Effect of Tempering on Cyclic Loading of Medium Carbon Steel

A thesis submitted in partial fulfilment of the

requirements for the degree of

Master of Technology

in

Mechanical Engineering
[Steel technology]

By

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CERTIFICATE

This is to certify that the work in this thesis report entitled "**Effect of Tempering on Cyclic Loading of Medium Carbon Steel"** which is being submitted by **Mr. Gaurav Kumar Gupta**, National Institute of Technology, Rourkela has been carried out under my guidance and supervision in partial fulfilment of the requirements for the degree of Master of Technology in Mechanical Engineering (Steel technology) and is bonafide record of work.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Prof. Sudipta Sen

Date:

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May, 2015 **Gaurav Kumar Gupta**

Contents

Abstract

The utility of Medium Carbon steel is well known now-a-days. It has got such a variety of uses in distinctive commercial ventures because of its moderately low cost and great mechanical properties. The failure due to cyclic loading or dynamic loading is a crucial topic in the field of mechanical behaviour of materials since cyclic loading counts about ninety percent of the failures resulted from mechanical causes. In this work the cyclic loading behaviour of Medium Carbon Steel has been studied. The properties of steel are greatly influenced by various heat treatment techniques and tempering is the most common and important heat treatment technique. In the present work the effect of tempering on microstructure, tensile properties, hardness and most importantly on cyclic loading behaviour has been studied. The emphasis is given to the endurance limit. Attempts have been made to find out the best set of tempering conditions. The Medium Carbon Steel specimens were first austenitized at 850^{o}C, hold for 1hr for soaking and then quenched in water bath maintained at room temperature. The quenched specimens were then tempered at three different temperatures 200^{o}C, 400^{o}C and 600^{o}C the duration of tempering treatment was 60min., 90min., and 120min. for all of the above temperatures. Attempts have been made to correlate the microstructure with the mechanical properties of Medium Carbon Steel.

The cyclic loading test was carried out in R.R. Moore Rotating Beam Testing Machine with a completely reversed stress pattern. Here the maximum stress and minimum stress are equal in magnitude but opposite in sense so the stress ratio i.e. the ratio of maximum stress to minimum stress becomes **R= -1,** the mean stress becomes zero.

From this work, it may be concluded that tempering significantly improves the mechanical properties as well as the fatigue life of the material, and the best results have been seen for low temperature tempering at 200^{0}C, for 60 min.

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Chapter 1

Introduction

It has been observed by the researchers way back in around 1850, that a material fails at a lower stress when subjected to cyclic or dynamic loading, as compared to the stress required for failure in static loading. Scientists used the term fatigue to indicate a cyclic or dynamic loading. Also it has been found that 90% of the failures occurred due to mechanical reasons are resulted from fatigue. Hence, from research point of view the fatigue failure becomes a very important topic. Since the discovery of fatigue many researchers have conducted different works to study different aspects of failure due to fatigue or cyclic loading and to improve the fatigue life of the materials.

In this work the effect of Tempering (at different temperatures and different time durations) on cyclic loading of medium carbon steel has been studied. The steel is a very useful and important material used in different engineering application, and the medium carbon steel is the most commercially used steel. For this work the material selected is the medium carbon steel (0.524% Carbon by wt.), because medium carbon steel has good mechanical properties such as high strength and toughness. Also the properties of medium carbon steel are greatly influenced by various heat treatment techniques and tempering is most common amongst them. The change in microstructure, variation in mechanical properties and fatigue life due to different tempering conditions has been studied in this work.

Attempts have been made to get the relation between microstructure of medium carbon steel and the mechanical properties. Fractographical studies of specimens after tensile and fatigue tests have been carried out in a scanning electron microscope (SEM). Also attempts are made to correlate the tensile properties of the medium carbon steel with the endurance limit.

Chapter 2

Literature review

2.1 Introduction to Steel

Steel is an interstitial solid solution of carbon in iron with a maximum carbon content of 2.1% by weight [1]. Steel is a crucial alloy which finds its vast application in different industries and structures. In most recent twenty years, there have been tremendous advances in steelmaking process. Which makes steel most versatile and essential material. The properties of steel can be altered by different heat treatment techniques to suit the requirements. The microstructure can be related with the mechanical properties of steel and the microstructure of most of the steels are well known.

Lacktin [1] studied that carbon goes into the interstitial space in the iron and due to size of carbon atom it is the only useful material to make solid solution with iron to form an alloy. Also by varying the amount of carbon in steel the properties like ductility, hardness, and strength can be altered. An increase in percentage of carbon gives more hard material with increased strength [2].

In steel some other elements such as Molybdenum, Silicon, Cobalt, Copper, Phosphorus, Sulphur, Chromium, Manganese etc. may present and termed as alloying elements. The variation in amounts of these alloying elements can alter the properties of steel significantly. The steel which has only carbon as alloying element is called Plain Carbon Steel.

2.2 Classification of Steel

On the basis of alloying conditions the steel can be classified as: Plain Carbon Steels and alloy steels. Further the plain carbon steel are subdivided into Low Carbon Steels (mild steel), Medium Carbon Steels, and High Carbon Steels.

There are a variety of alloy steels properties of which depends upon the alloying elements added to the steel. Fig. 1 shows the classification of steels.

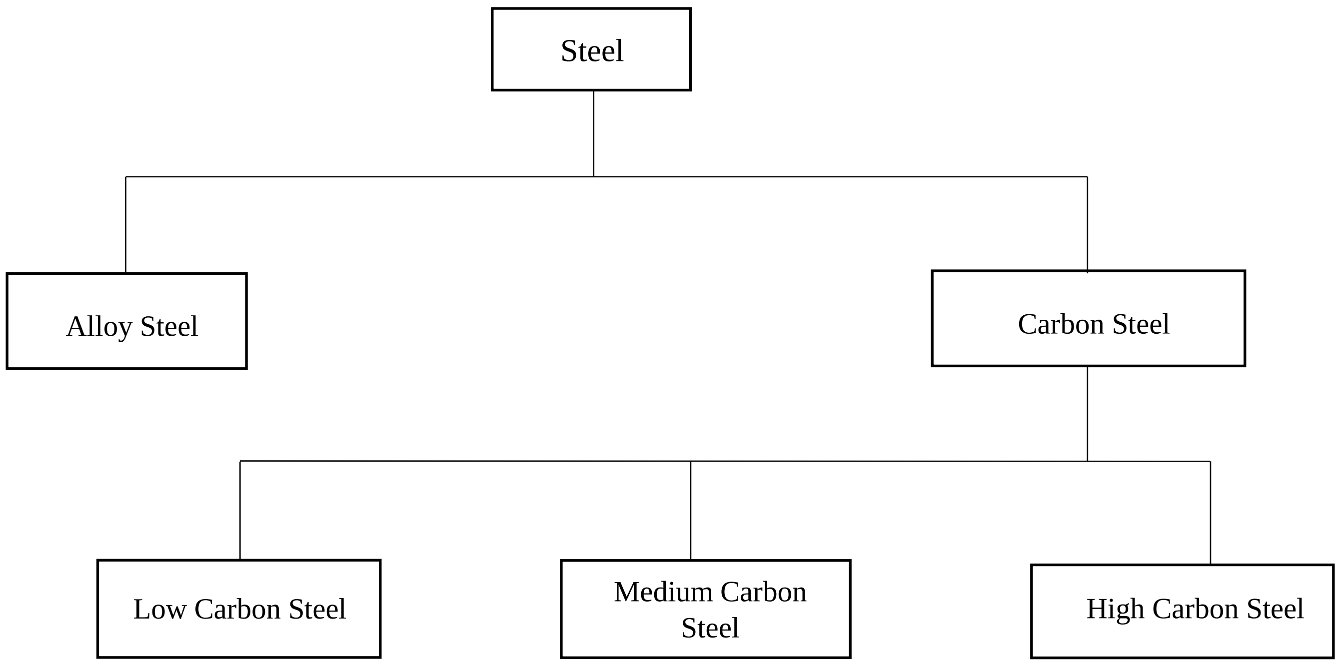

Fig 2.1: **Classification of Steels (Lovatt and Shercliff, 2002)**

2.2.1 Plain Carbon Steel

Plain carbon steel is a solid solution of carbon in iron. In considerably low amounts some other elements are also present in Plain Carbon Steel. According to AISI (American iron and steel institute) Plain Carbon Steel should contain less than 1.65% weight Mn, a maximum of 0.6% weight Si, and lower than 0.6% weight Cu. The Carbon content controls the property of steel, an increase in carbon content increases the hardness as well as strength of the steel at the cost of loss of ductility and weldability. Also high carbon content generally decreases the melting point of steel and impairs the temperature resistance [3].

The Plain Carbon Steels contain a maximum carbon content of 2.1% by wt. in addition to some more elements such as silicon, vanadium, cobalt, phosphorus, molybdenum, tungsten, nickel, titanium etc. The carbon content plays an important role in deciding the properties in these steels and other elements have a lower influence on properties comparatively. The maximum weight % of elements in plain carbon steel are shown in Table 2.1

Table 2.1: **Percentage of Weight of Residual Elements in Plain Carbon Steel**

Elements	Maximum wt. %
C	2.1
Mn	1.65
P	0.40
Si	0.60
S	0.05

Advantages of Plain Carbon Steel -

- Significant weldability and formability.
- Ductile and tough.
- Good wear resistance.

Disadvantages of Plain Carbon Steel -

- Low hardenability.
- Loss of physical properties (strength and embrittlement) by both high and low temperatures and subject to corrosion in most environments.

2.2.2 Kinds of Plain Carbon Steel

Based on carbon percentage the plain carbon steel can be categorised in three different groups as shown in figure 2.2

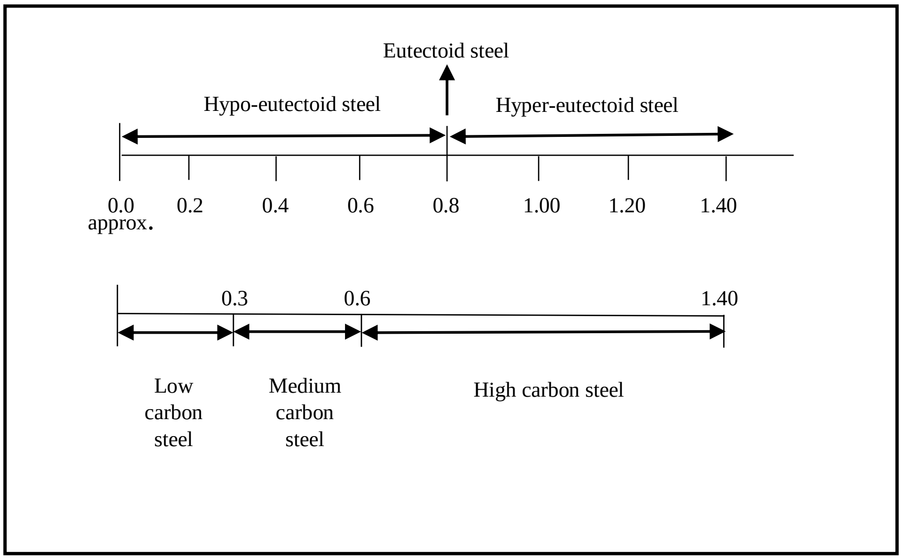

Fig. 2.2 **Classification of plain carbon steel**

Low carbon steel

Low Carbon Steel contains maximum carbon of 0.3% by weight. Low carbon steel is refined in basic oxygen or open hearth furnace. Low carbon steel lacks in tensile strength but possesses good ductility. Low carbon steel finds its application in forging works, riveting, and making low strength machine parts. To improve tensile strength, dimensional tolerances, and surface finish low carbon steels are cold rolled between polished rollers under very high pressure and the product is called cold rolled steel.

Akay S.K. et al. [4] studied the microstructure of 0.05% wt. carbon steel as shown in fig. 2.3 which has ferrite and pearlite matrix. The dark areas show ferrite and light areas represent pearlite. The pearlite is uniformly distributed in ferrite matrix as irregular shaped volumes. The Fraction of ferrite is very large as compared to pearlite. Ferrite being a softer phase gives significant ductility to the low carbon steel.

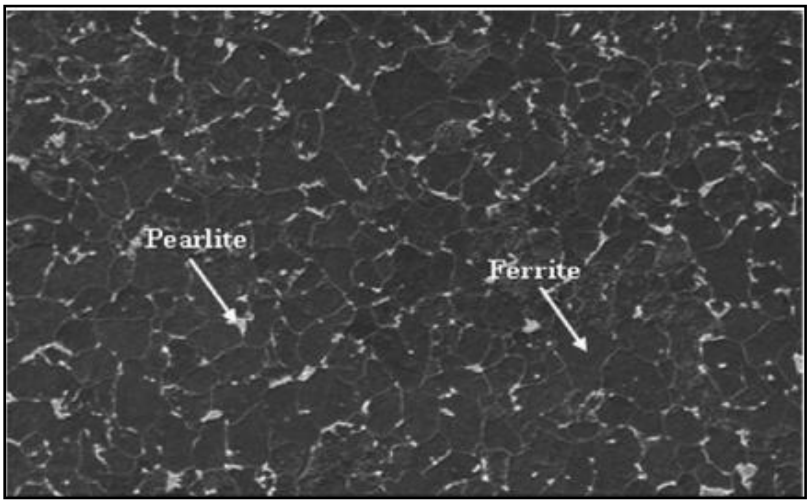

Fig. 2.3: **SEM micrographs of the microstructure of 0.05%wt C steel ferrite(dark) and pearlite(light) [4].**

The standard mechanical properties of low carbon steel is given in table 2.2.

Table 2.2 S**tandard Mechanical Properties of Low-Carbon Steel (Everett, 1994)**

Properties of Low Carbon Steel	**Value (Unit)**
Young‟s Modulus, E	209 GPa
Yield Strength	215 – 250 MPa
Tensile Strength	400 – 500 MPa
Elongation	23%

Medium carbon steel

Medium carbon steel is more strong and tough as compared to low carbon steel. The carbon content varies between 0.3% and 0.6% by weight. Medium carbon steel is difficult to weld, bend, and cut as compared to low carbon steel. It is the most commercially used steel. Medium carbon steel possesses good strength and toughness.

Uses of Medium carbon steel

- 0.3-0.4 Axles, lead screws, connecting rods, spindles, drop forging, worms.
- 0.4-0.5 Gears, rails, tool shanks, boilers, machine parts.
- 0.5-0.6 sledges, hammers, laminated springs, wire ropes.

Medium carbon steel can be heat treated to get different combinations of properties. Attention of many researchers is focused in this area. Different heat treatments have been studied on medium carbon steel such as annealing, normalizing, and quenching followed by tempering.

The microstructure of Medium carbon steel suggests that it has more amount of pearlite as compared to the amount of pearlite in low carbon steel [5]. The optical micrograph of medium carbon steel is shown in fig. 2.4 the light areas show ferrite and dark areas show pearlite.

Fig. 2.4 **Optical micrograph of 0.4% wt. Carbon steel in 1100X [5].**

In this work, Medium carbon steel with 0.524% carbon is to be studied for fatigue response, the further studies will be discussed in the upcoming chapters.

High carbon steel

The plain carbon steel having a carbon content between 0.6% and 1.40% by weight is known as High carbon steel. High carbon steel is very hard and generally used in cutting applications. Typical uses of High carbon steel

- 0.6-0.7 screw drivers, table knives, drop hammer dies.
- 0.7-0.8 anvil faces, band saws, shear blades.
- 0.8-0.9 cold chisels, springs, rock drills, threading dies.
- 0.9-1.0 hacksaw blades, taps, small punches, needles.
- 1.0-1.30 ball bearings, circular tools, twist drills, turning and planning tools.
- 1.30-1.40 Surgical instruments, razors, boring tools, fine cutters.

The microstructure of a High carbon steel containing 0.8% wt. carbon is shown in fig. 2.5. It is a eutectoid composition and hence pearlite is only phase present.

Fig 2.5 **Optical micrograph of a 0.8% wt. carbon steel in 1000X.**

Advantages of High carbon steel

- High hardness and wear resistance
- Good formability.

Disadvantages of High carbon steel

- Less tough and brittle
- Lacks in weldability.

2.2.3 Alloy steels

When steel is combined with one or more other elements, alloy steel is formed. Usually metallic elements are added to the steel. These elements are intentionally added to steel to obtain desired properties which are not possible to achieve in plain carbon steels. Generally alloying is done to improve following properties:

1. Corrosion resistance
2. Wear resistance
3. Hardenability
4. Machinability
5. Strength and hardness at high temperature.

The alloy steels are also heat treated to alter the properties as required. The important elements which are added to form alloy steels are Chromium, vanadium, manganese, Nickel, Tungsten, cobalt, and molybdenum.

2.2.4 Effects of alloying elements

The different alloying elements have different effects on properties of steels. Effects of some important alloying elements is discussed in following paragraphs:

Nickel

Nickel improves the corrosion resistance of steel. Nickel and chromium together are used to make stainless steels. It also increases strength and toughness to some extent. Steel with Nickel is significantly hard. It adds some elasticity to the material and the response to vibration and wear is improved. Used to make wire ropes, axles, rails etc.

Chromium

Chromium hardens the steel and increases its toughness. It makes the steel rust resistance by making grains finer. It is the main alloying element of stainless steel, stainless steel contains about 11-25% chromium. Chromium is used to make steel for rock crushers and bearings.

Cobalt

The main application of cobalt is in making cutting tools. The important property of cobalt is that it improves the red hardness or the hardness at high temperature of the alloy. Wear resistance is also improved by use of cobalt.

Manganese

Manganese is very hard and brittle metal it makes. It adds toughness to the steel. Manganese makes steel so hard to cut and generally these steels are cast shaped. Alloy steel formed by adding Manganese is used in Jaws of rock crushers, chains, gears etc.

Molybdenum

Molybdenum increases strength and hardness of steel. The important property is, it improves the heat and shock resistance. The application of these alloys are in automobile parts and bearings.

Tungsten

Tool steels, High speed steels, and cemented carbide are made by Tungsten as an alloying element. Tungsten makes the alloy hard and increases the melting point. It allows the alloy to withstand heat. These steels are also used in armor plates.

Vanadium

Vanadium makes steel shock resistance. Vanadium makes the steel tough, increases the strength and corrosion resistance. Due to good damping properties these steels are used in springs, automobile gears and axles.

2.3 Heat Treatment

Heat treatment is an important tool by which the properties of the steels can be altered depending on the requirement. By distinct heat treatment processes a steel with wide range of properties can be made [6]. Heat treatment is the process of heating and cooling of materials in controlled atmosphere to alter their mechanical and physical properties as per the work requirements. The heat treatment processes is carried out in following three stages:

1. Heating the material to a required temperature
2. Holding at this temperature for soaking
3. Cooling at different rates to get different physical and mechanical properties.

Microstructural change, phase change and crystallographic change occurs during the heat treatment process [7]. Fig. 2.6 shows the microstructural variation of AISI 1020 steel before and after heat treatment at 750^{0}C for 150min. air cooled.

