle, unless otherwise specified.

CLEARANCE-OPERATING (c) is the amount by which the dedendum in a given gear exceeds the addendum of its mating gear.
CONTACT RATIO (m_c) in general, the number of angular pitches through which a tooth surface rotates from the beginning to the end of contact.

DEDENDUM (b) is the depth of a tooth space below the pitch line. It is normally greater than the addendum of the mating gear to provide clearance.

DIAMETRAL PITCH (P) is the ratio of the number of teeth to the pitch diameter.

FACE WIDTH (F) is the length of the teeth in an axial plane.

FILLET RADIUS (r_f) is the radius of the fillet curve at the base of the gear tooth.

FULL DEPTH TEETH are those in which the working depth equals 2.000 divided by the normal diametrical pitch.

GEAR is a machine part with gear teeth. When two gears run together, the one with the larger number of teeth is called the gear.

HUB DIAMETER is outside diameter of a gear, sprocket or coupling hub.

HUB PROJECTION is the distance the hub extends beyond the gear face.

INVOLUTE TEETH of spur gears, helical gears and worms are those in which the active portion of the profile in the transverse plane is the involute of a circle.

LONG- AND SHORT-ADDENDUM TEETH are those of engaging gears (on a standard designed center distance) one of which has a long addendum and the other has a short addendum.

KEYWAY is the machined groove running the length of the bore. A similar groove is machined in the shaft and a key fits into this opening.

OUTSIDE DIAMETER (D_o) is the diameter of the addendum (outside) circle.

PITCH CIRCLE is the circle derived from a number of teeth and a specified diametrical or circular pitch. Circle on which spacing or tooth profiles is established and from which the tooth proportions are constructed.

PITCH CYLINDER is the cylinder of diameter equal to the pitch circle.

PINION is a machine part with gear teeth. When two gears run together, the one with the smaller number of teeth is called the pinion.

PITCH DIAMETER (D) is the diameter of the pitch circle. In parallel shaft gears, the pitch diameters can be determined directly from the center distance and the number of teeth.

PRESSURE ANGLE (ø) is the angle at a pitch point between the line of pressure which is normal to the tooth surface, and the plane tangent to the pitch surface. In involute teeth, pressure angle is often described also as the angle between the line of action and the line tangent to the pitch circle. Standard pressure angles are established in connection with standard gear-tooth proportions.

ROOT DIAMETER (Dr) is the diameter at the base of the tooth space.

PRESSURE ANGLE-OPERATING ($ø_r$) is determined by the center distance at which the gears operate. It is the pressure angle at the operating pitch diameter.

TIP RELIEF is an arbitrary modification of a tooth profile whereby a small amount of material is removed near the tip of the gear tooth.

UNDERCUT is a condition in generated gear teeth when any part of the fillet curve lies inside a line drawn tangent to the working profile at its point of juncture with the fillet.

WHOLE DEPTH (h_t) is the total depth of a tooth space, equal to addendum plus dedendum, equal to the working depth plus variance.

WORKING DEPTH (h_k) is the depth of engagement of two gears; that is, the sum of their addendums.

1.3 Types of Gear

Spur gears

Spur gears are the simplest and most common type of gear. Their general form is a cylinder or disk. The teeth project radially, and with these "*straight-cut gears*", the leading edges of the teeth are aligned parallel to the axis of rotation. These gears can only mesh correctly if they are fitted to parallel axles.

Fig.:1.4 spur gear

Helical gears

Helical gears offer a refinement over spur gears. The leading edges of the teeth are not parallel to the axis of rotation, but are set at an angle. Since the gear is curved, this angling causes the tooth shape to be a segment of a helix. The angled teeth engage more gradually than do spur gear teeth. This causes helical gears to run more smoothly and quietly than spur gears. A pair of helical gears can be meshed in two ways: with shafts oriented at either the sum or the difference of the helix angles of the gears. These configurations are referred to as parallel or crossed, respectively.

Fig.:1.5 helical gear

Bevel gears

Bevel gears are essentially conically shaped, although the actual gear does not extend all the way to the vertex (tip) of the cone that bound it. With two bevel gears in mesh, the vertices of their two cones lie on a single point, and the shaft axes also intersect at that point. The angle between the shafts can be anything except zero or 180 degrees. Bevel gears with equal numbers of teeth and shaft axes at 90 degrees are called **miter gears**.

The teeth of a bevel gear may be straight-cut as with spur gears, or they may be cut in a variety of other shapes. '**Spiral bevel gears**' have teeth that are both curved along their (the tooth's) length; and set at an angle, analogously to the way helical gear teeth are set at an angle compared to spur gear teeth. '**Zero bevel gears**' have teeth which are curved along their length, but not angled. Spiral bevel gears have the same advantages and disadvantages relative to their straight-cut cousins as helical gears do to spur gears.

Fig.:1.6 Bevel gear

Crown gear

A crown gear or contrate gear is a particular form of bevel gear whose teeth project at right angles to the plane of the wheel; in their orientation the teeth resemble the points on a crown. A crown gear can only mesh accurately with another bevel gear, although crown gears are sometimes seen meshing with spur gears. A crown gear is also sometimes meshed with an escapement such as found in mechanical clocks.

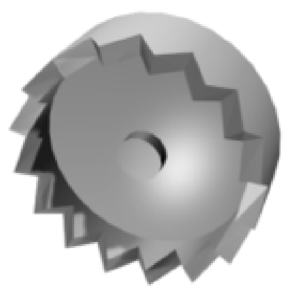


Fig.:1.7 Crown gear

Worm gear

A worm is a gear that resembles a screw. It is a species of helical gear, but its helix angle is usually somewhat large (i.e. somewhat close to 90 degrees) and its body is usually fairly long in the axial direction; and it is these attributes which give it its screw like qualities. A worm is usually meshed with an ordinary looking, disk-shaped gear, which is called the "gear", the "wheel", the "worm gear", or the "worm wheel".

Fig.:1.8 Worm gear

Rack and pinion gear

A rack is a toothed bar or rod that can be thought of as a sector gear with an infinitely large radius of curvature. Torque can be converted to linear force by meshing a rack with a pinion: the pinion turns; the rack moves in a straight line. Such a mechanism is used in automobiles to convert the rotation of the steering wheel into the left-to-right motion of the tie rod(s). Racks also feature in the theory of gear geometry, where, for instance, the tooth shape of an interchangeable set of gears may be specified for the rack (infinite radius), and the tooth shapes for gears of particular actual radii then derived from that. The rack and pinion gear type is employed in a rack railway.

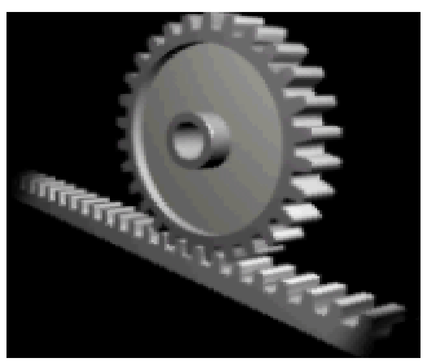


Fig.:1.9 Rack and pinion gear

1.4 Gear Materials

Gears are manufactured from a wide variety of materials, both metallic as well as non metallic. As in the case with all material used in design, the material chosen for a particular gear should be cheapest available that will ensure satisfactory performance. Before a choice is made, the designer must decide which of the several criteria is most important to the problem at hand if high strength is the prime consideration, a steel should usually be chosen and if possible cast iron. If wear resistance is the most important consideration, a non-ferrous material is preferable to a ferrous one. Some of the materials used are described below.

Cast Iron

Cast Iron is one of the most commonly used gears materials. Its low cost, case of casting, good machinability, high wear resistance and noise abatement property make it a logical choice. The primary disadvantage of cast iron as a gear material is its low tensile strength, which makes the gear tooth week in bending and necessitates rather large teeth. ASTM numbered cast irons between 20 and 60 are commonly used for gears. It should point out that the corresponding AGMA numbered cast irons have the same tensile strength as the ASTM ones.

Another type of cast iron is nodular iron, which is made of cast iron to which a material such as magnesium or cerium has been added. The result of the alloying is a material having a much higher tensile strength while retaining the good wear and machining characteristics of ordinary cast iron. Very often the combination of cast iron gear and a steel pinion will give a well balanced design with regard to cost, strength, and wear.

Steel

Steel gears are made of plane carbon steels or alloy steels. They have a advantage, over cast iron, of higher strength without much increase in cost. However they usually require heat treatment to produce a hard surface enough to give satisfactory resistance to wear.

Unfortunately, the heat treatment process usually produces a surface hard distortion of the gear, with the result that the gear load is not uniformly distributed across the gear tooth face. Since alloy steels are subject to less distortion due to heat treatment than carbon steels, they are often chosen in preference to the carbon steels. The various heat treatment methods and their effect on the properties of materials so treated, the designer should be aware of possible problems arising from the use of heat treated materials. Gears are often through-hardened by water or oil quenching in order to increase their resistance to wear. If a low degree of hardness is satisfactory, through-hardening is probably the most desirable heat treatment process to be used because of its inexpensiveness.

Case hardening is used for gears that require a hard surface and for which good accuracy is not necessary. The case hardening process results in gears is that, while the surface become hard and wear resistant, the toughness associated with the core remains. The effect of case hardening a gear tooth is the hardened case, while the major portion of the tooth (lighter area) remains unaffected as shown in figure 1.10

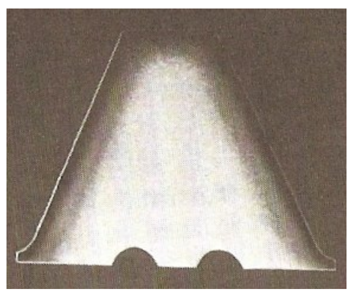


Fig.:1.10 Case hardening of gear tooth

Carburizing, cyaniding, nitriding, flame hardening, and induction hardening are some of the processes commonly used to produce the case hardening effect. If great accuracy is required, the gear must be ground. For problems in which corrosion resistant surface are desirable, nitriding is the process most often used. However, nitriding is relatively expensive process and is used only if other processes do not produce satisfactory results. Flame hardening and induction hardening are the methods usually used to harden larger gears.

Nonferrous metals

Copper, zinc, aluminum, and titanium are materials used to obtain alloys that are useful gear materials. The copper alloys, known as bronzes, are perhaps the most widely used. They are useful in problem where corrosion resistance is important and also where large sliding velocities exist. Because of their ability to reduce friction and wear, they are usually used as the material for making the worm wheel in a worm gear set. Aluminum and zinc alloys are used to manufacture gears by the die-casting process.

1.5 Types of Gear Tooth Failures

The gears generally fail when tooth stress exceeds the safe limit. When failure occurs, they are expensive not only in terms of the cost of replacement or repair but also the cost associated with the downtime of the system of which they are a part. So, it is important to understand various problems that can occur in gears.

The types of gear tooth failures can be categorized into following classes:

- Wear
- Scoring
- Interference
- Surface Fatigue
- Plastic Flow
- Fracture
- Process Related

Wear

Wear occurs when the film of lubricant that exists between the mating surfaces of the teeth is not sufficient to prevent surface-to-surface contact. Other factors responsible for wear, such as abrasive particles in the lubricant, corrosion of tooth surfaces, aberrations in the tooth surfaces themselves that penetrate the lubricant film, relative surface roughness of the tooth flanks, and the amount of contamination in the lubricant.

Depending on the extent and the cause of wear, it can be of following types:

- Polishing Wear
- Moderate Wear
- Excessive Wear

- Abrasive Wear
- Corrosive Wear

Scoring

Scoring is generally observed on high-speed, high- load gearing. Most often these gears are operating with low- viscosity, synthetic lubricants. If the combination of load, sliding velocity, and inlet oil temperature reaches a critical value, the oil film separating the mating surfaces is destroyed, and metal-to- metal contact occurs. If the surface pressure and sliding velocity are high enough, instantaneous welding of the asperities will then occur. As the gears continue to rotate, the welds break. This phenomenon is known as Scoring.

Depending on the extent and the cause of scoring, it can be of following types:

- Frosting
- Light Scoring
- Moderate Scoring
- Destructive Scoring
- Localized Scoring

Interference

Interference of one tooth with another, can wreak havoc on the operation of the system. A wide variety of conditions, such as operating on tight centers, insufficient involute, thermal expansion, misalignment and insufficient or incorrect profile modifications can cause interference.

Depending on the region of interference, it can be of following types:

- Tip Interference
- Root Interference

Surface Fatigue

Surface fatigue is a time-dependent phenomenon; thus its effects may not be apparent for a considerable period of time. The surface of a gear tooth is subjected to varying load. This

condition is referred to as fatigue. When the fatigue capacity of the material is exceeded, it will fail. It generates substantial quantities of chips in their later stages of progression.
Depending on the extent of surface fatigue, it can be of following types:

- Initial Pitting
- Destructive Pitting
- Spalling
- Case Crushing

Plastic Flow

Plastic flow does progress with time and can ultimately be catastrophic. It is not strictly a fatigue phenomenon. Very heavy loads, usually combined with relatively slow speed rotation can cause gear materials to flow plastically.
Depending on the specific conditions encountered, plastic flow may take any of several forms:

- Cold Flow
- Hot Flow
- Rippling
- Ridging

Fracture

Fracture is a much more insidious type of failure. It produces no debris in its early stage, gives little warning, and usually results in either immediate loss of serviceability or greatly reduced power transmitting capacity. All the failure modes discussed above are progressive, i.e. the time between failure initiation & complete loss of serviceability is frequently quite long. This is of particular importance in the design of devices such as helicopters, elevators, cranes, and so forth in which a complete failure to transmit rotation may result in human injury or death. For these reasons, gears are generally designed with a larger margin of safety when considering the fracture modes.
Depending on the way in which the fracture occurs, it can be of following types:

- Classical Bending Fatigue

- Overload
- Random Fracture
- Root/Rim/Web
- Resonance

Process Related

There are many types of failures that occur even before the gears are placed in service. The very best design, on paper, can be a total disaster if it is not faithfully executed in the manufacturing phase. Process Related failure can be of following types:

- Quench Cracks , Grinding cracks
- Grinding cracks
- Nicks, Scratches
- Electric Arcing
- Grinding “Burns”
- Improper Edge Breaks and tool marks

CHAPTER 2

LITERATURE REVIEW

2.1 FRACTURE

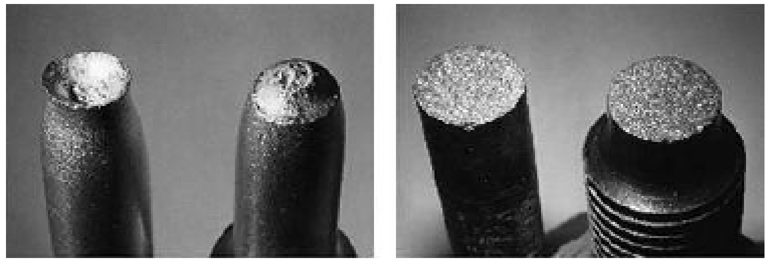
Fracture is a form of failure and is defined as separation or fragmentation of solid body into two or more parts under the action of stress at temperature below the melting point. The process of fracture can be considered to be made up of two components crack initiation and crack propagation. Fracture can occur under all service conditions. Material subjected to alternating or cyclic loading fail due to fatigue. The fracture under such circumstances is called fatigue fracture.

Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined- ductile and brittle fracture.

Figure 2.1 Illustrating fracture

2.1.1 Ductile

It is characterized by appreciable amount of plastic deformation prior to and during propagation of the crack. It is characterized by extensive plastic deformation ahead of crack tip. The growth of crack is stable and resists further extension unless applied stress is increased. Ductile material can absorb shock or energy (during the deformation) before failure. It occurs in most metals which are not too cold. FCC metals are usually ductile because of the presence of large number of active slip systems.

