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# Damage and Failure of Steel Wire Ropes

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# ABSTRACT

Being one of the most important and widely used load-bearing component, steel wire ropes are extensively utilised in various systems and environments. The systems vary from mine hoists and cranes to ropeways and elevators and from oil rigs to cable-stayed bridges. The ultimate goal of this thesis is to develop a comprehensive literature overview of fatigue and fracture of steel wire ropes. Although primarily concerned with the fatigue - fracture behaviour of steel wire ropes, a broad review of literature, right from the microstructure and metallurgy to the ultimate fracture is reported. Wire rope types, their functions and standardisation authorities have been given a thorough walkthrough with the intent of getting the reader up to speed with the subject. The production process beginning in furnace to the final product is analysed and the development of microstructure is evaluated right through the process. Then the degradation mechanisms are evaluated, and a vast literature overview is provided for the varying mechanisms like fatigue, corrosion, fretting, and wear. Further on a comprehensive evaluation of the state of the art of testing methods is presented and the shortcomings of the present methods are discussed. And the new advances in the technology of testing are presented which aim to make away with the shortcomings of the present methods. The maintenance and control methods are analysed with respect to industrial standards. The shortcomings are discussed with the help of recent research work done by the experts and the improvement areas are suggested. Finally, the fracture and failure of the wire rope is analysed. Special focus is given to the progressive fracture and the fracture surfaces are dealt with in detail to understand the fatigue regions, the overload regions and the type of fracture whether brittle or ductile.

# CHAPTER 1: INTRODUCTION

## 1.1 History and Background

We all are well aware of the oft repeated phrase “History Repeats Itself”. However, when it comes to component and system failures, be it the engineer, the designer, the manufacturer or for that matter the user, nobody wants this phrase to be true. The repercussions and ramifications of fractured, cracked, corroded, damaged and malfunctioning equipment are unpalatable, perilous, and exorbitant. But throughout the history there have been many instances of failures and the consequences have been tragic. To counter these failures engineers have developed and keep developing new strategies. During the 20th century, there were some historical failures which are listed in Figure 1 below. These failures are just some of various accidents which forced the hand to revolutionize not only the design principles, but also all the processes related to inspection, manufacturing and material handling and redefined the failure phenomenon.

| Failure | Year | Reason for failure | Life-assessment developments |
|---|---|---|---|
| *Titanic* | 1912 | Ship hits iceberg and watertight compartments rupture. | Improvement in steel grades<br>Safety procedures established for lifeboats<br>Warning systems established for icebergs |
| Molasses tank failures | 1919, 1973 | Brittle fracture of the tank as a result of poor ductility and higher loads | Design codes for storage tanks developed<br>Consideration given to causes for brittle fracture |
| Tacoma bridge failure | 1940 | Aerodynamic instability and failure caused by wind vortices and bridge design | Sophisticated analytical models developed for resonance<br>Bridge design changed to account for aerodynamic conditions |
| World War II Liberty ships | 1942–1952 | 1289 of the 4694 warships suffered brittle fracture or structure failure at the welded steel joints. | Selection of increased toughness material<br>Improved fabrication practices<br>Development of fracture mechanics |
| Liquefied natural gas (LNG) storage tank | 1944 | Failure and explosion of an LNG pressure vessel due to a possible welding defect and improperly heat treated material resulting in subsequent fatigue crack growth | Selection and development of materials with improved toughness at the service temperature of –160 °C (–250 °F) |
| Comet aircraft failures | 1950s | Fatigue crack initiation in pressurized skins due to high gross stresses and stress-concentration effects from geometric features | Development of the fatigue “safe-life” approach<br>Evaluation of the effects of geometry and notches on fatigue behavior<br>Evaluation of the effects of stiffeners on stress distribution<br>Establishment of aircraft structural integrity program (ASIP) in 1958 |
| F-111 aircraft No. 94 wing pivot fitting | 1969 | Fatigue failure due to material defect in high-strength steel | Improved inspection techniques<br>Change from fatigue “safe-life” to damage-tolerant design philosophy<br>Development of materials with improved toughness |
| Seam-welded high-energy piping failures | 1986–2000 | Cavitation and creep voids in welds resulting in catastrophic high-energy rupture | Development of elevated-temperature life-assessment techniques for cavitation and creep failure |
| Aloha incident, Boeing 737 | 1988 | Accelerated corrosion and multiple fatigue crack-initiation sites in riveted fuselage skin | Improved aircraft maintenance and inspection procedures<br>Life-assessment methods developed for multiple-site damage (MSD) |
| Sioux City incident | 1989 | Hard alpha case present in titanium fan disk resulted in fatigue crack initiation and catastrophic failure. | Increased process controls on processing of titanium ingots<br>Development of probabilistic design approach and analytical life assessment using dedicated computer programs for titanium disks |
| Earthquake in Kobe City, Japan, and Northridge, California | 1994, 1995 | Failure occurred in I-beams and columns due to joint configuration and welding practices that resulted in low ductility of the steel. | Development of earthquake-resistant structures<br>Improved joint designs and welding practices for structural steels<br>Improved controls on steel manufacture |

Fig.1: Historic failures and their impact on life-assessment concerns [1]

## 1.2 Fatigue and its Significance

According to ASMEE, fatigue is defined as, “The process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point (or points) and that may culminate in cracks or complete fracture after a sufficient number of fluctuations."

A schematic of the fatigue process is shown in Fig.2. The load varies from zero to a maximum value, and then falls back to zero, and the same happens for the negative direction i.e., reaching a maximum negative value then to a maximum negative value and eventually increases to zero thereby constituting one cycle. After multiple repetition of such cycles, a little crack is initiated, at a discontinuity on or near the surface. With the buildup of more and more cycles, the crack keeps on growing leading to failure and fracture.

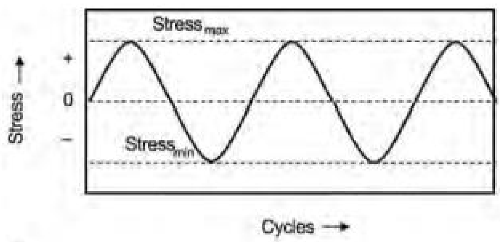



Fig.2: Fatigue (Cyclic Loading)

Previously it was considered that various materials show a certain endurance limit like steel while some materials do not have an endurance limit like Aluminum. Materials with endurance limit imply that theoretically they can withstand the stress cycles forever, while those without the endurance limit will fail even at low stress cycles. The endurance limit diagrams are shown in Fig.3. This approach has come under scrutiny in recent times, and has been disproven in time. The generally accepted fact these days is that defining or measuring an actual infinite-life fatigue limit is not possible in any material, not even in steel. Only the fatigue strength for a certain finite number of cycles can be determined. Experiments with ultra-fast fatigue machines for testing steels at billions of cycles have shown that fracture can occur after so many cycles even at loads well below the conventional "endurance limit" calculated by testing for a few millions of cycles.

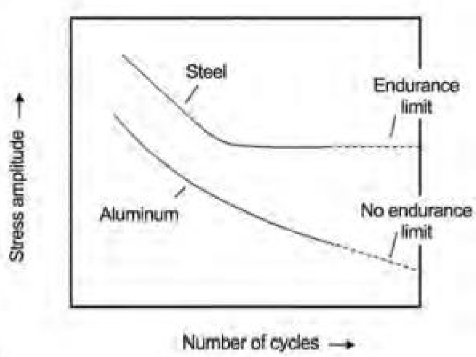



Fig.3: Schematic of materials with endurance limit and without endurance limit

## 1.3 Fracture

Fracture phenomenon is evident when a material splits into two or more pieces under the effect of stress/stresses. Fracture is usually classified based on the how the material breaks and as such is classified either as ductile fracture or brittle fracture. The main characteristic of the ductile fracture is the visible plastic deformation prior to and during crack propagation. While as, brittle fracture is characterized by very small visible plastic deformation, and it usually takes place at stresses below the yield strength. Brittle fracture occurs suddenly with little or no warning. The goal of structural engineering is to invent and deploy strategies to avoid such fractures, as the results are massive economic losses and usually involve loss of life. Figure.4 displays the difference between the two fractures.

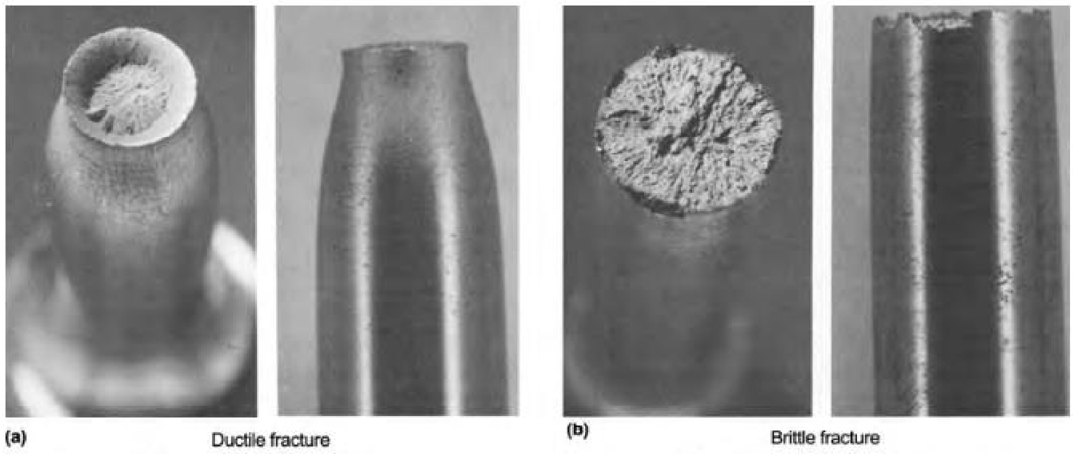



Fig.4: Ductile and Brittle Fracture

## 1.4 The Objective

The goal of this paper is to go through various experimental and theoretical resources and to evaluate pros and cons of these research available on fatigue and fracture of steel wires, to avoid economic and life losses

# CHAPTER 2: DESCRIPTION AND MECHANICAL PROPERTIES OF WIRE ROPES

## 2.1 Why a wire rope

Wire rope is the collection of metal threads that are twisted and wound in the shape of a helix with the goal of shoring/propping/supporting and lifting heavy-duty loads and performing tasks that are beyond the limits for standard wire. Wire rope can be considered as a complex machine, with a number of functioning parts working together in order to provide support or move the load. Wire ropes are used everywhere ranging from but not limited to the lifting and rigging industries, suspension bridges, towers, and elevators. Steel Wire ropes are usually employed for lifting devices owing to its unique construction. The wire rope has a unique design consisting of multiple steel wires that form individual threads which surround the core in a helical pattern. The advantage of this structure is high strength and flexibility, and the quality to handle bending stresses. Various configurations of the material and wire arrangements provide vastly varied benefits like Strength, Flexibility, and resistance to Crushing, Fatigue, Corrosion etc. The property common to many structural elements like rope is the capability to resist relatively large axial loads with regard to bending and torsional loads [2] [3]. Owing to this property, ropes are one of the oldest tools that human civilization have utilised.

## 2.2 Basic Components

The basic component is a single thin metallic wire. The different constituents and the arrangement of the strands around the main core is depicted in Fig.5 [2]. The core can be made of different materials. It can be a wire rope or natural fibres, or polypropylene. Metallic wires are often wrapped helically around a centre wire that serves as the axial component It is worth noting that strands are the major load bearing components of a wire rope. The purpose of core is to provide the required support under normal bending and loading conditions for the strands

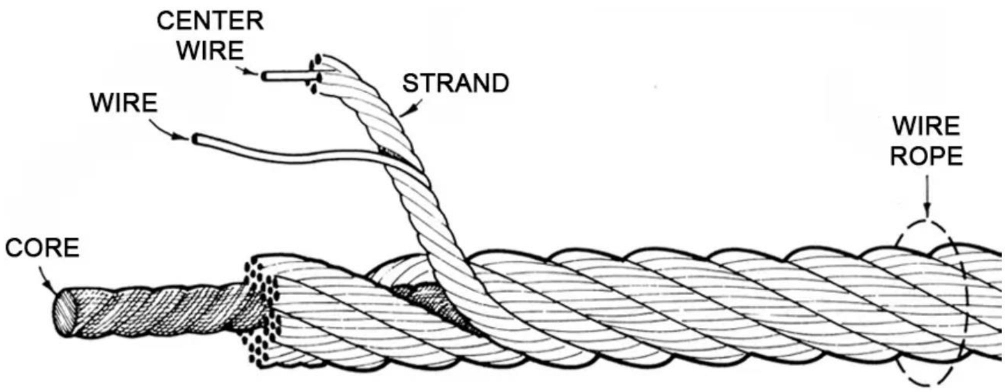



Fig.5: Wire Rope

The four basic components of a  finished wire rope can be enlisted as:

1. A singular stranded metallic wire
2. Many wired strands durrounding a core in a helical pattern
3. A core made of fibre or steel
4. Lubrication

### 2.2.1 Wire

The smallest part of wire rope, they make up each of the rope's distinctive individual strands. Wires can be made from a pleothera of metallic materials like steel. Different classes of wires are produced according to their strength and resistance to wear, fatigue, and corrosion. Usually the wires are either uncoated or have a bright finish. The most common cross section of wires is the round cross-section. But In special circumstances profile wires are used. Profile wires are the wires with cross section other than the round section. The other cross-sections can be seen in Fig.6.

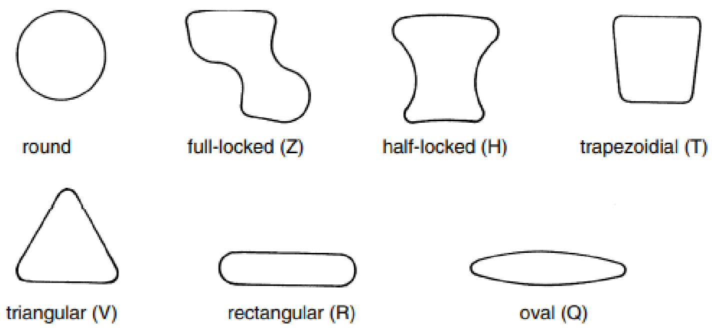



Fig.6: Wire cross-sections for wire ropes [4]

### 2.2.2 Strands

Multiple wires that have been twisted and organized in a precise way make up strands. The various strands are then placed around the core in a helical configuration. More abrasion resistance is associated with larger diameter wires, but greater flexibility is associated with smaller diameter wires.

The strands can be

**a) Round Strands**

**Lay length and lay angle**: The strand is made up of three or four twisted wires in its earliest and most basic form, as was the case with Albert's first wire rope (1837), which had three simple strands with four wires each. But today, the most basic strand consists of a single layer of wires that are arranged helically around a central wire. Fig. 7 shows an example of one such strand with six outer wires arranged around a central wire.The important values are clearly defined: the wire lay length $h_W$, the lay angle α and the wire winding radius $r_W$. The wire lay length $h_W$ is the length of the strand in which an lay wire makes one complete turn [4]. The wire lay angle α is given by the equation.

$$\tan \alpha = \frac{2\pi r_w}{h_w}$$

The lay direction of the lay wires in the strand can be right (symbol z) or left (symbol s). Fig.8 illustrates the origin of these symbols [4].

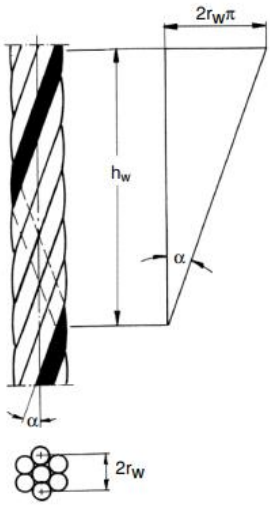



Fig.7: Simple Strand [4]

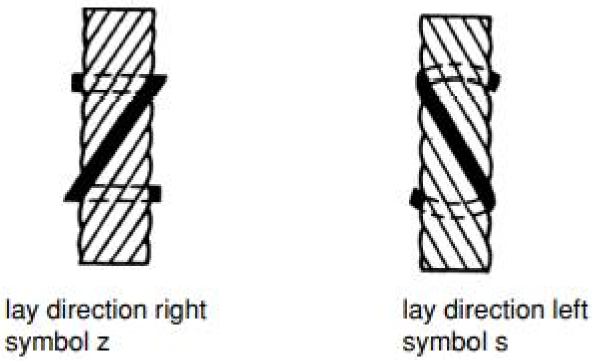



Fig.8: Lay direction of wires [4]

**Cross lay strands (reperesneted by symbol M)**:In this arrangement, wires of different layers have varying lay length and as such they cross each other. The lay angle and the lay direction is usally same for all layers. Owing to the same lay angle, the wires of all layers must transfer the same tensile stress, but the advantage achieved by the same tensile stress is outweighed significantly by effect due to the the pressure between the crossing wires. Owing to this fact Cross lay strands are rarely used. Two cross lay strand configuration still used are 1 + 6 + 12 or 19M and 1 + 6 + 12 + 18 or 37M. The centre wire is thicker and other wires have the same diameter. These cross section are shown in Fig.9

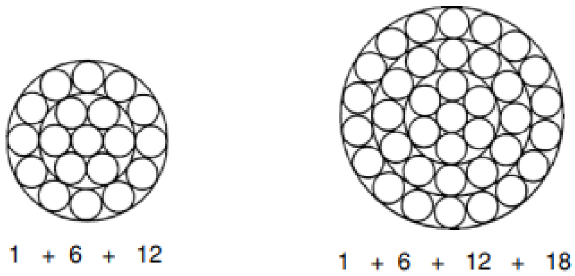



Fig.9: Cross lay strands [4]

**Parallel lay strands.** In this configuration, the wires that make up the two overlaid layers run parallel and all the wire layers have an identical lay length, resulting in a linear contact. The wire of the outer layer is supported by the two inner layer wires. The strands are created in a single distinctive process. In comparison to cross-lay strands, parallel wire strand ropes have a higher endurance. The construction of Parallel lay strands with two wire layers can have three arrangements viz. Filler, Seale or Warrington. The most widely employed version has 19 wires – the six very thin Filler wires are not counted. It is shown in Fig.10.