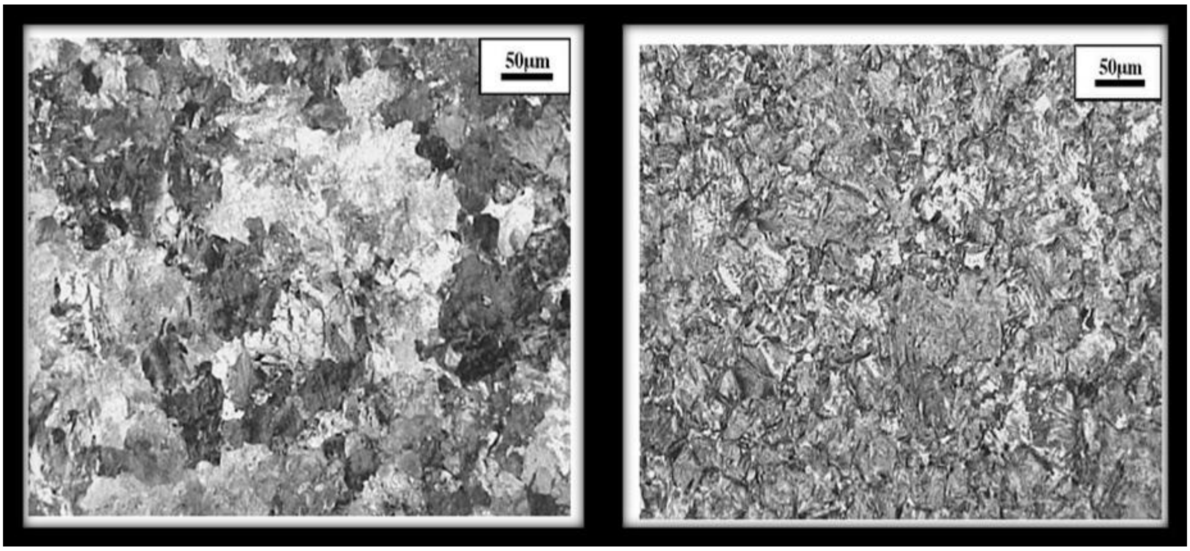

Fig 2.6 **(a) Microstructure of AISI 1020 Steel (Etching: Nital 0.3%)**
(b) Microstructure of the AISI 1020 Steel heat treated at 750 ^{0}C for 150 min. [12].

The carbon steels are heat treated to get different combination of mechanical properties such as ductility, toughness, hardness, tensile strength, impact strength etc. Heat treatment processes have less impact on properties like corrosion resistance and thermal conductivity. In steels, depending upon the heat treatment process different microstructures such as ferrite and pearlite, martensite, tempered martensite, and bainite can be obtained. Martensite is a very hard and brittle phase and generally has no application so the martensitic steels are usually tempered at relatively low temperatures to retain some ductility and toughness.

When subjected to carbon steels, before going for a heat treatment process one should precisely know the temperature, composition and other parameters. The temperature for the heat treatment is decided by the Iron-carbon equilibrium diagram given that the composition of carbon steel is well known. Fig. 2.7 shows the Iron-carbon diagram.

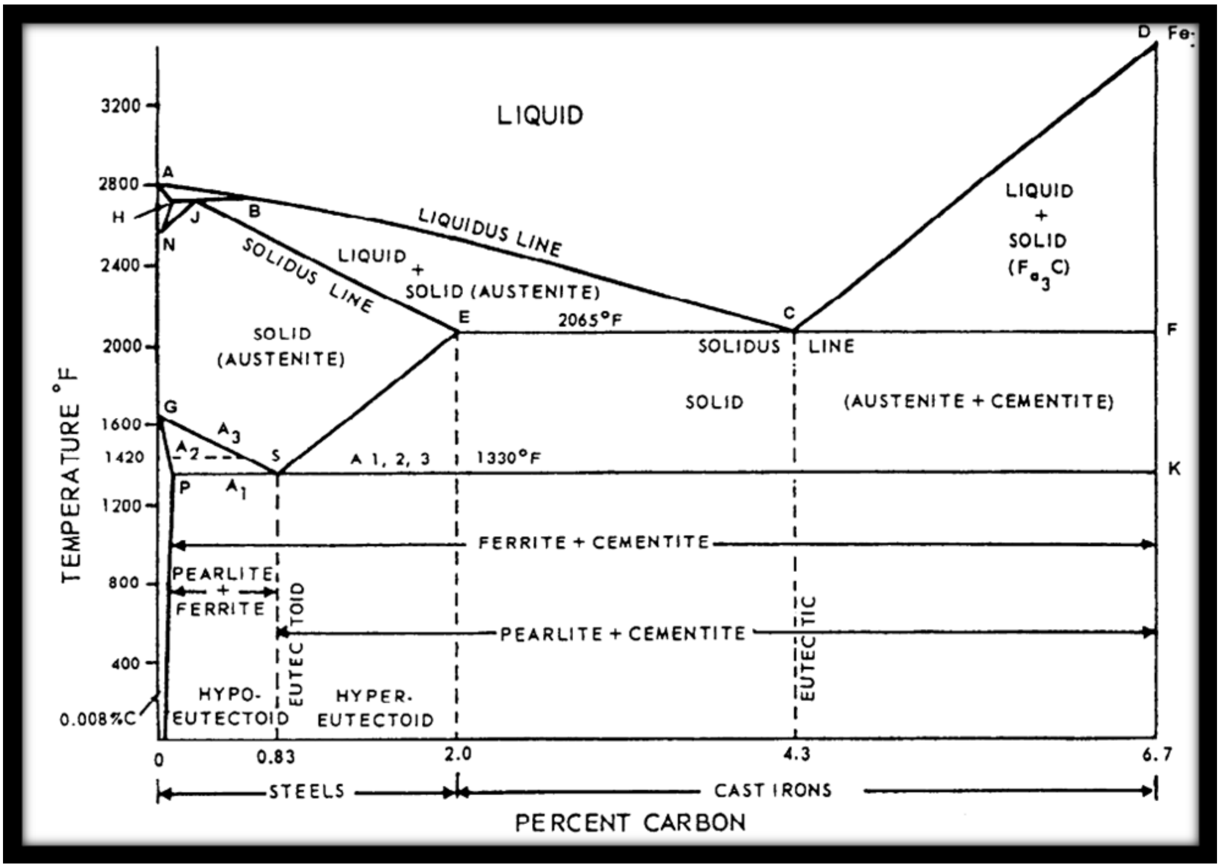

Fig 2.7 **Iron-Carbon Phase Diagram**

It is well known that iron is an allotropic material (it can exist in more than one lattice structure depending upon temperature). In Fig 2.7, it can be seen that at 2800^0F when iron solidifies, the iron in body centred cubic delta (δ)-ferrite form [6]. On further cooling to a temperature of 2554^0F, again phase change occurs and the atoms rearrange themselves into the face cantered cubic gamma (γ) form, which is non-magnetic. Again, on cooling up to a temperature of 1666 ^{0}F, phase change occurs from face centred non-magnetic gamma (γ) iron to body-centred non-magnetic α iron. Finally, the α iron becomes magnetic without a change in lattice structure at a temperature of 1414 ^{0}F called Curie temperature.

The carbon composition is responsible for variation in the temperature at which allotropic changes occur. The iron-carbon alloy system is shown in the figure Fig 2.5. It is that part between pure iron and iron-carbide (cementite), containing 6.67% carbon by weight. This diagram is not a true equilibrium diagram, since equilibrium means phase will not change with time. It is a fact that the cementite will decompose into iron and carbon (graphite). This decomposition is a very long process at room temperature, and even at 1300 ^{0}F it will take several years to form graphite. Cementite is a metastable phase. Therefore, this diagram rightly can be called an iron-cementite diagram instead of iron-carbon diagram. The plain carbon steel having less than 0.8% carbon by wt. has a ferrite-pearlite structure [8]. On quenching martensite will be formed and tempered martensite is obtainable by quenching and tempering. Fig. 2.8 shows microstructure of a 0.45% carbon steel.

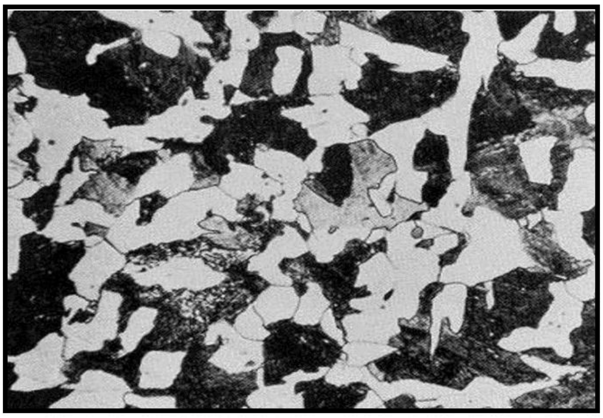

Fig 2.8 **Microstructure of 1045 Steel Bar [9]**

2.3.1. Annealing

Annealing is a heat treatment process which is used in order to obtain some amount of softness in material and to refine the grains. Annealing generally consists of three stages:

1. Heating to a specific temperature
2. Soaking for sufficient time
3. Slow cooling (usually in furnace).

Carbon steels are generally heated to upper critical temperature to form austenite, the soaking time is given to homogenise austenite grains.

Spherodizing

The main purpose of this heat treatment is to induce significant softness in high carbon steels. Spherodite forms when plain carbon steel is heated to approximately 700^{0}C and hold at this temperature to more than 30hours. The purpose is to allow more formability. The steel becomes very ductile and soft after spherodizing.

Full Annealing: -

Full annealing is a heat treatment process which is used to relieve the internal stresses and to get soft and ductile steel. The material is heated above the upper recrystallization temperature, soaking at this temperature for sufficient time and then cooling in furnace (normally at a rate 30-50^{0}C per hour) This results in a coarse pearlite structure.

Process Annealing: -

The Process Annealing is done to relive stresses in a cold worked carbon steel. The process consists of heated to a temperature close or below to the lower critical temperature, soaking at this temperature for some time and then cooling slowly.

2.3.2. Normalizing

Objectives of Normalizing:

- To refine the grains of as-cast steel
- To get improvement in the mechanical properties of carbon steels
- To eliminate the microstructural irregularities
- To enhance machinability
- To break the cementite network in hypereutectoid steels.

The Normalizing temperatures are a bit higher than annealing temperatures for hypoeutectoid steels, considering the fact that, austenite for normalizing should be more homogeneous so that it can be cooled to a much lower temperature to form fine pearlite. The process consists of heating of metal to a temperature 20-30^{0}C more than upper critical temperature, soaking for sufficient time and then air cooling.

The resulting structure is fine pearlite and ferrite for a hypo eutectoid steel, and that is harder and stronger than the as-cast product.

2.3.3. Quenching and Tempering

The as-quenched martensitic structure is very hard and brittle and hardly finds any application.

By tempering the as-quenched steel, significant amount of ductility can be induced with good strength and toughness. The process quenching and tempering consists of reheating the hardened martensitic steel which is water quenched from the soaking temperature to usually room temperature at a higher rate for getting a high hardness value [10]. The purpose is to induce some softness, reliving internal stress, and to induce toughness so that the steel can resist shock and fatigue. Conventional quenching followed by tempering heat treatment processes have been applied to get good combination of toughness and strength. [11].

The quenching can be done in water as well as in oil. The water quenched steels possess good tensile properties while the oil quenched steels have good impact strength [12].

Aims of Tempering

- To relieve the internal stresses (during hardening internal stresses are developed)
- To regain ductility and toughness
- To decompose retained austenite so that dimensional stability can be improved
- To transform non-magnetic retained austenite hence magnetic properties will be enhanced

By different heat treatment techniques different microstructures are evolved for different instances.

Each microstructure gives unique properties. Some of the typical microstructures that evolve during the various heat treatments are shown in fig. 2.9

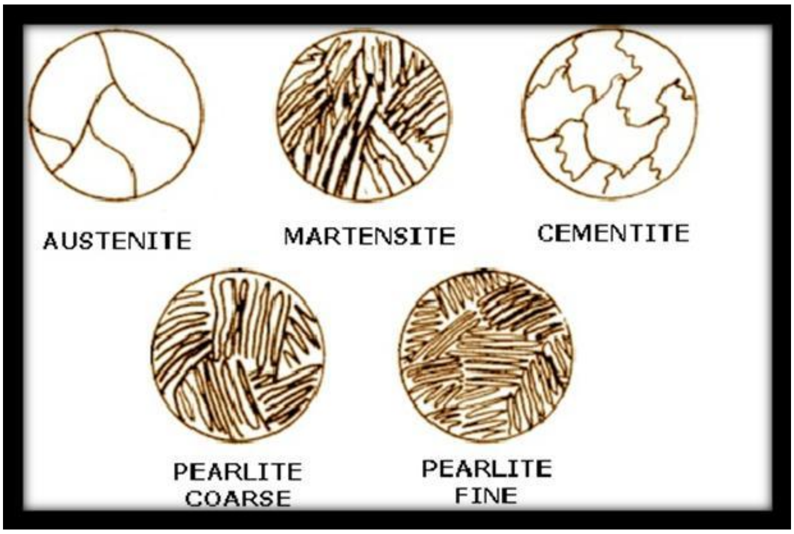

Fig 2.9 **Heat Treated Microstructures**

2.4. Fatigue of steel

In 1830, it was discovered that when a metal is subjected to cyclic stress (dynamic loading) it would fail at a considerably lower stress as compared to the stress that will cause a failure in case of static loading. It has been seen that these failures take place after a considerable service span and called fatigue failures [13]. The fatigue failure is more prominent in aircrafts, automobiles, turbines, and other machineries that are subjected to repeated loading or vibration. Also, 90% of the mechanical failures are due to fatigue [14]. Since its discovery, the fatigue has been a very crucial topic in the field of mechanical behaviour of materials and many researchers have carried out research in order to study the mechanism of fatigue, factors affecting fatigue behaviour, and other aspects of fatigue. In this work, a brief discussion on the factors, the effects on mechanical properties and physical properties associated with the quenching and tempering heat treatment have been incorporated with the most common techniques used in fatigue.

2.4.1. Fundamentals of Fatigue

The fatigue failure occurs immediately and instantly without any warning, and it is a brittle appearing fracture, which has no gross deformation. Here the fracture surface is parallel to a plain which is normal to the direction of the principal tensile stress. The fractured surface shows a very smooth region, probably due to the rubbing action, and a rough region where ductile failure has been occurred when it was not possible for the cross section to carry the load which is shown in the Fig 2.10. Usually the fatigue failure occurs at a point where the stress concentration is higher such as at sharp corners, notches, and intrusions. The progress of fatigue failure can be indicated by “beach marks”, or series of rings going inwards from the initiation point. A tensile stress of high value, large value of fluctuation, or a sufficiently high cycle might be the factors responsible for fatigue failure.

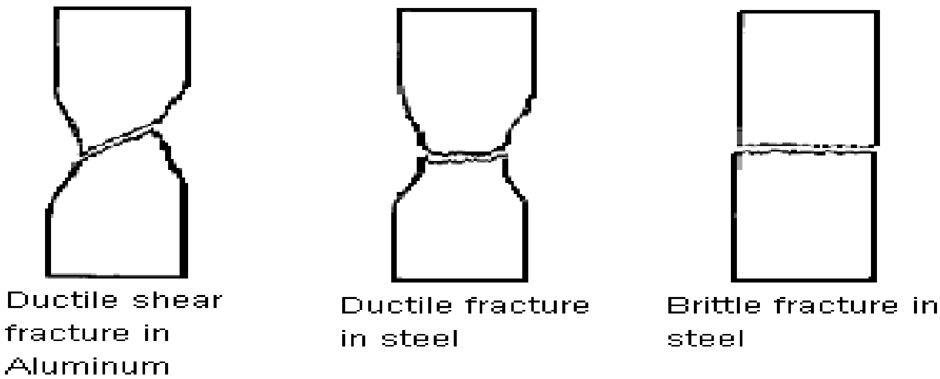

Fig 2.10 **Different types of Fatigue Fractures [15]**

2.4.2. Stress Cycles

Depending upon the maximum and minimum principle stresses, there are various stress cycles as shown in Fig 2.11.

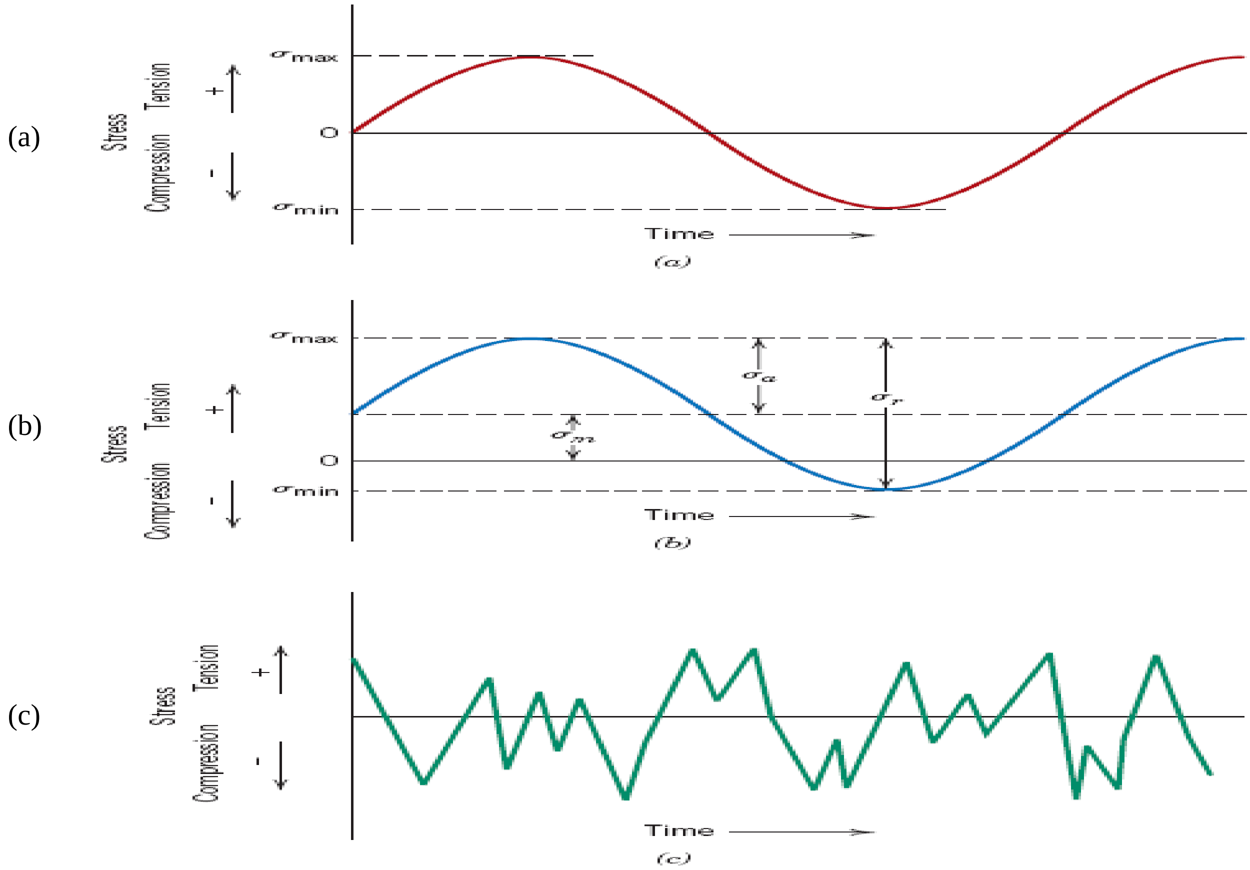

Fig. 2.11 **Stress Cycles (a) Completely Reversed loading, (b) Repeated loading, and (c) Random loading**

(a). ***Completely reversed cycle***: In Completely reversed stress cycle the magnitude of maximum stress (σ_{max}) minimum stress (σ_{min}) are same but the sense is opposite.