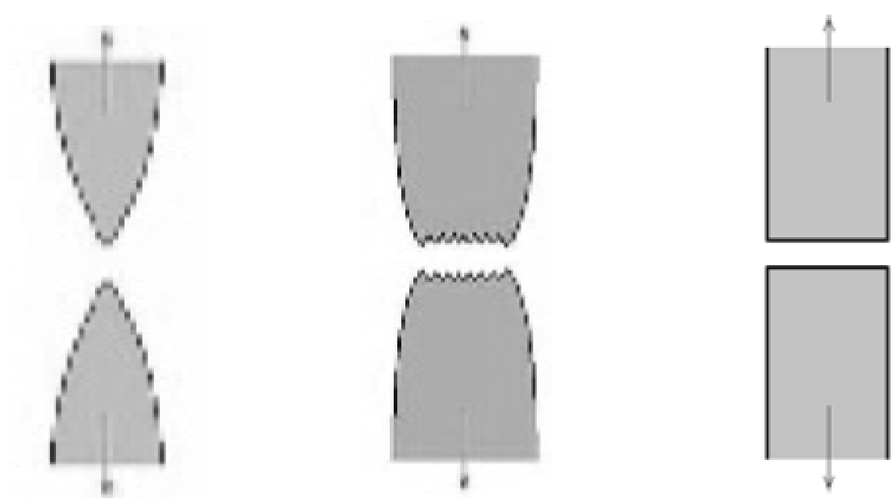


. Ductile fracture Brittle fracture

Figure 2.2 Illustrating types of fracture.

2.1.2 Brittle:

It is characterized by a rapid rate of crack propagation, with no gross plastic deformation and very little micro deformation. Crack propagates by cleavage nearly perpendicular to direction of applied stress with breaking of atomic bonds along specific crystallographic plane (cleavage plane). It is caused by decreasing temperature, increasing strain rate and triaxial stress condition. Less amount of energy absorption occurs before fracture. It occurs mostly in cold metals and ceramics. BCC and HCP metals are susceptible to brittle fracture because there are very less number of active slip planes or slip systems for plastic deformation.



Highly ductile fracture Moderately ductile fracture, Brittle fracture e.g. pure gold e.g. most metals e.g. ceramics

Figure 2.3 Illustrating crack propagation

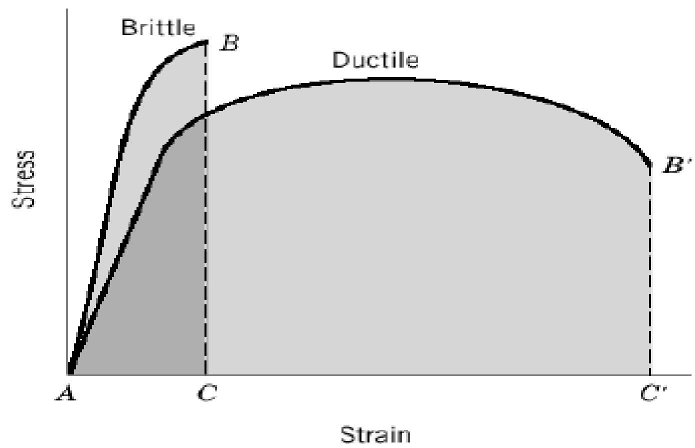


Figure 2.4 stress-strain curves

Figure 2.4 represents the degree of plastic deformation exhibited by both brittle and ductile materials before fracture.

2.2 Importance of Failure Analysis in Automotive sector:

Failure Analysis is conducted to determine how and why components like gears, pistons, ball-bearings, rods, crank-shafts, valve-springs and rear–axle etc. failed and serves to define corrective actions to avoid future similar failures.

Failure due to ductile to brittle transition:

At very low temperature ductile to brittle transition take place. A famous sheep named "**TITANIC**" is a strong example of this transition.

Fig 2.5 **Fracture of sheep due to ductile to brittle transition**

2.3 Classifications of failure modes:

Table 2.1: Describing different failure modes

Ductile failure	**Brittle failure**
1. Tensile overload	**1. Intergranular fracture mech.**
2. Shear overload	**a) Stress-corrosion cracking**
a) Transfer Shear	**b) Liquid-metal embrittlement**
b) Torsional Shear	**c) H-embrittlement**
	d) Creep
3. Bending Overload	**e) Grain-boundary embrittlement**
	2. Transgranular fracture mech.

	a) Cleavage
	b) Stress-corrosion cracking
	c) Fatigue

Depending upon the working conditions applied on material, it may undergo different type of failure modes. It depends upon the type of stress applied and other environmental conditions. These are described in table 2.1 given above.

Analysis of engineering failures is a complex process that requires information from personnel having expertise in many areas. From the information gathered, a failure analyst tries to discover what was fundamentally responsible for the failure. This fundamental cause is termed the ‘‘root cause’’ and helps in the determination of the sequence of events that led to the final failure. Root cause analysis also helps in finding solutions to the immediate problem and provides valuable guidelines as to what needs to be done to prevent recurrence of similar failures in future. However, experience suggests that most failure analyses fall short of this goal. A significant number of failure analysts incorrectly use the term ‘‘root cause’’ when what they really establish is the primary cause of failure or simple physical cause. Analysis of engineering failures is a formidable, complex, and challenging task. Nevertheless, the following general approach is recommended for a successful failure investigation [1].

1. Identify and describe the apparent problem or reason(s) that the system was not working properly

2. Collect information related to the problem, separating facts from assumptions and inferences

3. Define the real problem and look beyond the immediate cause(s)

4. Generate data by evaluations and analysis and identify primary cause(s)

5. Identify all probable root causes

6. Identify most likely root cause(s)

7. Generate probable solutions and courses of action

8. Evaluate the merits, risks, potential for success and implications of respective options

9. Select the best option available and develop a suitable plan of action

10. Implement the plan of action

11. Follow-up and obtain feedback

Many failure analysis practitioners follow an established procedure for the evaluation of failed components systems, and in the process they ignore the complexity involved in establishing the facts of the failure. They may adopt a preset procedure without even trying to discover the situations or conditions under which the failure had occurred. The use of a preset procedure generally occurs because of lack of appreciation that the same physical failure can be arrived at in many ways. Because of the many potential paths to a specific physical failure, an understanding of the relative importance of various factors in the specific case at hand is essential. It must be borne in mind that all failures are unique, and, hence, each of them should be treated uniquely. As described by Dennies [2], established ‘‘recipe’’-type procedures are generally inadequate in determining the root cause(s) of a failure. According to Zamanzadeh etal. [3], case studies can be broadly classified into the following three categories:

• Errors of knowledge

• Errors of performance (which might be caused by negligence)

• Errors of intent (which might even be acts of greed or sabotage)

The materials of the camshaft and crankshaft gears are 42CrMo steel, which corresponds to the specified material [4]. A failure investigation was conducted on a gear system (by Z.Yu. X.Xu) consisting of a driven camshaft and drive crankshaft gears. The gears are made from a nitrided 42CrMo steel. Adjacent teeth fracture and plastic deformation regions appeared on the gears after a 400 h run test of the gear system. Fractography indicates that fatigue fracture is the dominant failure mechanism for the gear teeth. Although the appearance of needle-like nitrides in the nitrided layer and the narrow depth of the compound layer may decrease the fatigue strength of the camshaft gear, these do not suffice to lead to the premature fracture of the gear teeth. Geometrical analysis of the gears was performed and compared with an analysis of unfailed gears that had experienced a run test for 1800 h. The comparison reveals that the small fillet radius at the root area of the camshaft gear concentrated the stresses and is mainly responsible for fatigue fracture of the teeth. The camshaft gear is the component that initiated trouble in the gear system. The appearance of severe plastic deformation on the gear faces is caused by the fractured teeth crushing the teeth faces and being embedded in the grooves between teeth.

Failure types are fracture, surface fatigue, abrasion and plastic deformation in gear mechanisms. Fracture damage results from surface fatigue, high loads or abrasions. Surface fatigue results from tensile stress, compression stress and sliding stress under the gear surface. Abrasion damage is defined as loss of material at touching gear surfaces. Failure reasons are faults of usage, heat treatment, design, manufacture and material. Usage faults are caused by incautious operation and insufficient technical knowledge. These faults can cause important damage in machinery. Design faults include incorrect shape, dimensional errors, bearing faults, selection of wrong material and insufficient technical knowledge. In studies of gear design, usually a dimensional error has been made or the wrong material has been selected. In research [5] on gear failure types and reasons, 931 gears were investigated during 35 years of its working of different gears. Results show that the failure types were fractures of 571 gears, fatigue of 188 gears, abrasion of 122 gears and plastic deformation of 50 gears. The most encountered failure is fracture (61.2%) and the least is plastic deformation (5.3%). The failure reasons were determined as usage faults of 696 gears, heat treatment faults of 151 gears, design faults of 64 gears, manufacturing faults of 13 gears, material faults of 7 gears. Consequently, the most encountered failure is usage fault (74.7%) and the least one is material fault (0.8%).

Fredette and Brown [6] studied the stress analysis of gear tooth. For this analysis they drilled holes across the entire tooth as a function of size and location. The ultimate objective of this work was to find the overall effect of hole size and location on the critical stresses in the gear. Many of these researchers used the finite element analysis techniques for the analysis of the gear tooth. Wilcox [25] gave an analytical method for calculating stresses in bevel and hypoid gear teeth. More recently number of authors had also done the analysis of the gears for the applied bending forces.

Litwin, Chen, Lu [27] and Handschuh [7] again applied finite element analysis on a loaded tooth for the determination of load share, real contact ratio, precision of motion and the stress analysis [7]. It was the work done in parts by these authors i.e. Litwin did the determination of the load share, real contact ratio was determined by Chen and Lu and Handschuh did the stress analysis.

A program was given by Gosselin, Claude, Clautier [8] predicting the motion error of spiral bevel gear sets under load, and explored some of the influences of the unloaded motion error curve shape and amplitude over the kinematical behavior under load [8]. The effects of tooth composite deflection caused by bending and shearing, tooth contact deformation and initial profile separation due to profile mismatch were considered in the development.

Chen and Tsai [9] developed a finite element model applied to an involute gear considering friction effects. The loss of Torque transmission due to friction and effective friction coefficient were evaluated and computed.

Moriwaki [10] developed a technique named Global Local Finite Element Analysis (GLFEM) and applied it to a gear tooth for its stress analysis. He realized that for doing the stress analysis of the gear using the finite element analysis, a load acts at a point on the tooth profile and for that a fine subdivision is required at the applied load point. In GLFEM, no fine subdivision is required for the analysis. This method also guarantees an easy determination of the critical section. In fact, GLFEM is a numerical analysis technique that combines finite element solutions and the classical analytical ones on the basis of the energy principle. The application of finite element method for LTCA was also the subject of research by Chao and Baxter [26], Drago and Uppaluri [11].

Chen and Tsay [12] investigated the contact stress and bending stress of a helical gear set with localized bearing contact, by means of finite element analysis (FEA). They proposed a helical gear set comprised of an involute pinion and double crowned gear. Mathematical models of the complete tooth geometry of the pinion and the gear had been derived based on the theory of gearing. A mesh generation program was also developed for finite element analysis.

Chien-Hsing Li, Hong-Shun Chiou [13] established a batch module called, “integration of finite element analysis and optimum design” by taking gear systems as testing examples. This batch module consisted of I-DEAS, ABAQUS/Standard and MOST software, which serve as the preprocessor, the numerical solver and the optimizer, respectively. A simple and practical method was developed, through which this module enabled to locate the contact surfaces for contact analysis. For the testing example, a simple gear-pair system and a complete planetary gear system were used for this integrated module. The module would automatically construct the geometrical model, analyze the contact stress and solve for the optimal solutions when gearing parameters are input.

Simon [14] performed stress analysis in hypoid gears, by using finite element method, in order to develop simple equations for the calculation of tooth deflections and stresses. He developed a method for the automatic finite element discretization of the pinion and the gear. The full theory of mismatched hypoid gears was applied for the determination of the nodal point coordinates on the teeth surfaces. He developed a corresponding computer program. With the help of this program the influence of design parameters and load position on tooth deflections and fillet stresses is investigated. On the basis of results, which were obtained by performing a big number of computer runs, equations for the calculation of tooth deflections and fillet stresses were derived.

Zhang and Fang [15] used an approach for the analysis of tooth contact and load distribution of helical gears with crossed axis. This approach was based on a tooth contact model that accommodates the influence of tooth profile modifications, gear manufacturing errors and tooth surface deformation on gear mesh quality. In this approach the tooth contact load was assumed distributed along the tooth surface line. As an example, the computer program analyzed the contact of a pair of helical gears with small crossing angle. It was found from this analysis that helical gears with small crossing angles have meshing characteristics and load distribution similar to those of parallel axis gears.

Spitas and Costopoulos [16] studied the idea of spur gear teeth with circular instead of the standard trochoidal root fillet and it was investigated numerically using BEM. The strength of these new teeth was studied in comparison to the standard design by descretizing the tooth boundary using isoparametric boundary elements. In order to facilitate the analysis the teeth were treated as non-dimensional assuming unitary loading normal to the profile at their highest point of single tooth contact. It was demonstrated that the novel circular design surpasses the existing trochoidal design of the spur gear tooth fillet in terms of fatigue endurance without affecting the pitting resistance. The proposed geometry does not produce undercut teeth even for small number of teeth.

Kapelevich and Kleiss [17] gave an alternative approach to traditional gear design. The approach was direct gear design. It allowed analysis of a wide range of parameters for all possible gear combinations in order to find the most suitable solution for a particular application. This optimum gear solution can exceed the limits of traditional rack generating methods of gear design. Direct gear design for asymmetric tooth profiles opens additional reserves for improvement of gear drives with unidirectional load cycles.

Guigand and Icard [18] gave a method for simulating loaded face gear meshing. It simulated the loaded behavior of face gear meshing and provides information such as the instantaneous pressure distribution across the entire width of the teeth in contact and loaded transmission error. Analytical simulations were used to define the geometry and study the unloaded kinematics. The aim was to obtain the best possible loading of face gear meshing in order to avoid line contact sensitivity due to misalignment.

Beghini and Santus proposed a simple method to minimize the Peak to Peak Transmission Error (PPTE) for a spur gear set [19]. A parametric analysis using advanced software was performed to obtain a general understanding of the problem. The main aim was to develop a simple method for profile optimization in terms of PPTE, which was the main cause of whining noise in spur gears. A combined semi-analytical and FEM software had been used for performing meshing simulations.

Parker and Vijayakar investigated the dynamic response of a spur gear pair using a finite element/contact mechanics model [20]. The gear pair was analyzed across a wide range of operating speeds. The non-linearity source was contact loss of the meshing teeth, which occurred for large torques despite the use of high precision gears. Using a detailed contact analysis at each time step as the gears rolled through the mesh, dynamic mesh forces were calculated. A semi-analytical model near the tooth surface was matched to a finite element solution away from the tooth surface.

Hiremagalur and Ravani studied the effect of backup ratio in spur gear root stresses analysis and design [21]. Backup ratio was considered important in understanding rim failures that start at the tooth root. Here an analytical approach, based on theory of elasticity, was used to provide a computational formulation for root stress calculations in spur gears.

Now a day’s composite material finds increasing applications ranging from spacecraft to small instruments. Many types of gear pump use composite gears, however little literature is available on their use.

Vijayrangan and Ganesan [22] obtained results by static stress analysis of composite gears using a three dimensional finite element approach. Performance of two orthotropic material gears were presented and compared with mild steel gear. From the results it was concluded that composite material such as graphite/epoxy could be thought of as a material for power transmission gears.

Dally and Riley [23] tried to minimize the stress in a finite plate by drilling a hole in it. They optimized the hole profile for minimizing the photo elastic stress. For optimization they used the software ANSYS 5.3. They not only did their study on a hole profile but also on the square profile and got the results.

The idea of using holes to reduce stresses is not a new one. In 1990**,** Dippery experimented with the use of supplementary holes in a structure as a method of reducing the stress concentration that was already present. His result showed that stress concentration reductions are possible in a generic shape using holes as stress relief.