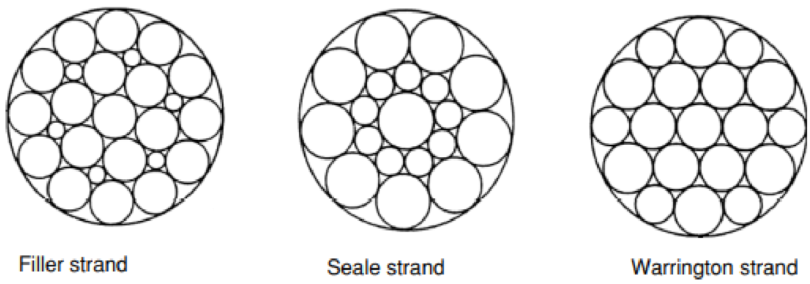



Fig.10: Parallel Lay Strands with two wires [4]

For three layered Parallel lay strand the most utilised construction is the Warrington-Seale strand (Central warrington and outside Seale layer) usually having 1+6+(6+6)+12 = 36 wires as shown in Fig.11

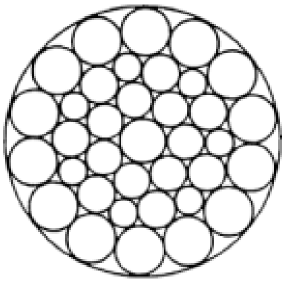


Fig.11:Warrington-Seale Strand [4]

**b) Shaped Strands**

Shaped strands are the strands whose shape is not round, Fig.12. The perpendicular cross section of triangular strand (symbol V) is approximately triangle shaped. The perpendicular cross-section of oval strand (symbol Q) is somewhat oval shaped. These are usually employed in applications where the effect of rotation is almost absent or very low.

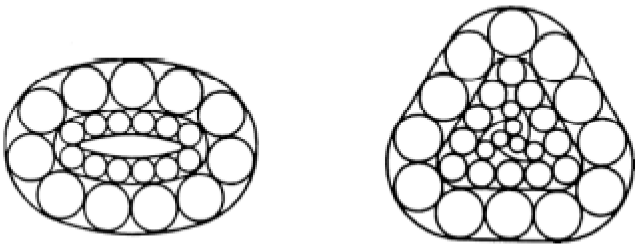


Fig.12: Shaped Strands [4]

**c) Compacted Strands (symbol K)**

These strands undergo certain compacting processes viz. drawing, rolling,swaging etc. which leads to modification of the wire and strand shape and dimensions. During the above mentioned processes only the mass of the strand $M_S$ remains constant while other parameters undergo change

$$M_S = d_{S,m}^2 . l_s . W_s = m_{S,comp} . l_{S,comp}$$

Where $d_{S,m}$ is the actual strand diameter

$l_s$ is the strand length

$W_s$ is the strand mass factor

**Compacting Grade :** It is dependent only on the metal portion of strand cross section and is defined as $\Gamma = 1 - \left(\frac{d_{s,comp}}{d_{s,m}}\right)^2$

$d_{s,m}$ is the measured diameter for not compacted

$d_{s,comp}$ is the measured diameter for the compacted strand

we also know that the diameter of not compacted strand is given by

$$d_{s,m}^2 = \frac{m_{s,comp}}{W_s}$$

Hence the compacting grade is given as

$$\Gamma = 1 - \frac{W_s^2 d_{s,comp}^2}{m_{s,comp}}$$

Strand Mass Factor can either be measured or evaluated using the equation

$$W_s = \frac{A_{S,e} \cdot \rho}{d_{S,m}^2}$$

Where $A_{S,e}$ is the effective strand cross section

$\rho$ is the wire mass density

$d_{S,m}$ is the strand diameter

### 2.2.3 Core

The core of a wire rope runs centrally and its function is to supports the strands and maintain the relative position of strands under loading and bending stresses. The choice of material for cores is vast. The classification of types of cores is listed in Fig.13.

| | | |
|---|---|---|
| Fibre core | fibre core | FC |
| | natural fibre core | NFC |
| | synthetic fibre core | SFC |
| Steel core | steel core | WC |
| | wire strand core | WSC |
| | wire rope core | WRC |
| | independent wire rope core | IWRC |
| | independent wire rope core with compacted strands | IWRC(K) |
| | independent wire rope core covered with a polymer | EPIWRC |
| | wire rope core enveloped with fibres | EFWRC * |
| | wire rope core enveloped with solid polymer | ESWRC * |
| Steel core in parallel-closed rope | parallel steel core with strands | PWRC |
| | parallel wire rope core with compacted strands | PWRC(K) |
| Multi-strand rope (rotation-resistant) | fibre centre | FC |
| | wire strand centre | WSC |
| | compacted wire strand centre | KWSC |

Fig.13: Symbols for rope cores based on ISO 17893

They are usually made of fibre or wires. The Fibre cores (FC) are either made up of natural fibres (Natural Fibre Core) or synthetic fibres (Synthetic Fibre Core). The usual production sequence is : fibres to yarns to strands and ultimately to fibre rope. In Fig.14 different fibre cores are shown.

The advantage of Fibre cores is that they can withhold a relatively bigger amount of lubricant. The fibre core ought to be well rounded and knots are avoided. Over the course of lifetime of a wire, the fibre core diameter will shrink. The reduction of diameter is around 3–5% for natural and polypropylene fibre cores and for polyamide fibre cores the reduction is about 0.5–1% [5]. Hence, to stop the development of any strong pressure arising the between the strands, alrge enough clearance should be maintained. The dimension and the form of the fibre core greatly influence the endurance of the wire rope endurance of the wire rope.

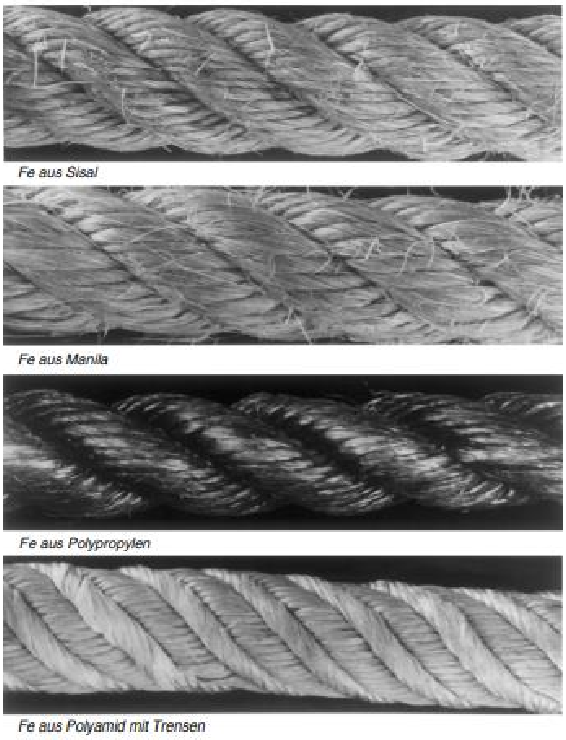



Fig.14: Fibre cores [5]

Steel cores (WC) are fabricated from steel wires which are either arranged as a wire strand (WSC) or normally as an independent wire rope (IWRC). The utility of strand core is only limited to small ropes or it can also be used for multi-strand ropes. The steel wire rope core is usually wrapped either with fibres (EFWRC) or with solid polymer (ESWRC). Sometimes a “double parallel ropes” configuration is used. In this configuration outer strands parallel close the wire rope core .The different types of steel cores are shown in Fig. 15. Unlike the wire ropes with fibre cores, clearance between the outer strands is minimal  for wire ropes with independent steel core, to prevent lateral strand movements.

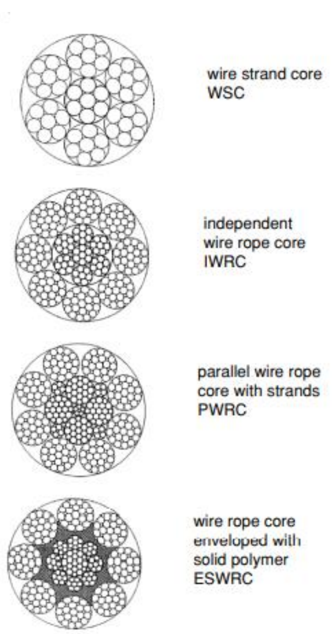



Fig.15: Steel Cores in wire ropes [4]

### 2.2.4 Lubrication

Application of lubricants is done during the manufacturing process atself and it is made sure that it penetrates right to the core. The lubrication has two principle benefits:

1. Friction is reduced when individual wire or/and strands move over each other

2. Acts as protector from corrosion

While bending a wire rope, wires and strands scrape and move relative to each other. Friction causes relative movements between the wires in stranded ropes, affecting the tensile forces. Wire ropes and sheaves also have relative movement, particularly in the event of wire rope side deflection (relative to the flank of the sheave groove) and traction sheaves.The aim of lubrication is to minimise the friction between the wires and strands and between the wire ropes and sheaves [4]. This leads to a case of reduced secondary tensile stresses induced due to the wear and the friction.

**Types of lubrication**

Lubrication for wire ropes can be of two types viz. penetrating and coating. In Penetrating lubricantion a solvent carrying the lubricant is introduced into the core which ultimately evaporates, therby a film is left behind that covers every strand. In the Coating type alongwith penetration the outside of the cable is protected from corrosion and rust.

Mineral oil or petroleum jelly are used to lubricate the core of wire rope with a fibre core, which therefore acts as a reservoir for longer lubrication when in use. To provide optimum coverage on steel core rope, grease or oil lubricants are applied to the wires before they are twisted into strands.

**Lubrication during manufacture**

**The Main core**:While manufacturing the Fibre cores efforts are made to provide an optimum dressing. This process is much more effective than dipping the completed core in heated grease [6].

**The Strands**: Individual wires take a helical shape, resulting in a succession of spiral tubes in the completed strand. If the product is to withstand corrosive attack, these tubes must be filled with lubricant. During the stranding process, lubricant is always applied at the spinning point [6].

**The Rope**: The final rope structure will be made up of a number of strands ranging from three to fifty, resulting in spaces that must be filled with lubricant once again. If a heavy surface thickness is necessary, the lubricant can be applied during the manufacturing process when the strands are closed to form the rope, or it can be added later by immersion in a bath. The stranding and closing procedure will be lubricated with either a petrolatum or bituminous-based compound, depending on the application of the rope. The manufacturer may employ customized lubricant application techniques for specific applications. Increased rope performance is directly related with adequate and proper lubrication of the rope in service, regardless of the lubrication carried out during rope fabrication [6].

## 2.3 Wire Rope Identification and Construction

For Wire rope identification it is necessary to take into consideration its component parts as well as its construction i.e., the manner of arrangement of wires in which have been laid to form strands, and the arrangement of strands around the core.

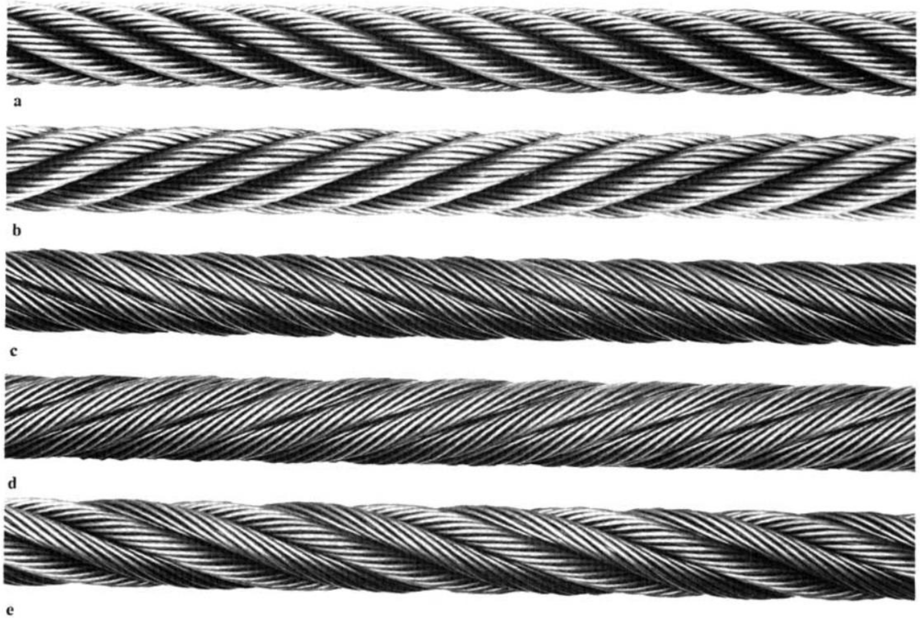



Fig.16: A comparison of typical wire rope lays: a) right regular lay, b) left regular lay, c) right lang lay, d) left lang lay, e) right alternate lay [2].

In Fig.6, “a” and “c” strands are normally laid to the right into the rope like the threading in a right-hand bolt. Alternatively, the “left lay” strands (“b” and “d”) are in the opposite direction.

Again in Fig.6,“a” and “b” show regular lay ropes. While “c” and “d” show what are called as lang lay ropes . It can be observed that the wires in regular lay ropes line up with the axis of the rope, while as in lang lay rope the wires are at an angle with the axis. This variation in appearance is a result of different manufacturing techniques employed. Finally, “e” , known as alternate lay consists of alternating regular and lang lay strands.

## 2.4 Wire Rope Terminations

As an end-user of wire rope, we ought to be aware of the various types of terminations or even treatments which can be applied to wire rope ends. These terminations are designed to be a permanent end termination on the wire rope where it links to the load and are normally formed by making an eye or adding a fitting.

The versatility of wire rope as a mechanical device enables it to support a load or move it. Wire rope is hooked to a crane or hoist and supplied with swivels, shackles, or hooks to attach to a cargo and move it in a controlled manner in the lifting and rigging industries. It can also be used to pull heavy objects.

### 2.4.1 Classification of wire rope terminations:

The termination on a length of wire rope can be done in two major ways [7]:

1) By forming a loop

2) By attaching a fitting to the wire end

A mechanical splice with a swaged sleeve, a hand-tucked splice, or wire rope clips can be used to make eyes, or loops, at one end of a length of wire rope. Swaging, pouring molten zinc or a resin that adheres to the wires, or utilizing a wedging arrangement are all options for securing fittings to wire rope.

**Types of rope terminations**

There are seven main types of rope terminations [8]:

1. **Wire rope clips**: To fasten a loop of wire rope created around a thimble, a U-bolt and saddle combination or a "fist grip" nut and bolt configuration is employed.
2. **Open-wedge terminations (wedge sockets**): The cable is coiled around a wedge that is put into a socket or "basket" and kept in place by line tension.
3. **Poured-socket termination (Spelter sockets):** To connect the wire rope inside the fitting, molten zinc or an epoxy compound is fed into the socket.
4. **Compressed sleeves (Nicopress terminations):** usually by the application of hand tools the sleeve is compressed around the cable.
5. **Swaged terminations**: Connected via cold forming at high pressure such that the fitting's metal flows around and between the rope's strands and wires.
6. **Mechanical terminations (Electroline fittings):** To retain the wire inside a threaded lock sleeve, these devices employ wedge or plugs of various sizes and designs.
7. **Helical terminations (Preformed Dyna-grip terminations):** Helical gripping wires wrap around the cable and are finished in a thimble or epoxy filled fitting in this device.