(b). ***Repeated stresses cycle***: In repeated stress the maximum and minimum stresses are not same neither in magnitude nor in direction.

(c). ***Irregular or random stress cycle***: In this type of stress cycle the variation of stress does not follow a definite pattern as shown in fig. 2.11 (c).

Fluctuating stress cycles are made up of two components:

1. Mean or steady stress (σ_m): $\sigma m = \frac{(\sigma max + \sigma min)}{2}$

2. Alternating stress (σ_a): $\sigma a = \frac{(\sigma max - \sigma min)}{2}$

2.4.3. S-N Curve

The fatigue data is represented by using S-N curve. S-N curve is a plot between the bending stress (S) and number of cycles to failure (N) in log scale. Typical S-N curves are shown in fig 2.12 (a) and (b) [16].

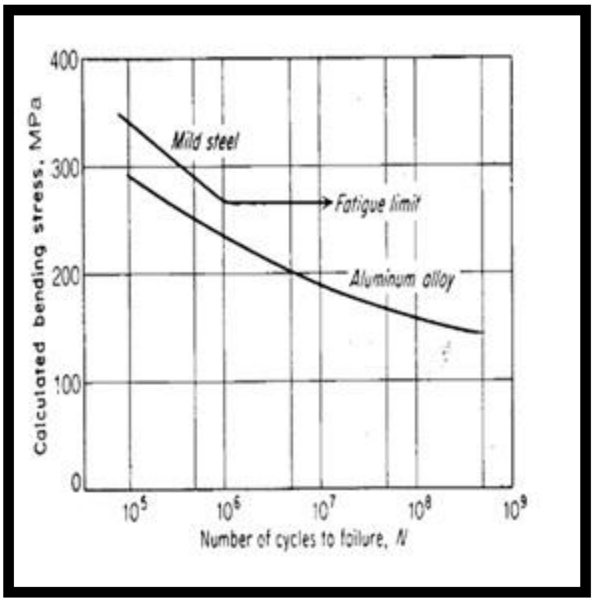

Fig 2.12 **Typical Fatigue Curve for Ferrous and Non-Ferrous materials.**

Most of the fatigue tests of materials have been made in completely reversed cyclic loading where the mean stress (σ_m) becomes zero and tests are performed in rotating beam test machine. In high cycle fatigue to determine the S-N curve the specimen is first loaded at a high stress, where failure is expected to occur in short number of cycles. Then the stress is decreased subsequently up to a stress where one or two specimens does not fail after the specified number of cycles, which is usually about 10^6 to 10^7 cycles.

The S-N curve becomes horizontal for certain engineering materials such as titanium and steel this limiting stress is called fatigue limit or endurance limit. Most nonferrous metals, like copper, aluminium, and magnesium alloys have an S-N curve which slopes gradually downwards with increasing number of cycles. For these materials the S- N curve never becomes horizontal and hence does not have a true fatigue limit.

For the low cycle fatigue test ($N<10^5$cycles), tests are conducted with controlled cycles of elastic and plastic strain rather than controlled load or stress. The conventional fatigue problems can be divided into the following kinds according to the number of cycles of fatigue:

- Super cyclic fatigue (over 10^7)
- High cyclic fatigue (from 10^5 to 10^7)
- Low cyclic fatigue (from 10^3 to 10^5).

2.4.4. Fatigue Mechanism

Ewing and Humfrey [17] in 1903, studied the fatigue behaviour of Swedish iron. They found that after exceeding proportional limit the metal was deformed by slipping on certain plains. Different theories were put forward and concluded that the fatigue cracking was associated with slip. Gough [18] in 1923 gave another explanation about the fatigue mechanism. He explained that the fatigue failure of the ductile materials are consequence of slip.

Around 1960, the electron microscope observation was a crucial development for fatigue investigations. The Fractographic image revealed striations marks with respect to every load cycle [19]. Crack formation in fatigue can be studied by interrupting the test and removing the deformed surface by electro-polishing. After polishing several slip bands will be found which are more persistent than the others and they will remain visible while others have been polished away. These slip bands are observed only after 5 percent of the total life of specimen [20]. The persistent slip bands becomes wide cracks when a small tensile strain is applied.

Initially fatigue cracks propagate along slip planes and later they propagate in a direction normal to the maximum tensile stress. The Fatigue crack propagation is ordinarily trans-granular.

An important structural feature appears in the fatigue deformation and that is the formation of ridges and grooves called slip band intrusions and slip band extrusions as shown in fig.2.13 [21].

A careful metallographic study on taper sections thorough the surface of the specimen has shown that the fatigue cracks initiate at intrusions and extrusions [22].

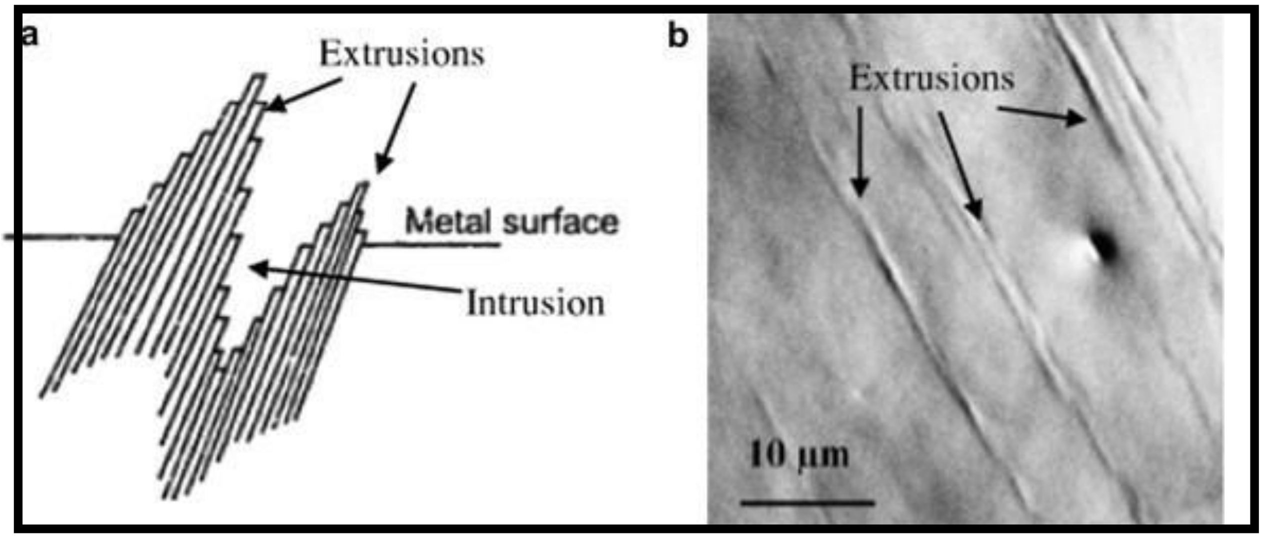

Fig 2.13 **Slip Mechanism [23]**

Chapter 3

Experimental Techniques

Fig 3.1 shows the experiments involved in this research work. The tests have been done in two groups, in first group the as received specimen is prepared for the different tests according to the required dimensions, and in the second group the specimens are quenched and tempered at different set of conditions and the test have been performed.

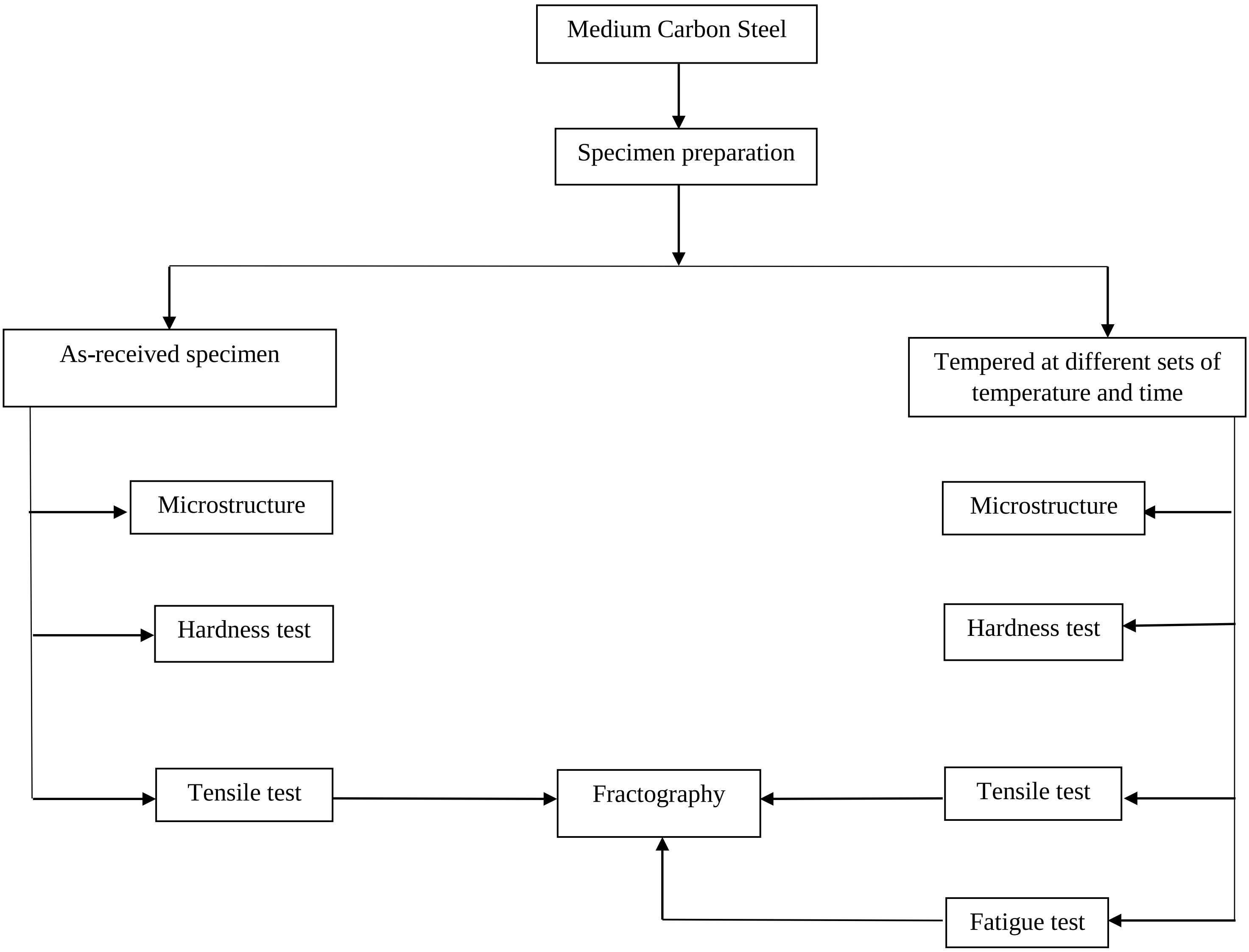

Fig 3.1: **Experimental layout**

The experimental techniques associated with the work are listed below:

1. Specimen preparation
2. Heat treatment (Quenching and tempering)
3. Microstructural analysis
4. Hardness test
5. Tensile test
6. Fatigue life estimation
7. Fractography.

3.1. Specimen preparation

The composition of the as received Medium carbon steel is given in the table 3.1. The microstructure of the Medium carbon steel contains ferrite and pearlite. Medium carbon steel has high hardness and strength with moderate ductility and significant amount of toughness.

Table 3.1: **Composition of specimen (% by weight)**

C	0.524 %
Mn	0.6903 %
P	0.014 %
S	0.02 %
Ni	0.015 %
Si	0.215 %
Cr	0.211 %
Mo	0.002 %
V	0.032 %
Cu	0.009 %
Fe	Balance

To carry out the experiments, the first job is to prepare the specimen as per the dimensions and design required. Fig 3.2 shows the design and dimensional specification for fatigue test. The specimen has a round cross section, the length of the specimen is 157 mm. and diameter at neck is 10 mm.

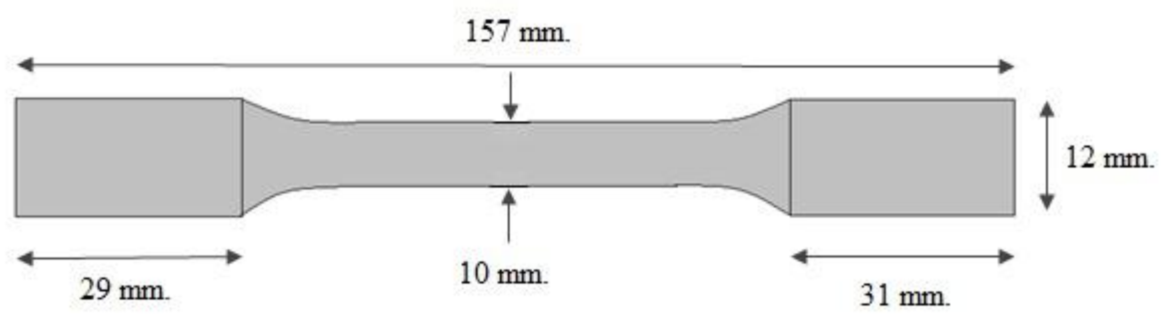

Fig 3.2: **Specimen specification for fatigue and tensile test.**

The specimens have been designed as per the R.R. Moore Rotating beam testing machine. Prior to the fabrication (machining) the heat treatments were done, keeping in mind that the heat treatment can result in some dimensional changes and scale formation.

For hardness test and microscopic investigations small pieces from rod were cut and polished.

3.2. Heat treatment (quenching and tempering)

Heat treatment is a process of subsequent heating and cooling to get different combinations of mechanical and physical properties. Quenching and tempering is most common and crucial heat treatment technique.

In this work tempering heat treatment has been done at three different temperatures 200^0C, 400^0C and 600^0C for different durations of 60 min., 90 min., and 120 min. The austenitizing temperature was selected from Iron carbon diagram. Steps followed in the heat treatment are as follows:

Quenching

1. Specimens were first heated to 850^0C, which is the austenitizing temperature for given composition.
2. At the temperature of 850^0C the specimens were held for one hour, this is called soaking and this was done to obtain homogeneous austenite.
3. The specimens were then rapidly cooled or quenched in water bath, maintained at room temperature.

Tempering

Tempering was done at three different temperatures 200^0C, 400^0C, and 600^0C.

1. Some specimens were heated at 200^0C for 60 min., some for 90 min., and remaining for 120 min.
2. Same procedure was followed at 400^0C and 600^0C.
3. Heated specimens were then air cooled.

To prevent oxidation the specimens were placed in a charcoal container inside the furnace.

3.3. Investigation of Mechanical properties

The study of mechanical properties is the basic objective of this work. It is essential to compare the mechanical properties of differently tempered medium carbon steel specimens. Hardness test and tensile tests have been carried out to know the properties variation with respect to tempering time and temperature.

3.3.1 Hardness test

The hardness of as-received specimens as well as tempered specimens were measured in Vickers micro hardness testing machine (LM248at), as shown in fig. 3.3.

Fig. 3.3. **Vickers microhardness testing machine**

Procedure-

1. The specimen was placed in the machine
2. Dwell time was 10 sec.
3. 2 kg load was applied
4. The hardness values in HV were noted down.

3.3.2 Tensile test

To determine various tensile properties such as percentage elongation, yield stress, ultimate tensile stress. The as-received as well as differently tempered specimens were tested in Instron 1195.

Procedure-

1. The gauge length was calculated and the cross sectional area of the specimen was measured by an electronic slide caliper.
2. The distance between jaws was fixed to gauge length.
3. Specimen was fixed to the gripper
4. Specimen was loaded till failure
5. Engineering stress vs. strain curves were plotted with the help of load vs. displacement diagrams and the values of the yield stress, percent elongation, and ultimate stress were calculated by using following formulae :

$$\%\text{ of Elongation} = \frac{\text{Change in gauge length}}{\text{Original gauge length}} \times 100$$

$$\text{Yield strength} = \frac{\text{Load at 0.2\% offset yield}}{\text{Initial cross sectional area}} \times 100$$

$$\text{Ultimate Tensile Strength} = \frac{\text{Maximum load}}{\text{Initial cross sectional area}} \times 100$$

$$\%\text{ Reduction of area} = \frac{\text{Change in gauge diameter}}{\text{Original gauge diameter}} \times 100$$

3.4. Microstructural analysis and Fractographical studies

The microstructures of as-received specimens and tempered specimens were studied in optical microscope. For that the specimens with 12mm. diameter and 10 mm. length were polished and etched by 2% Nital solution and then studied by optical microscope. Fig. 3.4 shows an optical microscope.

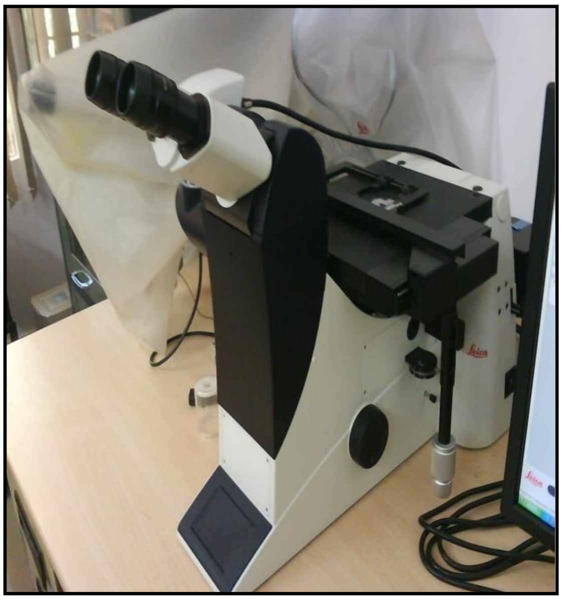

Fig. 3.4 **Optical microscope.**

The fractographs of the fractured specimens after tensile and fatigue tests were taken by Scanning electron microscope, shown in fig. 3.5.

Fig. 3.5 **Scanning electron microscope (SEM)**

3.5. Fatigue test

Fatigue life estimation is the main objective of this research work. R.R. Moore rotating beam testing machine is used to estimate the fatigue life. The schematic diagram of Rotating beam testing machine is shown in fig. 3.6.