Yang [24] showed that similar reductions are possible in gears. His work was limited to hole placement in the region of relatively low stress of the bending gear tooth.

2.4 Aim of the work:

Mahindra and Mahindra Ltd. is an automobile sector which is involved in manufacturing of different categories of automobile engines. Among the automobiles manufactured by Mahindra and Mahindra Ltd. Different type of gears are used. It was reported that teeth failure of gears are in majority after being used in service conditions. The failures were reported in three wheeler (alpha, champion), four wheeler (bolero, scorpio) and some mini buses. In order to study the failure cause, one specific gear of three wheeler (alpha) which failed during its working conditions (within 600 km. distance and in warranty period) was taken for present investigations.

The present work is conducted to analyze the failures existing in gears. In order to study the causes of the fractures, specimens were prepared from the damaged gears and subjected to hardness, chemical analysis and metallurgical tests. The effect of microstructure on the fracture was also considered. The detail of this analysis is presented in subsequent chapters.

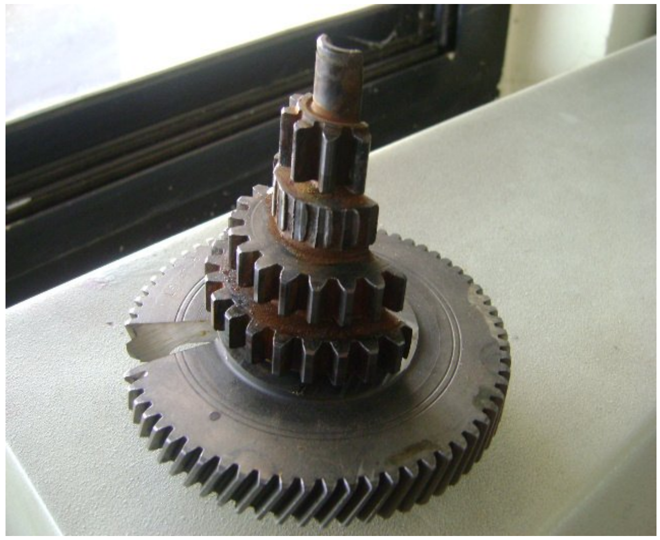


Fig 2.6 Failed Cluster gear

CHAPTER 3

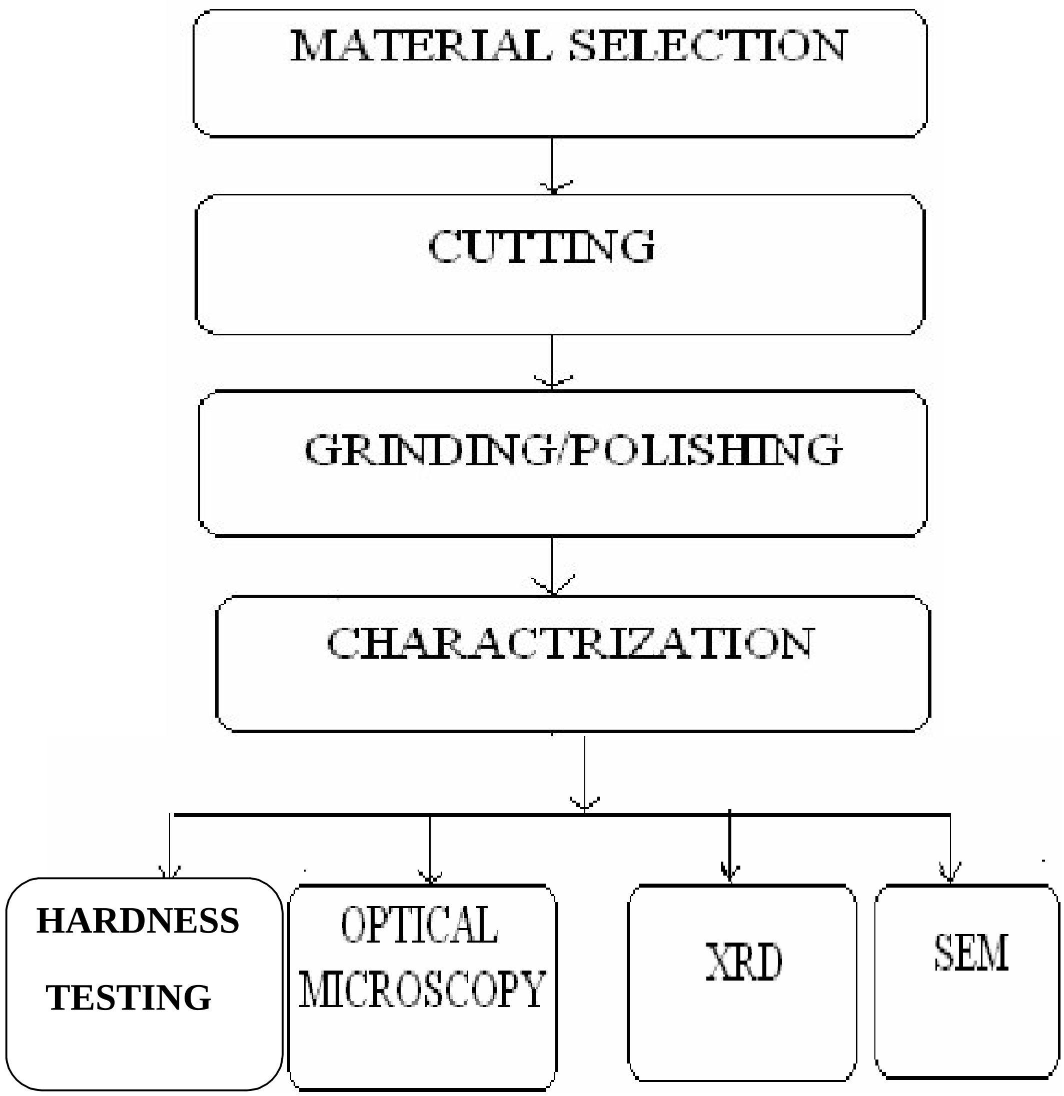
Experimental Work

In this chapter all the details about the preparation and characterization of samples has been described. The experimental techniques involves following steps:

3.1. Preparation of samples

3.2. Characterization and testing

Process Flow Chart



3.1 Instruments used in experiments

The instruments used in entire study including preparation and characterizations are:

3.1.1 Instruments for chemical analysis

EDAX" TSL model, Advanced microanalysis solutions AMETEK, for the detection of C, N, Cr, Mn, Mo, Ni, Cu, Si, P, S, Al, Fe

3.1.2 Cutting machine

• BAINCUT- UM Abrasive cut off machine, with coolant

3.1.3 Grinding, mounting and polishing unit

• BAILINE Belt linishing machine (Grinder)

• BAIN MOUNT-111 Pneumatic specimen mounting press

• CHENNAI METCO wet grinding and polishing machine

3.1.4 Hardness tester

• FM TECH. 700 Microhardness tester

• RAB 250 Rockwell hardness tester

3.1.5 Microscopes

• Optical microscope, NIKON Eclipse MA-100, magnification 50X - 1500X

• Scanning electron microscope, model: Quanta 200 FEG, with EDS

3.1.6 XRD

• LEO model diffractogram, with Cu (Kα) radiation (λ= 1.54 Å), Cu target with inbuilt Ni filter

3.3 Materials

The failed gear for present work was obtained from Mahindra and Mahindra Ltd., Automotive Sector-5, Haridwar. Samples of failed gears were prepared. Then these samples were subjected to mechanical and metallurgical testing techniques.

3.3.1) Material and Metallurgical information regarding standard gear:

1.	Description	Cluster gear
2.	Material	Alloy steel
3.	Material grade	20MnCr5
4.	Heat treatment	Carburizing, Hardening, Tempering
5.	Surface hardness	58~62 HRC
6.	Core hardness	35~45HRC
7.	Effective case depth	0.48~0.62mm.
8.	Microstructure	Case Tempered martensite

		Core Bainite, low carbon martensite

3.4 Sample preparation

3.4.1 Cutting

The samples of the failed gears were cut in the transverse direction with the help of cutting machine.

3.4.2 Grinding and polishing

The cut samples taken from different gears were subjected to mechanical grinding followed by polishing. The sample was first held over a grinding machine with a moving belt to obtain a smooth surface. The grinding was done in such a way so that all the scratches were in the same direction and the grinded surface becomes flat. After this the samples were polished properly using different grits of emery paper (400 and 600 grit emery paper). It was subsequentially polished on more finer paper so as to remove maximum scratches which have been appeared during course of grinding. Finally the samples were then polished on a fine polishing machine on a silvet cloth using submicron size alumina paste. This was done to get a well polished and a smooth surface required for the further characterization of the samples. Similarly all the samples were polished for a considerable amount of time till final finish (mirror like) is obtained. The entire polishing operation was performed carefully.

3.5 Characterization

- Hardness Measurement
- Microstructural Characterization

3.5.1 Hardness measurement through Vickers Hardness Test

It is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces. The surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond Fig.3.1. The diagonal of the resulting indention is measured under a microscope and the Vickers Hardness value is calculated by putting the valued in the formula. The Vickers Diamond Pyramid hardness number is the applied load (kgf) divided by the surface area of the indentation (mm^2). Microhardness test was done for the various samples using the Vicker's hardness machine (microhardness tester). The readings of the indent obtained were taken and the corresponding VHN (Hv), then converted HRC readings were obtained. Five to eight readings were obtained for each sample and at different phases,. The formula used for obtaining hardness value is:

$$H_V = 1.854\ F/\ d^2$$

Where:

F=Load in kgf

d = Arithmetic mean of the two diagonals, d1 and d2 in mm.

H_v = Vickers hardness

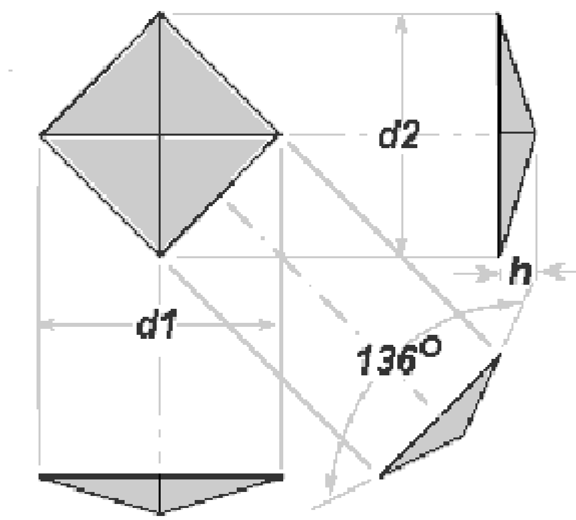


Figure 3.1: Vickers Pyramid Diamond Indenter Indentation

3.5.2 Microstructural characterization through optical microscope:

The well-polished samples were then observed under an optical microscope. Micrographs were taken with the help of CCD camera attached to the optical microscope and are further viewed on computer with optical image analyzer software at different magnifications (50X to 1500X) for all the samples.

3.5.3 Microstructural characterization through SEM:

Fracture surfaces of samples were examined in order to determine the exact mode of failure in the failed material. Sample were taken from the fractured surface and observed under

SEM. Extra care was taken during the cutting to avoid any contamination of the fracture surface. The bottom of the sample has been flatten and then mounted on a standard base with special glue.

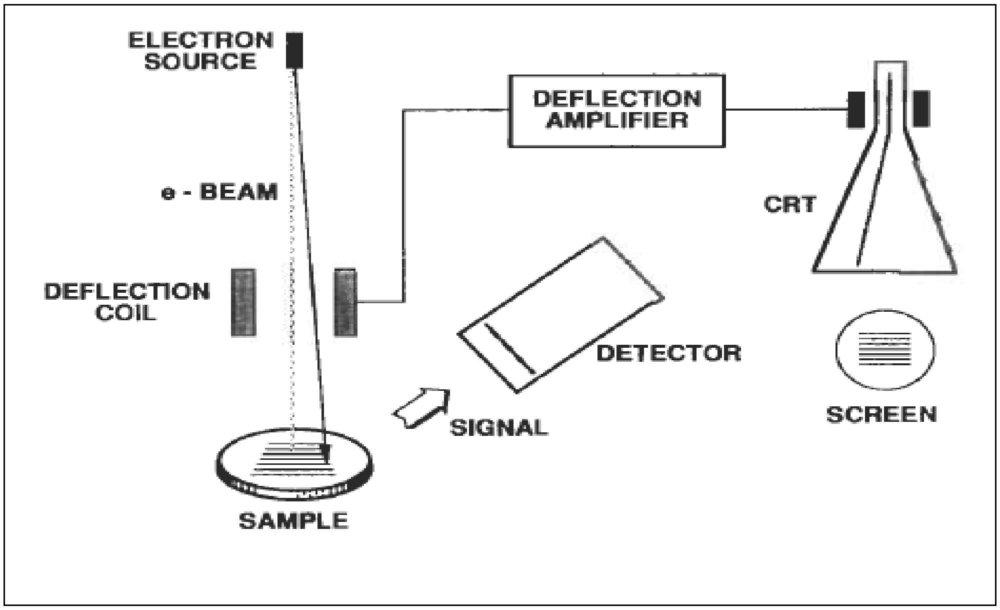


Fig: 3.2c) **describing the operation of SEM**

3.6 EDS (Energy Dispersive X-Ray Spectroscopy)

EDS is an extremely powerful analytical technique for identifying the existing elements present in the material. It is a technique of special value in conjunction with electron column instruments. In a few seconds a qualitative survey of the elements present in almost any sample can be made and in only a few minutes sufficient data can be collected for quantification. The most frequent application has been to highly polish metal samples, although non conducting samples may be studied if they can be coated with a thin conducting film (fig.3.2d)

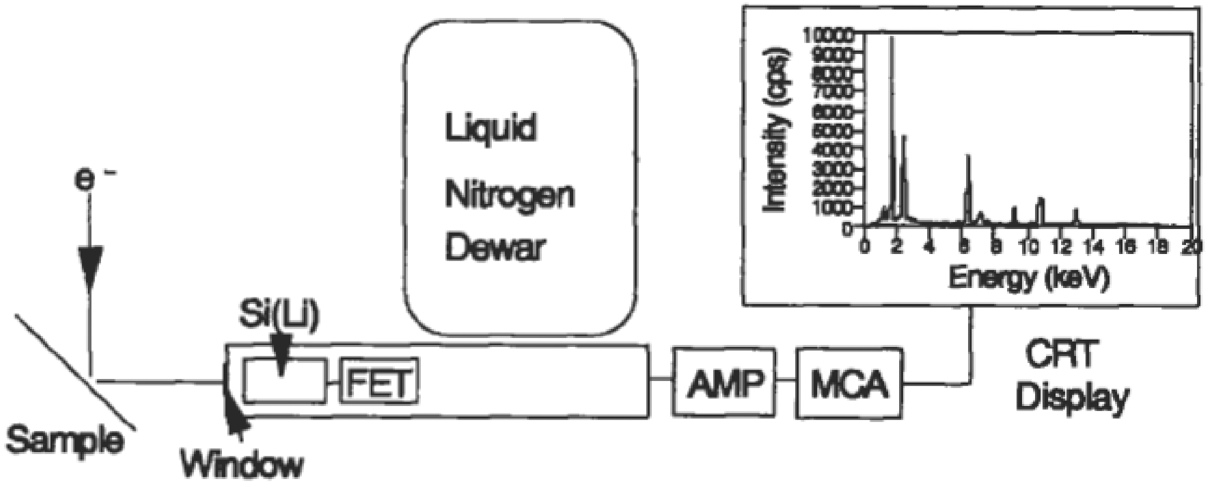


Fig 3.2d) **Schematic of an EDS system on an electron column.**

3.7: XRD Technique:

X-ray Diffraction (XRD) is a powerful technique used to uniquely identify the crystalline phases present in materials and to measure the structural properties (strain state, grain size, epitaxy, phase composition, preferred orientation, and defect structure) of these phases. XRD is also used to determine the thickness of thin films and multilayers, and atomic arrangements in amorphous materials (including polymers) and at interfaces.