Fig.17: Types of Terminations [7]

### 2.4.2 Selection of a wire or cable termination

There are certain criteria that need to be considered which are enlisted below [8]:

1. **Type and Size of Wire or Cable:** The terminations chosen must be compatible with the cable type and provide the highest possible effective holding strength. For hemp-core wire rope, armoured electrical cables, and synthetic cables, swaged terminations,

compressed sleeves, and wire rope clips are ineffective terminals. Utilising such terminations onto the cable necessitates squeezing them on, which decreases the termination's effectiveness owing to deformation of soft-core material. Mechanical, poured socket, and open wedge terminations can be used successfully with these types of cables because they work by bonding or compressing only the wire or cable's steel**.**

Wire size is also important owing to the standard capacities of termination devices. The range for compressed sleeves is about 5/8 inches of diameter, while that for wire clips, open wedges and mechanical fittings it ranges from 1-1/2 inches. For swaged terminals we can have 2-1/2 inches and for sockets we have up to 4 inches.

2. **Corrosion:** The problems related to corrosion experienced when the cables are used in a moist environment especially in oceanographic use, where the cable and its terminations are subjected to alternate wet and dry cycles, is well known. Owing to this fact, it is necessary to take the standard materials available for termination devices into consideration.
3. **Fatigue:** For static and moderately cyclic loads developed by machines like cranes, hoists, guy wires, tie downs, slings, etc all the basic kinds of terminations are suitable. however, the shock and vibration loads imposed by winches, buoys etc in the marine environment can only be withstood by the mechanical and helical terminations. The cable enters the termination through a "transition zone" in the nose of the mechanical fittings. The tension, compression, and bending stresses in the rope strands are dispersed in this "semi-loose" transition zone. Other types of terminations have a difficult transition from the cable to the terminal due to the way they are attached to the cable, which can lead to reduced cable fatigue life. By absorbing stress and vibration loads due to the spring action of the helical gripping wires, the helical type of termination ensures a long cable life.
4. **Terminal Efficiency:** The efficiency of the terminal determines what the cost of the cable may be. Higher the efficiency lower is the cost. The rated breaking strength of the swaged and helical terminals is 100 percent of the cable's rated breaking strength. Poured sockets, compressed sleeves, and mechanical fittings have a 95% to 100% rating, while wire rope clips and open-wedge terminations have a 75% to 85% rating.
5. **Assembly Cost installation:** the cheapest and easiest to install termination are Wire rope clips. Their perfirmance efficiency depends only on attention to clip spacing, placement, and tightening torque. A marginally more expensive, but still as simple to install option could be the open-wedge termination, which needs only hand tools for the application. But both of these terminations are the the least efficient among the

other terminations. The Nicopress fitting is another cheap, but highly efficient wire terminating . Although it requires special tooling, to ensure proper compression of the sleeve, the tools are readily available from the manufacturers. Only the required number of compressions must be matched to the sleeve size chosen for usage by the installer.

The swagged and Spelter terminations typify a somewhat moderately priced and highly efficient fitting . large hydraulic presses are utilised for proper installation Swaged terminations and reapplication in the field in most cases is difficult. The spelter socket solves the reapplication problem utilising either molten zinc or an epoxy to achieve wire bonding. This method however requires a keen eye for detail.

The mechanical termination and helical termination are the most expensive fittings, with fairly simple installation requiring knowledge of manufacturer’s literature and eye for detail.

Ease and accuracy of inspection is another key factor while selecting the termination. The swaged and compressed sleeve terminals are inspected by measuring the final diameters, while the clips are inspected by utilising torque wrench.Spelter termination can not be inspected. Mechanical termination has a hole for inspection and the helical terminal is inspected such that no wires are crossing each other.

# CHAPTER 3: MICROSTRUCTURE AND PRODUCTION

## 3.1 Steel Composition

One of the most widely used materials in the world is steel, which is a bluish grey metal alloy with a hard and strong feel. It is also used in various engineering and construction projects. Depending on its composition and physical properties, steel can have a carbon content of up to 2.1 percent. Besides carbon, other elements such as chromium, nickel are also used in the production of steel. It is mainly used as a structural material and as an intermediate. Besides being used as a structural component, high alloy steel is also used in many other applications. The strength, ductility, and hardness of steel are mainly determined by the amount of alloying elements it has and the presence of carbon in it and by the microstructure as resulting from the thermo-mechanical history of the material. The higher the carbon content, the stronger and more ductile the steel.

### 3.1.1 Classification of steels

Most commercial steels can be classified into two groups based on composition

1) Carbon Steel: This steel contains less than 1% carbon and contains traces of manganese, sulphur, silicon, and phosphorus. The properties and features of this form of steel are defined by the carbon content, and alloying and residual elements have a little influence on this type of carbon. Plain carbon steel is of four types: a) low carbon steel (<0.3% carbon) b) medium carbon steel (0.3%-0.45% carbon) c) high carbon steel (<0.45%-0.75% carbon) d) very high carbon steel (0.75%-2% carbon)
2) Alloy Steel: This type of steel has one or more than one element added apart from carbon, to achieve a required physical property. Some of the commonly used elements are molybdenum, manganese, nickel, silicon, boron, chromium, boron and vanadium. Alloy steels are of two types: a) low alloy steel b) high alloy steel

### 3.2.1 Phases and structures

Steel can have a wide range of microstructures and properties depending on how it is produced. Heating in temperature ranges where a phase or combination of phases is stable (causing changes in the microstructure or distribution of stable phases) and/or heating or cooling between temperature ranges where various phases are stable produce the desired results (thus producing beneficial phase transformations). The iron--carbon equilibrium phase diagram serves as the foundation for all steel heat treatment. The temperature--composition zones in which the various phases of steel are stable, as well as the equilibrium borders between phase fields, are depicted in this diagram as in Fig. 18

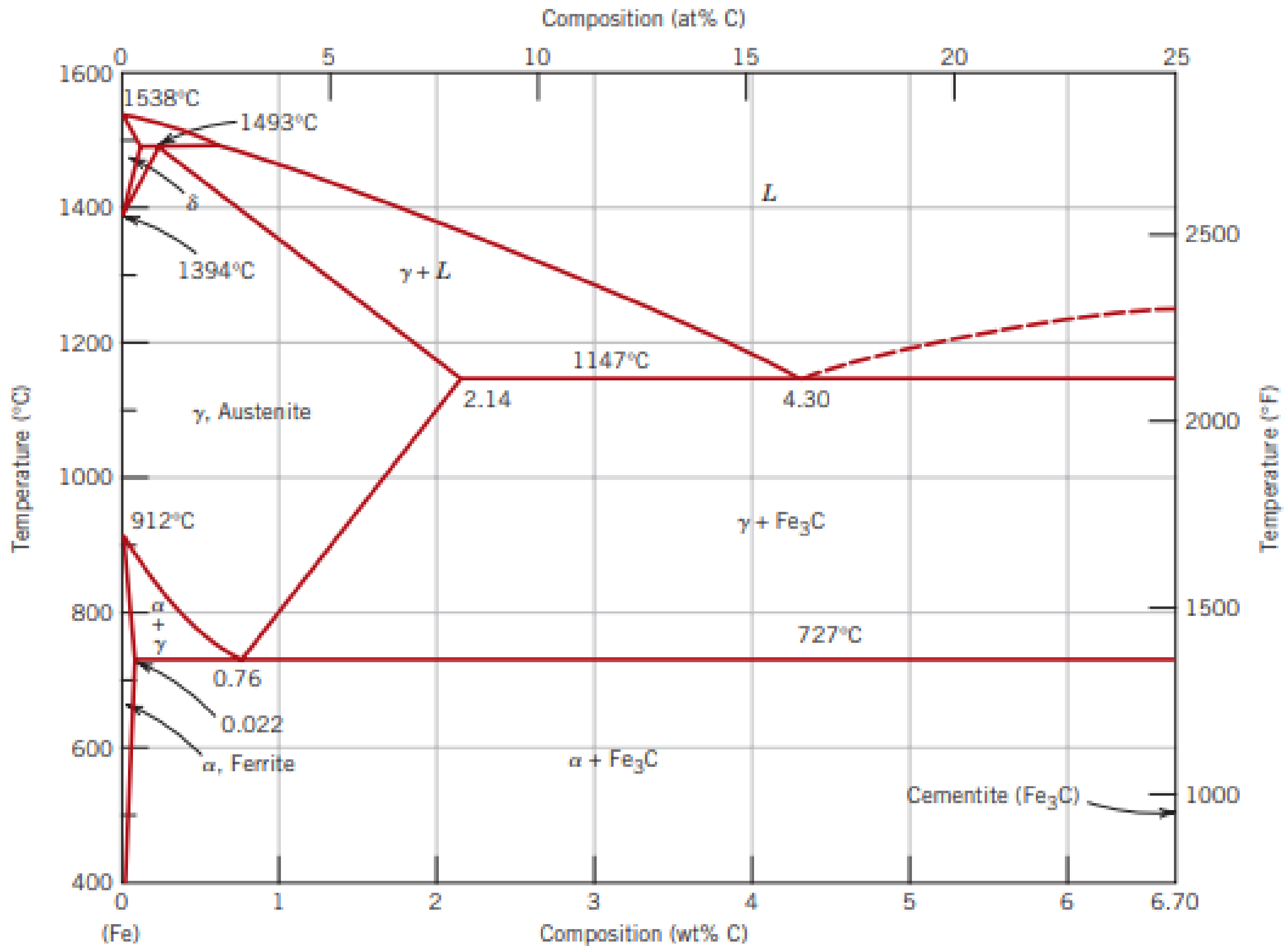



Fig.18: Iron-Iron Carbide phase diagram [9]

**The Iron Carbon Equilibrium diagram**

The iron-carbon (Fe-C) diagram is a diagram that shows the right order of operations for thermomechanical and thermal treatments of a specific steel. Though use of iron-carbon diagram is limited a) since most steels contain other elements which effect and change the positions of the phase boundaries b) some heat treatments are intentionally done to produce non-equilibrium structures, whereas in many cases equilibrium is hardly achieved. Yet, being informed of the changes that occur in a steel as equilibrium is approached in each phase field, or those that occur as a result of phase transformations, offers the scientific foundation for steel heat treatment. Fig.18 shows the Fe-C equilibrium diagram for carbon contents up to 7%. Steels, as previously stated, are iron-carbon-and-other-element alloys containing less than 2% carbon, and most commonly 1% or less. As a result, for steel heat treatment, the area of the diagram is of primary interest. Cast irons are also defined as alloys containing greater than 2% carbon. In fact, Fig.18 depicts two diagrams: The blue lines represent the equilibrium between Fe3C and various iron phases, whereas the black lines represent the equilibrium between graphite and the other phases. Graphite is a more stable form of carbon than Fe3C, and Fe3C will degrade to graphite over very long periods of time. The existence of the austenite phase field in the Fe-C system underpins the art and science of steel processing. The wide range of microstructures and attributes achieved by heat treatment of steels is due to the controlled transformation of austenite to other phases after cooling. At temperatures where austenite is the stable phase, rolling or forging can hot-form strong parts into useful shapes and sizes. Iron being an allotrope can be present in multiple crystalline forms at atmospheric pressure, depending on the temperature. Alpha iron (ferrite) exists up to 912 ° C. Gamma iron (austenite) is present between 912 and 1394 ° C. Delta iron (delta ferrite) is present from 1394 ° C to the melting point of pure iron, 1538 ° C. The temperature range where various crystalline forms of iron are stable forms the vertical limit (edge of pure iron) on the left side of the range shown in the figure. In the two-component iron-carbon system, the three horizontal blue lines in the iron-carbon diagram represent three invariant three phase equilibria (At this equilibrium the three phase compositions and the temperature at which these phases operate under equilibrium at constant pressure are fixed. If we presume $Fe_3C$ to be the stable high carbon phase, the three-phase equilibrium is characterised as [10]:

1) **At 1495 °C (2725 °F):** a peritectic reaction i.e., a three-phase reaction in which on cooling a solid phase combines with liquid phase to form a single solid phase and the reaction is **δ-ferrite + Liquid = γ-iron (austenite)**
2) **At 1148 °C (2100 °F**): a eutectic reaction i.e., on cooling two solid phases are formed from a liquid phase. **Liquid = $Fe_3C$ + γ-iron,**
3) **At 727 °C (1335 °F):** a eutectoid reaction i.e., on cooling a solid phase forms two other solid phases. **γ-iron = α ferrite + Fe3C**

**Effects of Carbon**

Significant alterations are produced in the phases and phase equilibria due to the introduction of carbon to iron. Differences in ferrite and austenite's propensity to assimilate carbon result in not only crucial Fe-C diagram properties, but also the creation of $Fe_3C$. Carbon atoms are introduced into the interstices or interstitial spaces between iron atoms in the crystal structures of BCC ferrite and FCC austenite. As such Austenite and ferrite are interstitial solid solutions in Fe-C alloys and steels. Carbon acts as austenite stabilizer and hence increases the austenite formation range in steels. Fig.19 demonstrates how the austenite field expands substantially when carbon is added, from 912 to 1394 °C in pure iron to a wide range of temperatures and compositions. At 1148 °C, austenite has a maximum carbon solubility of

2.11 percent. Ferrite has a far lesser ability to dissolve carbon than austenite, with a maximum solubility of only 0.02 percent at 727 °C and a continual reduction from there. The very small ferrite field depicted in Fig.19 emphasizes carbon's poor solubility in ferrite. The temperature-composition range of ferrite and the decreasing solubility of carbon in ferrite with decreasing temperature are depicted in an extended part of the low-carbon end of the Fe-C diagram. The solubility of carbon in ferrite at ambient temperature is almost non-existent.

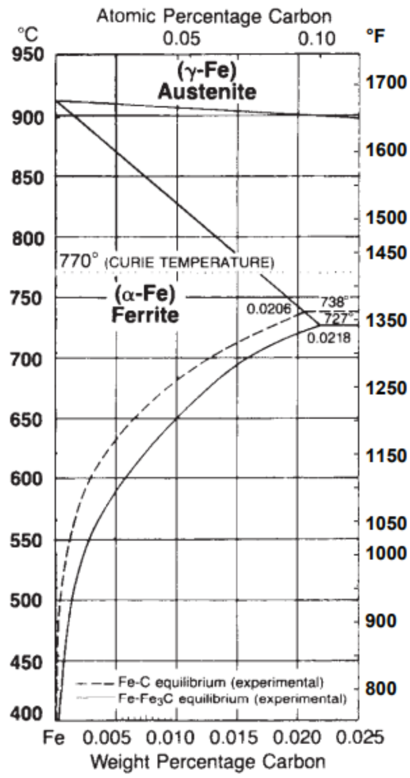



Fig.19: Ferrite phase field and decrease of carbon solubility with decreasing temperature [9]

In iron-carbon alloys and steels, when the carbon solubility limit in austenite is exceeded, a new phase called iron carbide or cementite emerges. Cementite crystals come in a wide range of shapes, sizes, and configurations, which, when combined with ferrite, contribute to the wide spectrum of microstructures found in steels. The different types of cementite are closely related to their thermal history or heat treatment.

**Crystal Structures in Steels**

1) **Austenite:** The unit cell of austenite is face centred cubic (fcc) as shown in Fig.20. Iron atoms are placed at the corners and the centre of faces and are depicted by black circles. One view shows an interstitial octahedral site between iron atoms, while the other shows an interstitial tetrahedral site in the unit cell. A particularly essential property of austenite is its high solubility of carbon atoms in octahedral interstitial

spaces, which allows carbon existing in carbides stable at low temperatures to be dissolved into austenite created on heating. After cooling, the carbon gets reconfigured into a variety of different microstructures.

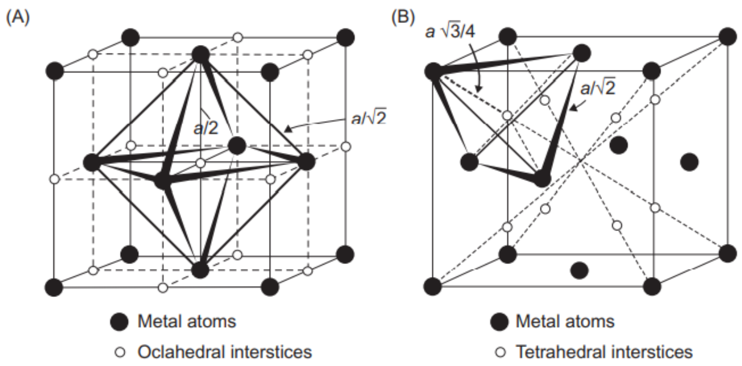



Fig.20: Interstitial voids in fcc structure [11]

2) **Ferrite and cementite**: On cooling from austenite, owing to extremely low solubility of carbon in ferrite, more often than not cementite forms together with ferrite. body-centred cubic unit cell of ferrite is shown in Fig. 21. Iron atoms are located at cell corners and the body centre. Cementite, a high-hardness carbide phase, features a more sophisticated orthorhombic crystal unit cell, with a three-iron-atom-to-one-carbon-atom ratio

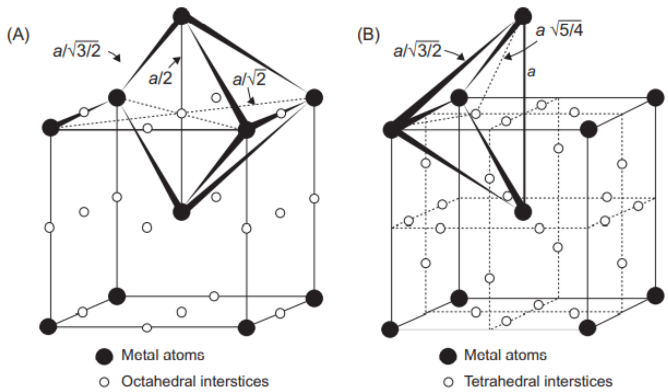



Fig.21: Unit cell structure of ferrite [11]

Even though ferrite has a more open atom structure than close-packed austenite, yet ferrite has low carbon solubility, which is connected to the interstitial sites being small. When ferrite cools from austenite, carbon is rejected from it, generating cementite or sometimes enriching austenite, but in some cases carbon atoms are held mostly in octahedral positions in the ferrite.