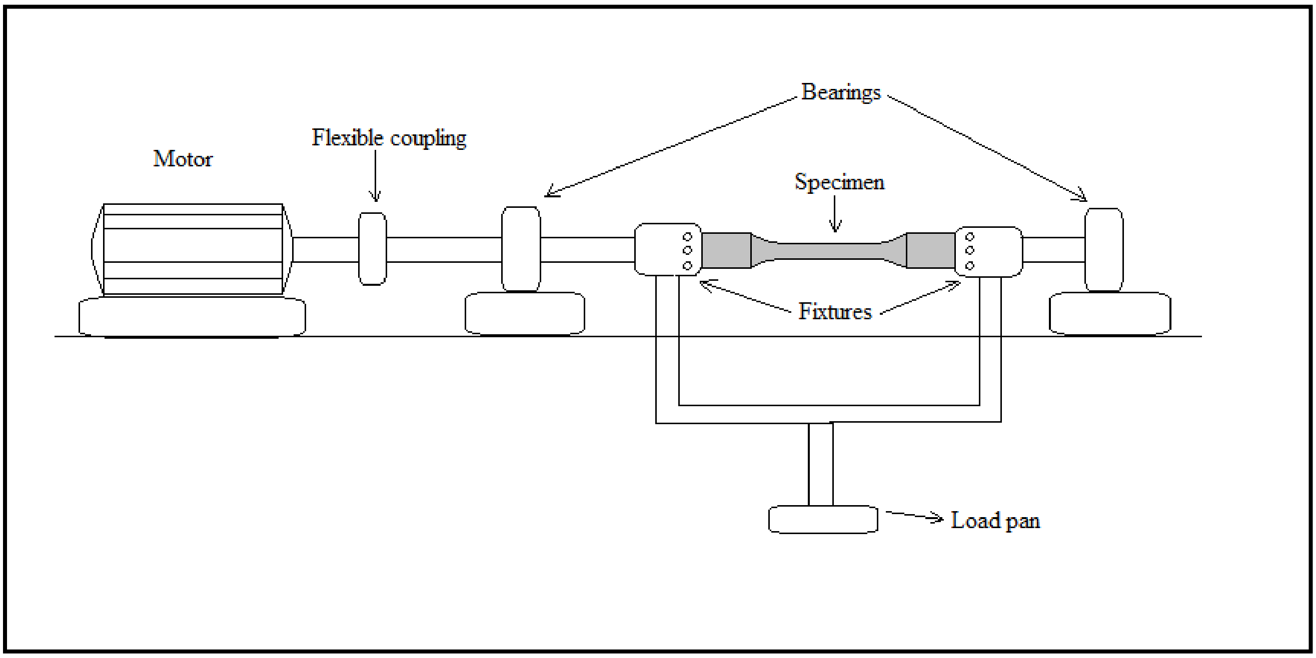

Fig. 3.6 **R.R. Moore rotating beam testing machine.**

Procedure-

The specimen is clamped between two bearings and rotated by a motor about its longitudinal axis. A constant load is applied with the help of load pan. This results in application of a constant load with pure bending. The completely reversed stress pattern is achieved when specimen is rotated by spindles. In fig. 3.7 a completely reversed stress pattern with stress ratio **R= -1** and zero mean stress is shown. In the present work specimens were loaded in the machine at a frequency of 100HZ.

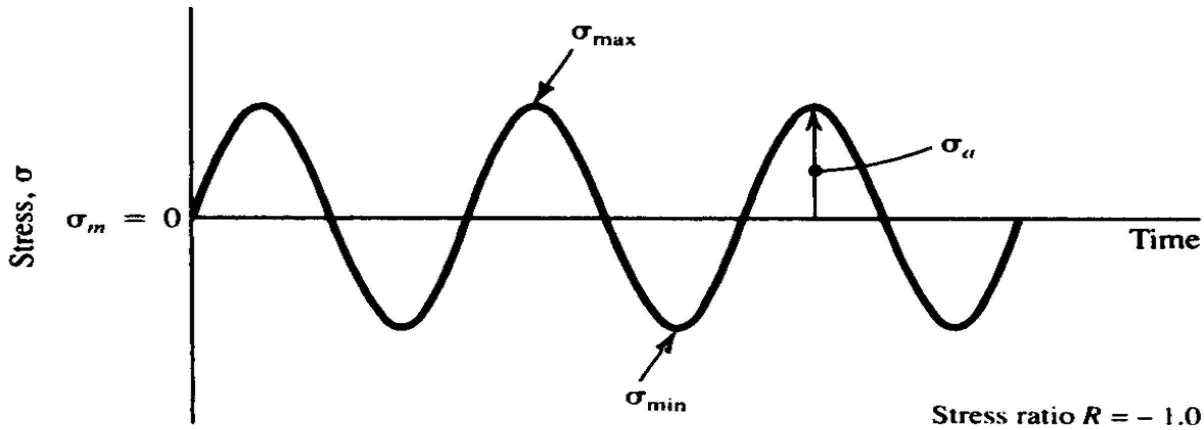

Fig. 3.7. **Completely reversed stress pattern**

Working-

The symmetrically loaded specimen is rotated in the R.R. Moore testing machine. After half revolution the stresses originally below and above the neutral axis interchange their senses. At first the upper fibres are subjected to compression and lower fibres are subjected to tension. The formula of bending is applied to correlate the load and bending stress:

$$\frac{M}{I} = \frac{\sigma}{Y}$$

Where,

M = Bending moment N-m

I = Moment of inertia m^4

σ = Bending stress (pa)

Y = Distance from neutral axis.

Chapter 4

Results and discussions

4.1 Introduction

The microstructure, mechanical properties, and fatigue life of medium carbon steel have been investigated in this research work. Mechanical properties such as hardness, tensile strength, and percentage elongation of as-received and differently tempered specimens have been measured and compared. The mechanical properties have been correlated with the microstructure.

The Fatigue life of differently tempered specimen have been studied and endurance limit has been calculated. The S-N curves are plotted for each set of Tempering temperature and time. Attempts have been made to correlate the endurance limit with the strength of the medium carbon steel specimens.

4.2 Microstructural analysis

Microstructure of as-received medium carbon steel

Microstructural analysis is essential because the mechanical properties are greatly influenced by the microstructure of the material. The microstructure of as-received medium carbon steel specimen has been studied in optical microscope. The optical micrograph is shown in fig. 4.1. The microstructure of medium carbon steel consists of ferrite (shown in light areas) and pearlite (shown in dark areas).

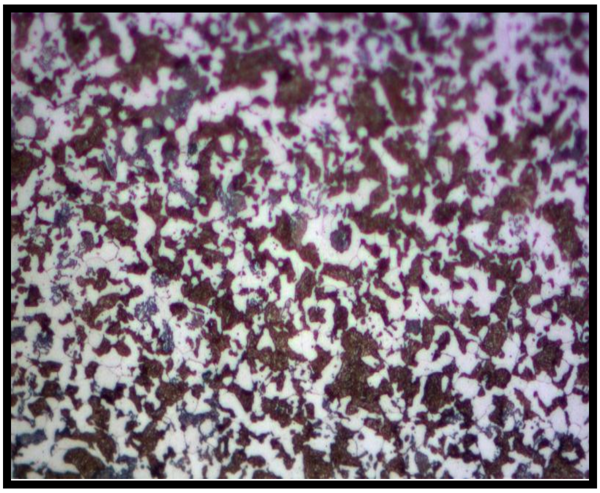

Fig. 4.1 **Optical micrograph of as-received specimen (medium carbon steel) in 200X**

Microstructure of tempered medium carbon steel

The microstructure of medium carbon steel after tempering has been studied on optical microscope. Fig 4.2, fig. 4.3, and fig. 4.4 show the microstructure of medium carbon steel tempered at 200^0C, 400^0C, and 600^0C respectively.

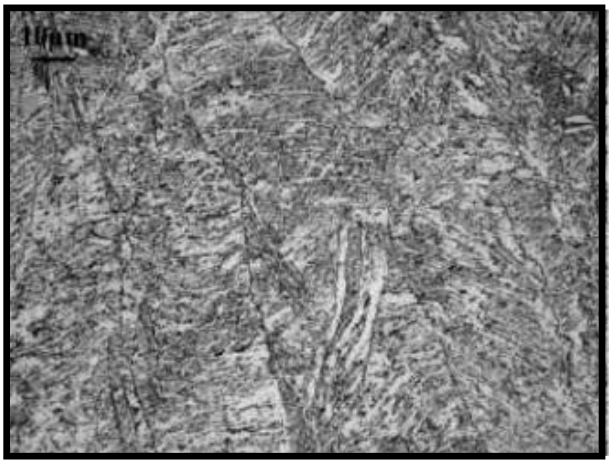

Fig. 4.2 **Optical micrograph of medium carbon steel tempered at 200^0C, 200X**

In the low temperature tempering i.e. at 200^0C the tetragonality of martensite decreases and precipitation of epsilon- carbide occurs [6]. The resulting structure is called tempered martensitic structure.

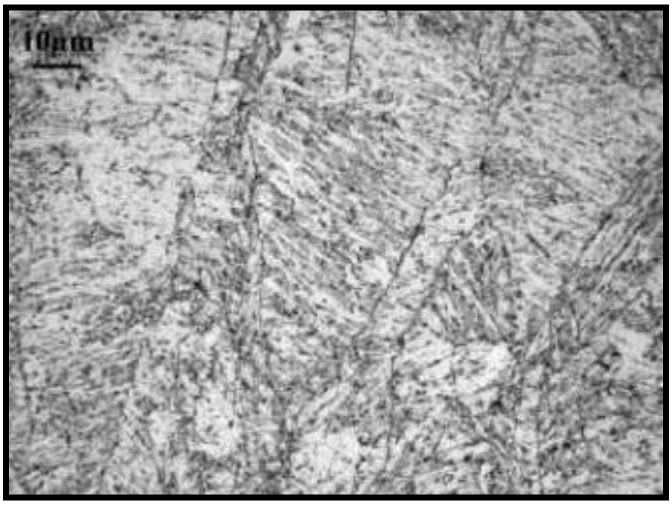

Fig. 4.3 **Optical micrograph of medium carbon steel tempered at 400^0C, 200X**

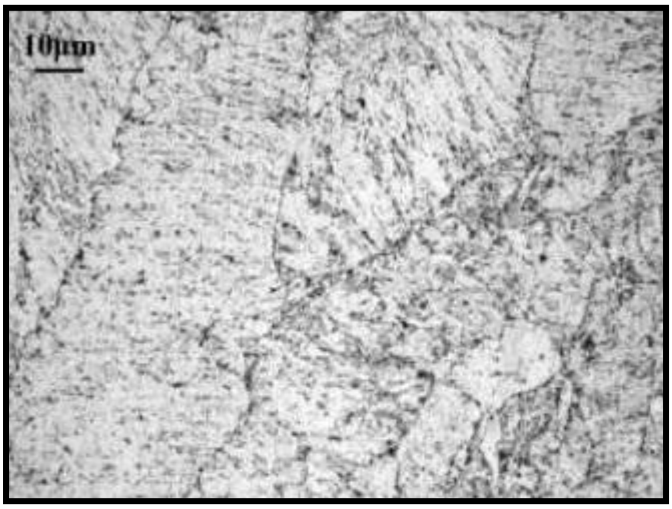

Fig. 4.4 **Optical micrograph of medium carbon steel tempered at 600^0C, 200X**

In the intermediate temperature tempering at 400^0C decomposition of retained austenite occurs and tetragonality of martensite is completely lost, and cementite rods are formed.

The high temperature tempering at 600^0C results in coarsening and spheroidisation of cementite. Due to spheroidisation considerable amount of softness is induced in the material [24].

4.3 Mechanical properties

The study of mechanical properties comprises of hardness test and tensile test of as-received and tempered specimens. The comparison of properties between as-received and tempered specimens as well as between differently tempered specimens will be discussed later.

4.3.1 Hardness test

The hardness tests have been done under the microhardness testing machine, the test procedure has been already described in section 3.3.1. The results of hardness test has been given in table 4.1.

Table 4.1 **Results of Hardness test**

Specimen	Tempering duration	Vickers hardness (HV)
As-received	nil	350
Tempered at 200^0C	60 min.	778
	90 min.	740
	120 min.	718
Tempered at 400^0C	60 min.	665
	90 min.	585
	120 min.	560
Tempered at 600^0C	60 min.	512
	90 min.	490
	120 min.	478

Fig 4.5 shows the comparison of hardness between as-received and tempered medium carbon steel. It can be seen that the quenched and tempered specimens have higher hardness than the as-received medium carbon steel specimens. It can be seen that, as the tempering temperature is increased some amount of softness is induced in the material.

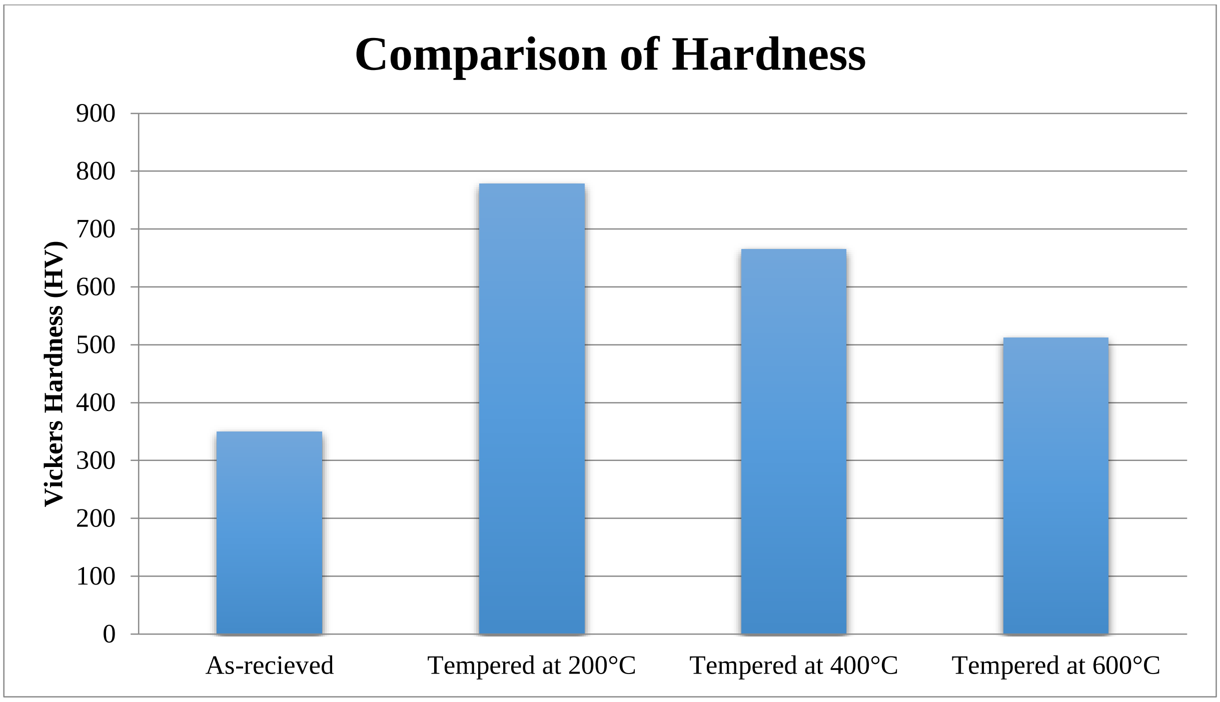

Fig. 4.5 **Comparison of hardness between as-received and tempered conditions**

The hardness values for different tempering conditions are compared and shown in Fig. 4.6. The variation of hardness with respect to tempering time and tempering duration is shown in the graph.

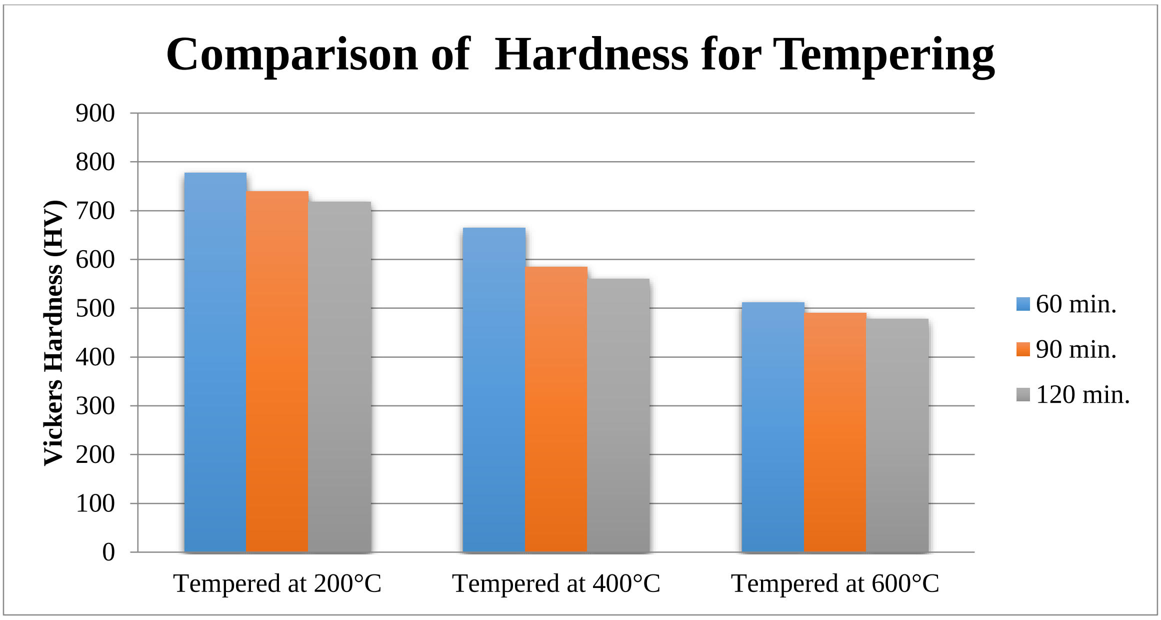

Fig. 4.6 **Comparison of hardness between different tempering conditions.**

It can be seen that the tempering temperature as well as the tempering duration can alter the hardness of the material. For tempering at any of the three temperatures the hardness is maximum for the specimens tempered for 60 min. and minimum for 120 min. this is due to the fact that the phase which is tempered for lower time duration has a finer structure [25-26].

The decrease in hardness with increase in tempering temperature is due to the formation of low tetragonality tempered martensitic structure which was martensitic after quenching. Martensite has a BCT structure and is a very hard phase in which carbon is occupied in the tetrahedral voids. The transformation of martensite is diffusion less and called athermal transformation. On tempering of martensite carbon diffuses from the tetrahedral voids which reduces the tetragonality of the martensite, due to this the hardness of tempered martensite becomes less than the original martensite [27].