In XRD experiment, the diffracted intensity is measured as a function of 2θ and the orientation of the specimen, which yields the diffraction pattern. The X-ray wavelength λ is typically0.7-2A**,** which corresponds to X-ray energies (E = 12.4 keV/A) of 6 - 17 keV.

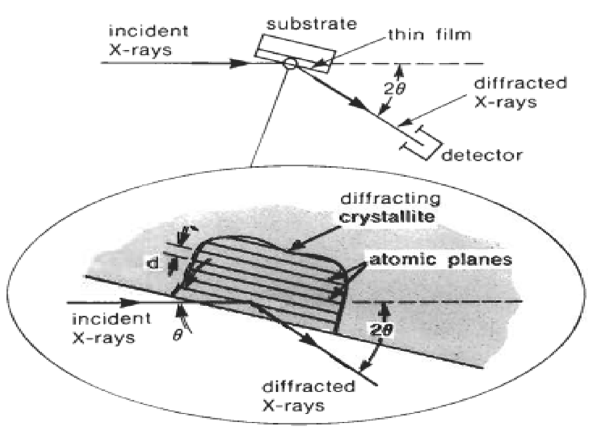


Fig 3.2e) **Basic features of a typical XRD experiment**

CHAPTER 4

RESULT and DISCUSSION

4.1 HARDNESS ANALYSIS OF FAILED GEAR:

In order to know the cause of failure, hardness of each gear sample was measured. The hardness measurements were tabulated in table (4.1- 4.5).

Table 4.1: Hardness measurement for sample1:

Case depth(mm)	.10	.20	.30	.40
HV	644	617	548	507
HRC	57.5	56.2	52.3	49.7

Surface Hardness = 58~59 HRC
Core Hardness =41~ 42 HRC
Case depth =0.29 mm

Table 4.2: Hardness measurement for sample 2:

Case depth(mm)	.10	.20	.30	.40	.50	.60	.70	.80
HV	735	729	715	695	633	597	560	540
HRC	61.5	61.4	60.8	59.9	56.9	55.1	53	51.7

Surface Hardness = 61~62 HRC
Core Hardness= 39~40 HRC,
At (Total case depth) T C D =7.02 mm. hardness observed = 56 HRC
Case Depth = 0.75 mm

Table 4.3: Hardness measurement for sample 3:

Case depth(mm)	.10	.20	.30	.40	.50	.60	.70	.80	.90	1.0
HV	720	705	695	687	657	655	620	600	590	550
HRC	61	60.2	59.9	59.6	57.7	58	56.3	55.2	54.7	52.3

Surface Hardness = 61~62 HRC

Core Hardness = 39~40HRC
Case Depth = 1mm

Table 4.4: Hardness measurement sample 4:

Case depth(mm)	.10	.20	.30	.40	.50	.60
HV	674	681	650	620	575	535
HRC	59	59.2	57.8	56.3	53.9	51.4

Surface Hardness = 59~60 HRC
Core Hardness = 36 HRC
Case Depth = 0.58 mm

Table 4.5: Hardness measurement for sample 5:

Case depth(mm)	.10	.20	.30	.40	.50	.60
H V	683	699	681	636	595	541
HRC	59.3	60.1	59.2	57	54.9	51.7

Surface Hardness = 59-60 HRC
Core Hardness = 38-39 HRC
Case Depth = 0.58 mm

Hardness analysis shows that among all the five samples, second and third sample show abnormal case depth which could be observed after etching with nital (96% methanol +4%HNO_3). In the second sample, total case depth observed i.e. total hardened region is 7.02mm. Hardness value at the total case depth of 7.02mm. is 56 HRC, whereas after the case depth of 0.68mm, the hardness should be 39~40 HRC. Due to this abnormal rise in hardness at the total case depth of 7.02 mm, the shock bearing capacity of gear decreases and ultimately it may break. It may be one of the major causes of gear failure.

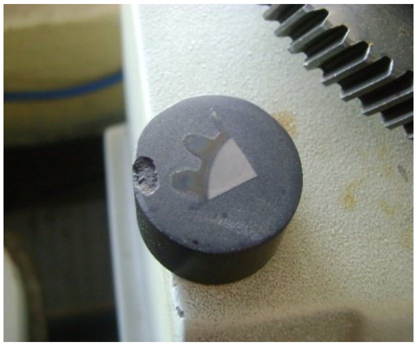


Fig.4.1 Showing increased case depth at etched surface of sample 2

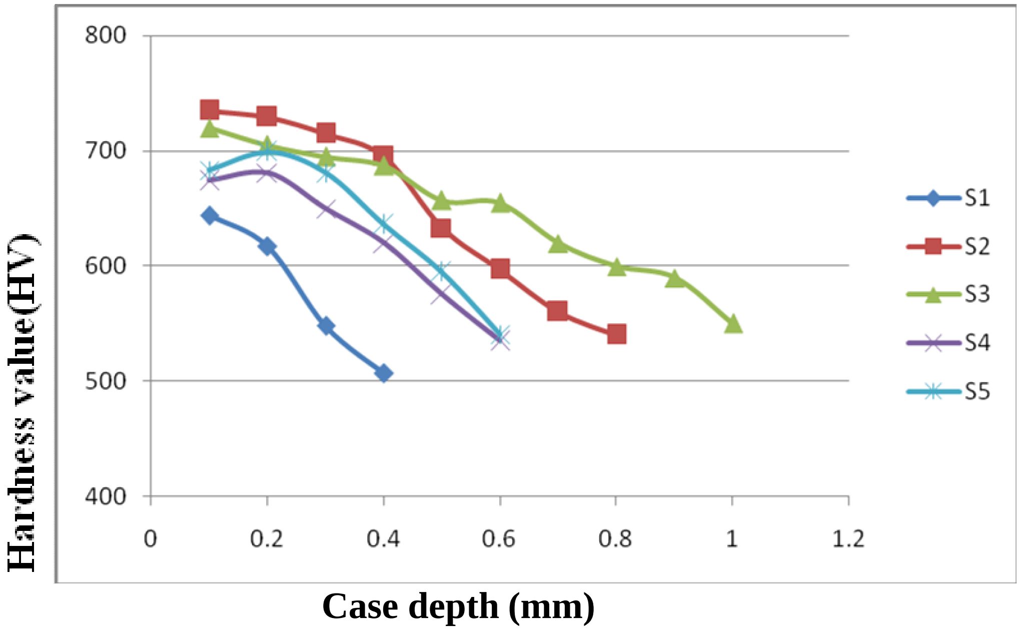


Fig.4.2 Comparison of hardness values wrt. case depth for all samples

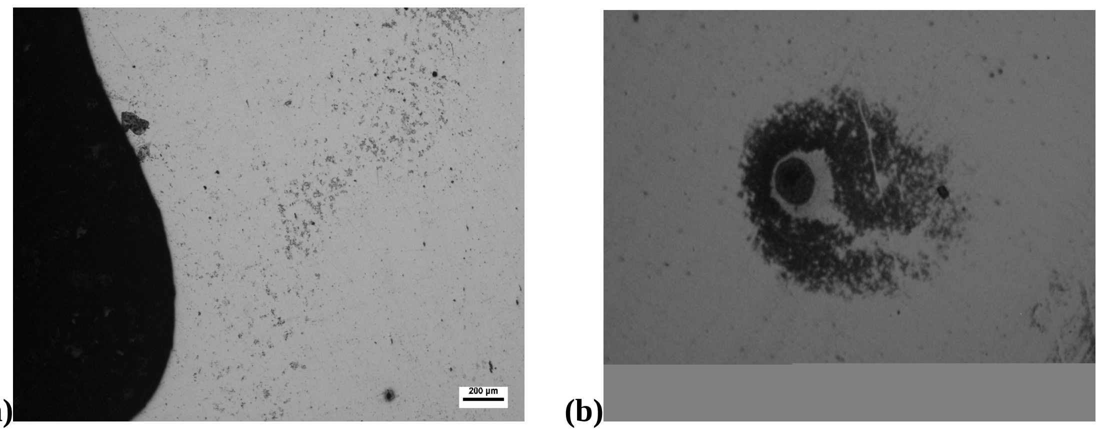
Fig 4.2 shows comparative hardness measurement for all the samples. It can be observed that hardness values keep on decreasing from surface to the core. It is because of the reason that the case (surface) of gear is hard and strengthened while the core is ductile. The reason for making ductile core and hard case is that when high stresses are impacted against the gear, load transfer takes place from surface to the core.

4.2 Metallographic Analysis

In order to see the surface defect the polished samples were analysed under microscope in unetched condition. Inclusions were observed in entire area. These were observed to be segregated as in Fig4.3 (a). Such type of inhomogeneities may provide path for movement of cracks along the segregated inclusions. Moreover, at some places typical bull's eye structure was observed indicating that during carburizing treatment excess of carbon has diffused inside, causing the development of ferrite and carbon zone in Fig. 4.3b)

For Sample 1:

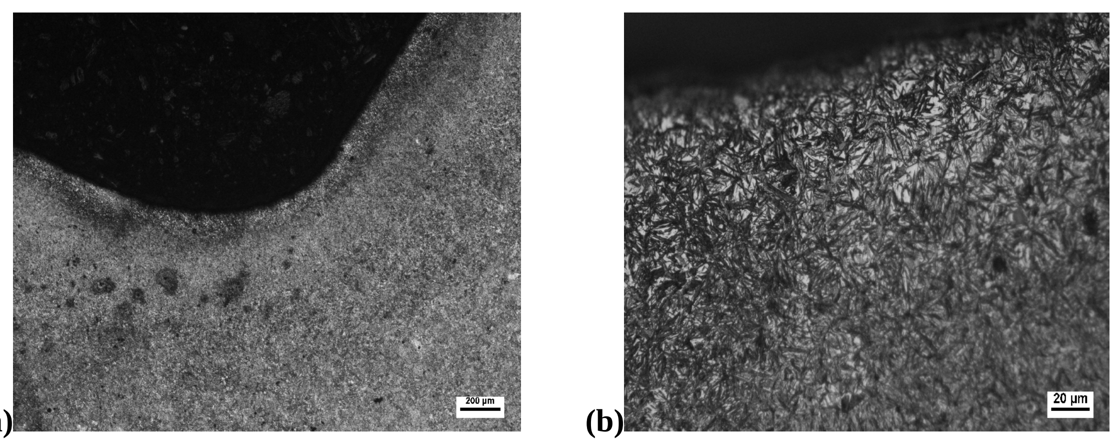
(a)



(b)

Fig 4.3 Optical micrograph of unetched sample 1 (a) at 50 X (b) at 100X

(a)



(b)

Fig.:4.4 Optical micrograph of etched sample 1 (a) at 50 X (b) at 500X, 1

After etching sample 1 shows the presence of number of pits beneath the case in Fig 4.4(a). The case was having martensitic and bainitic needles. Apart from this pits were clearly observed in Fig 4.4(b) at higher magnification. The important feature observed was the presence of needle type structure which do not have feature of either martensite or bainite in Fig 4.5(a). However the entire structure developed as colonies of martensite and bainite in Fig 4.5 (b), 4.6(a).The periphery of these colonies were decorated by carbides. The core areas were not free from pits as the presence of pits could be seen clearly in Fig 4.6(b).

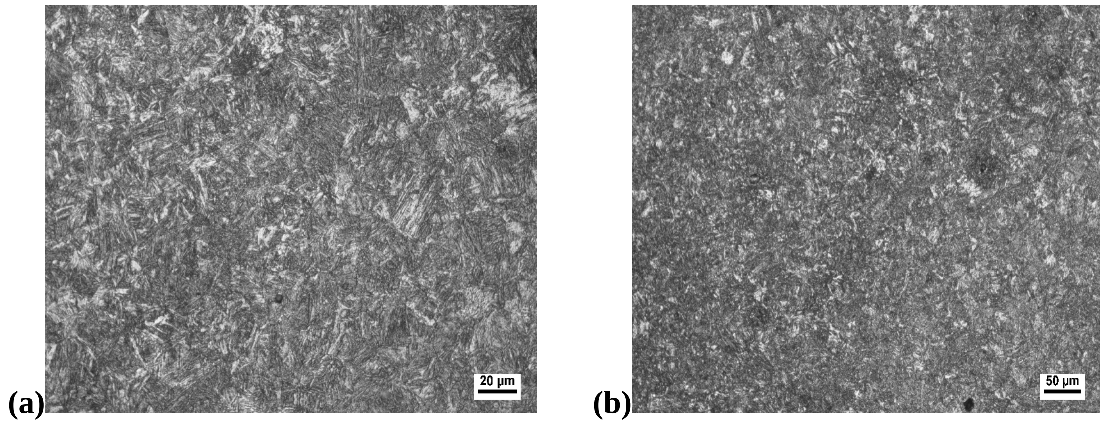


Fig4.5 Optical micrograph of etched sample 1 (a) at 500 X, 2 (b) at 200X

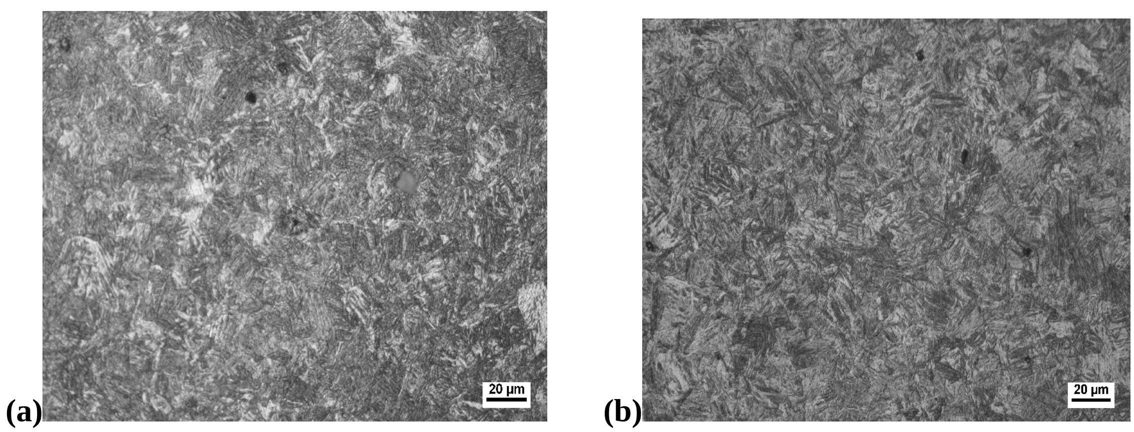


Fig.:4.6 Optical micrograph of etched sample 1 (a) at 500X, 3 (b) at 500X, 4

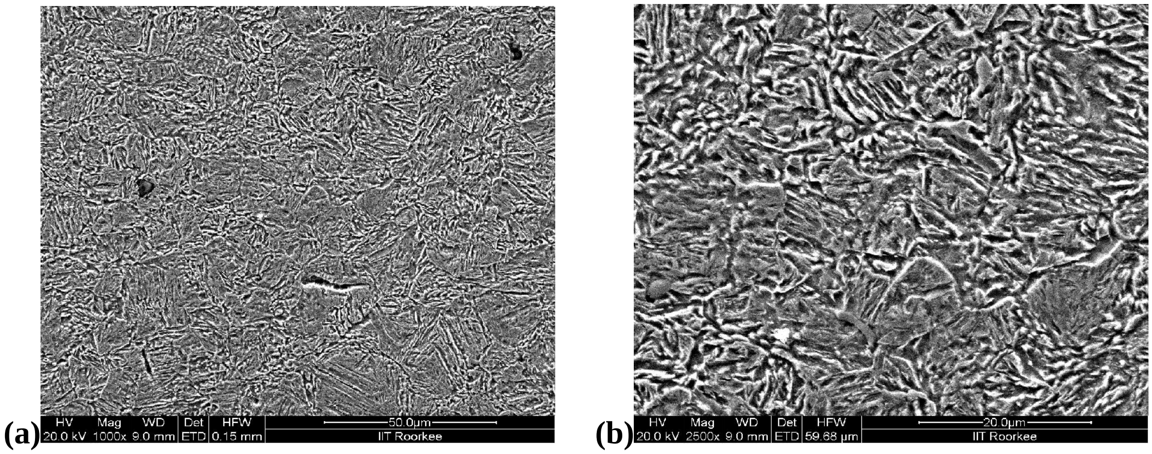


Fig.4.7) SEM micrograph for etched sample 1 (a) at 1000X (b) at 2500X

SEM micrographs revealed colonies of carbide as indicated in Fig 4.7(a) and 4.7(b). EDAX analysis at defect sites (segregated zone) indicates that accumulation of carbon has occurred in microstructure of the sample.