## 3.2 Microstructure Development

The microstructure development depends on both the carbon content and the heat treatment [12]. The transformation of austenite to ferrite and cementite results in various arrangements of microstructures. We will try to understand the various microstructures produced due to diffusion and relatively slow cooling of austenite.

### 3.2.1 Eutectoid Transformation

The Fe-C diagram serves as a foundation for comprehending the phase changes and microstructures. The area's most relevant to the transition of austenite in slowly cooled steels are shown in Fig.22, which is an expanded part of the Fe-C diagram. Consider the Fe- 0.77C alloy, which is totally austenitic up to the $A_1$ temperature (727 °C, or 1340 °F) at all temperatures. The phase diagram illustrates that austenite must be replaced by a mixture of ferrite and cementite if held at this temperature for a long time or cooled slowly through $A_1$ (under the restricting conditions of approaching equilibrium). As mentioned earlier this transformation in which one solid phase is replaced by two solid phases is referred to as Eutectoid Transformation. The transformation is written as [10]

$$\gamma(0 \cdot 77\%C) \underset{heating}{\overset{cooling}{\rightleftharpoons}} \alpha(0.02\%\,C) + Fe_3C(6.67\%\,C)$$

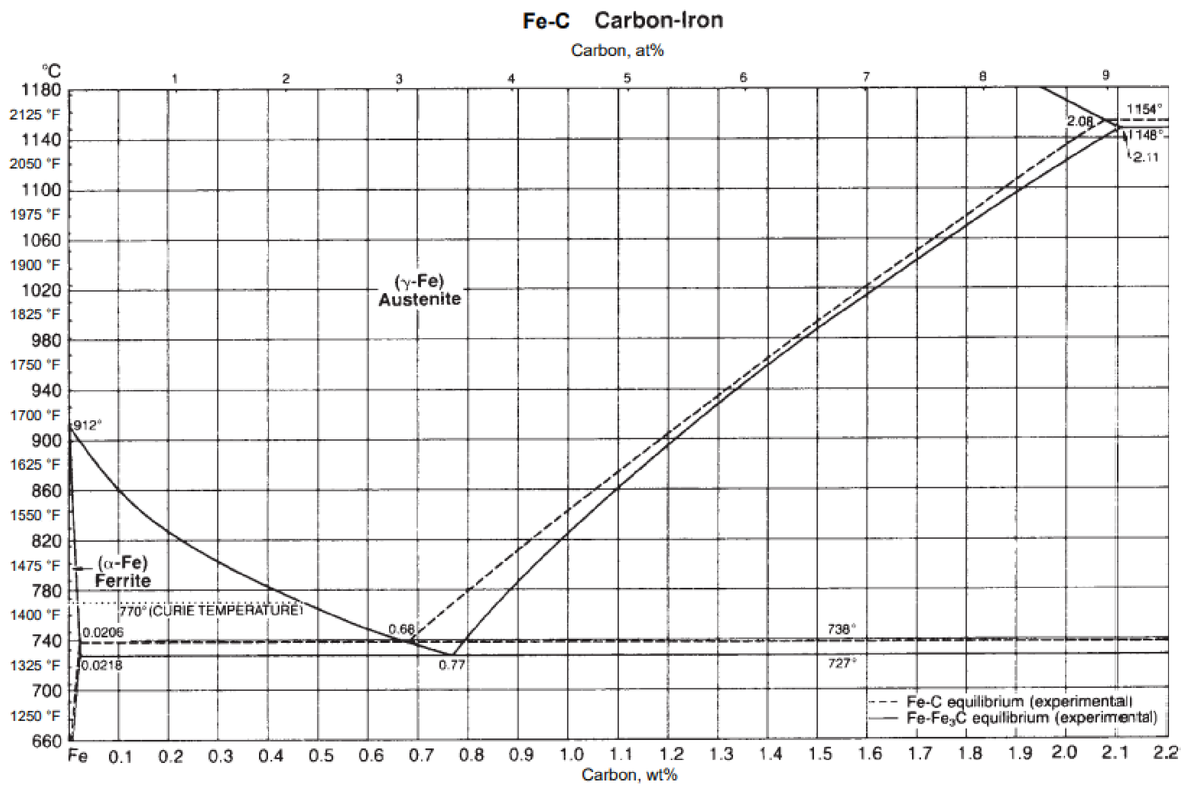


Fig.22: Portion of Fe-C diagram pertinent to transformation [9]

This equation demonstrates that the eutectoid reaction's phases have fixed compositions and that the reaction is reversible depending on whether heat is applied or removed. In Fe-C alloys, the eutectoid reaction occurs isothermally at 727 °C. In practice, however, equilibrium conditions are rarely achieved, and the eutectoid reaction can occur at a wide range of temperatures below $A_1$.

### 3.2.2 Structure of pearlite

Pearlite is a distinctive microstructure produced by the eutectoid transition in steels. As seen in Fig. 23, a light micrograph of a furnace-cooled specimen of a Fe- 0.75C alloy, pearlite consists of alternate closely spaced platelets or lamellae of ferrite and cementite. The microstructure is characterized by colonies of lamellae of varied orientations and spacings. The spacing variances between cementite lamellae in different places could be owing to differences in the angles the lamellae make with the polish plane, as well as the fact that the pearlite could have developed at different temperatures. The colonies with lamellae perpendicular to the plane of polish would reveal the true spacing or closest spacing of the ferrite and cementite lamellae, if it was assumed that all the pearlite was created at the same temperature, thereby having almost identical spacing.

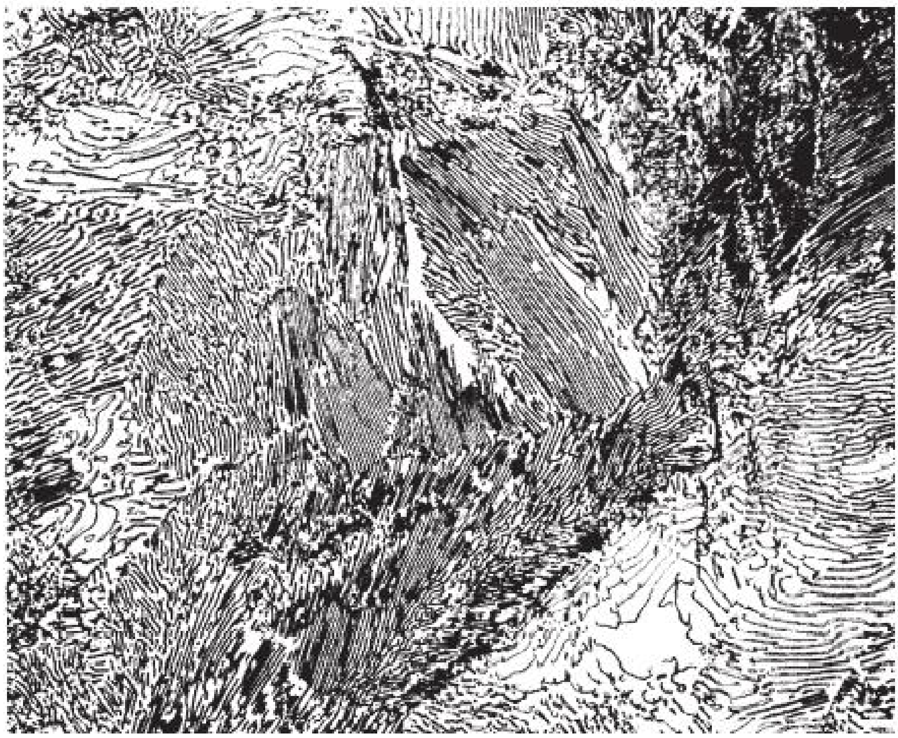


Fig.23: Pearlite in a furnace-cooled Fe-0.75C alloy [10]

Those lamellae with angles less than 90° would have more space between them. The genuine pearlite spacing must be determined from metallographically prepared specimens where the lamellae form a variety of angles with the specimen surface, which necessitates the use of particular quantitative metallographic investigations [13]. The word pearlite (literal meaning mother of pearls [12]) comes from the uniform arrangement of lamellae in colonies, as well as the fact that etching destroys the ferrite phase more severely than the cementite phase. The elevated and regularly spaced cementite lamellae of the colonies then act as diffraction gratings, causing diffraction of light of various wavelengths from the various colonies to form a pearl-like shine. The pearlite colony development initiates from either ferrite or cementite crystals [14]. In contrast to the initial belief that, the lamellar structure developed only by sidewise nucleation of separate lamellae it has been demonstrated that branching of a single cementite crystal into parallel lamellae with spacing characteristic of a given transformation temperature can also produce the lamellar structure. Hence with regard to the latter mechanism, a pearlite colony may be considered as amalgamation of two single crystals of ferrite and cementite. The said structure was shockingly unearthed during a serial polishing experiment of 1 µm steps by repeated photography [14]. The supposedly different cementite lamellae surprisingly had a common origin. The lamellae are thought to grow by extending their edges into the austenite once a pearlite colony has been generated via sidewise nucleation and/or branching of the ferrite and cementite, a process known as edgewise growth [14].

### 3.2.3 Kinetics of Pearlite Transformation

So far, we discussed about lamellar structure of pearlite and its formation by a eutectoid reaction. In practice, however, pearlite rarely forms near to the $A_1$. An isothermal transformation diagram for eutectoid 1080 steel is shown in Fig.24. The beginning and finish of pearlite formation are depicted as curves produced by cooling from the austenite phase field and holding at various temperatures below $A_1$. The transformation curve's commencement is asymptotic to $A_1$, indicating that pearlite would not form at temperatures near to $A_1$ unless the steel was maintained at that temperature for a long time.

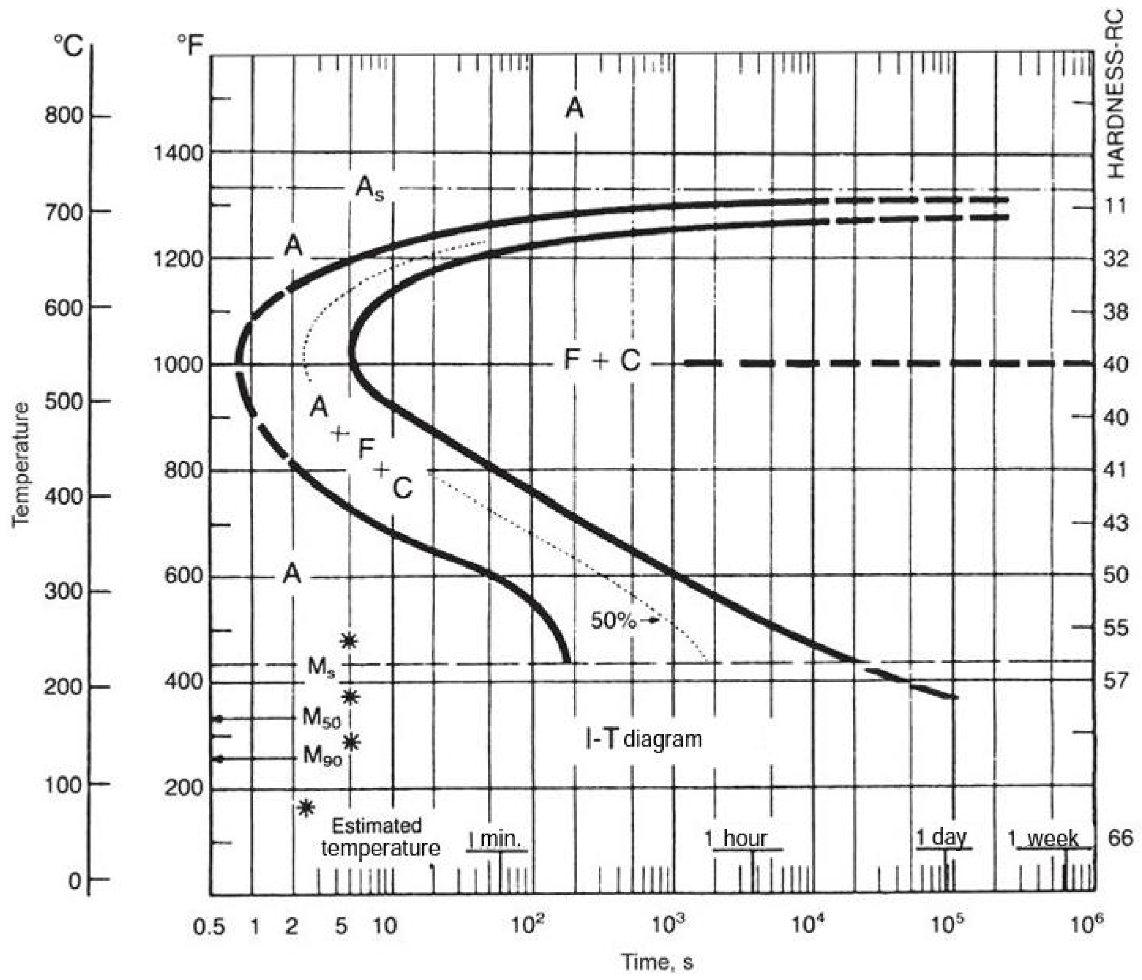



Fig.24: Isothermal Transformation of 1080 steel [10]

Slow cooling rates that would allow pearlite production close to the $A_1$ are only approached in very heavy sections or by furnace cooling in industrial heat-treating practice. The time durations for the commencement and end of pearlite transformation are significantly decreased with increased undercooling below $A_1$. Only seconds are necessary for complete transformation at the tip of the transformation curve, 540 °C (1005 °F), the lowest temperature at which pearlite occurs in this steel. Bainite, a non-lamellar microstructure of ferrite and cementite, is generated below 540 °C. The rate of pearlite generation is influenced by a number of factors. The fact that significant carbon atom rearrangement is required to change austenite (having nominally 0.77 percent C) to low-carbon ferrite and high-carbon cementite is perhaps the most crucial factor. The diffusion of carbon, as characterized by its diffusion coefficient, is temperature dependent. One equation that has been developed to show the temperature dependence of carbon diffusion in austenite is [15]

$$D_C^{\gamma} = 0.12e^{-32000/RT}$$

$D_C^{\gamma}$ is the average carbon diffusion coefficient ($cm^2/s$)

R is the gas constant

T is the absolute temperature

The diffusion coefficient drops exponentially with decreasing temperature, as shown in the above Equation, a powerful impact that drastically lowers the diffusion coefficient for modest temperature changes. The temperature dependency of diffusion appears to contradict the empirically established fact (Fig.24) that pearlite formation is faster at lower temperatures than it is at higher temperatures at first glance. The decrease in interlamellar spacing as the temperature of pearlite transformation falls explains this apparent oddity. As a result, the distance that carbon must diffuse to disperse itself between the ferrite and cementite decreases, and the growth of pearlite colonies accelerates, despite the fact that diffusion becomes more sluggish at lower temperatures. The relation between diffusion and the lamellar structure of pearlite explains the “how” but not the “why” of the transformation. The phase and microstructure stability of metals and alloys is dependent on minimum free energy principle. When a given microstructure or system does not have a minimum free energy, a phase transformation (like austenite to pearlite transformation) or rearrangement of microstructure without a phase change (like grain growth or particle coarsening) takes place to achieve the minimum possible value of free energy.

## 3.3 Production and Metallurgy

The manufacture of wire starts from billets or slabs of steel which then undergo various processes like drawing, surface treatment, patenting etc. The metallurgical processes involved in the wire making start from continuous casting and end at wire drawing as can be seen in Fig.25.We will discuss the main metallurgical processes in the sections below.