4.3.2 Tensile test results

The tensile test and its procedure has been discussed in section 3.3.2. Tensile test is essential to study the static loading behaviour as well as strength and ductility of the material. The Engineering stress vs. strain curves for different tempering conditions are shown in Fig. 4.7 to 4.15.

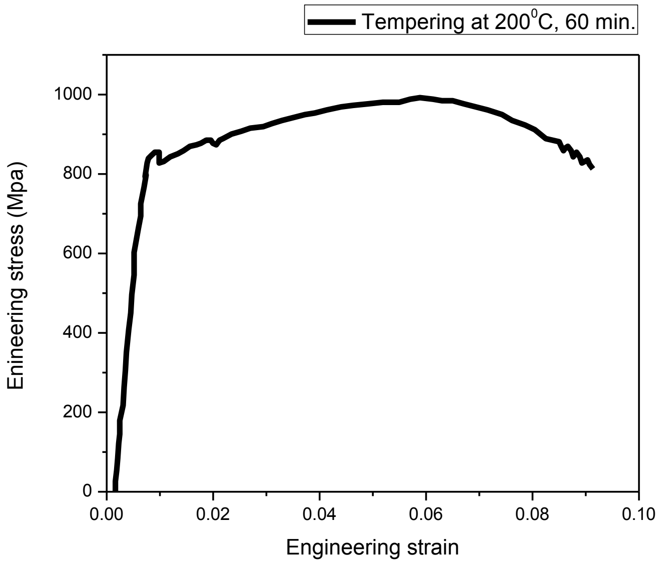

Fig. 4.7 **Engineering stress vs. strain curve, Tempering at 200^{0}C, 60 min.**

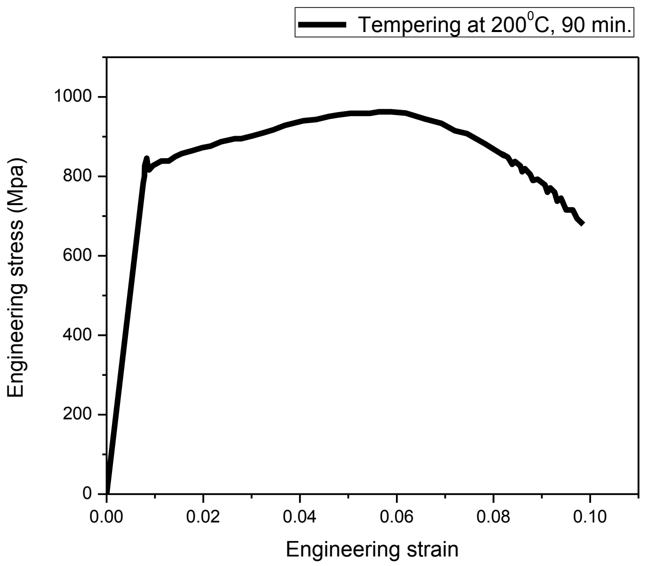

Fig. 4.8 **Engineering stress vs. strain curve, Tempering at 200^{0}C, 90 min.**

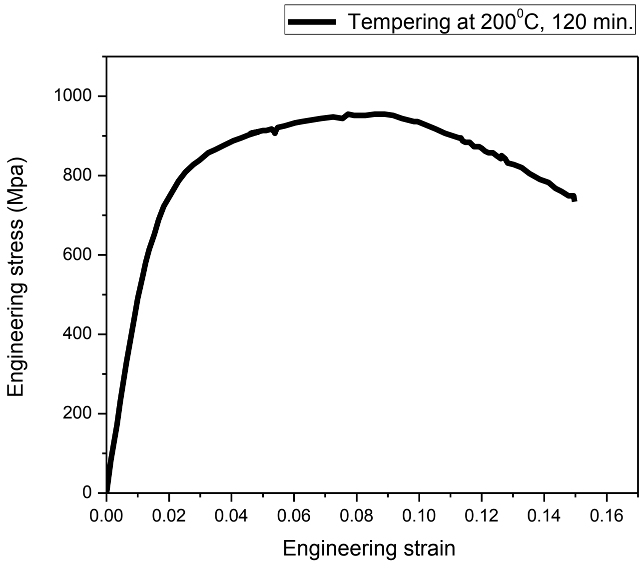

Fig. 4.9 **Engineering stress vs. strain curve, Tempering at 200^{0}C, 120 min.**

Fig. 4.7, fig 4.8, and fig 4.9 show the engineering stress vs. strain curve for tempering at 200^{0}C with tempering duration of 60 min., 90 min., and 120 min. respectively. The yield strength and ultimate tensile strength of the specimens tempered at 200^{0}C, 60 min. are maximum. The yield strength is 830.21 Mpa and U.T.S. is 989.38 Mpa which is more than Y.S. and U.T.S. for 90 min. and 120 min. with a minimum value for 120 min.

Another important property is the ductility. The percentage elongation is maximum for the specimens tempered for a duration of 120 min. and minimum for the 90 min. For tempering at 200^{0}C, 120 min. the percentage elongation is found to be 15 while it is 10 for tempering duration of 90 min. and 9 for 60 min. tempering duration. So it can be seen that with increase in tempering duration the strength is decreased and the ductility is increased.

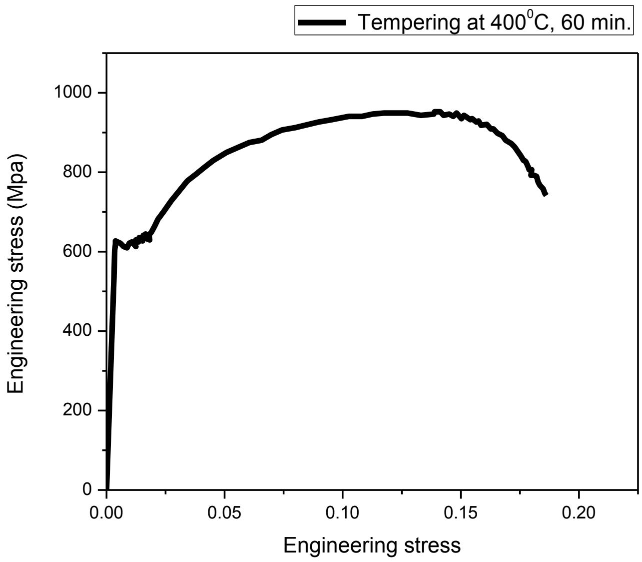

Fig. 4.10. **Engineering stress vs. strain curve, Tempering at 400^{0}C, 60 min.**

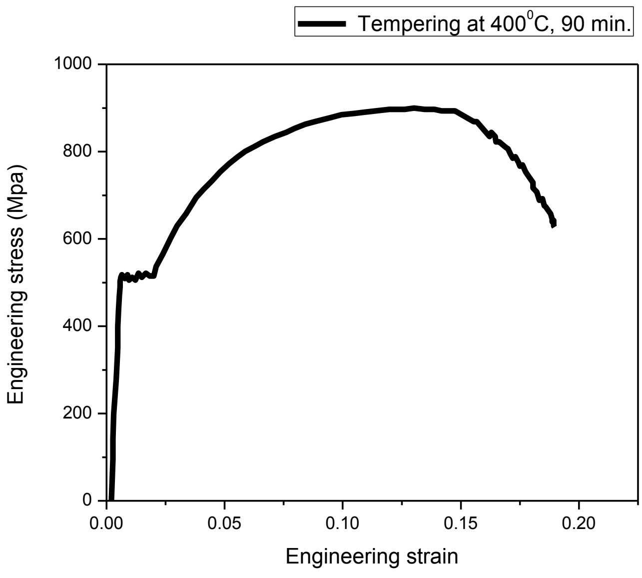

Fig. 4.11 **Engineering stress vs. strain curve, Tempering at 400^{0}C, 90 min.**

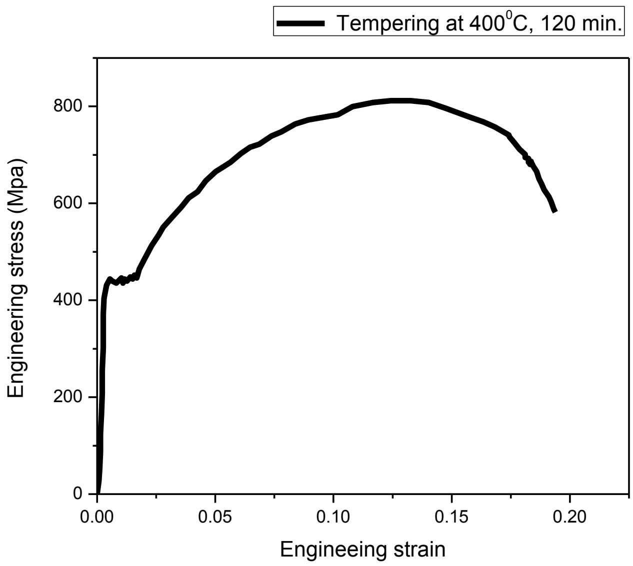

Fig. 4.12 **Engineering stress vs. strain curve, Tempering at 400^{0}C, 120 min.**

The Engineering stress vs. strain curves for medium carbon steel tempered at 400^0 for 60 min., 90 min., and 120 min are shown in fig. 4.10, fig. 4.11, and fig. 4.12 respectively. Here we can see that the medium carbon steel tempered at 400^{0}C has more ductility than the specimens tempered at 200^{0}C. The maximum percentage elongation is 19.5 for tempering at 400^{0}C, 120 min., this indicates significant amount of softness has been induced in the material after tempering at 400^{0}C. For tempering at 400^{0}C, 60 min. the percentage elongation is 18.5 which is lowest for this temperature but still higher than the maximum percentage elongation at 200^{0}C range. The Y.S. and U.T.S has been decreased due to tempering at 400^{0}C as compared to tempering at 200^{0}C. At 200^{0}C, 60 min. the Y.S. was 830.21 Mpa and the U.T.S. was 989.38 Mpa, which decreased to 650 Mpa and 940 Mpa respectively, when tempered at 400^{0}C, 60 min. Even at 400^{0}C the best results as per the strength are for 60 min. duration. The tempering at 400^{0}C for 120 min. leads to loss of strength but increase in ductility.

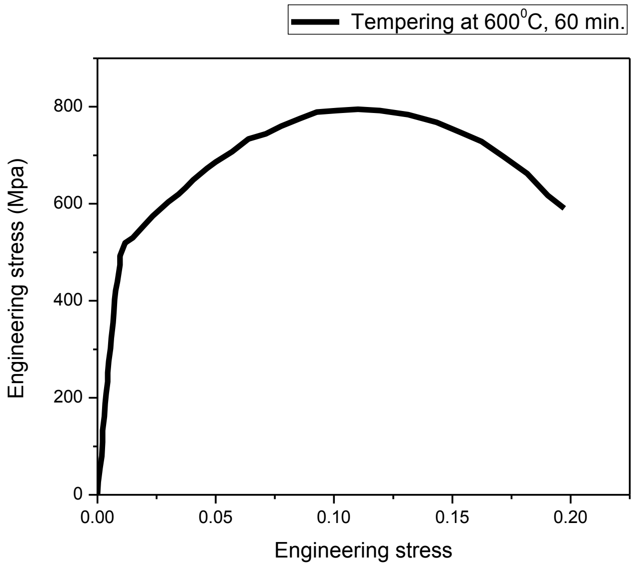

Fig. 4.13 **Engineering stress vs. strain curve, Tempering at 600^{0}C, 60 min.**

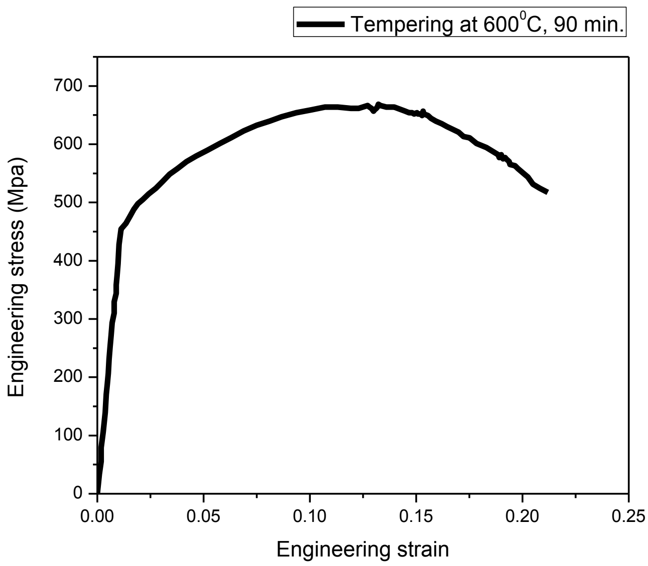

Fig. 4.14 **Engineering stress vs. strain curve, Tempering at 600^{0}C, 90 min.**

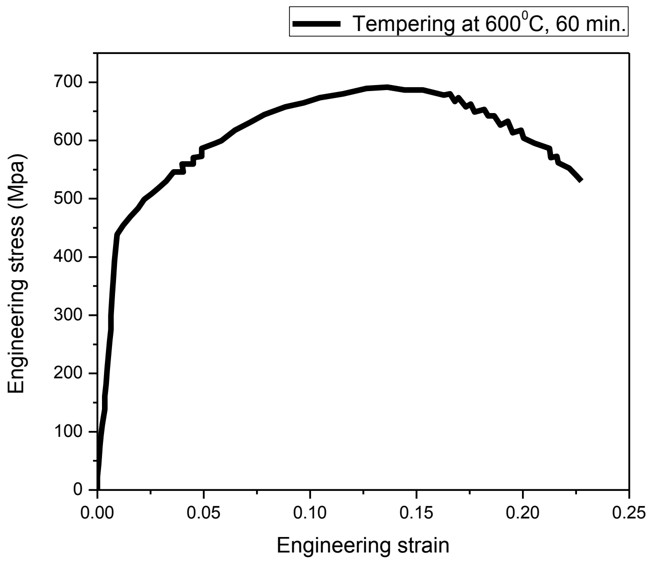

Fig. 4.15 **Engineering stress vs. strain curve, Tempering at 600^0C, 120 min.**

Tempering at 600^0C follows the same trend as 200^0C and 400^0C as far as the tensile properties are concerned. The ductility is highest for the tempering at 600^0C for any duration. This may be due to the formation of spheroidal cementite. The maximum percent elongation is 22 when tempered at 600^0C, 120 min. For tempering at 600^0C the minimum percentage elongation is 20.5, which is higher than percentage elongation for tempering at both the 200^0C and 400^0C range. As the material tempered at 600^0C is very soft, it lacks in strength. The maximum Y.S. for 600^0C tempering is 470 Mpa and maximum U.T.S. is 794.12 Mpa when tempered for a duration of 60 min., which is less than the Y.S. and U.T.S. of medium carbon steel tempered at 200^0C and 400^0C range.

The values of yield strength, Ultimate tensile strength, and percentage elongation were taken from the engineering stress vs. strain curves. These values are tabulated with respect to different tempering conditions in table 4.2.

Table 4.2 **Tensile properties of as-received and differently tempered medium carbon steel**

Specification of Specimen	Tempering duration	Yield Stress (YS) in MPa	Ultimate Tensile Stress in MPa	% of Elongation	Maximum Load in KN
As-received	---	410.61	597.78	19.5	46.94
Tempered at 200^0C	60 min.	830.21	989.38	9	77.70
	90 min.	818	974.31	10	76.52
	120 min.	739	959.78	15	75.38
Tempered at 400^0C	60 min.	650	940	18.5	73.82
	90 min.	527	907.71	19	71.29
	120 min.	489.28	812.14	19.5	63.78
Tempered at 600^0C	60 min.	470	794.12	20.5	62.37
	90 min.	457	720	21	56.54
	120 min.	443	698.73	22	54.87

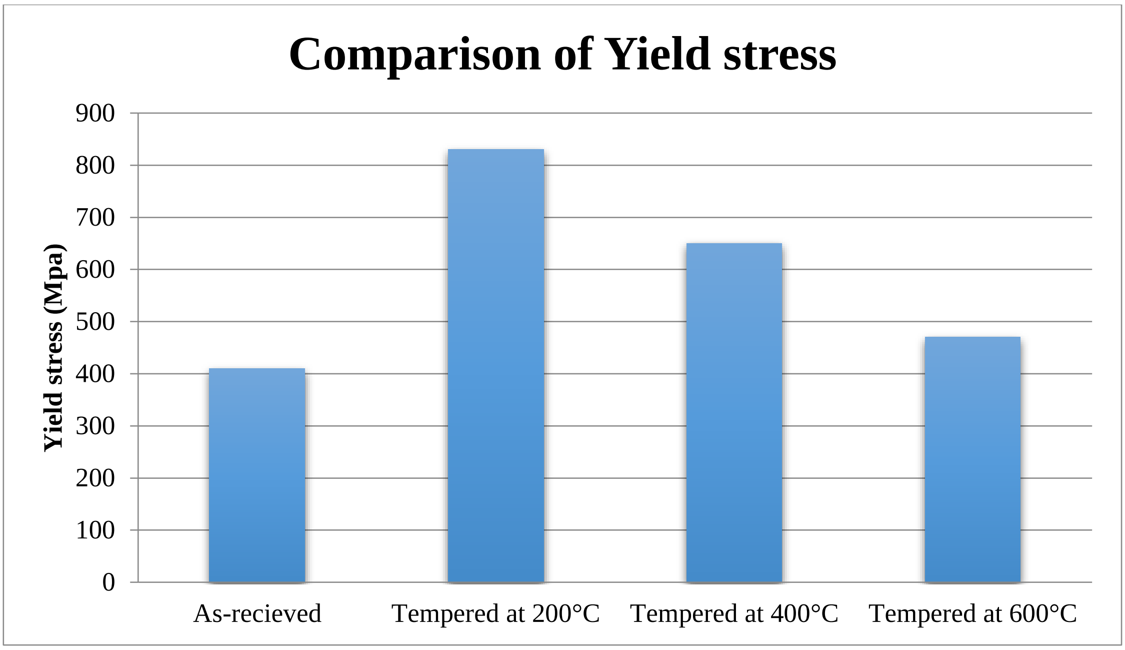

Fig. 4.16 **Comparison of Yield stress between as-received and tempered conditions**.