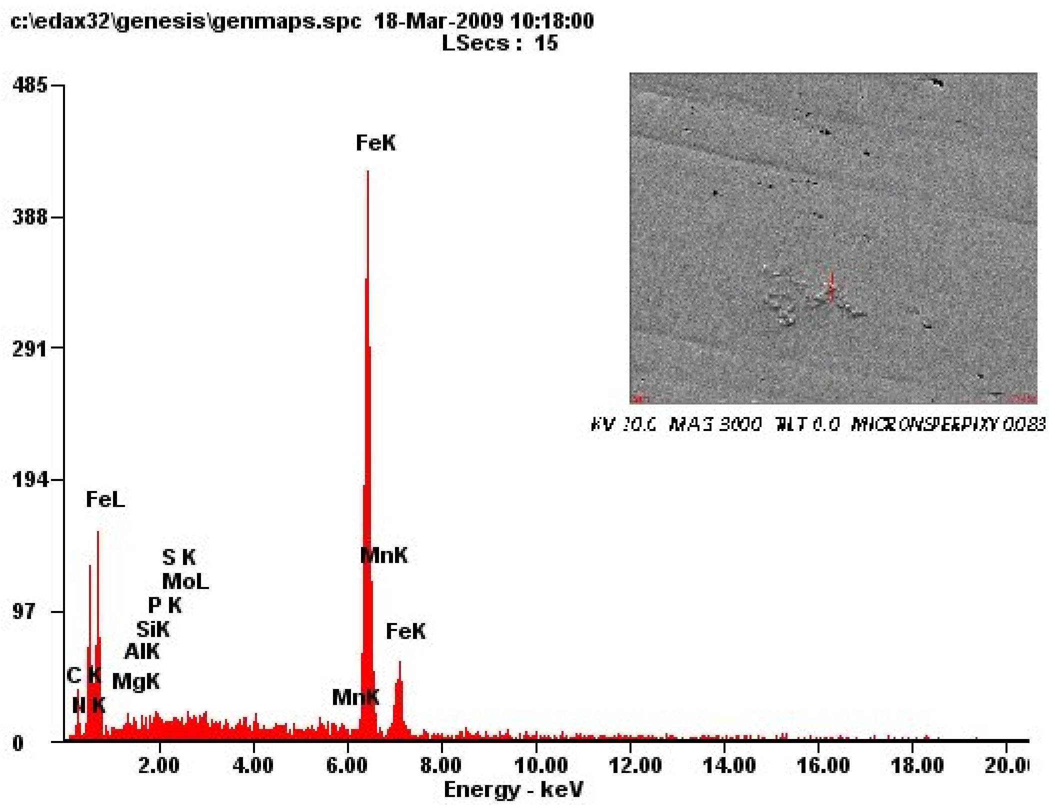


Fig 4.8 EDAX pattern for sample 1

For Sample 2:

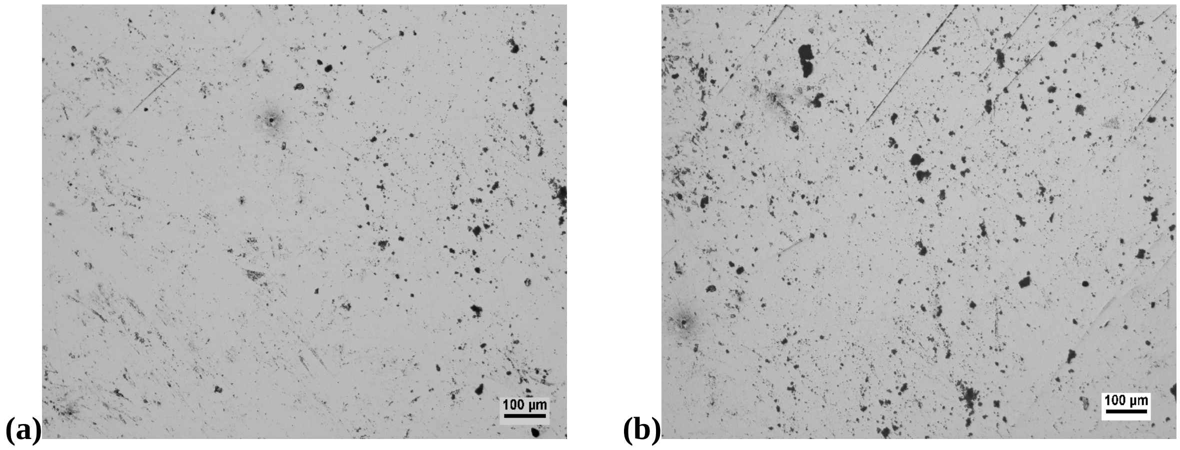


Fig.:4.9 Optical micrograph of unetched sample 2 (a) at 100X, 1 (b) at 100X, 2

In Fig.4.9 (a), 4.9(b) inclusions were observed in microstructures of unetched sample 2. The volume fractions of these inclusions in microstructure of sample 2 are more as compared to sample 2. Though inclusions were uniformly distributed but at some places they seems to be segregated in Fig 4.9(a) and 4.9(b)

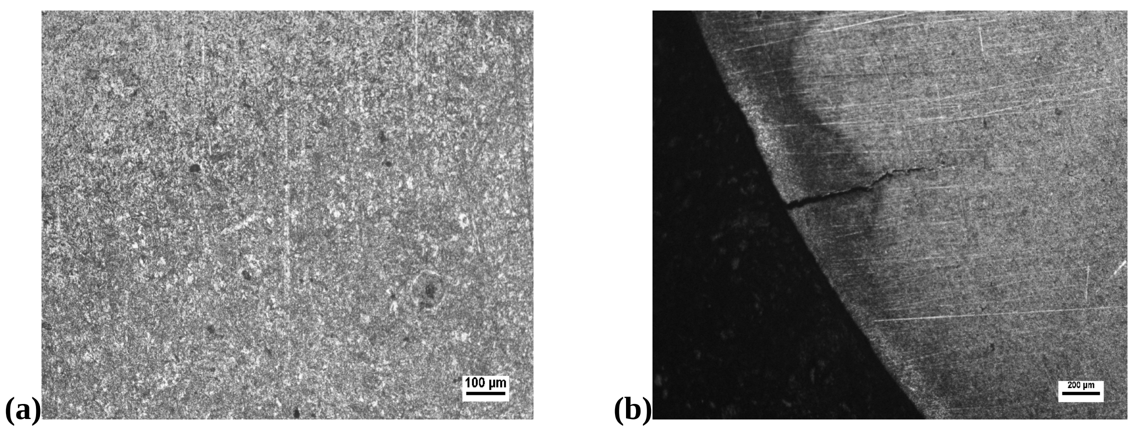


Fig.:4.10 Optical micrograph of etched sample 2 (a) at 1000X (b) at 2000X

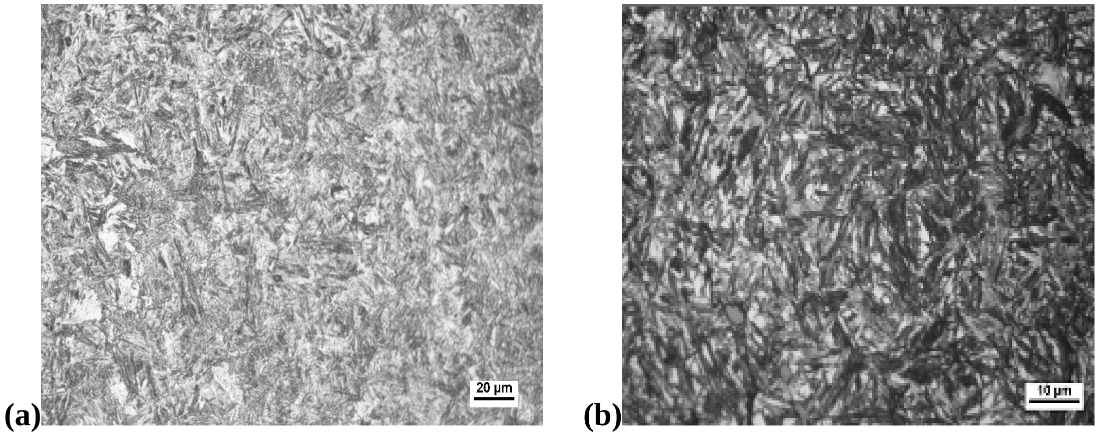


Fig.:4.11 Optical micrograph of etched sample 2 (a) at 500X (b) at 1500X

Optical microstructures of etched samples exhibit the presence of martensitic zone along with pits. Moreover, formation of massive carbide (aligned one) has been seen in Fig 4.10(a). These carbides were observed to be aligned as well as segregated at grain boundaries in Fig 4.10(a). Due to the carbide segregation, the formation of cracks can be seen originated from the surface in Fig. 4.10(b). One of the important features observed was the presence of ferrite and austenite (white area). The alignment of carbides can be seen at higher magnification in Fig.4.11a).However, at some places presence of martensite or bainite is also seen in Fig.4.11b)

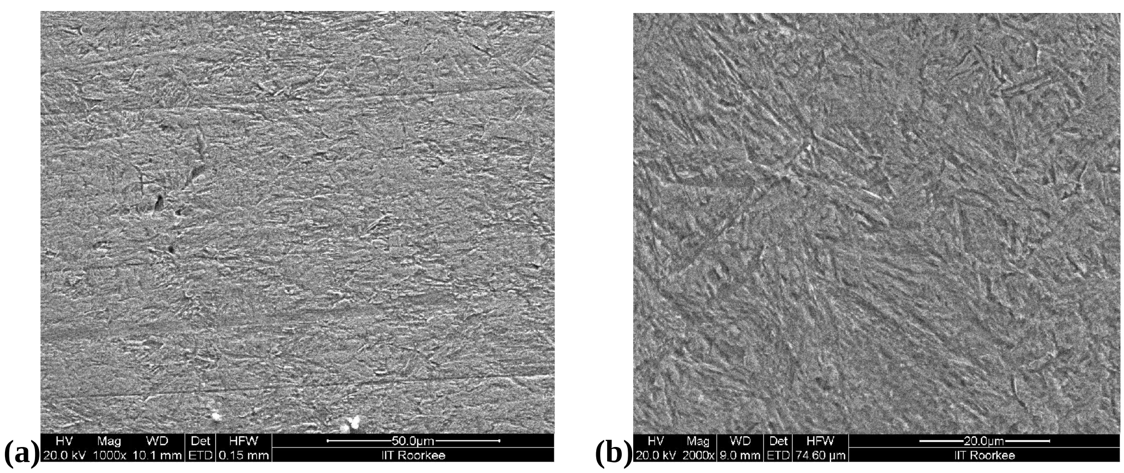


Fig.:4.12 SEM micrograph of etched sample 2 (a) at 1000X (b) at 2000X

SEM micrographs revealed that the presence of pores and formation of aligned carbide structure in Fig 4.12(a) and 4.12(b).

EDAX analysis of these areas revealed the presence of high amount of carbon as shown in Fig 4.13. Moreover, silicon content was observed to be very high at these places. This indicates the presence of silicate inclusions in these areas. The overall analysis shows heterogeneity in this sample. These inclusions were observed to be segregated which can act as the stress concentration point and may lead to the formation of cracks under adverse working conditions.

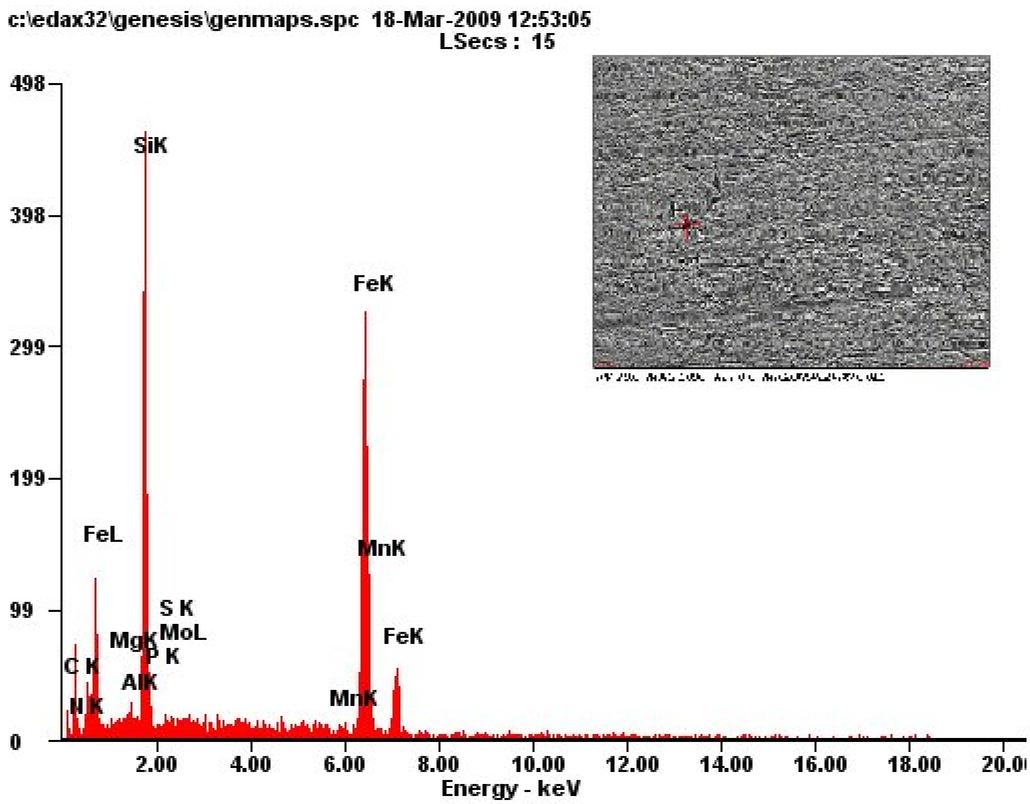
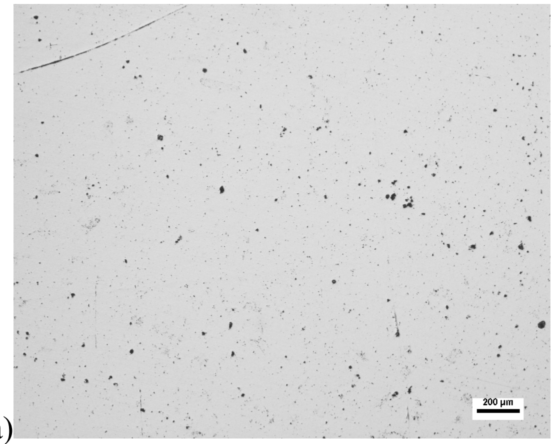


Fig 4.13 EDAX pattern for sample 2

For Sample 3:

(a) 

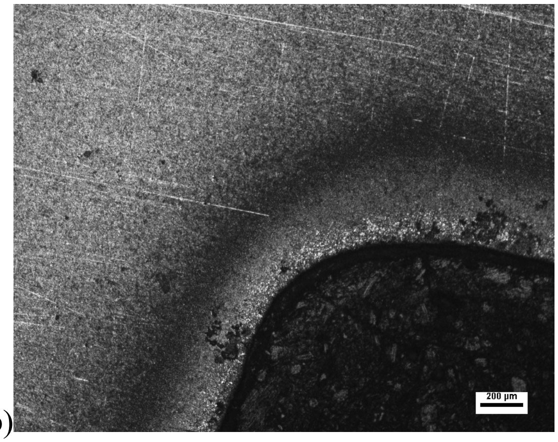
(b) 

Fig.:4.14 Optical micrograph of sample 2 (a) unetched at 50X (b) etched at 50X

A micrographic observation at lower magnifications for sample 3 shows the presence of inclusions. These inclusions were higher in rating. These inclusions were distributed uniformly, but at certain places they were observed to be aligned. Such type of alignment is not good for mechanical strength. At higher stress level, the probability of crack propagation along these inclusions is higher.