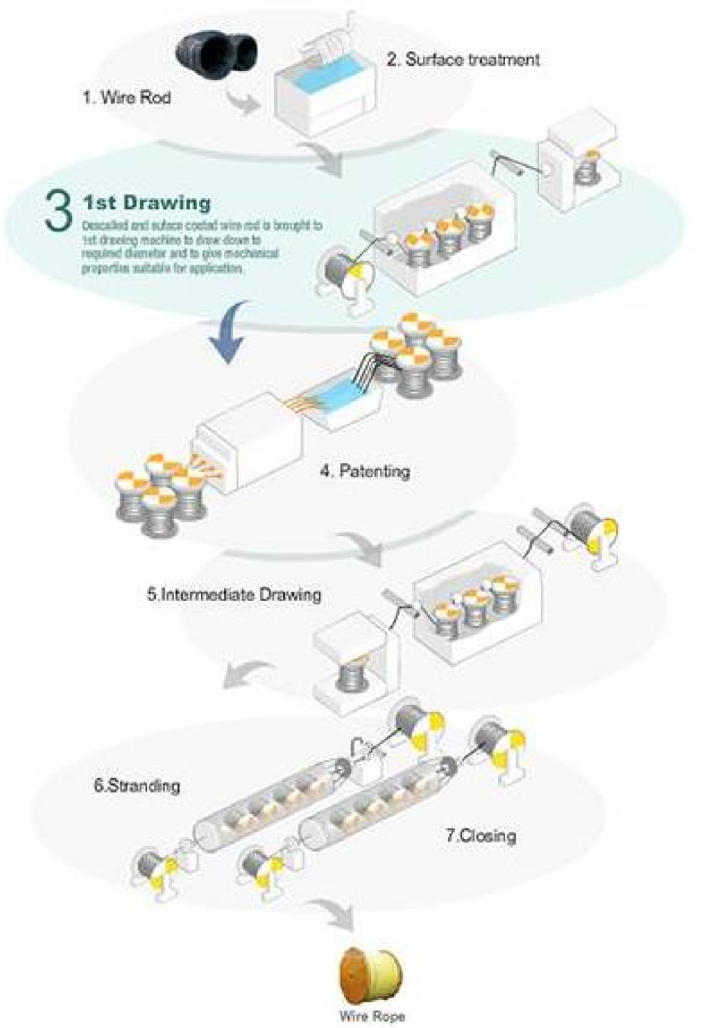



Fig.25 Manufacturing of wire rope

### 3.3.1 Continuous Casting

Continuous casting, also known as strand casting, is a method of casting a continuous length of metal in the manufacturing business. Molten metal is poured into a mold, which takes on the mould's two-dimensional profile but has an unknown length. The casting will continue to descend, with its length increasing over time. To maintain pace with the solidifying casting, new liquid metal is constantly supplied to the mold at precisely the right rate. Continuous castings are made in a factory and are a very precise activity.

**The Process**

A tundish is filled with molten metal poured from a neighbouring source. A tundish is a vessel that rests above the mold and holds the casting molten metal. The force of gravity is utilised in this casting operation to fill the mold and propel the continuous metal casting along. The tundish is where the procedure starts and is consequently positioned high above ground level, up to 25 or 30 metre. Right through the production process, the tundish's role is to keep the mold filled to the proper level. Because the metal casting is constantly moving through the mold, the tundish must constantly replenish the molten metal supply. It is pertinent to mention here that the supply replenishment has to be done accurately. This task is aided by the use of a control system. Essentially, the system can detect the amount of molten metal, determine what that level should be, and manage the metal flowing from the tundish to guarantee that the casting process runs smoothly. The slag and impurities from the melt are removed are removed in tundish. Steel has historically been difficult to cast due to its high melting point and reactive behaviour at high temperatures. As such in a continuous steel casting operation, the molten steel's reactivity to the environment must be managed. An inert gas, such as argon, can be used to fill the mold entry for this purpose. During continuous production of the metal part, the metal casting moves rapidly through the mold. As such the casting does not solidify completely owing to short period of time. However, a protective solidified skin of appropriate thickness is developed due to spending enough time in water cooled mold. By using rollers, the long metal strand is moved at a steady speed. The rollers guide the strand and ensure that the metal casting flows smoothly out of the mold and along its intended course. To bend the strand to a 90-degree angle, a set of special rollers can be employed. After then, a different set will be employed to straighten it out. The process is shown in Fig.26

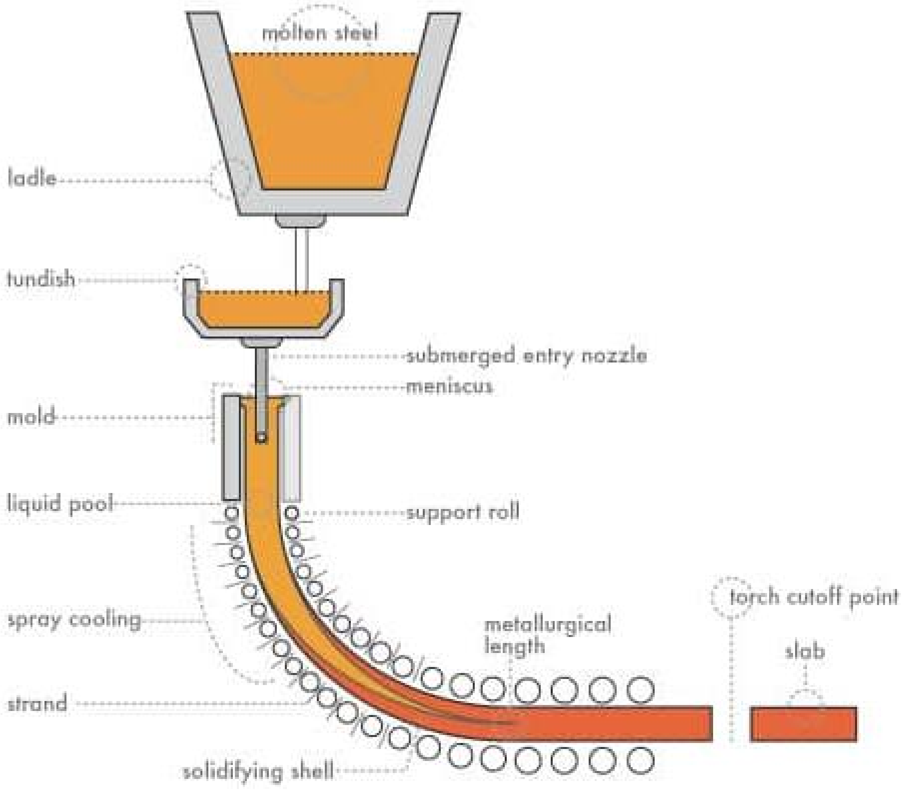



Fig.26: Continuous Casting [16]

### 3.3.2 Rolling

Rolling is a procedure that involves passing metal through a gap between two rollers that rotate in opposite directions (clockwise and anti-clockwise) to form it into a thin long layer. The separation distance between the two rollers ought to be less than the thickness of the material to be formed as shown in Fig.27. When the metal piece passes through the gap, it ought to have enhanced length and width compared to the original, but thickness should be lessened. Two important terms used for rolling are a) Draft (reduction in thickness) b) absolute elongation and spread (length and width increase) [17]

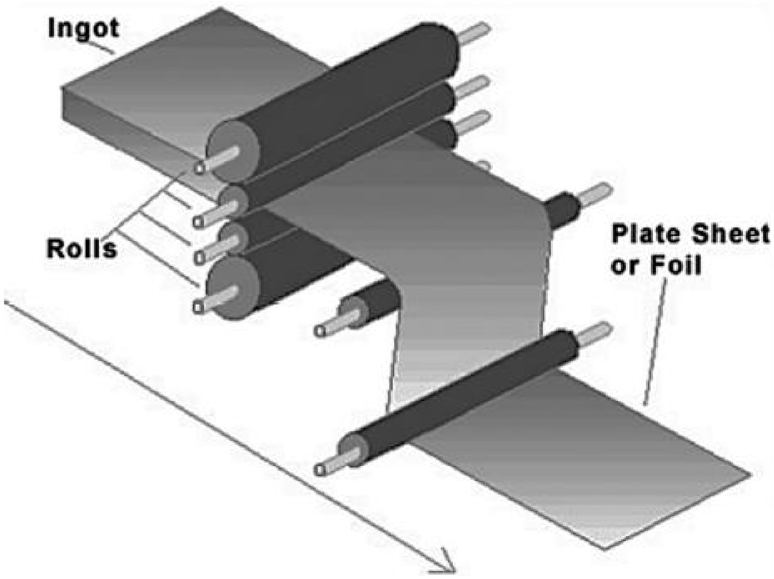



Fig.27: Rolling operation explained [17]

**Hot Rolling:** As shown in Fig. 28, the process of metalworking that takes place when metal parts are heated beyond their recrystallization temperature. This is the most tonnage-intensive of all metal processes, because an equiaxed microstructure is maintained by the material grain deformation thereby inhibiting work hardening. The large metal from unfinished casting viz. billets, slabs and booms that act as raw material undergo processing and in turn are heated to elevated temperature to facilitate manoeuvrability before they are fed into the rollers. In the rollers additional heat is introduced and is increased in small increments. For large material heating can be achieved by soaking the workpiece in oil pits in order to have an efficacious heating process, meanwhile induction is responsible for the temperature achieved by smaller workpieces [18]. The foregoing techniques have a number of benefits, including a reduction in energy costs in a timely and effective manner. As a result, process performance is improved while cracks and other defects are avoided as a result of the obstacles. Regardless, the heating procedure prior to rolling may cause tensile characteristics to deteriorate in the direction of thickness. Furthermore, residual stresses induced by uneven cooling may have a deleterious impact on the metallic material's microstructural and mechanical properties.

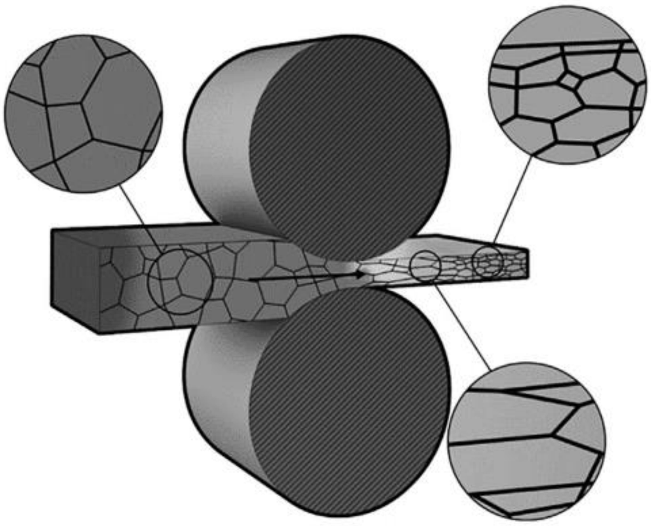


Fig.28: Hot Rolling Process Illustration [17]

**Evolution of Microstructure during Hot rolling**

During hot rolling he composition, percent reduction of respective dimensions, thickness of strip, strip speed, and heat transfer are the governing factors of changing microstructure and mechanical properties owing to the varying thermomechanical state. The temperature range between 850–1200°C is usually where hot rolling is performed on steels [19]. Strain is imparted to the material during each rolling pass, causing a rise in dislocation density and, as a result, work hardening. Elongation of the grains in the rolling direction occurs as well, as seen in Fig. 29. Softening mechanisms, both dynamic and static, begin to function as internal energy increases. Microstructural changes constitute dynamic deformation, on the other hand processes that occur between successive passes are known as static deformation. The key softening mechanisms in the austenite phase are static recovery and dynamic and static recrystallization.

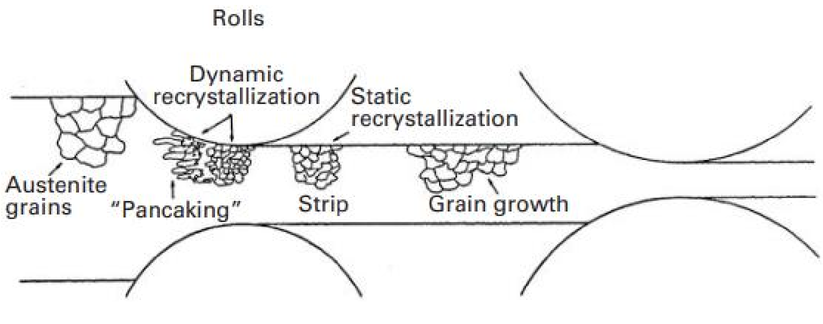



Fig.29: Changes in Microstructure during Hot Rolling [19]

In contrast with recrystallization, where the nucleation of new, strain-free grains occurs at grain boundaries, a limited amount of softening characterises recovery. During rolling of steels, dynamic recrystallization can occur at high temperatures and low strain rates, which are typical of the roughing mill and early passes of the finishing mill. Owing to elevated temperatures, some grain growth occurs even after recrystallization in steels. Between subsequent passes, the recrystallized grain size tends to be substantially finer during the process of recrystallization, which is due to the elevated values of residual strain. Fine-grained ferrite is obtained from austenite during the ensuing cooling, resulting in better yield and tensile strength than coarse-grained steel.

### 3.3.3 Patenting of steel

In the first phase, an isothermic transition of supercooled austenite, i.e., at 450-550°C, is required for patenting. The wire is heated to 150-200 degrees over the critical point (at 870 to 920 degrees) in order to achieve austenite homogeneity and fast isothermal transformation of the supercooled austenite at the temperature of the supercooling bath (fused salt or molten lead). Steel wire researchers place a premium on the grain size of the steel in thin lamellar pearlite, assuming that a coarse grain will facilitate in the manufacture of long wires in drawing processes with significant total area reductions, owing to the higher twin density and fast exhaustion of twins in the large grained steel during wire drawing process [20]. Wire ruptures are caused due to fissures in reticulate cementite at the beginning of drawing process. Effect of pearlite carbides in coarse lamellar form fall somewhere in the middle. Many cold plastic deformation techniques can be undertaken owing to the granular carbides which include but not restricted to rolling drawing etc. When area reductions are significant, grainy carbides deform plastically to an expanded shape during the wire-drawing process. Steel with carbides in thin lamellar form has the most remarkable ductility properties in drawing, given its high strength characteristics (patenting sorbite). The concentration of the pearlite depends on temperature (through the colony of the carbide particles). as the temperature of the bath (molten lead or fused salts) lowers, the dispersions of the pearlite increases. Patenting is performed at 450-550 degrees and usually on steel with a carbon content ranging from 0.45 to 0.85 percent [21].

### 3.3.4 Wire Drawing

Wire Drawing is a technique of reducing cross section area of the rod. Because the volume of the drawn wire or rod remains constant throughout drawing, the length of the drawn wire or rod increases. Pulling the wire/rod through a single or a series of drawing dies is how it's done. The successive drawing die in a sequence of drawing dies should have a smaller bore diameter than the prior drawing die. Drawing is characterized as a cold working process because it is usually done in round pieces at room temperature. By dragging (thus the term drawing) a long rod or wire through a die called a draw die, the cross section of the rod or wire is reduced or modified. The rod is pulled through the die by a tensile force supplied to the exit side of the die. Cross-sectional area reduction, die angle, friction along the die-work piece interface, and drawing speed are the main processing variables in drawing. The drawing force is influenced by the die angle and ultimately determines the quality of the drawn product. Wire/rod drawing has the following process characteristics: (i) pulling the wire rod/round through the die to reduce its diameter; (ii) drawing increases the length of the wire/rod as its diameter decreases; (iii) for small diameter wire, several dies are used in succession (tandem); (v) drawn wire/rod properties improve due to cold working; and (v) wire temper can be controlled by swaging, drawing, and annealing treatments. Because the drawing process involves dragging a rod or wire through a die, the material is stretched or elongated, and the cross-sectional area is reduced, and the reduction is determined by the yield strength of the material [22]. The process of drawing is shown in Fig.30.

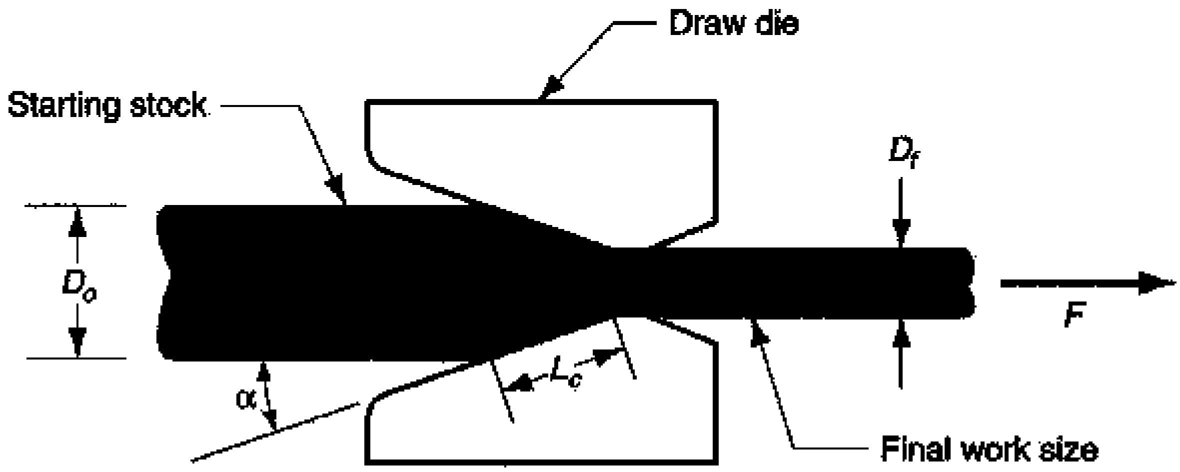



Fig.30: Drawing Process

**The Process of Drawing**

The material to be drawn is adequately prepared before the actual sketching. Three main processes viz. annealing, cleaning, pointing is utilised for drawing process. annealing increases the ductility of the material so that it can withstand the distortion during drawing. To avoid damage to the work surface and draw die, the wire rods/rounds must be cleaned. Chemical pickling or shot blasting are used to remove surface impurities (such as scale and rust). Pre-lubrication of the work surface is sometimes done after it has been cleaned. The diameter of the starting end of the wire rods/rounds is reduced to allow them to be placed through the draw die to begin the process. Swaging, rolling, or turning are common methods for accomplishing this. The carriage jaws or another mechanism hold the pointed end of the wire rods/rounds to start the drawing operation.