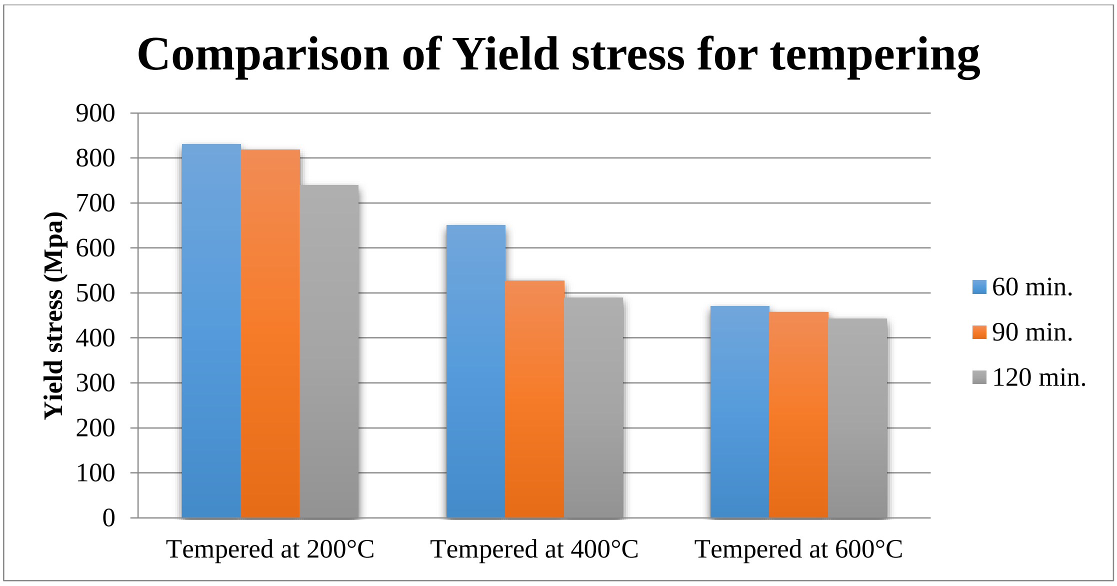

Fig. 4.17. **Comparison of Yield stress between differently tempered conditions**.

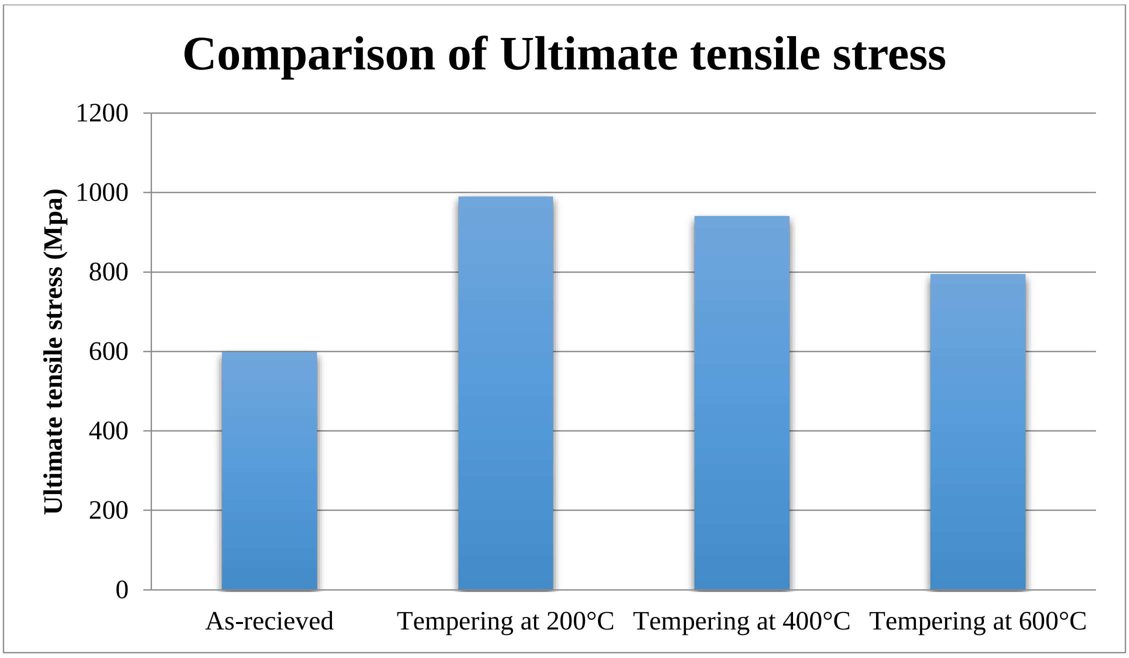

Fig. 4.18 **Comparison of Ultimate tensile stress between as-received and tempered conditions**

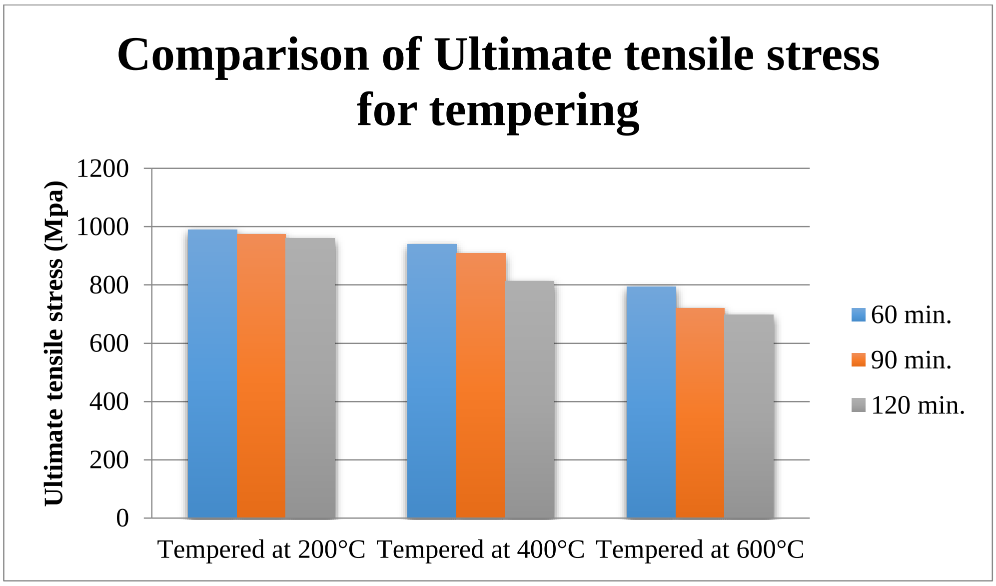

Fig. 4.19. **Comparison of Ultimate tensile stress between differently tempered conditions**.

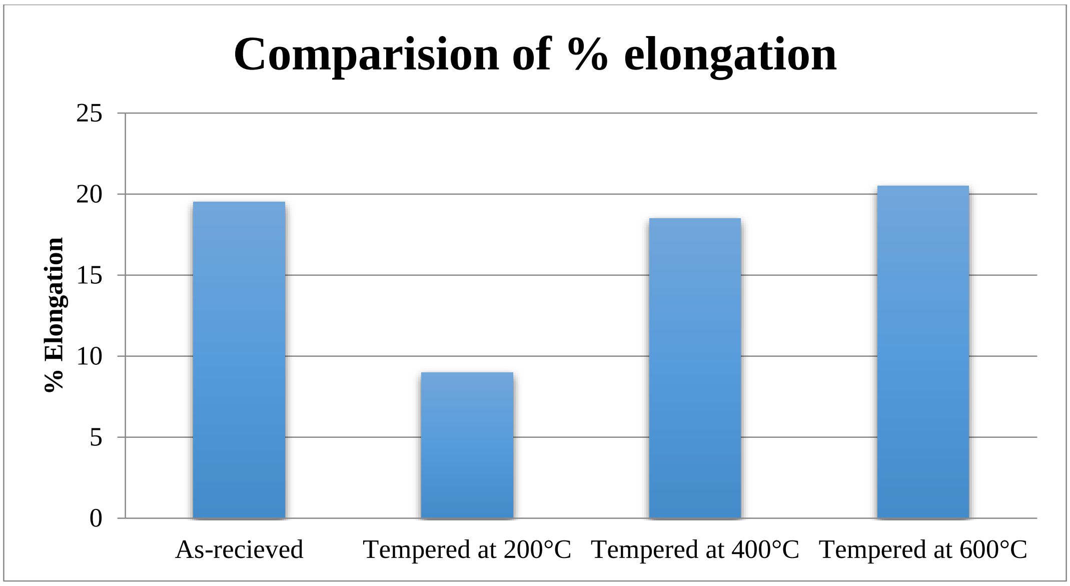

Fig. 4.20 **Comparison of % Elongation between as-received and tempered conditions.**

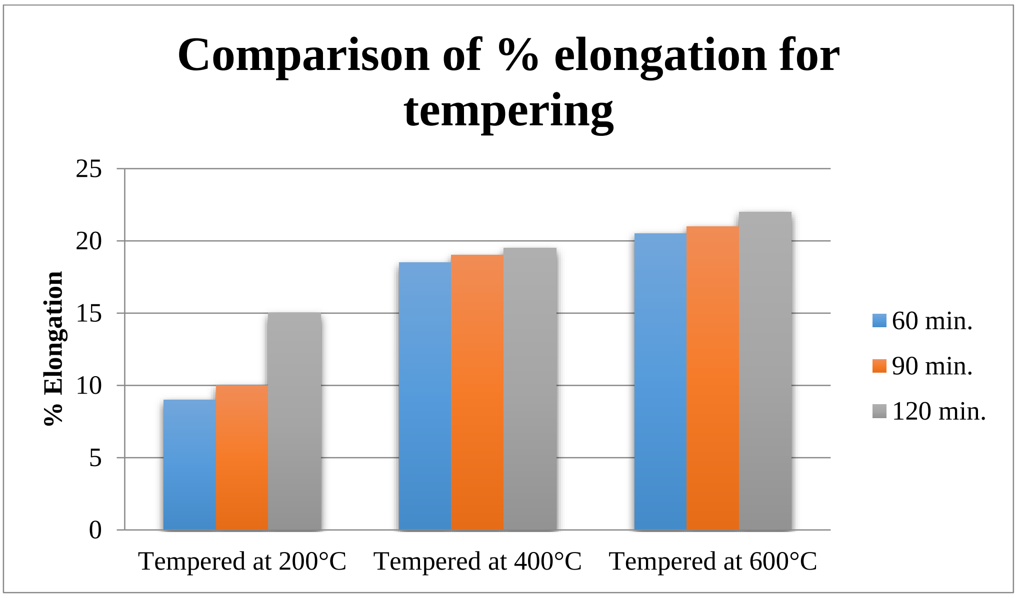

Fig. 4.21. **Comparison of % Elongation between differently tempered conditions**.

From the results of tensile tests it can be seen that there exists a structure-property relationship. Some observations have been made as follows:

1. Quenching followed by tempering improved the mechanical properties of the medium carbon steel.
2. The microstructural analysis indicated that the medium carbon steel specimens tempered at low temperatures have tempered martensitic structure [28-30]
3. Low temperature tempering gave the best results, the microstructure of specimens tempered at low temperature(200^0C) are tempered martensite, which is comparatively harder than the structures obtained during intermediate(400^0C) and high temperature(600^0C) tempering.
4. The ductility is maximum for the high temperature (600^0C) tempering while hardness and tensile strength are maximum for low temperature (200^0C) tempering.
5. With an increase in tempering duration at same tempering temperature, the ductility is increased with significant decrease in hardness and tensile strength.

4.4 Fractographical studies after tensile test.

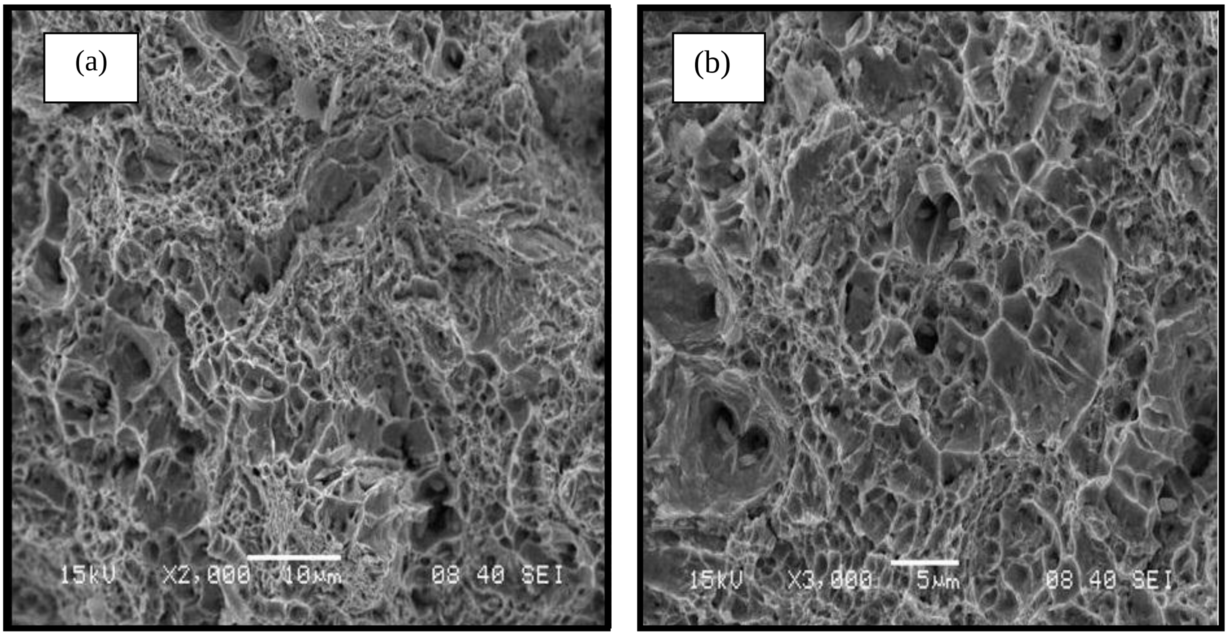

Fig 4.22 **Fractograph after tensile test, 200^{0}C Tempering, (a) 2000X, (b) 3000X**

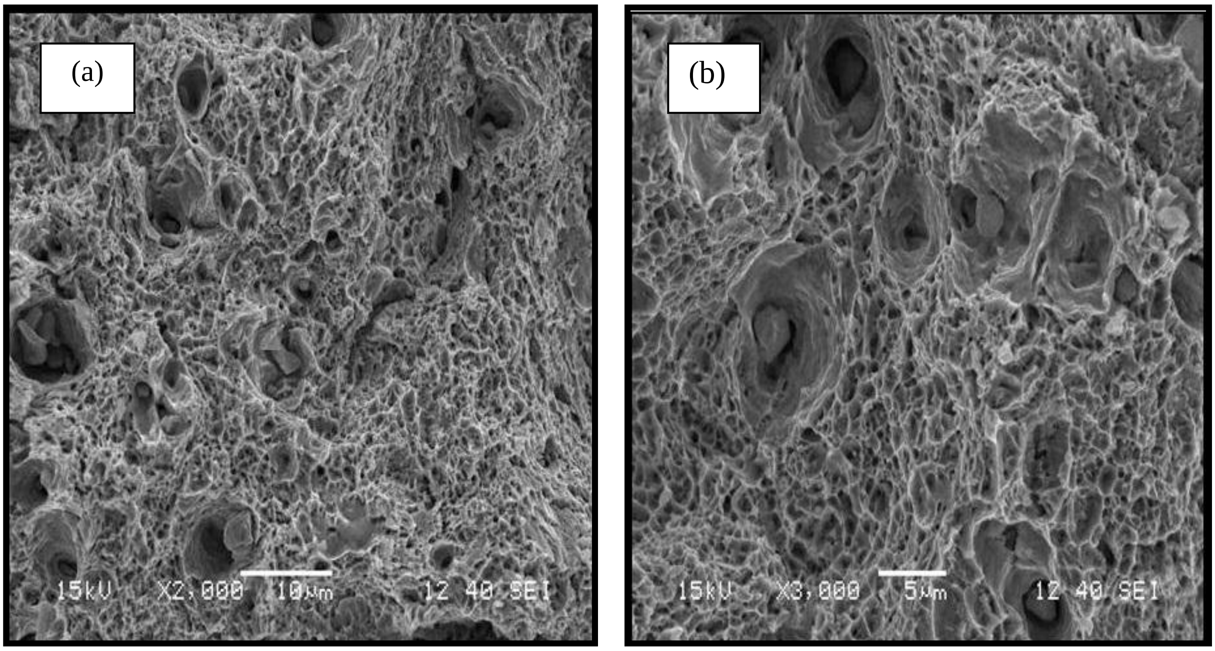

Fig 4.23 **Fractograph after tensile test, 400^{0}C Tempering, (a) 2000X, (b) 3000X**

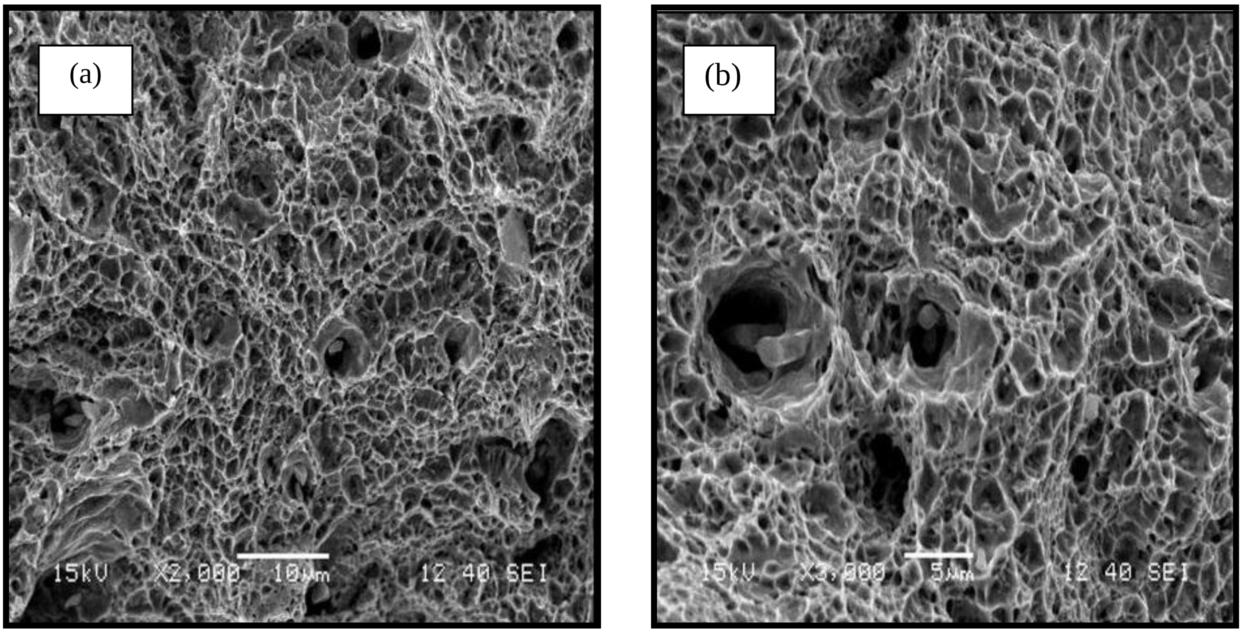

Fig 4.24 **Fractograph after tensile test, 600^{0}C Tempering, (a) 2000X, (b) 3000X**

The fractographs of fractured surfaces after tensile test are shown in Fig. 4.22, 4.23, and 4.24. The medium carbon steel specimens tempered at 200^{0}C show a mixed pattern of fracture, may be due to presence of comparatively hard and brittle phase tempered martensite. The medium carbon steel specimens tempered at comparatively high temperatures show mainly a ductile fracture. In Fig. 4.24 tensile fractograph of medium carbon steel tempered at 600^{0}C is shown which indicates a ductile fracture with dimpled structure [11]. It shows that considerable amount of ductility is induced in the material.