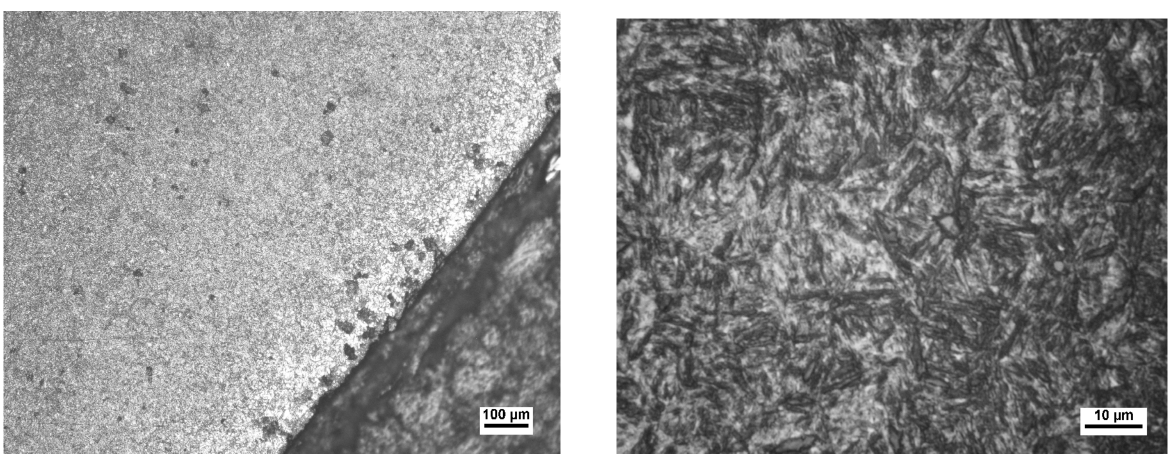
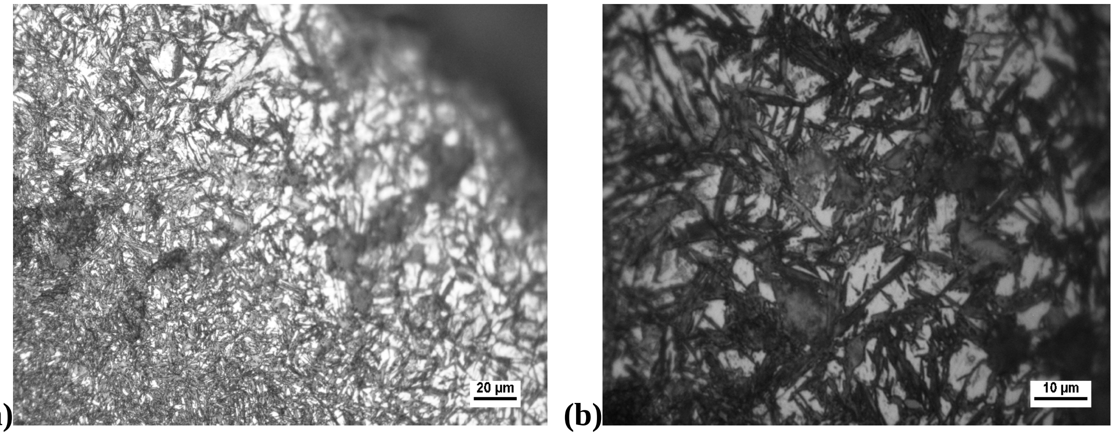


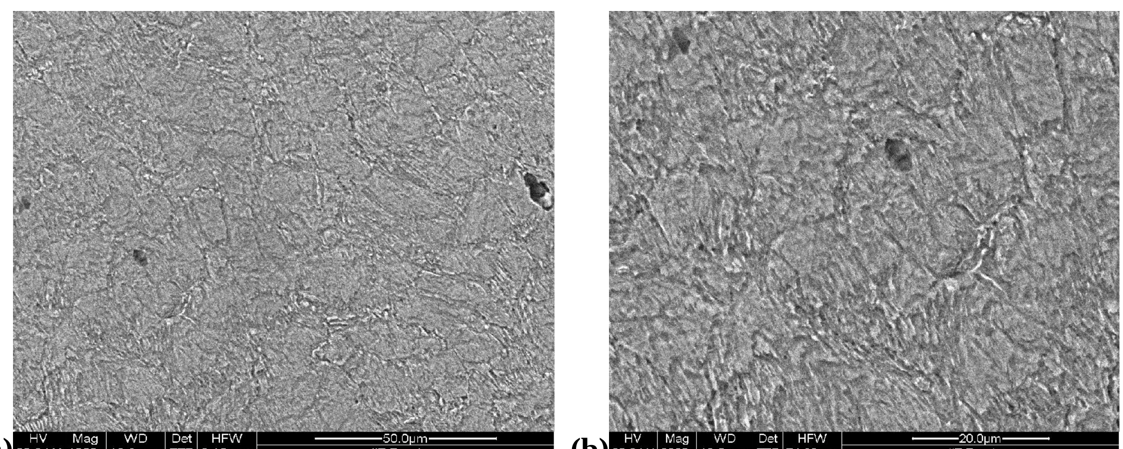
Fig.:4.15 Optical micrograph of etched sample 3 (a) at 100X (b) at 1500X, 1



(a) (b)

Fig.:4.16 Optical micrograph of etched sample 3 (a) at 500X (b) at 1500X, 2

The etched sample 3 exhibited typical porous morphology. There were pores even in hardened zone. These pores were present all along the case as can be seen in the Fig 4.14(b) and 4.16a). These pores have appeared in large scale. Moreover even in core also pits and pores could be seen in Fig 4.16(a). Fig. 4.15(a) illustrate same area at higher magnification where in the case zone, loss of carbon has occurred leading to the formation of ferrite and martensite structure. There is loss of carbon because of over burning which has led to formation of aligned pores. At higher magnification, the formation of martensite and bainite were seen in Fig 4.15(b) and 4.16(b). However, considerable amount of retained austenite and ferrite could be also found in Fig 4.16b).



(a) (b)

Fig.:4.17 SEM micrograph of etched sample 3 (a) at 1000X (b) at 2000X, 2

SEM micrographs clearly reveals that there is formation of carbides. These carbides have segregated along grain boundaries in Fig 4.17(a) and 4.17(b). Because of segregation of carbides it has facilitated the path for crack formation. Delamination can also be seen at some places in Fig 4.17(b). EDAX analysis also show the presence of higher amount of carbon in Fig.4.18. The higher content of Al indicate the presence of alumina in the system. The sample contain alumina and silicate inclusions as depicted from Fig 4.18

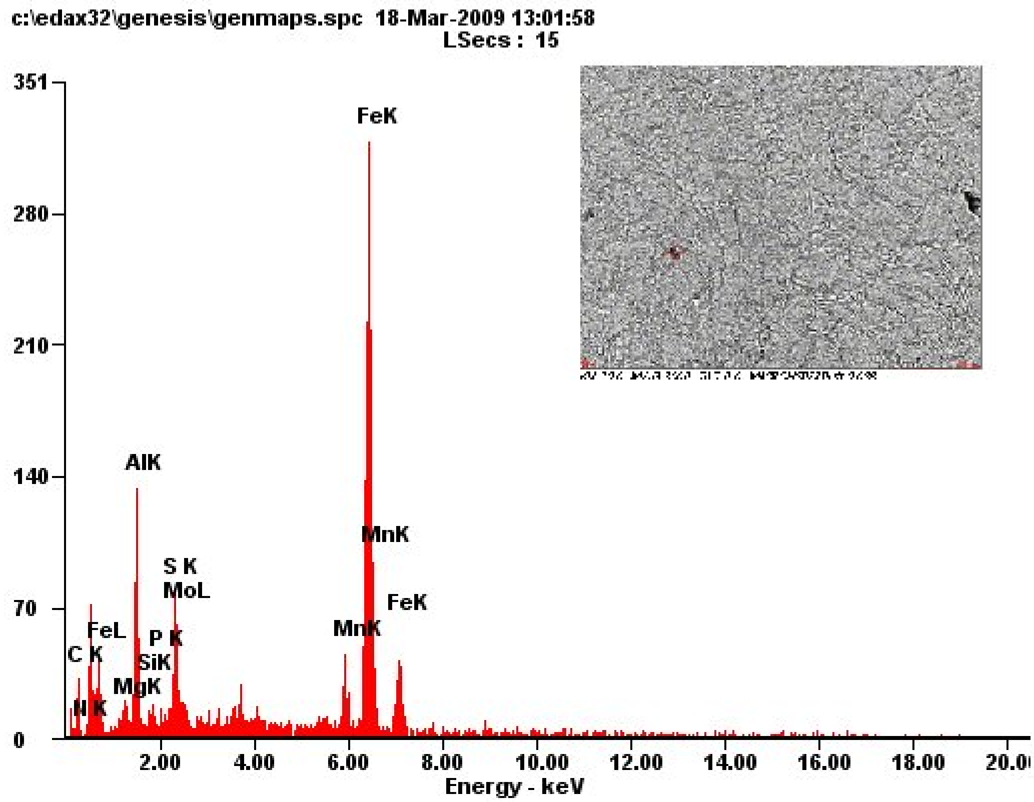


Fig 4.18 EDAX pattern for sample 3

For Sample 4:

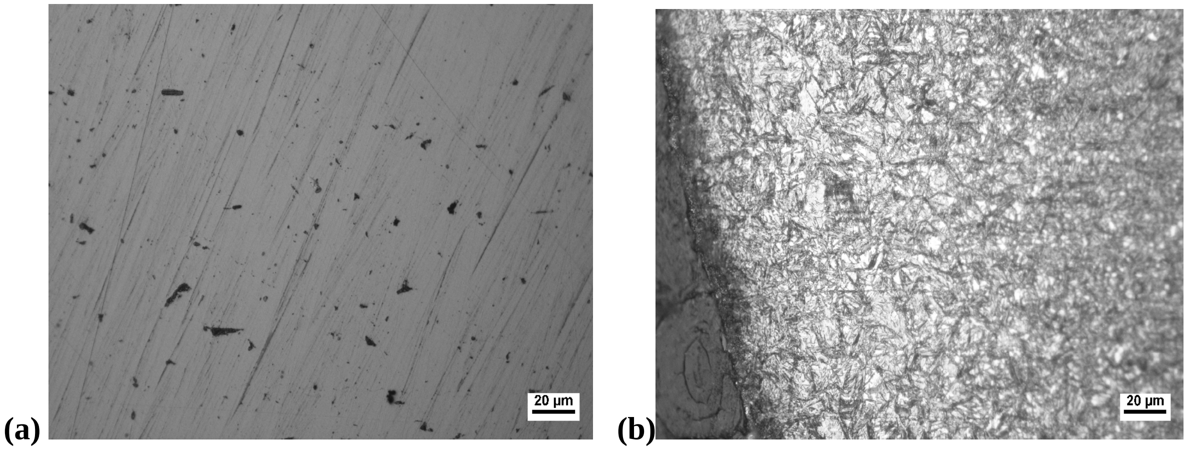


Fig.:4.19 Optical micrograph of sample 4 (a) unetched at 500X, 1 (b) etched at 500X, 2

The sample 4 exhibited totally different morphological features. The number and size of inclusions were very high. Moreover, their distribution was also of higher rating shown in Fig. 4.19(a) and 4.20(b). The important feature observed was the accumulation of carbon in almost all areas. A typical characteristic of bull's eye structure is visible in Fig. 4.20(b) and 4.21(c). This structure appeared due to overheating of the sample.

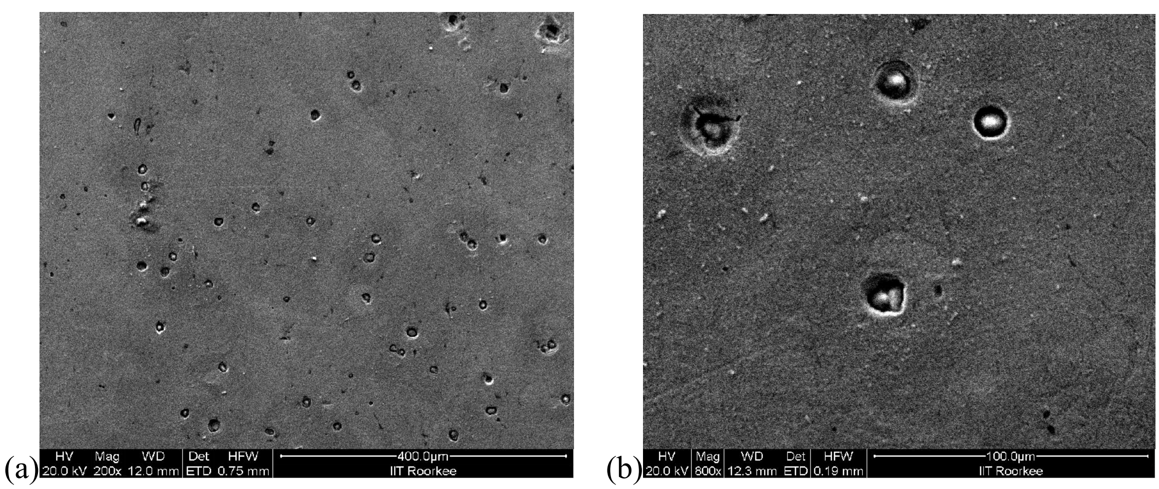


Fig.:4.20 SEM micrograph of etched sample 4 (a) at 200X (b) at 800X

(c)

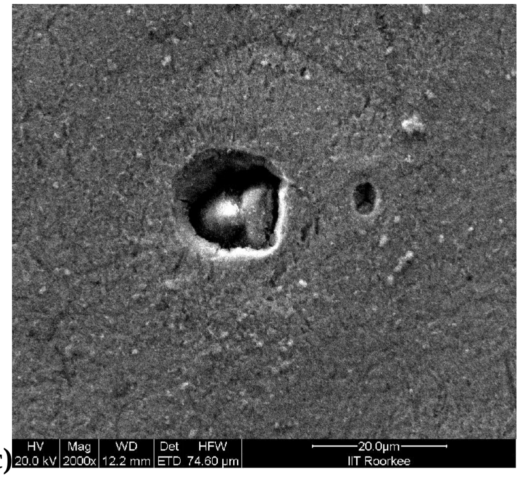


Fig.4.21 c) SEM Micrograph for Sample 4 (etched) at 200X

The carburizing process was done at higher temperatures. Because of carbon segregation, the structure has acquired non homogeneity. This pattern contribute for the failure and wearout in critical service conditions.