**Drawing equipment**

The diameter of the starting end of the wire rods/rounds is reduced during pointing so that they can be placed through the draw die. Continuous drawing machines, which consist of many draw dies separated by accumulating drums between the dies, are used to draw wire. Each drum, also known as a capstan or block, is powered by a motor to generate the necessary pull force to pull the wire stock through the upstream die. As it moves on to the next draw die in the series, it keeps a light tension on the wire. Each die reduces the wire by a particular amount, allowing the series to accomplish the desired overall reduction. Draw Bench for wire drawing is shown in Fig.31.

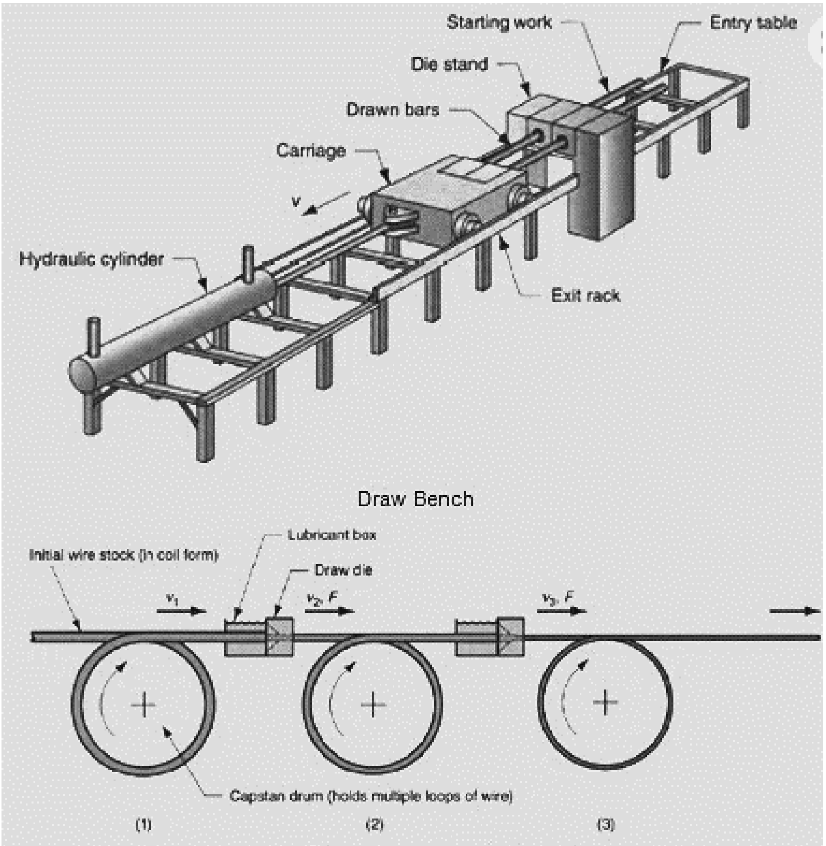



Fig.31: Continuous Wire Drawing Draw Bench

# CHAPTER 4: DEGRADATION MECHANISMS

High contact stresses and sliding at point of contact with sheaves or drums characterise the wire ropes and the ensuing result are the prominent changes, be it geometrical or for that matter, mechanical characteristics of its components. This leads to a reduction of bearing capacity and ultimately to failure. As such to ensure the safety of the people involved, it is imperative to forecast the mechanical performance, so as to organize a proper course of action.

Several degradation mechanisms that may take place on their own or in tandem are experienced by the Wire rope in service. Owing to the expertise, the deterioration phenomena initiate from mechanical and environmental causes. The main causes being fatigue, fretting fatigue, wear or corrosion

## 4.1 Fatigue

Fatigue is a phenomenon that occurs due to loading and unloading repeatedly. It begins in the locations where there is a high concentration of stress. Usually, the nominal maximum stress which results in damage are lower than the wire rope's ultimate tensile stress limit. Wire ropes are virtually always subject to loads and cyclic deformations and operate at high stress levels. However, fatigue is the main player in well-maintained and operated ropes over long periods of time. The frequent bending of ropes as they run over sheaves is a key source of fatigue in running ropes [23].

Steel ropes constitute of steel wires strung together. Because of its high carbon content and fine grain structure, the steel used has a higher strength. The load carrying capacity is divided across several parallel wires, ensuring the critical combination of high axial strength and stiffness along with bending flexibility. In fact, under the influence of applied tension, the helical construction of wire rope, leads to the development of a radial load component. As such normal contact stresses between wires are developed, allowing broken wires to quickly recover their share of the applied load on a given length after a break; this point is critical in ensuring that the wire rope is tough in the sense that it is tolerant of local damages, especially in the case of broken wires [24] [25].

In practice, wires are subjected to a micro-damage during each solicitation, which has no effect on the wire rope in the near term. Rope failure, on the other hand, occurs when a large number of wires break in a single location, causing total failure. Palmgren-Miner developed a method for evaluating the combined effect of cycles at multiple load levels until the material breaks; it's known as "the Palmgren-Miner cumulative damage technique," and it also works well with wire ropes. Basic fatigue forms of wires are shown in Fig.32

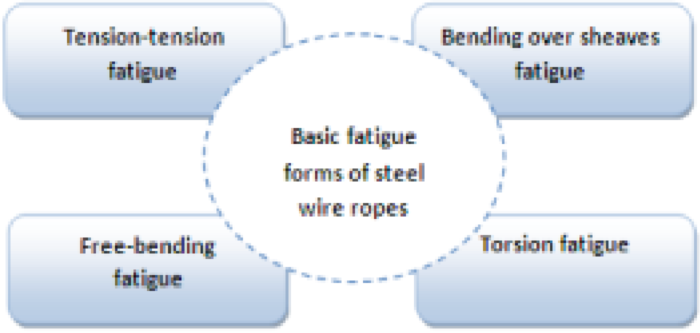



Fig.32: Fatigue forms of steel wires

### 4.1.1 Tension-Tension Fatigue

This is the most basic type of rope fatigue, featuring stress variations caused by changes in axial tensile loading. Even a static rope used apart from a sheave or drum has a finite lifespan. Fatigue can be encountered in a variety of applications where attached mass changes, acceleration, and deceleration are the primary sources of axial load variation, such as mooring ropes, lifting, and hoisting. The fluctuation in load sharing between wires and along any one wire, which arises from the dynamics of the production process, lies at the heart of the rope quality issue [23]. This can have a substantial impact on the relative performance of originally similar ropes (from different manufacturers or lengths), as well as a major impact on fatigue life [24] and the quantitative components of this manufacturing functionality were observed by Evans et al who confirmed that for ropes in tension wire strains varied significantly not only for different wires at the same cross section but also along the length of same wire [26]. Without ignoring the benefits of overloading on rope longevity, which can increase tension-tension fatigue endurance by establishing a uniform load distribution, especially in a rope of initially poor quality. It should also be assured that the terminations are properly applied so that the rope's performance is not harmed throughout its employment.

Steel wire ropes have been subjected to a number of tension-tension fatigue tests. The effects of various variables on tension-tension fatigue were evaluated by Matanzo in 1972, including rope manufacture and environment, as well as the applied mean load and tensile load range and concluded that the tensile load range is the most important factor and had the strongest effect, while the mean load showed negligible effect with regard to tensile load spectrum [27]. The findings of fatigue experiments on steel wire ropes conducted by Hanzawa et al in 1981 revealed that fatigue cracks induced by wire-to-wire abrasion cause wire breaks in the rope. Under the conditions of variable wire diameter and same wire strength and contact pressure, the contact pressure is lowered, and the area of abrasive wear increases rapidly in larger diameter wires, which delays the progression of the abrasive dent, and reduces the coefficient of stress concentration which lead to an increase in fatigue strength. Also, the cuts in the free length of wires occur under high tension, whereas cuts in sockets occur under low stress and are caused by stress concentration [28].

During the fatigue testing on multilayer strands by Hobbs and Ghavami (1982), it was discovered that the number of cycles between the first wire break and total rope failure grows in direct proportion to the number of wires in the rope [29]. The estimate of the state of fatigue in internal and external wires of steel wire ropes for airplane rescue hoists was evaluated by various analytical formulations by Giglio and Manes (2003). Based on their testing, they discovered that at significant oscillation angles, internal fissures appear, but they are not visible to the naked sight [30].

### 4.1.2 Bending over sheaves fatigue

This type of fatigue has been the subject of a huge collection of literature published on wire endurance and a fair number of experimentations. Wire ropes that flex dynamically (for example, bending over sheaves) have a finite lifespan. Local changes in the curvature as the rope adapts to the radius of a sheave or drum are the principal drivers of stress fluctuations in this device. Every time a rope piece passes over a sheave, it completes a bending cycle (passage from a straight state to a flexed State and a return to a straight state). The number of bending cycles a rope may do in a hoisting system is determined by numerous factors. The D/d ratio (where D is the sheave diameter and d are rope diameter) and tensile load are two of these parameters that have a greater impact on this form of fatigue as shown in Fig.33 [23].

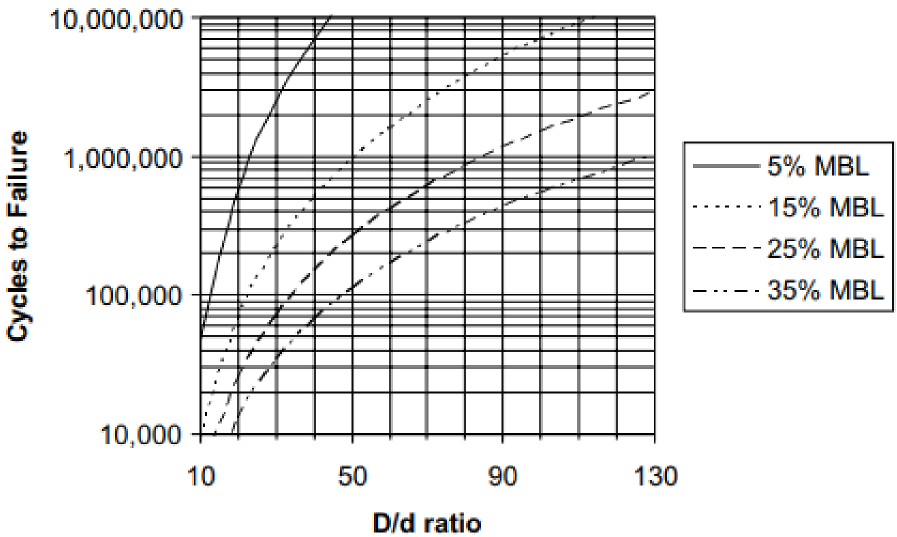



Fig.33: The mean number of cycles to failure in bending-over sheaves fatigue as predicted by Feyrer (1995) as a function of D/d Ratio in terms of minimum breaking load [23]

When compared to a rope traveling over a sheave with a similar D/d ratio, the bending life of a steel wire running on and off a multi-layer winch drum may be significantly too short [31].

Owing to the response to transverse loading on sheaves or drums, the rope construction plays an important role in bending fatigue. Line contacts transmit forces between wires in ropes with 'equal layers' and a single layer of outer strands, whereas point contacts transmit forces between wires in compound strands. This causes internal wire fatigue failures which are not visible from the outside in the later scenario [23]. As a result, when defining inspection policies and rope discard criteria, this attribute must be appropriately considered. Moreover, there is also the matter of lubrication criterion which states that a well lubricated rope ought to attain a greater number of cycles compared to a poorly lubricated rope of the same design.

Ridge et al. (2001) investigated the impact of simulated degradations, (which included but were not limited to wire breakage, corrosion, abrasive wear, plastic wear, slack wires, slack strands, and torsional imbalance) on the fatigue endurance of steel wire ropes subjected to repeated bending at constant strain. The ratio of the diameter of pulley and rope, the rope construction, and thereby the variation of the wire curvature determines the value of cyclic strain in wires which leads to final fatigue failure [32]. Urchegui et al. (2008) looked at the wear evolution of a 6*19 seale stranded rope that had been subject to bending and concluded that wear was more severe when the sheave diameter was reduced and as such coefficient of wear depends on the contact pressure [33]. Using the finite element method, Erdonmez and Imrak (2009) created a realistic structural model of a strand bending over sheave. The maximum stress and maximum displacement positions of the strand were respectively located over the upper middle of the sheave and at the fixed edge of the strand, according to the numerical results [34]. Other researchers looked into the impact of several factors on the bending over sheave fatigue life of steel wire ropes, including rope core type, tensile load, sheave diameter, bending length, sheave geometry and material, lubrication, zinc coating, and winding angle. Onur and Imrak (2012) conducted experimental experiments to demonstrate the impact of tensile load and sheave diameter factors on bending over sheave fatigue lives of 6* 36 Warrington-seal steel wire ropes. They found that as the tensile load increases and the sheave diameter decreases, the bending over sheave fatigue life decreases [35]. Giglio and Manes (2003) investigated the impact of the rope-to-sheave winding angle parameter on the bending fatigue life of non-rotating ropes used in airplane rescue hoists and concluded that there is a possibility of extensive not visible inner breakage taking place parallel to the visible, but less extensive breakage of exterior wires at bigger angles [30]. Gorbatov et al. (2007) investigated the impact of wire rope core type on the bending fatigue life of 6*36 Warrington-Seale rope (came to the conclusion that jute core had more fatigue strength and the service life was enhanced than the hemp core [36].. Zhihui and Jiquan studied fatigue failure behaviour of wire ropes caused by bending over sheave, together with analysing damage mechanisms of wire rope caused by fleet angle and angle of wrap and came to the conclusion that it is required to appropriately design the principle parameters, such as tensile load, diameter ratio of sheave to wire rope, groove material, rope structure, and wire grade, in order to optimize fatigue endurance of wire ropes bending-over-sheaves [37].

#### 4.1.3 Free Bending Fatigue

The bending fatigue of a rope is not always linked to its passing over drums or sheaves; there is also the case of free bending fatigue, which encompasses the rope's fluctuating bending deformation without coming into contact with other bodies. This mechanism produces curvatures which are less severe than those observed in ropes going over sheaves or drums, which have a significantly higher frequency. Kim (2012) observed that accumulation of bending fatigue leads to rapid deterioration of strength and when the fracture load of the experimental setup was small fatigue dominated the wear and vice versa [38]. In fixed rope applications, this type of bending frequently occurs near to a termination, causing extra local problems and the life of the wire can be of concern [23]. Some research has been done on the fatigue behaviour of ropes in free bending at terminations in this regard. Hobbs and Smith (1983) conducted a series of tests on spiral strand mast guy ropes that were ordained to cyclic transverse displacement at the centre. It was concluded that wire breakage began in the outer wires and progressed to the second layer, eventually leading the strand to total failure [39]. In another paper, Raoof and Hobbs (1984) claimed that the earliest wire breakages invariably happened around the neutral axis, rather than at the extreme fibre in bending terms [40].

#### 4.1.4 Torsion Fatigue

Wire ropes made up of a collection of interconnected wires that share the tensile load have overall qualities that mix axial strength and stiffness with bending flexibility. Because of this structure, the rope has a low torsional rigidity, which can result in low natural frequencies for torsional oscillations. If oscillations like these are excited and have the potential to reach large amplitudes, they can cause local "de-stranding" of the construction, which can be followed by kinking of individual strands if the line slackens [41]. Chaplin et al (2000) considered the moorings of floating offshore systems with hybrid mooring lines are an example of torsional fatigue. The concluded that Axial twisting can occur as a result of interactions between mooring line components with mismatched tension/torsion characteristics, which can be permanent or dynamic. Moreover dynamic twisting affects adversely upon fatigue endurance [42].