4.5 Fatigue life estimation

The procedure and working principle of R.R. moore rotating beam testing machine is already discussed in section 3.5. S-N curves of differently tempered specimens have been plotted and shown in fig.4.25 to fig.4.33.

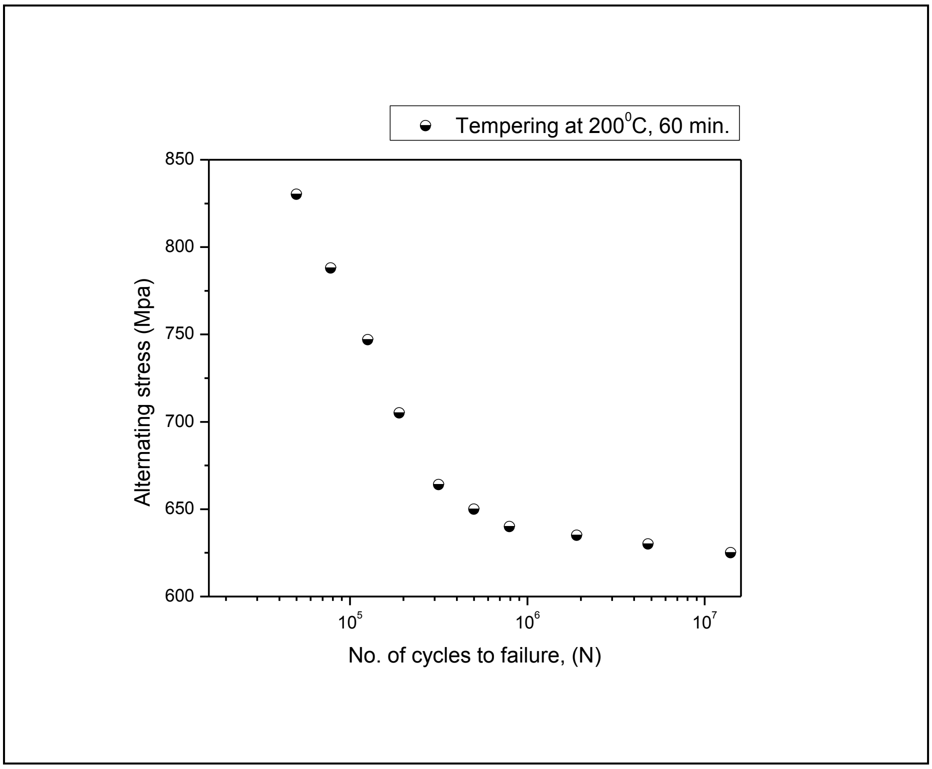

Fig 4.25 **S-N Curve, Tempered at 200 ^{0}C, 60 min.**

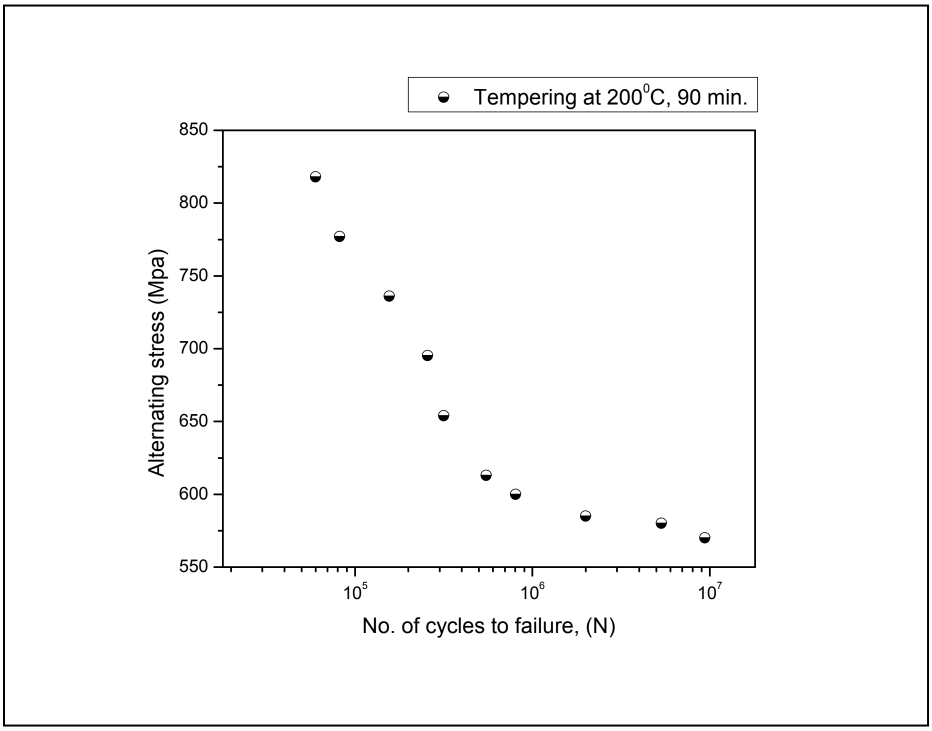

Fig 4.26 **S-N Curve, Tempered at 200 ^{0}C, 90 min.**

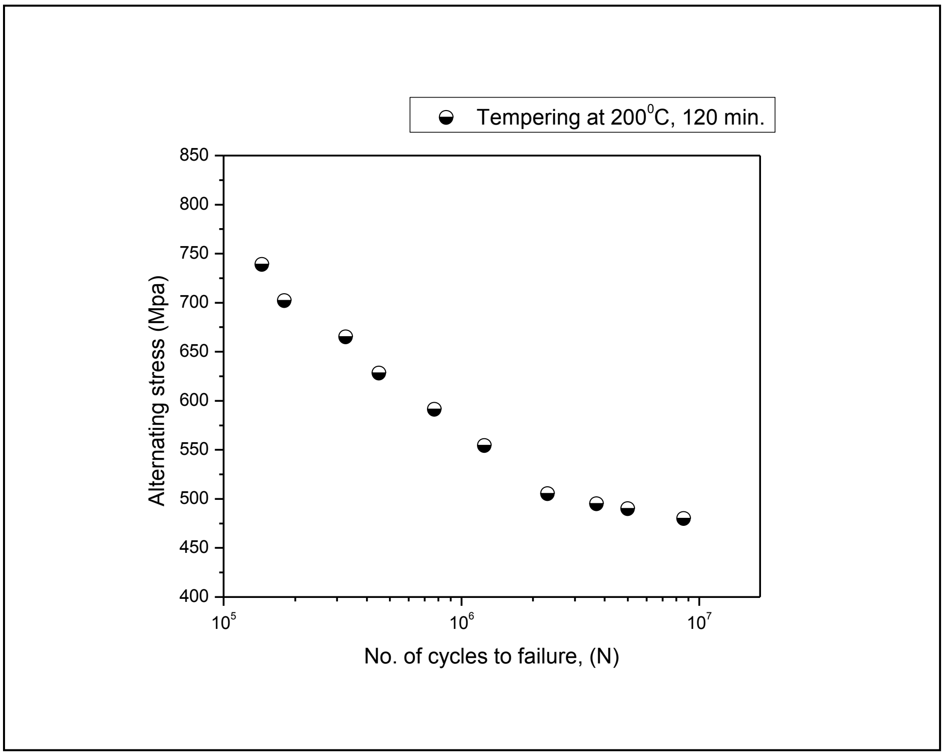

Fig 4.27 **S-N Curve, Tempered at 200 ^{0}C, 120 min.**

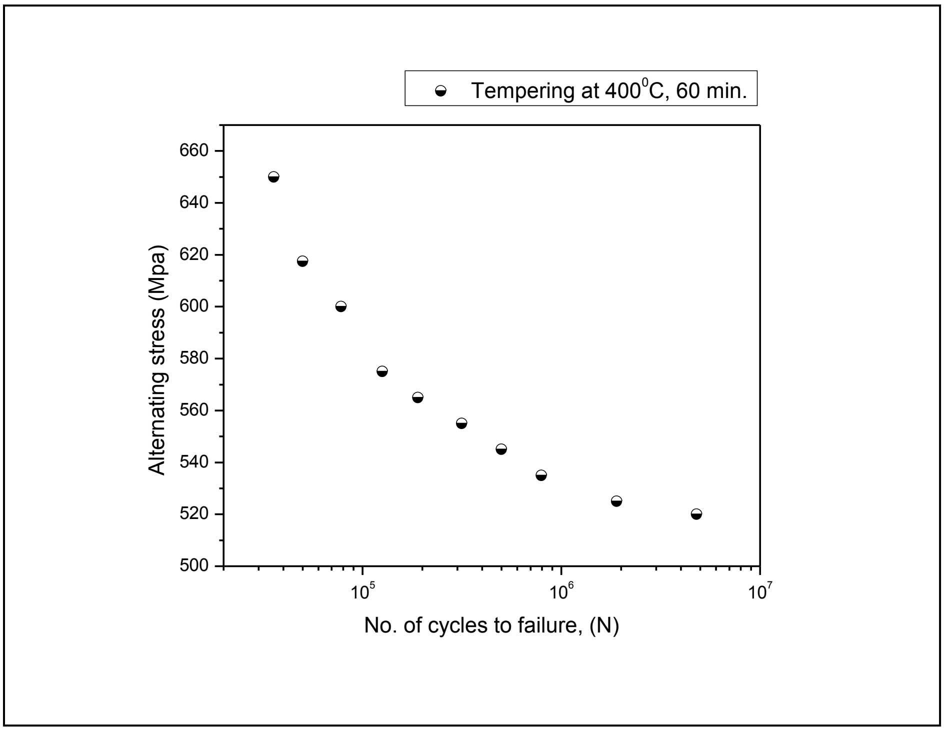

Fig 4.28 **S-N Curve, Tempered at 400 ^{0}C, 60 min.**

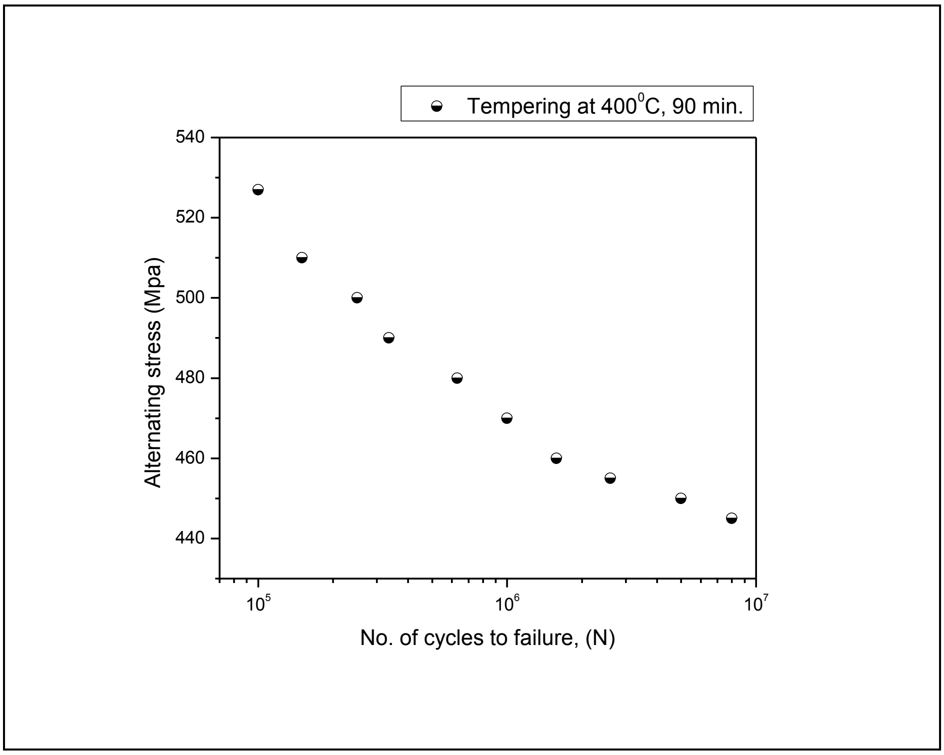

Fig 4.29 **S-N Curve, Tempered at 400 ^{0}C, 90 min.**

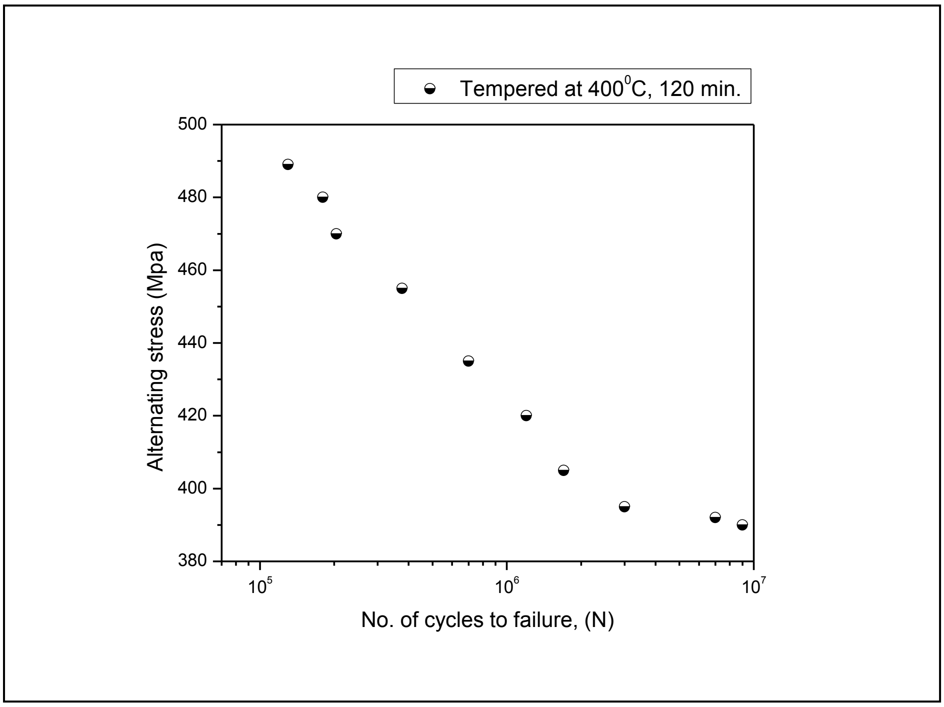

Fig 4.30 **S-N Curve, Tempered at 400 ^{0}C, 120 min.**

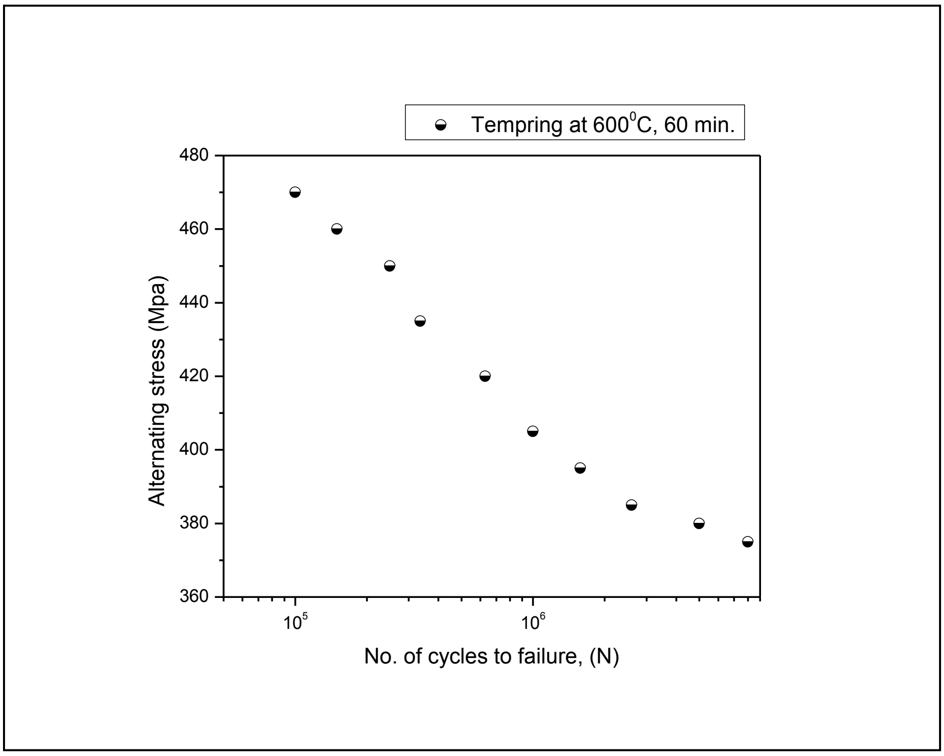

Fig 4.31 **S-N Curve, Tempered at 600 ^{0}C, 60 min.**

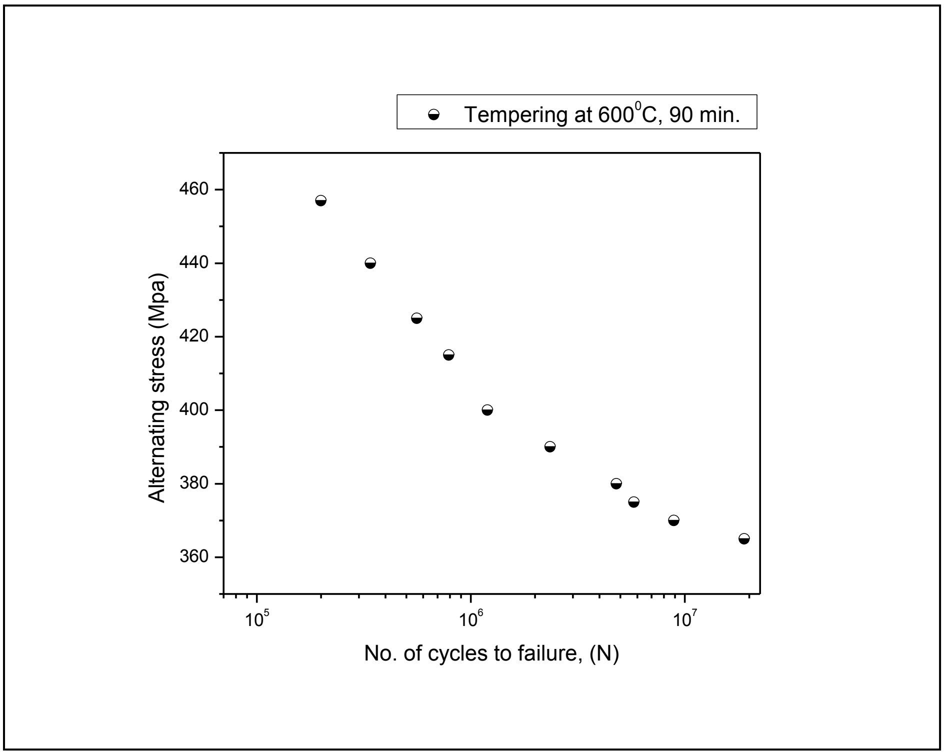

Fig 4.32 **S-N Curve, Tempered at 600 ^{0}C, 90 min.**

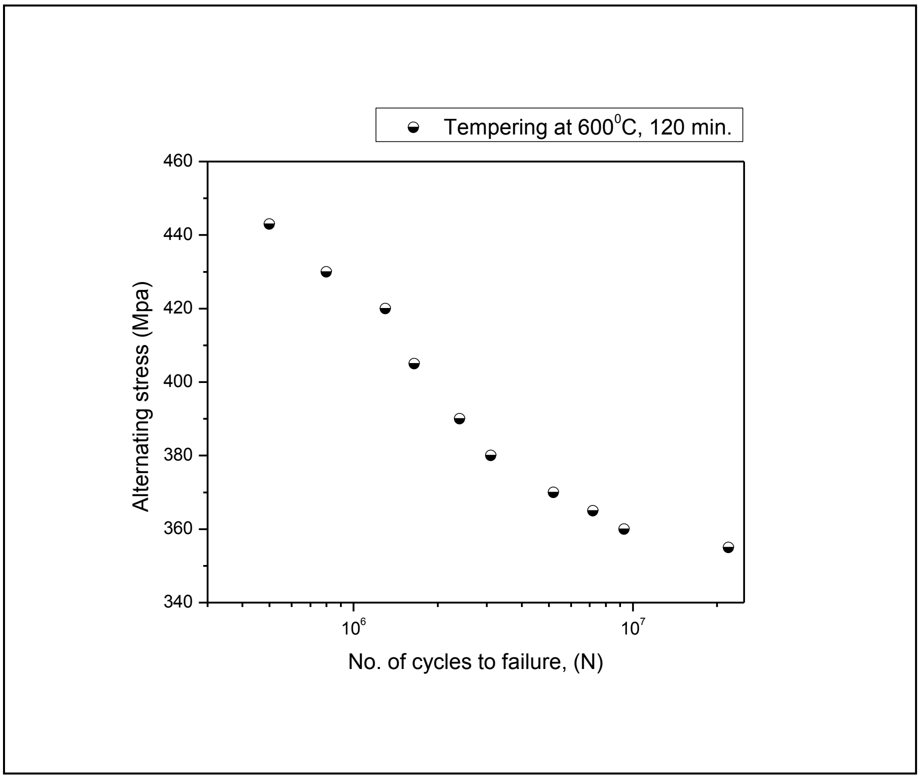

Fig 4.33 **S-N Curve, Tempered at 600 ^{0}C, 120 min.**

S-N curve is very useful in showing the variation of stresses with respect to number of cycles to failure. In fig. 4.34 comparison of fatigue limits of medium carbon steel tempered at different sets of temperature and time is shown.