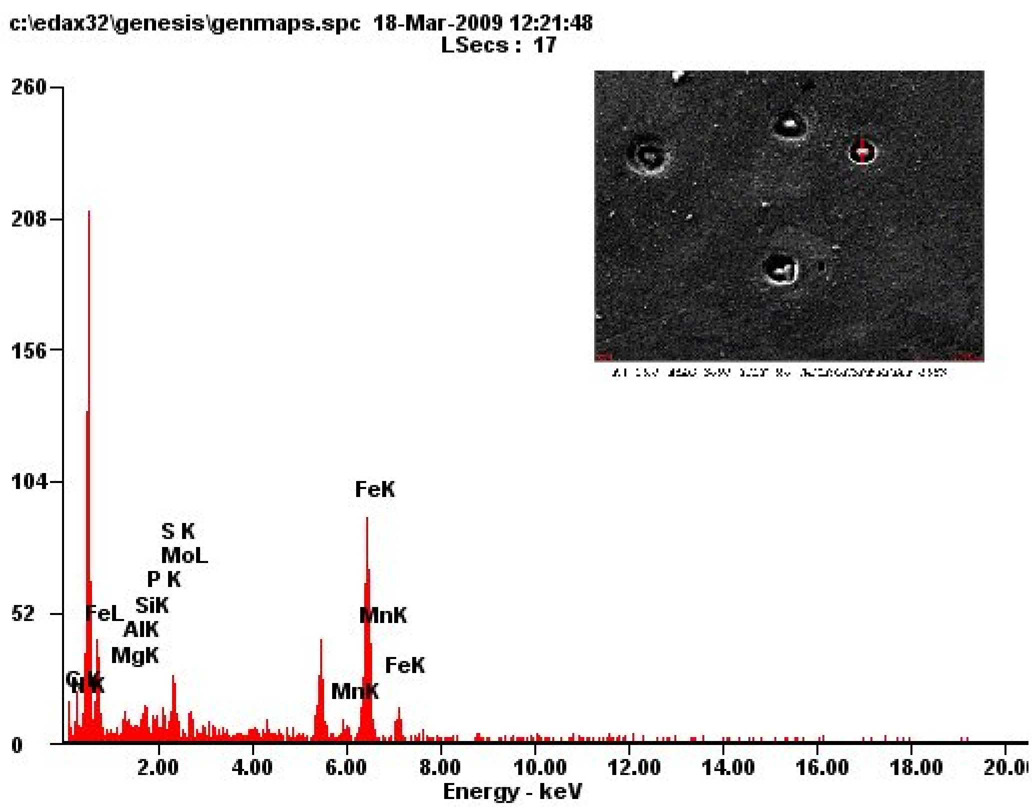


Fig 4.22 EDAX pattern for sample 4

For sample 5 :

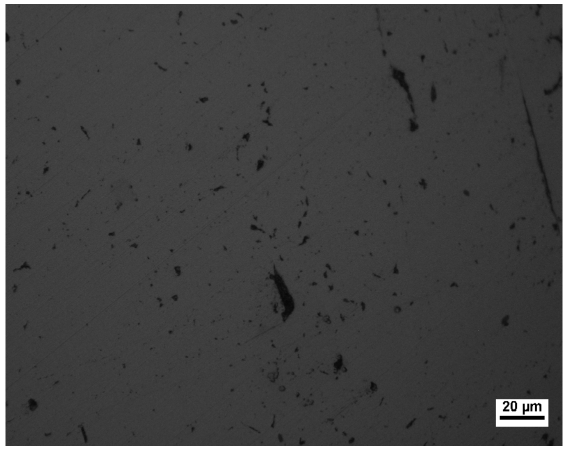
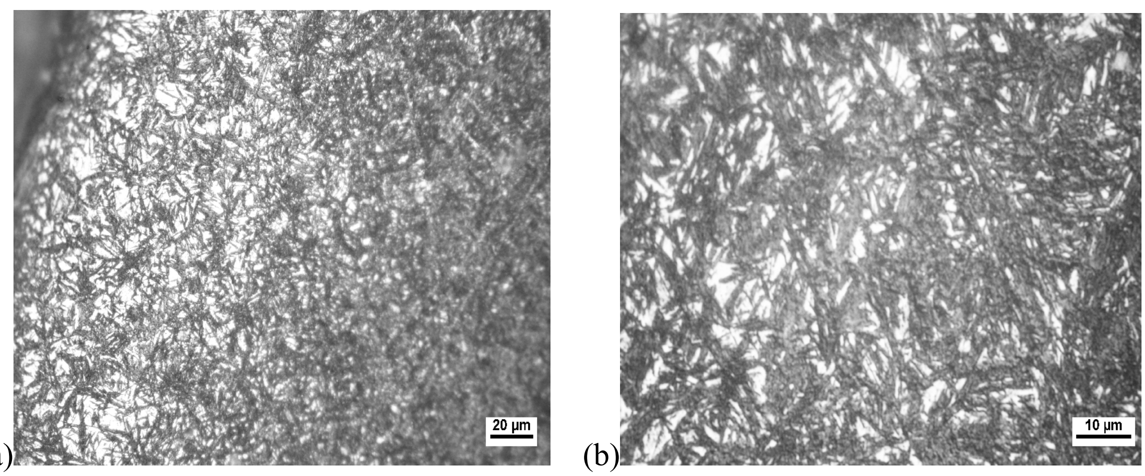


Fig.:4.23 Optical micrograph of sample 5 (unetched) at 500X, 1

Similar features were also observed in sample 5. Micrograph in Fig.4.23 show sulphide inclusions (elongated) and thin oxide inclusions (globular) in the matrix. The martensite and bainite structures were also seen after etching of the sample.



(a) (b)

Fig.:4.24 Optical micrograph of etched sample 5 (a) at 500X, 2 (b) at 1500X

In Fig 4.24(b), micrograph shows needle like structure which resembles tempered martensite. Whitish region in Fig.4.24 (a), 4.24(b) contains low carbon ferrite and retained austenite. This indicates that perhaps tempering process may not be done in proper manner during heat treatment.

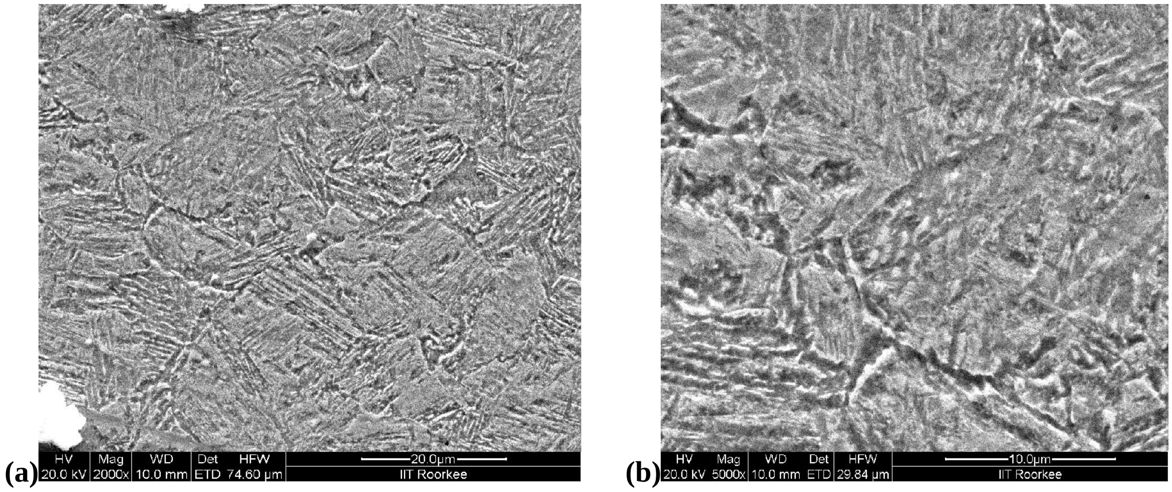


Fig.4.25 SEM micrograph of etched sample 5 (a) at 2000X (b) at 5000X

SEM analysis clearly revealed the segregation of carbide along grain boundaries in Fig. 4.25(a) and 4.25(b)**.** EDAX analysis also shows higher carbon content in Fig.4.26

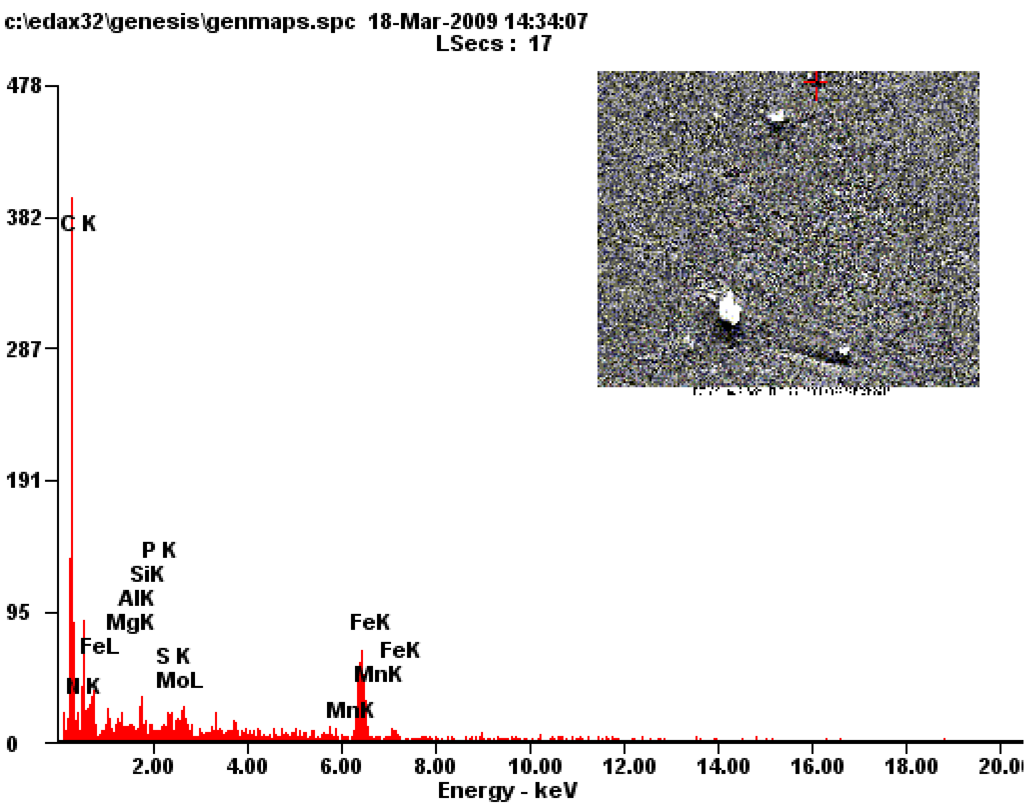


Fig 4.26 EDAX pattern for sample 4

It has been observed that metal to metal contact during mechanical damages initiate the fatigue crack at high stress concentration region. Detailed investigation discovered that there were two reasons for the mechanical damages to occur: (a) misalignment between mating gears resulting thermal gradient across gear face and (b) metal to metal contact due lubrication breakdown. Metallurgical failure analysis showed that the tooth of the gear had failed by fatigue and there were multiple fatigue crack initiation sites at the dedendum of the working flank. Detailed examination revealed that the fatigue crack initiation was promoted by severe spalling on the tooth flank.

4.3 Fracture surface analysis through SEM:

Fracture surface study for all the samples was done under SEM. A micrograph surface reveals dimple marks in Fig.4.27 (a). Moreover, river-like pattern which is a typical characteristics of cyclic brittle failure mode is visible in Fig.4.27 (a) and 4.28(a). However, striations, which is a typical characteristic of cyclic failure mode is embodied in the fracture surface.

For Sample 1

(a) (b)

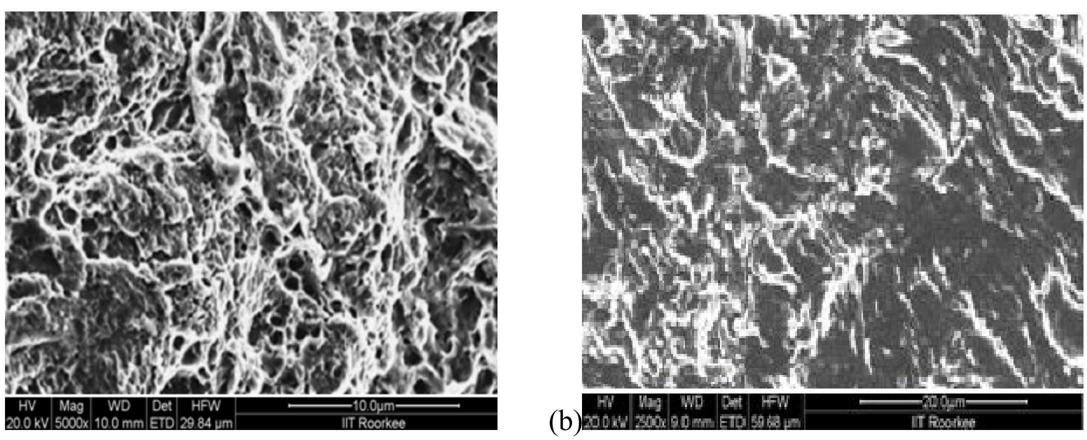


Fig 4.27 Fractograph of etched sample 1 (a) at 5000X (b) at 2500X

For S 2

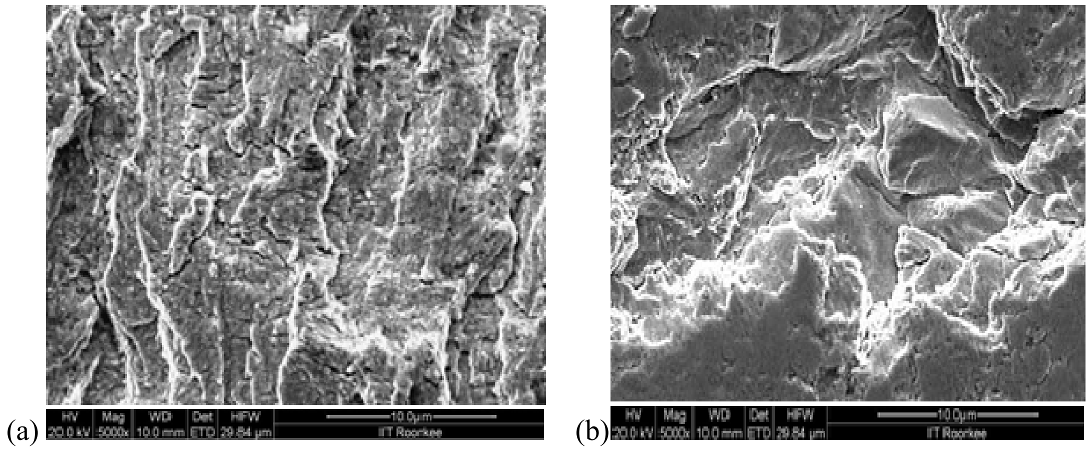


Fig 4.28 Fractograph of etched sample 2 (a) at 5000X (b) at 2500X

The carbide precipitation along the grain boundary has lead to the failure of this material. Fig. 4.28(b) shows the typical micrograph containing carbides particles sample 2.

For Sample 3

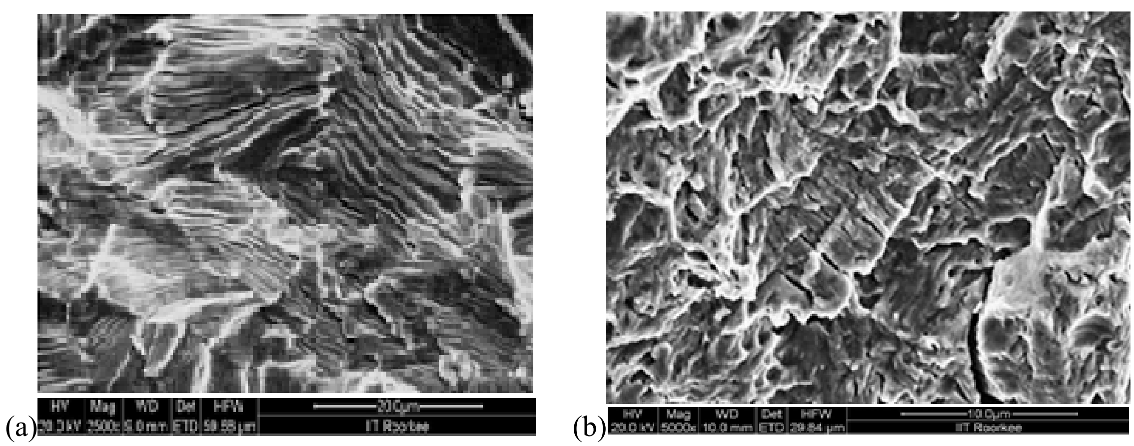


Fig 4.29 Fractograph of etched sample 3 (a) at 2500X (b) 5000X

In case of sample 4, fatigue failure mode can be observed. Since the fatigue striation are oriented in same direction. The crack has propagated along grain boundaries. Carbides are visible in Fig 4.29(b).