There are alternate rope constructions that are designed to lessen this tendency to rotate, but these typically have other drawbacks, such as a tendency to break up internally [43]and an exorbitant cost. This sort of ropes is known as non-rotating ropes and are made up of numerous layers of strands wired in opposite directions from one layer to the next. They prevent the suspended load from rotating at significant hoisting heights. In a wide load range, the geometric composition of non-rotating ropes is set so that the turning torque of the steel cores and the outer strands cancel each other. It prevents rope kinking in this way. Torsional oscillations can be formed in response to tensile fluctuations in some applications, particularly when components with varied torsional characteristics are linked end to end. Torsional fatigue is especially problematic in mooring lines that include six-strand wire and torque-balanced polyester ropes [44].The rope can experience torsional mode of fatigue in this application, with the twist amplitude appearing to be the most important parameter.

#### 4.1.5 Fretting Fatigue

Wire ropes operate at high stress levels and are nearly always subject to fluctuating loads and cyclic deformations; given enough time and a sufficiently enough stress range variation, fatigue is unavoidable. The fatigue of a wire, on the other hand, is not necessarily related to stress variation, because there is usually another mechanism that worsens and accelerates fatigue and concentrates it in well-defined places. This is referred to as fretting fatigue. Fretting is a prominent cause of axially loaded wire rope fatigue failure. Trellis fretting is caused by twisting at places of contact between wires when an outer layer crosses an inner layer of the opposite lie, whereas longitudinal fretting is caused by sliding along the lines of contact of neighbouring wires. It is caused by friction between adjacent wires, which causes the steel wires' fatigue life to be reduced and the rope's failure to be accelerated. The interwire contact area grows as a result of cyclic loading. As a result, the interwire friction generates more heat, lowering the viscosity of the grease and allowing it to escape to the rope's outer layers. The fretting wear between contacting wires accelerates at this point, and the degradation accelerates until full rupture occurs. As a result, fretting fatigue plays a significant part in the degradation of ropes in use. Hurricks studied fretting and divided into three main processes viz. the first process is the initial adhesion and metal transfer, the second is the oxidised debris production and the third is the steady wear rate [45].

Several investigations were carried out to determine the fretting parameters of wire ropes. Waterhouse (1971) observed that the fretting is dependent on the stress concentration between slip and non-slip regions [46]. Gnanamoorthy observed that the most important parameters of fretting as slip amplitude, contact pressure and frequency of applied loads [47]. Following up on Hobbs and Raoof's (1994) investigation, in which they discovered that quasi-punctual connections have more breakings than linear contacts, they determined that the smaller the contact area, the higher the contact stresses [48]. Raoof and Kraincanic (1995) looked at how Von Mises stresses were distributed in two wires of consecutive layers in punctual contact with fretting [49]. Based on a Cartesian iso-parametric formulation, Nawrocki and Labrosse (2000) created a finite element model of a simple straight wire rope strand. They showed that for axial and bending loads, interwire pivoting and interwire sliding dictate the rope response, respectively [50]. Kumar and Botsis (2001) used the linear deformation derivative results to derive analytical formulas for the maximum contact stresses for multi-layered wire rope strands under tension and torsion in their study [51]. Sun et al. (2005) proposed a Cartesian iso-parametric formulation for modelling a simple straight strand using finite element analysis to tackle the contact problem between the helical wire and the multi-layered strand's centre wire [52]. Ghoreishi et al. (2007) went on to build and evaluate an analytical model for steel wires under axial loads with infinite friction between the wires and the core [53]. Jiang et al. (2008) used a finite element model to investigate the contact problem of basic 1*7 wire strands and concluded a simultaneous contact between the core and helical wires and between adjacent helical wires [54]. Meriaux et al. (2010) used an acoustic emission device to execute a fretting fatigue test in order to determine the crack propagation phases and identified three stages of global crack propagation [55]. Argatov (2011) solved the nonlinear model of interwire contact deformation using the approach of matched asymptotic expansions and found the constitutive equations for a helical wire rope strand subjected to axial and torsional loads [56]. Wang et al. (2012), on the other hand, investigated the effect of several kinematic parameters on hoisting rope fretting parameters [57].

## 4.2 Corrosion

During use, wire ropes are dynamically complex systems with several moving parts that function in a variety of environments. They are not only liable to internal and external abrasion, but they are also susceptible to corrosive effects, which limit the load-carrying capacity and service life of the wire. The presence of moisture or precipitation, allows water to penetrate the fasteners, causing the rope to corrode. Corrosion is a chloride reaction whose rate is accelerated by temperature, air pollution, and water pollution. Corrosion of an unmaintained wire rope is not restricted to its external surface; it damages each wire separately. As a result, the metallic area of each wire is constantly reduced, as is the wire's vulnerability to corrosion fatigue during bending over a sheave. Deep corrosion pitting on the inside surfaces of wires can also significantly reduce their service life. The use of lubricants to working ropes, on the other hand, provides a dual sort of protection in that it reduces friction between individual wires while also protecting the entire wire from the corrosive action of sea water.

For a long time, researchers have been interested in the corrosive effects of sea water on wires that have been immersed for extended periods of time. When the wire in use is not protected by either a lubricant or a rust preventive, corrosion rates vary from one spot to another in the ocean. Suzumura and Nakamura (2004) conducted experimental investigations into zinc dissolution rates of galvanized wires extracted from suspension bridge cables, and concluded, the side and bottom wires were the most corroded while the top and centre wires were least affected. Also relative humidity above 60% rapidly escalates corrosion and the corrosion rate increases exponentially with temperature [58].

The endurance performance of steel wire rope mooring lines in seawater has been studied through research. At the Marine Corrosion Research Laboratory in the warm waters near Key West, Florida, Lennox and colleagues studied fully and partially immersed wire ropes. They discovered that galvanization only protected the rope for 12 months. Swam (1970) conducted the seawater exposure experiments on wire ropes. In a seawater environment, he reported the lifetimes of different thicknesses of galvanized plating and concluded that coating the strand is more effective than coating the wire and the life of a galvanised coating is primarily a function of its thickness. On observing the appearance of 14-gauge galvanized steel wires with four different zinc coating weights after 13 and a half years of exposure in the atmosphere at a distance of 800 feet from the ocean, It was evident that increasing coating weight results in better performance [59].

British Ropes Ltd (1979) selected a number of samples from galvanized six-strand mooring rope that had been used as a mooring line for ten years and evaluated them for residual breaking load. They discovered that, despite the significant loss of zinc coating on the strands' outer wires, the residual breaking load after ten years of service was only around 6% less than the original breaking load and only slightly less than the manufacturer's rated breaking load [60]. However, in an experiment conducted by Li et al. (2012), it was discovered that employing other zinc-aluminum alloys as an alternative to zinc can provide a useful extension. Plastic sheathing, which is mostly used for spiral strand, provides far more effective long-term protection. Li has been using Acoustic Emission (AE) technology to track the progression of fatigue damage on corroded and non-corroded steel wires in recent years. They discovered that the mechanical performance of corroded cables differs significantly from that of non-corroded cables [61]. In their work, Wang et al. (2012) used Slow Strain Rate Tests to investigate the stress corrosion behaviour of steel wires in coalmines under various corrosive media and found that tensile strength in all corrosive media was significantly lower than in air (SSRT) [62]. Sung, on the other hand, employed a bending fatigue test to perform repeated bending tests on corroded wire ropes used in elevators. They came to the conclusion that an increase in accumulated corrosion fatigue and repeated bending cycles could result in a rapid reduction in fracture strength and an increase in the number of broken wires, lowering wire rope life expectancy. Meknassi et al. (2015) recently conducted an accelerated test to assess the impact of corrosion on steel wire mechanical properties. And the results achieved from tensile tests on virgin and corroded specimens distinguished the three phases of corrosion damage and the proportionality between decrease in strength and number of immersion hours was proven by the experiment [63].

## 4.3 Wear

Wear is one of the main modes of degradation for steel wire ropes. Internal wear happens as a consequence of friction between the rope's wires, and exterior wear occurs as a result of the rope bending over sheaves or drums. In the vast majority of rope applications, the latter is the more common. The bending stresses generate point contacts and excessive wear, reducing the rope's safe working life. Abrasive wear occurs most commonly between the wire rope and the sheave, as well as between the wire rope and the drum, but the most common cause of abrasion is interference at the drum Reverse bending over sheaves is another cause of severe wear in wire ropes, which cuts the rope's lifespan in half. Reverse bending is defined as the bending of a rope over sheaves, first in one direction and then in the opposite way. Furthermore, a new wire rope may be damaged and not perform properly if the sheaves have grown worn or the grooves have become uneven in shape. It is also more acceptable to replace worn or damaged sheaves than allowing excessive wear on the wire rope. Twisting of the hoisting rope is one of the reasons of significant rope wear in the hoisting application. The wear created by twisting the rope and making a hoist is equal to that caused by weeks of typical use. According to Schrems (1995) inter strand wire to wire contact is the most severe and is the major cause of wire breakage [64]. Chang (2020) concluded that corrosion reduced the wear resistance and enhance the wear evolution [65].

# CHAPTER 5: FATIGUE AND WEAR TESTING

The steel wire rope is one of the most significant loading and bearing tools in industries, and has received more attention in ensuring safety and health monitoring owing to devastating accidents which have not only resulted in economic losses but also loss of precious human lives. A number of problems or defects, including broken wire, abrasion, wear, and corrosion, manifest due to the prolonged loading and functioning of wire rope as mentioned in the previous section, and if care is not taken, catastrophic results are inevitable. The wire rope defects are categorised into two main types viz. the localised faults (LF), and loss of metallic area (LMA) [66]. The LF damage includes locally produced damage like broken wires and corrosion pitting. The LMA refers to the deterioration of wear and abrasion. Although there are a number of testing techniques that can be used to test steel wire ropes, including magnetic flux leakage (MFL) testing, eddy current testing (ECT), acoustic emission (AE), ultrasonic guided wave testing (UGWT), and radiography testing techniques, the electromagnetic non-destructive testing (ENDT) method is the most effective and practical. The fundamental detection principles, procedures, pertinent instrument, and calibration method through electromagnetic testing methodology are prescribed in detail in related standards including the European norm EN 12927-8 [67], the ISO 4309 [68] , and ASTM E1571 [69]. More and more electromagnetic non-destructive testing devices have been developed and patented as the physical mechanisms of highly accurate and sensitive sensors, like the hall element and magneto resistive element, have been discovered by researchers. Despite the gradual rise in popularity of visual inspection methods using cameras and machine vision techniques in the literature, these techniques are only effective for evaluating steel wire rope's surface deterioration. The process of signal processing, after the signal acquisition and pre-processing, is crucial for improving the signal-to-noise ratio (SNR) and sensitivity of inspection, Numerous signal processing methods and techniques like frequency and spectra analysis, impulse filter design, feature extraction have been investigated and described.

## 5.1 Detection Methods

### 5.1.1 Magnetic Flux Leakage (MFL) Testing Method

MFL testing methods for steel wire rope is one of the widely used and the most popular electromagnetic non-destructive testing techniques [70]. The magnetic flux leakage will cause the magnetic resistance to change and be induced by the magnetic sensitive elements, like coil and hall sensors, when the wire rope defects viz. LF and LMA appear and are scanned by the leakage scanning instrument. The excitation sources for the magnetization devices can include permanent magnets, direct current (DC), or alternating current (AC) [71]. Wire rope defects or discontinuities are found and displayed following data collection and signal processing. The principle followed is, when a coil or permanent magnet activate the WR, internal and external damage will cause the magnetic flux to fluctuate. The signal is then detected by some devices like induction coil or an integrated sensor (such as a Hall sensor or magnetoresistance sensor), and via additional processing and analysis of the signal, the type or extent of damages can be determined to some extent. The typical detection concepts are diagrammatically displayed in Fig.35 [72]

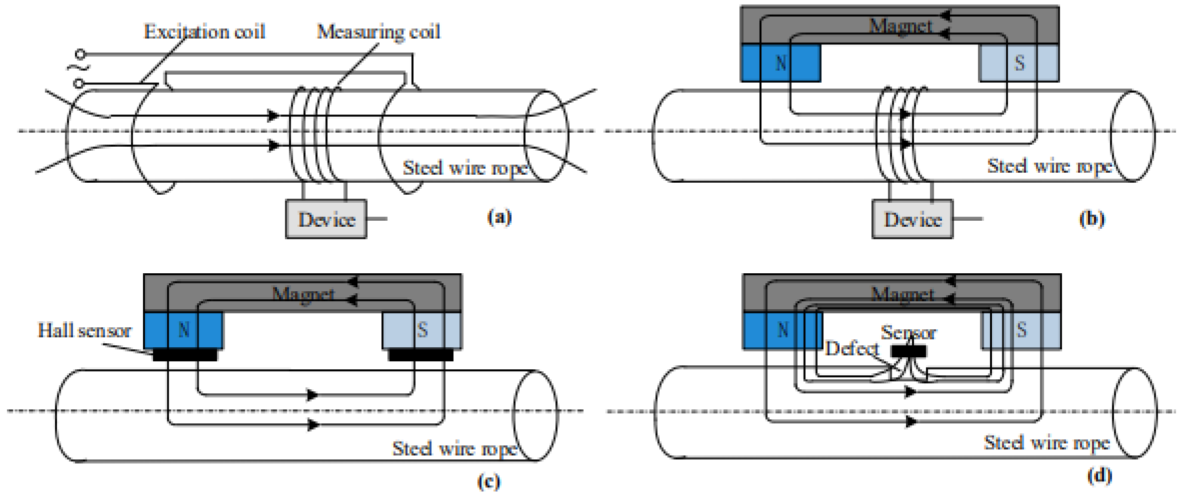



Fig.35: Electromagnetic non-destructive detection principle of steel wire rope.

Various MFL detection methods have surfaced and been proposed in recent years as wire rope detection methods. For instance, Seunghee Park et al. used a 4-channel MFL sensor to demonstrate the viability of wire rope LF fault detection [73]. In order to simulate the effects of sensor lift off, magnetizing condition, and angle change of the Hall sensor, Zhang analysed the eccentric issues between the exciting device and wire rope in the MFL testing. Zhang came to the conclusion that the eccentric state had an impact on the detection signals and the results of the quantitative analysis [74]. Wang evaluated and validated the efficiency of altering the air coupling distance in increasing the signal to noise ratio from the perspective of magnetic circuit design by simulating and computing the influence of sensor lift off fluctuations [75]. In addition, wire rope fault locating presents many difficulties. Through 20-channel signal analysis, parameter optimization, and COMSOL Multiphysics simulation, Liu looked into the viability of LF defect location and detection, and the results were later verified by the experiments [76]. The classic main-flux and return-flux methods, which are based on the idea that the strength of the flux is roughly proportionate to the loss of metallic cross-sectional areas of the wire ropes, are frequently used to measure LMA flaws such wear and corrosion. By applying magnetic energy directly to the steel wires in bridge cables, Wu et al developed a new LMA defect detection method, which was shown to be effective by an analysis of Kirchhoff's law and experimental verifications [77]. A new MFL measurement system was suggested by Zambrano that utilized two groups of sensors distributed axially and radially to accurately and reliably detect surface defects in wire rope [78]. The lift off effect, however, easily affects the MFL testing procedure for wire, making the detection signals weak and the defects challenging to spot. MFL testing methods can only detect surface or near-surface defects in large diameter wire ropes because of the wide range of magnetization intensity and structural complexity of ropes. The geometrical and physical parameters of the magnetization devices as well as the service circumstances also have an impact on the testing signals and findings, which present significant obstacles for MFL testing.