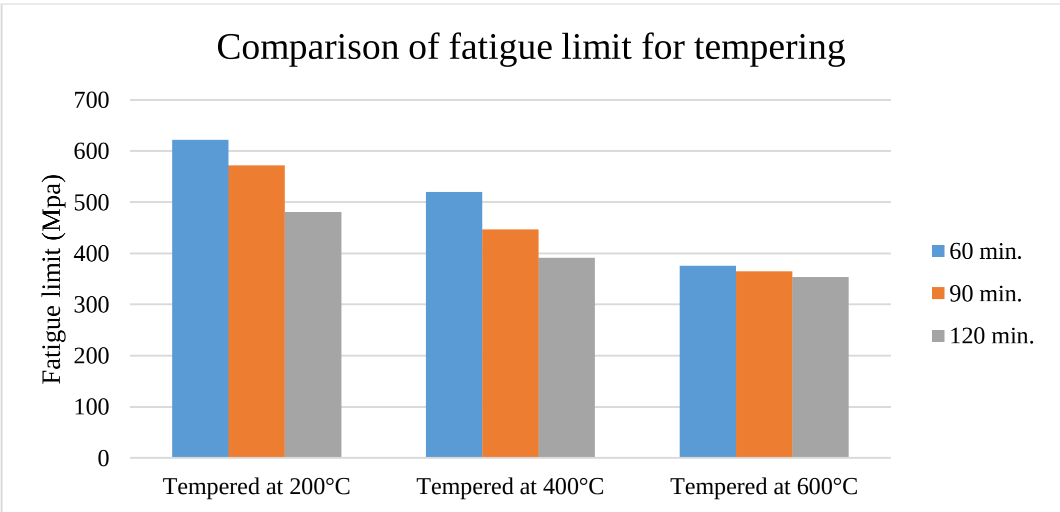

Fig. 4.34 **Comparison of fatigue limit between differently tempered conditions**

Some comparisons of S-N curves are shown in Fig. 4.35 (a), (b), and (c),

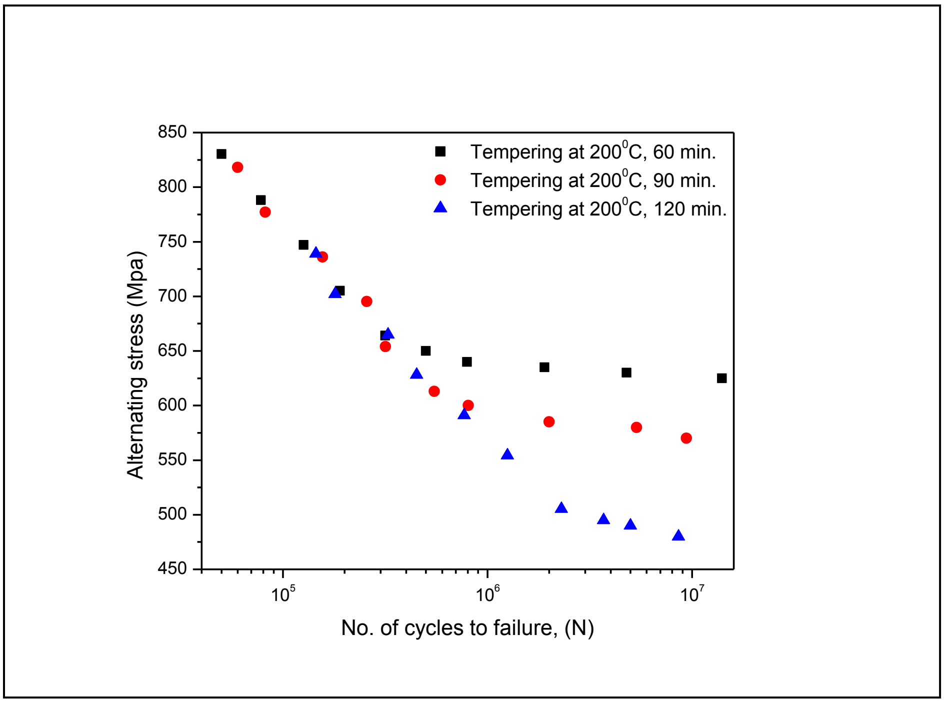

Fig. 4.35 (a) **S-N curves for tempering at 200^{0}C, for different time durations.**

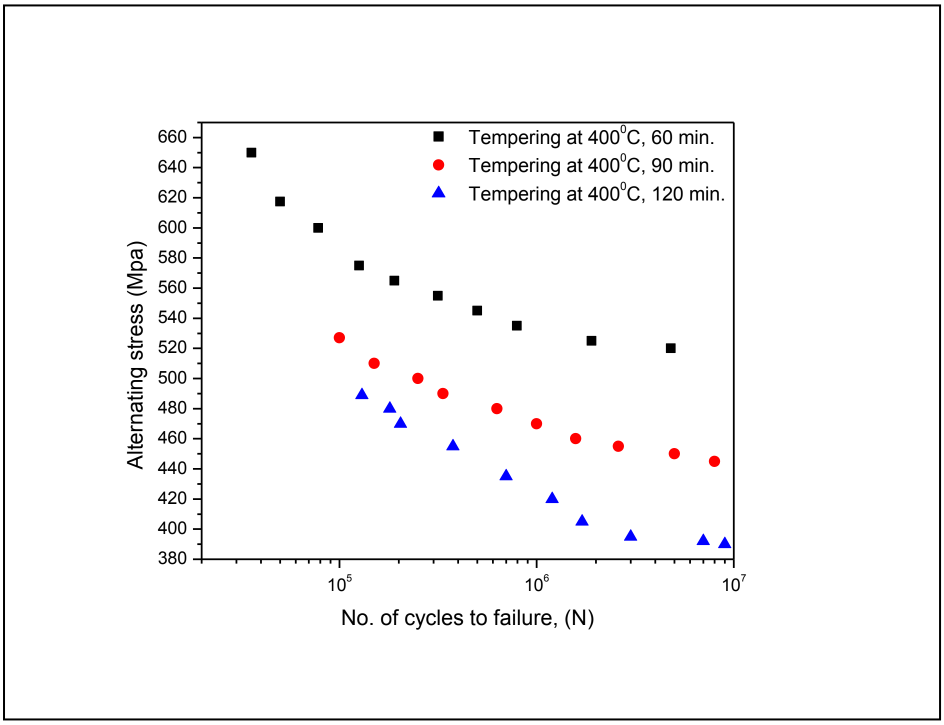

Fig. 4.35 (b) **S-N curves for tempering at 400^{0}C, for different time durations.**

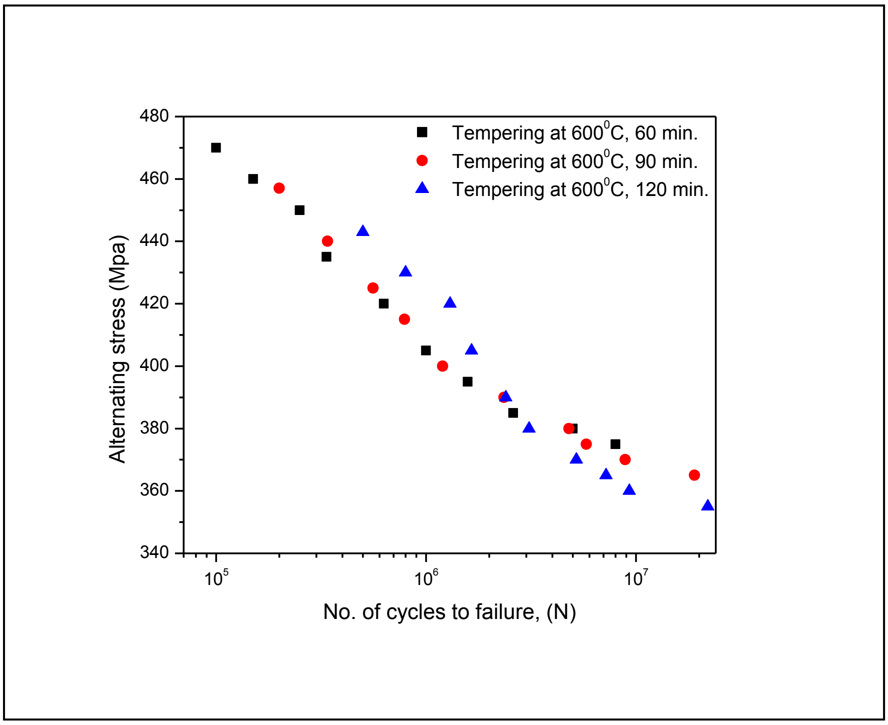

Fig. 4.35 (c) **S-N curves for tempering at 400^{0}C, for different time durations.**

From the S-N curves it is clear that the medium carbon steel specimens tempered at 200^{0}C have the maximum endurance limit, when compared to specimens tempered at 400^{0}C and 600^{0}C. For any temperature the maximum endurance limit is reached when the specimen is tempered for 60 min. which shows that the variation of endurance limit follows the same trend as yield stress.

The highest fatigue limit for tempering at 200^{0}C is 625 Mpa, for tempering at 400^{0}C is 520 Mpa, and for tempering at 600^{0}C is 375 Mpa. The low temperature tempering shows the best result in terms of fatigue limit. Also fatigue limit is higher for specimens with high yield stress.

From fig. 4.34 it can be seen that, while keeping the tempering temperature constant the endurance limit varies for different tempering durations. If variation of endurance limit at tempering temperature 200^{0}C is considered it can be seen that the endurance limit is maximum for a tempering duration of 60 min., while it becomes minimum for a tempering duration of 120 min. For tempering at 200^0C for 60 min. the endurance limit is 625 Mpa, for tempering duration of 90 min. endurance limit becomes 570 Mpa, and when tempered to 120 min. the endurance limit comes to a minimum value of at 200^0C of 480 Mpa. So it can be seen that with increase in tempering duration the endurance limit is decreased.

When tempering at a temperature of 400^0C is discussed it can be seen from the S-N curves for tempering at 400^0C in fig 4.28, 4.29, and 4.30 and the comparison graph in fig. 4.34, that the variation of endurance limit follows similar trend as it was for 200^0C tempering conditions. The highest value of endurance limit for 400^0C tempering is reached when the specimens are tempered for a duration of 60 min. and the value becomes 520 Mpa. As the tempering duration is increased to 90 min. the endurance limit decreased to a value of 445 Mpa and the endurance limit is minimum when the tempering duration is 120 min., the value becomes 390 Mpa. So the tempering at 400^0C does not show good results as per as endurance limit is concerned.

For high temperature tempering i.e. at 600^0C the S-N curves are shown in fig. 4.31, 4.32, and 4.33. Also the comparison of endurance limit with respect to tempering duration is shown in fig. 4.34. From the comparison graph it can be seen that at tempering temperature of 600^0C there is a very little variation of endurance limit with respect to tempering duration. The endurance limit for tempering duration of 60 min. is 375 Mpa, for 90 min. tempering duration it becomes 365 Mpa, and becomes minimum at a tempering duration of 120 min. the value being 355 Mpa.

4.6 Fractographical studies after fatigue test

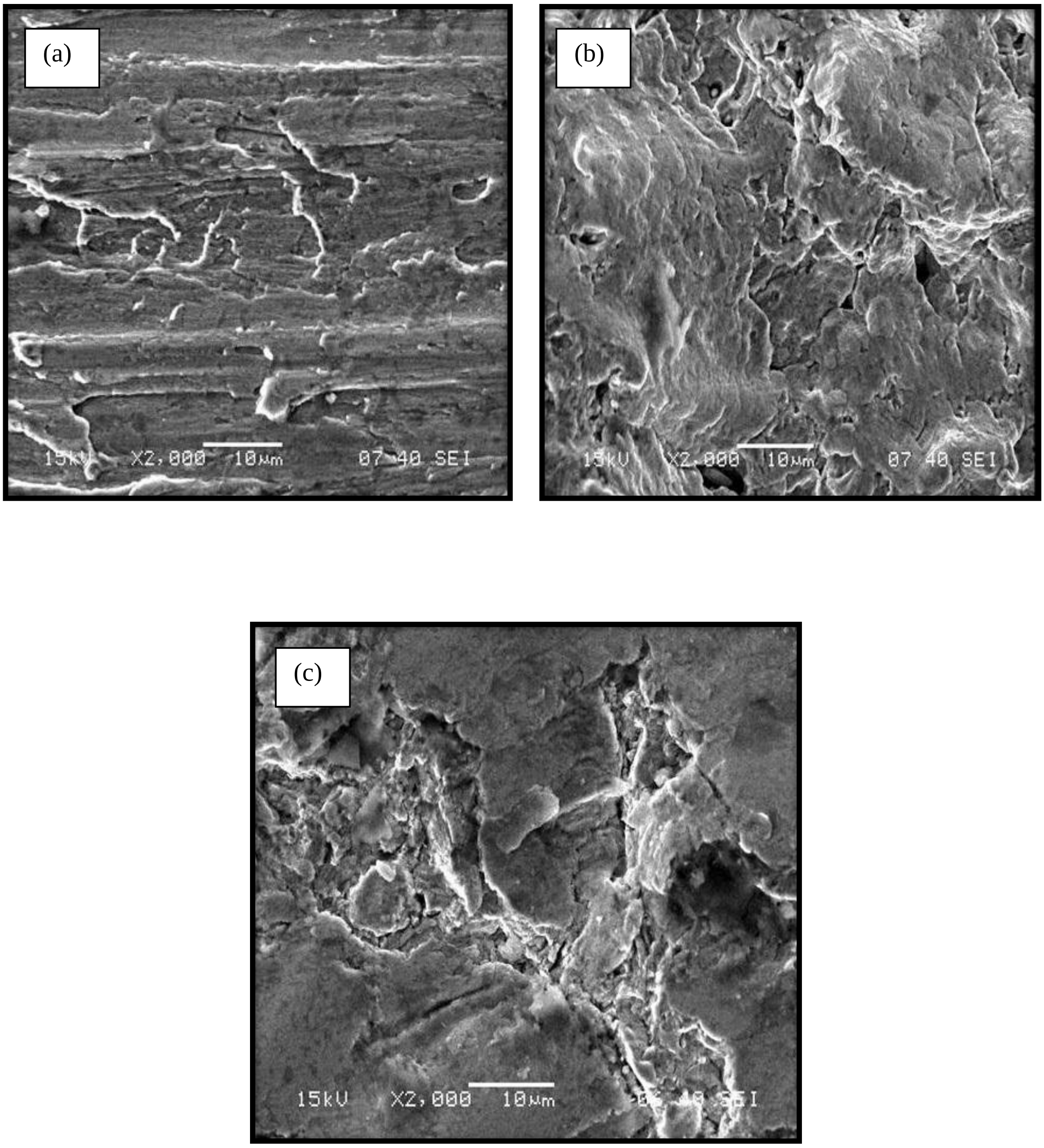

Fig. 4.36 **(a), (b), and (c) Fractograph of specimens after fatigue tests.**

The fractured surfaces of differently tempered medium carbon steel specimens were studied in scanning electron microscope (SEM). The fractured surface images are shown in the fig. 4.36 (a), (b), and (c). In the fig 4.36 (a) the saw tooth like structure is clearly visible, some striation marks are present here which gives an evidence of fatigue failure. The above shown fractographs only indicate that the failure is due to cyclic loading. As these fractographs were taken after a total life span of the specimen, not much information are obtainable. To study the crack formation the test must be interrupted and the deform surface should be removed by electropolishing [13].

Chapter 5

Conclusion

5.1 Conclusion

In this work the microstructure, mechanical properties, and Cyclic loading behaviour of the medium carbon steel has been investigated, and effect of different tempering temperatures and time on those has been studied. Attempts have been made to find structure property relationships and also the mechanical properties are correlated with the fatigue life. Various points of the conclusion are:

1. There exists a structure property relationship, for different microstructures of medium carbon steel (obtained by tempering) we have got different tensile properties.
2. The tensile properties can be correlated to the endurance limit, as it has been seen that endurance limit is higher for the materials having high yield strength.
3. The tempering temperature and tempering duration both play a crucial role to influence the mechanical properties and fatigue life of the material.
4. It has been investigated that the low temperature tempering (200^0C) for 60 min. duration gives the highest tensile strength and maximum endurance limit. The Y.S. and U.T.S. are 830 Mpa and 989 Mpa for tempering at 200^0C, 60 min. the endurance limit being 625 Mpa.
5. The mechanical properties and the fatigue life of medium carbon steel are greatly enhanced by the heat treatment quenching followed by tempering.

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