For sample 4

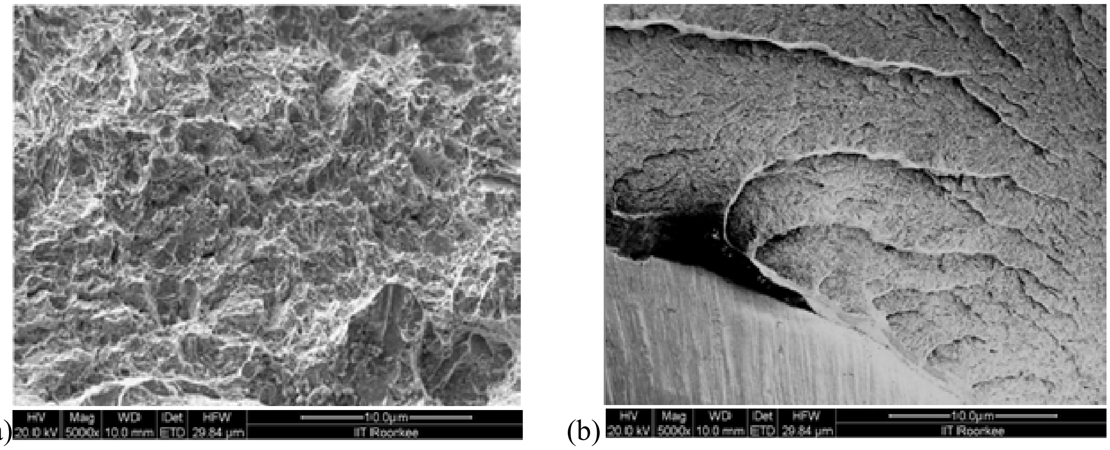
(a) (b)


Fig 4.30 Fractograph of etched sample 4 (a) at 2500X (b) 5000X

The fatigue failure is not observed to be dominant cause of fracture as depicted by Fig.4.30(a) of sample 4. The fracture surface exhibits typical characteristics where ductile and brittle both characters are present. However in certain area river like pattern is also visible.

For Sample 5

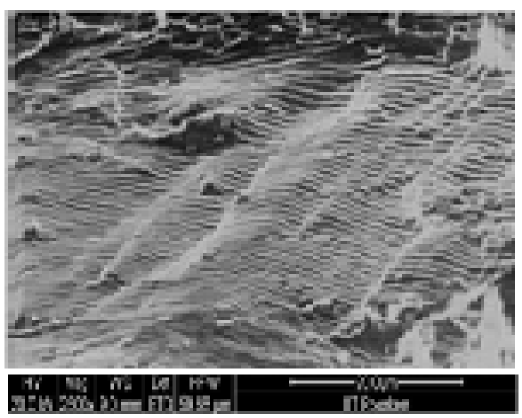


Fig 4.31 Fractograph of etched sample 5 at 2500X

Fig.4.31 of sample 5 exhibit a cyclic failure as evident from presence of striations. The fracture surface was characterized to be a brittle type failure with signs of fatigue striations. The failure mode was found to be low cycle, high stress fatigue from the morphology of the fracture surface. Due to the extreme forces applied to the gear, fracture propagated to the complete failure in very few cycles.

The presence of fatigue crack in most of the spline roots of the gear needs special attention. It may be recalled that in the earlier failure, excessive stresses on the splines of the gear were found to be responsible for the fatigue crack initiation. Also, there were severe deformation and wear on the flank of the gear splines.

Table 4.6: Mahindra and Mahindra specifications for material grade 20MnCr5 showing chemical compositions of elements.

Material Grade	**C %**	**Mn %**	**Si %**	**S%**	**P %**	**Cr %**	**Ni %**	**Mo%**
20MnCr5	**.17 - .22**	**1.10- 1.4o**	**.15- .40**	**.035**	**.035**	**.60 - .90**	**Nil**	**Nil**

The chemical composition of the elements present in gear materials was determined by energy dispersive analysis through x-ray analysis (EDAX). For material grade 20MnCr5, carbon percentage should be 0.17 to 0.22% and phosphorus percentage should be 0.035% as shown in table 4.12. EDAX analysis shows that the percentage of carbon and phosphorus is more than the specifications mentioned in Mahindra and Mahindra standards for given material grade. During heat treatment carburizing has done to increase surface hardness. Prolong carburizing condition led to high carbon percentage in this gear. Although tempering has done to optimize the hardness still carbon percentage is not being controlled, which becomes prominent factor for failure to occur.

There can be other reasons of failure such as (a) the component/system is subjected to an environment beyond its design envelope, (b) the choice of material and its condition is inappropriate for the design and operating conditions, (c) the material of construction is defective, or (d) the design itself is wrong. It is often seen that there is no single cause or no single train of events leading to the failure. Generally, several factors combine at a particular time and place to cause a failure to occur. When a failure occurs, an understanding of the failure process is required so that attempts can be made to determine how and why a component/system failed. The root cause analysis provides this understanding of these conditions.The critical analysis of Microstructural features and EDAX analysis led to conclude that higher case depth than specified, high hardness in the core region of gear, defective microstructure (containing several inclusions, pits, fatigue striations), high cyclic loading and high percentage of alloying elements all these factors equally contribute for the failure to occur.

4.4 Results from XRD Analysis

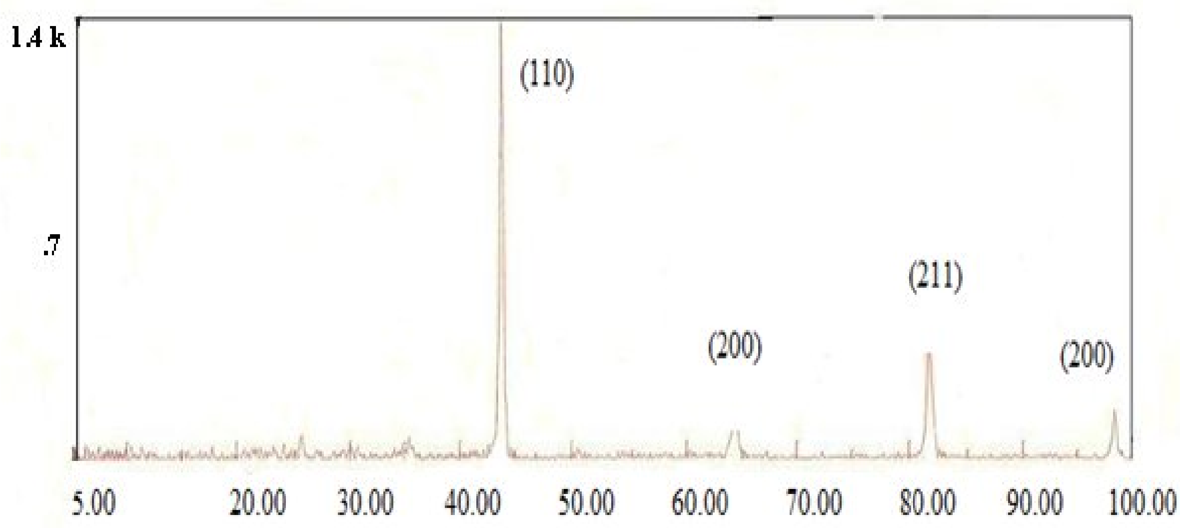


Fig.4.32 XRD pattern of Ist gear specimen

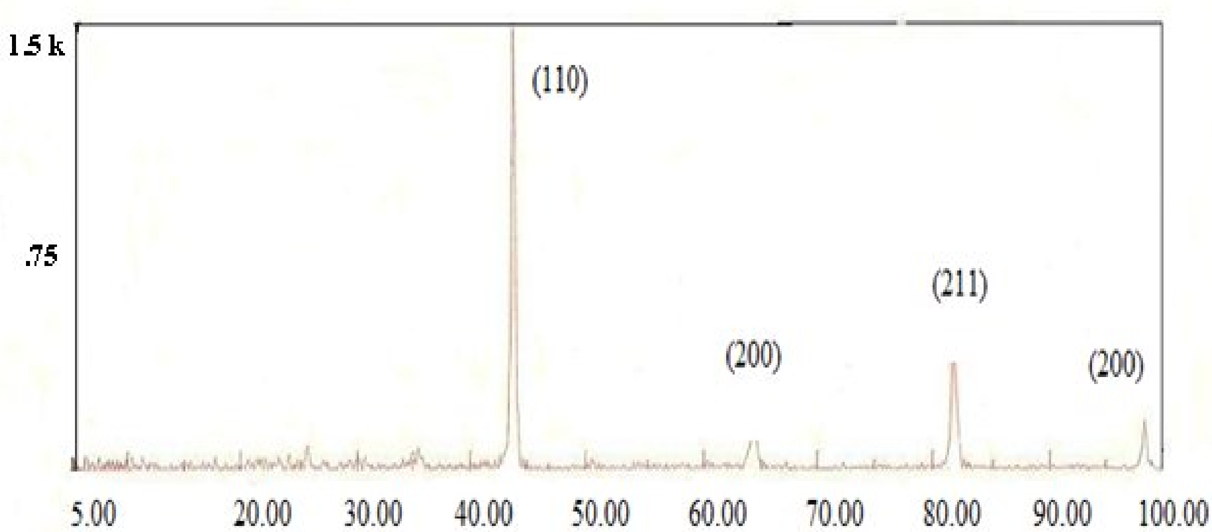


Fig.4.33 XRD pattern of 2nd gear specimen

From x-ray diffractogram pattern, it was observed that highest intensity of peaks belonging to pure iron phase (JCPDF card no. 60696) is present. The planes of diffraction are indicated above their respective peaks in the graph as shown in Fig. 4.32 and 4.33. Some other peaks having lower intensity are also found but are not clearly visible. So we can't compare them with any data file because these peaks are mostly due to impurities or mixture of phases.

X ray diffractogram shows only some variations in peak intensities in first and second gear specimen. However only pure iron phase have been detected in both of them.

4.5 Analysis related to failure types and failure trends

4.5.1Failure types

Failure types in gear mechanisms may be fracture, surface fatigue, abrasion and plastic deformation. The Fracture damage is caused by surface fatigue, high loads or abrasions. The tensile stress, compression stress and shear stress under the gear surface led to surface fatigue. Abrasion damage results from the loss of material when gear surfaces are in contact.

In the analysis of gear failure types and reasons, 165 gears were investigated. Results show that the failure types were fatigue fractures in 122 gears, abrasion wear in 34 gears and plastic deformation in 9 gears. The most encountered failure is fatigue fracture 73.9% and the least one is plastic deformation (5.4%).

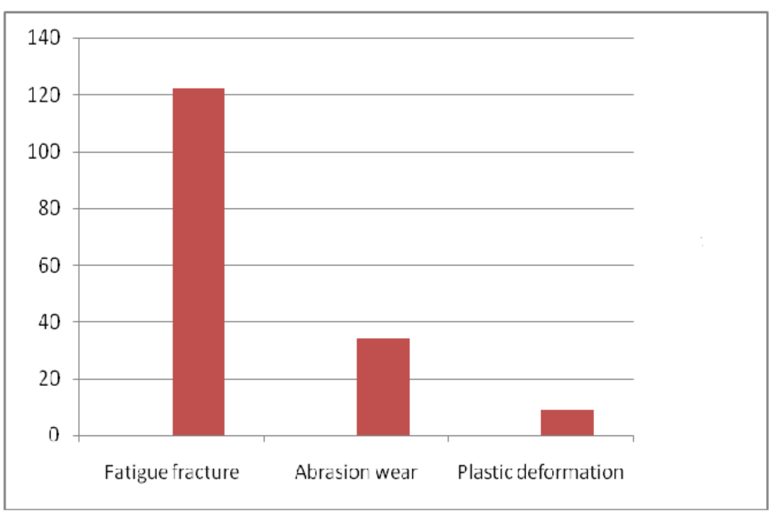


Fig.4.34 **Showing failure types in which gear has been failed**

Also another analysis has been done regarding number of failed gears with respect to distance travelled in table 4.7.

Table 4.7: Quantitative data of failed gears with respect to distance travelled

Distance travelled(in Kms)	No. of failed gears
0-500	10
500-2000	23
2000-5000	21
5000-10000	31
10000-20000	54
20000-40000	24

Table 4.7 shows that majority of gears have been failed within the highest travelling distance range 10000 to 20000 km.

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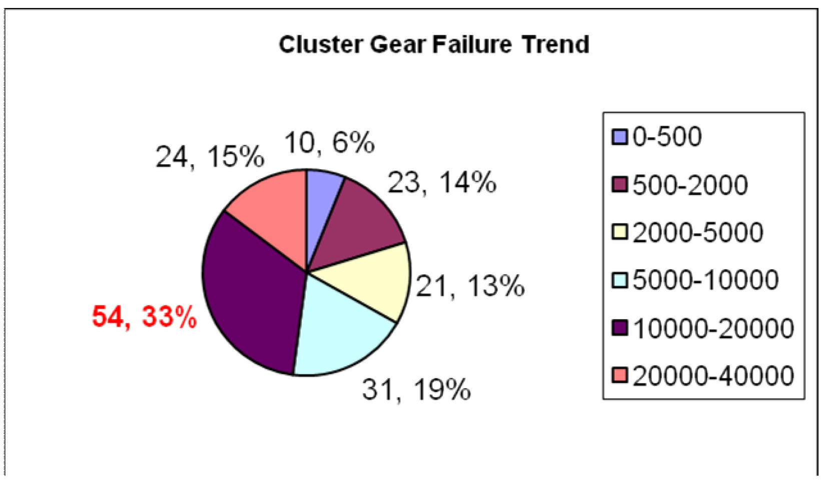

Fig: 4.35 **Showing no. of gears failed wrt. distance travelled (in kms)**

4.5.2 Failure reasons:

Failure reasons may be faults of usage, heat treatment, design, manufacture and material. Usage faults are caused by incautious operation and insufficient technical knowledge. These faults can cause major damage in machinery. Design faults include incorrect shape, dimensional errors, bearing faults, selection of wrong material and insufficient technical knowledge.

CHAPTER 5
SUMMARY AND CONCLUSIONS

In the present work, the influences of microstructure, chemical composition and hardness of the gear samples were investigated. From the experimental observations, the following conclusions can be drawn:

The critical analysis revealed that gear failed because of improper heat treatment where the carbide precipitation has occurred along the grain boundaries. Under cyclic loading conditions the material has failed because of the presence of carbides. The concentration of carbon and phosphorus is very high in most of specimen, which is highly responsible for failure to occur in critical service conditions. It is not necessary to use high alloy steel for these working conditions. Gears could be produced with low alloy steels. Also, using a nitride alloyed steel, case hardening can be done and a very hard and thin case depth can be obtained. The failed gear material grade was 20MnCr5 alloy steel. This type of material has very high hardness. So, material having optimum hardness and toughness can be used. After heat treatment, tempering should be performed in proper way in order to obtain optimum hardness and toughness. Tempering in the critical range (350-550°C) should be avoided because it causes temper brittleness. Mo (molybdenum) could be added to remove temper brittleness. The porosity was high in the keyway region, but was normal in the other regions.

Another possibility of failure is that the gear might be used at a higher working pressure than the pressure given by the manufacturer. It was observed that the stresses induced on the gear tooth were higher than the permissible/safe limit. Failures types in the most of the gear are high stress, low cycle fatigue fracture, abrasion wear and plastic deformation. The stresses induced on the gear tooth can be reduced considerably by making hole at the root of the gear tooth. So that stresses could be distributed throughout. The gear profile is somewhere trapezoidal shaped. Tooth roots should be rounded more.

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