### 5.1.2 Eddy Current Testing (ECT) Method

ECT is another electromagnetic testing technique that is sometimes used [72]. A small area of eddy current is produced in the steel wire rope when the alternating electric current is altered in an exciting coil that is placed above the tested items of steel wire ropes with a specific excitation frequency and lift off distance. The impedance of the receiving coil varies if any fault or discontinuity in the tested steel wire rope is manifested and is scanned by the ECT detector or the receiving coil; this causes the ECT signals to reflect the defect information. The principle is shown in Fig.36

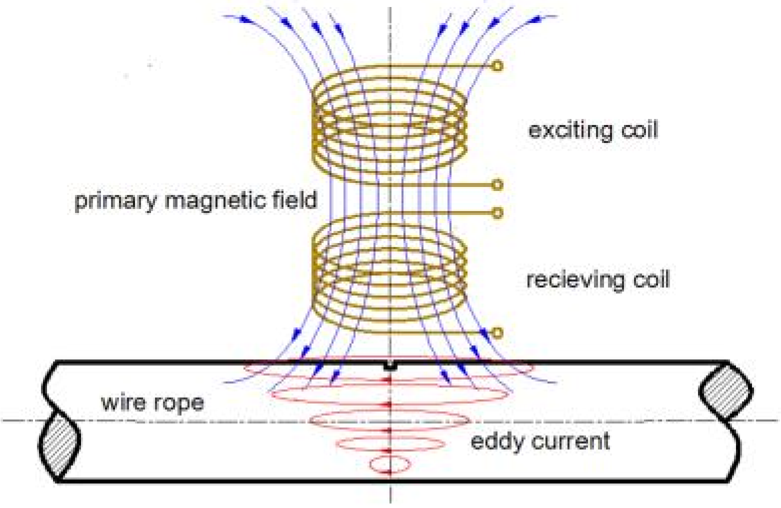



Fig.36: Principle of Eddy Current testing

Evidently because of the skin effect, ECT methods are typically effective for detection of surface defects only and are not suitable for detecting deep defects in wire ropes. Since the development of the theories governing wire rope electromagnetic testing, a variety of solution models have been put forth, like the theory of transfer impedance, the quasi-static theory, the infinite integrals etc [79]. For wire rope systems, early theoretical research and analytical evaluations tended to focus more on computing current density and impedance variation through solenoids or feed-through coils like the one performed by Hill and Wait who concluded that frequencies greater than 10Hz have a poor penetration and exciting solenoid and sensors should be as proximate as practically possible to maximise the effect of relative scatter field [80]. Some recent studies have tried to calculate the eddy current loss utilizing 3-D finite element analysis like the use of Back Propagation (BP) neural network by Dou and Wang owing to the use of lot of experimental data and subjective factors that result in errors. The outcome of the study was that this method did not require a sophisticated model and only required input and output parameters. Moreover, the ensuing experimentation proved this method to be more accurate in quantifying the number of broken wire than the traditional methods [81]. Although several advanced ECT setups were created when the eddy current loss was taken into account, it is challenging to balance the reactive and resistive components by properly adjusting the potentiometers. Judge et al used the finite element model to fully model the strands and observed that not only was this method able to predict the global responses like the axial stiffness and the load carrying capacity, it was also proficient in predict non-linear local effects like localised yielding and plastic hardening [82]. Hiruma et al. investigated the eddy current loss using fast 3D analysis utilising the Integral equation and observed the ease with which this method can be used to model complicated windings as there was no need to discretise the cross section for example into elements [83]. The development of the ECT method has led to the application of numerous novel techniques for the detection of steel wire rope defects. Wu et al. studied motion induced eddy current and evaluated its effect on the circumferential magnetisation [84]. She et al. studied the optimisation of remote field eddy current testing (RFECT) owing to it being unaffected by skin effect and material properties. They observed that the distance between the excitation coil and the detection coil can be shortened by adding a shielding plate. The detected signal can be amplified by the ferromagnetic ring, and the closer it is to the detection coil, the stronger magnetic flux density will be seen there [85]. These techniques are aimed at addressing the drawbacks of traditional ECT defect detection for wire ropes. The primary obstacle in the ECT is the skin effect and Eddy current loss which negatively impact the determining factors like the frequency and amplitude of the alternating current in the exciting coil and the conductivity and permeability of the steel wire rope.

### 5.1.3 Acoustic Emission Method

Acoustic emission (AE) is the term for the transient elastic wave phenomenon caused by the quick release of energy in the material's immediate vicinity when it is subjected to external influences. Based on the piezoelectric phenomenon, acoustic emission sensors can transform transient elastic waves into electrical signals and analysis of these signals can be used to infer changes in interior damage as shown in Fig.37 [72]

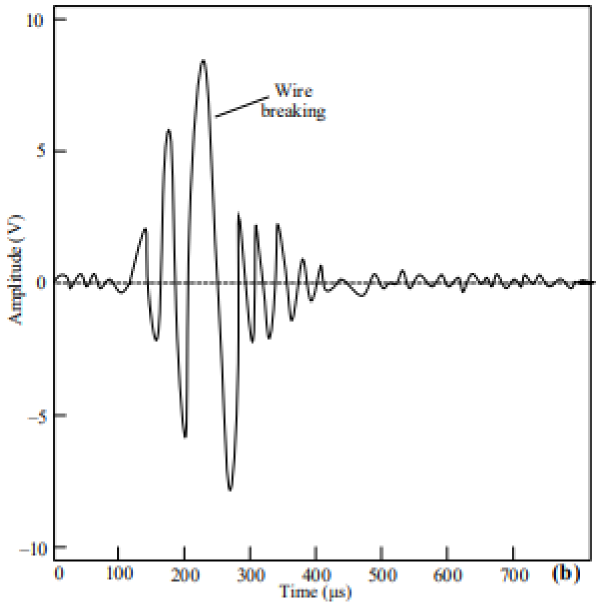



Fig.37: Sketch map of wire breaking signal

The underlying principle involves installation of the wire rope on the tensile test bench and two acoustic sensors are planted near the centre of the rope. The data from the loading is collected by the acoustic emission equipment and analysed to indicate the location and occurrence of defects. The schematic diagram is shown in Fig.38 [72] and the working principle is shown in Fig.39

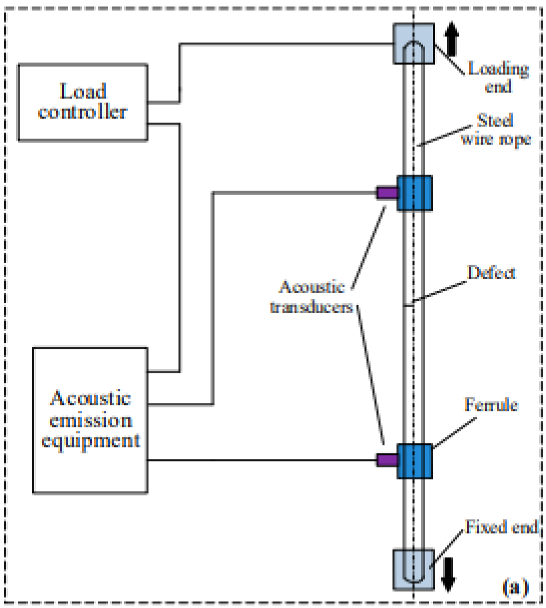



Fig.38: Schematic diagram of detection system

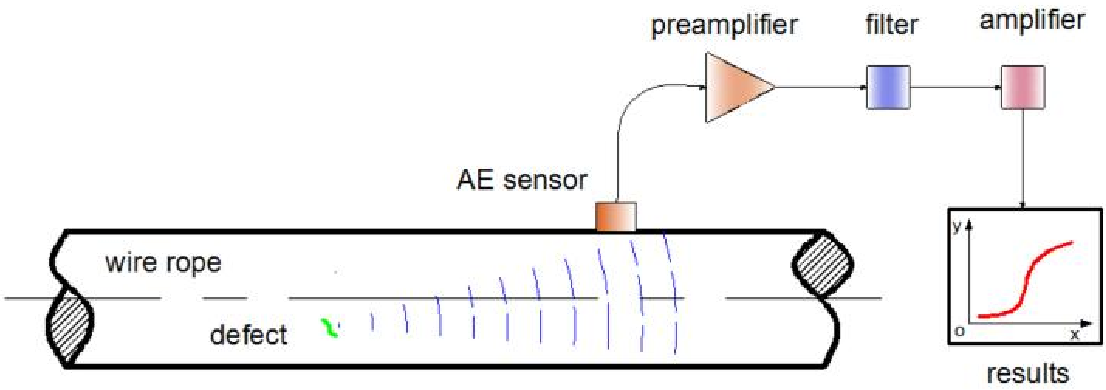



Fig.39: Principle of Acoustic Emission Testing Method

Laura et al were the pioneers of studying the available literature related to this method of testing [86] and observed the main utility of the AE Method is in detection and location of wire breaks with rope construction, rope diameter, length and number of broken wires being the constraints. Numerous studies have been reported in recent years, and the majority of them concentrate on the analysis of AE signals when the tested wire rope is subjected to static and cyclic load conditions and for the monitoring and evaluation of wire rope health like Salamone et al. They used eight piezometric sensors for real time tracking of damage progression. They observed amplitude distribution analysis which enabled the identification of yielding state and AE triangulation made it possible to locate the damage location which wasn't recognised during visual inspection [87]. In order to detect wire rope defects, more sensitive instruments and equipment have emerged, particularly for tensile, fatigue, and internal break and defect detection. There have been numerous reports of the AE method's use in fatigue testing, proof loads, and the detection of frayed steel wire rope and bridge cables. Zejli et al. used the AE method to find broken wires in the anchorage zone. The observed the huge influence change of surface conditions, contact strength between wires and the recovery length of the broken wire on the AE parameters and concluded the control of two main vibration like amplitude of bending and frequency is essential to detect broken wires [88] . Casey et al. used an AE transducer either attached to the end connection or remote from the wire rope to acoustically identify wire-break flaws for wire rope submerged in water. and also analysed the influence of the wire rope structure, the size and the number of broken wires on the AE monitoring results. They also looked into the frequency spectra and components of the discovered signals due to the lack of shear waves [89]. Acarnley et al. conducted an experimental investigation into enhancement of proof loading and fatigue testing procedures utilising AE signals and concluded that AE signal energy and amplitude could be used as a measure of wire rope defects as it is possible to distinguish acoustic transducer signals from wire breaks and other parts of wire rope, with best distinguisher being energy and amplitude [90]. By gathering AE signal waveform characteristics and frequency distributions for various defect kinds, Li et al. established the AE characteristic parameters for fatigue damage of bridge cable and observed that the fatigue damage evolution can be expressed according to the cumulative AE curves [91]. Shi et al proposed an innovative monitoring technique which utilised  waveguide and accurately located the transition section of the wire break defect and observed that when a wire breaks during a tensile test, the transverse position of the break cannot be determined by examining the AE signals collected by each sensor, but it can be determined during the process of defects prior to the wire breaking [92]. Neslusan et al presented a systematic evaluation of corrosion via Barkhausen noise emission. It was observed that the Barkhausen noise parameters show a good sensitivity to variable corrosion depth [93]. This method is potential for usage in real applications since it may be used to predict early faults and defects for wire rope before they happen thanks to the dynamic detection characterizations of AE methods. The AE approach has, however, shown to be challenging for differentiating between various wire strands when they break and other flaws occur at the same time, particularly when the wire rope is under harsh surface conditions like corrosion etc. Additionally, because the typical AE testing signals are so weak, it is more difficult to interpret the signals, identify microdefects, and pinpoint their locations.

### 5.1.4 Ultrasonic Guided Wave Testing Method (UGWTM)

One of the widely used techniques for examining non-homogeneities for the internal structure of wire ropes is the ultrasonic guided wave testing. The setup comprises of the computer, the ultrasonic measurement system, the preamplifier, the transmitter, and the receiver as can be seen in the schematic diagram in Fig.40.

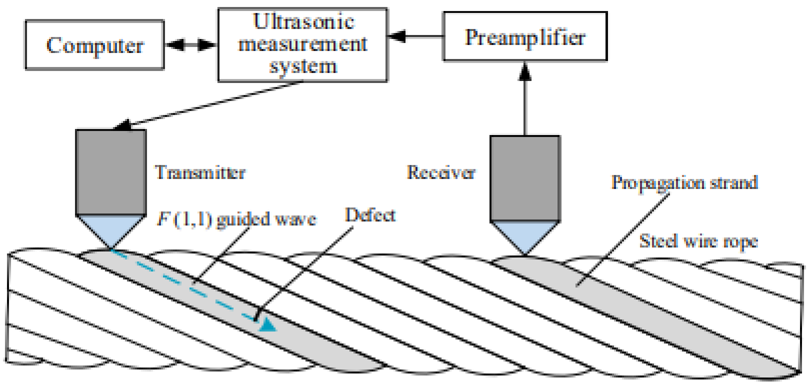



Fig.40: Schematic of Ultrasonic Guided Wave Testing Method

The principle involves launching a wave on the wire rope, and during the propagation, the sound wave is reflected (acoustic reflection) when it travels through the damage. The damage in wire rope is then examined by analysing the echo. The principle can be understood from Fig.41.

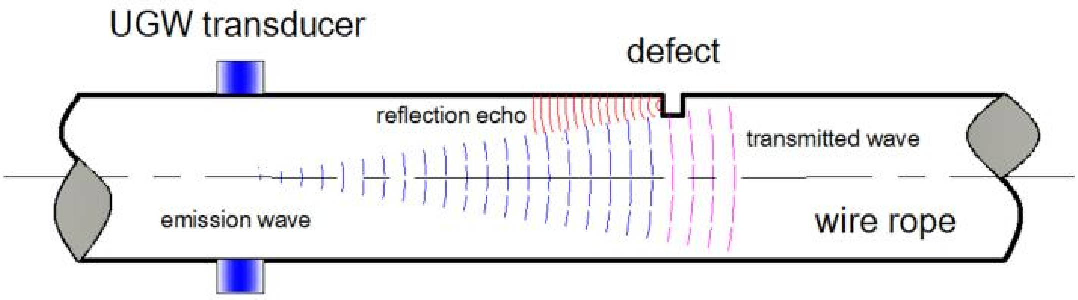



Fig.41: Working Principle of UGWTM

The ultrasonic guided wave testing (UGWT) approach could be considered an active testing method in contrast to the passive non-destructive testing method of AE. The most important part of UGWT is the transducer piezoelectric wafer which not only generates but also senses the guided wave. In practical applications of defect detection, the usual lamb wave and the shear horizontal wave are both extensively used. The Rayleigh wave has also received considerable attention in several papers. Another clear benefit of UGWT over conventional electromagnetic non-destructive testing is its capacity for long-range and non-contact defect detection.

Liu et al. optimized the magneto strictive transducers configuration for both transmitter and receiver for the generation and reception of ultrasonic longitudinal guided waves. Therefore, by employing ultrasonic guided waves in a pitch catch configuration, magneto strictive transducers with an optimal configuration, including permanent magnet distribution and multilayer coil connection, could be employed effectively for inspecting seven-wire steel strands [94]. Treyssede et al. investigated the elastic modes of propagation in multi-wire helical waveguides. By using a semi-analytical finite element approach and calculating the signal energy, the dispersion curve of a spiral wire rope was obtained, and the ideal excitation and receiving positions for an ultrasonic guided wave were computed [95]. Vanniamparambil et al. studied a novel optico-acoustic testing which combined digital image correlation guided ultrasonic waves and acoustic emission to detect wire breaks. The combined features demonstrated impressive potential for both load monitoring and wire breakage detection in real time [96].Xu et al. proposed the detection of broken wires at multiple locations using guided waves and it was observed that guided waves at higher frequencies attenuated energy more quickly, and elastic waves' reception lengths grew longer as frequency rose [97]. Raisutis et al. examined the propagation properties of various UGW across strands and cores of wire rope and their influence on the penetration depth of wire rope. They observed that UGW travel mostly along the same strand on which excitation by a normal force has been applied indicates that the acoustic contact between neighbouring strands of the genuine multi-wire rope is on the verge of slip [98]. The effectiveness of using the magnetostriction of ferromagnetic materials was investigated by Tse et al. relying on the UGW method for wire rope damage inspection, and the location and severity of damages were roughly identified and characterized using the short-time Fourier transform and wavelet analysis [99]. By using a laser ultrasonic experimental setup and wavelet transform signal processing techniques, Rizzo et al. investigated the wave propagation issues in multi-wire strands and described the longitudinal and flexural waves in terms of dispersive velocity and frequency attenuation [100]. Xu et al. utilised magnetic flux leakage and magneto strictive guided wave hybrid transducer to inspect bridge cables and the experimental findings demonstrate the viability of the new approach and transducer for broken wire inspection [101]. Salamone et al. estimated corrosion damage using guided ultrasonic waves. They proposed a reference-free algorithm to estimate the cross-section loss by employing dispersion curves and wave velocity measurements [102]. However, due to the attenuation of the reflected UGW signal energy generated by the covering dirt and grease as well as the harsh operating circumstances for various types of steel wire ropes, the inspection distance will be drastically reduced. The UGW parameter tuning and quantitative evaluation for on-site wire rope defect detection may present additional difficulties and emerging directions. Additionally, the transducer's novel design is essential for enhancing detection sensitivity and accuracy.

#### 5.1.5 Radiography Testing Method

Since part of the radioactive rays are absorbed by the tested wire rope and the remaining radioactive rays can penetrate the tested steel wire ropes and be captured or reflected on the film, producing the black and white test images, radiography testing has been used extensively in wire rope inspection and other engineering industries. Evidently, the density, thickness, and other properties of the material affect how much radiation is absorbed by or penetrates the tested wire rope. As a result, the degree of blackness in the testing photos on the film accurately depicts the state of the steel wire ropes that were put to the test. The schematic is shown in Fig.42. Poranski et al. studied X-ray backscatter tomography for non-destructive evaluation and observed that while the X-ray testing method and apparatus were applicable, they weren't always the best choice for a given NDT application [103]. Peng et al. utilised gamma rays in the inspection of steel wire ropes in suspension bridges and developed two assessment techniques viz. exposure time formula and sensitivity assessment of steel wire ropes. Later experimentation proved the use of the gamma rays being helpful in improving the safety of bridges [104]. Chakhlov et al. examined various digital radiography system topologies and proposed a the approach of proximity of the invariants for the unit cross section of wire rope to analyse digital radiographic image algorithms [105].

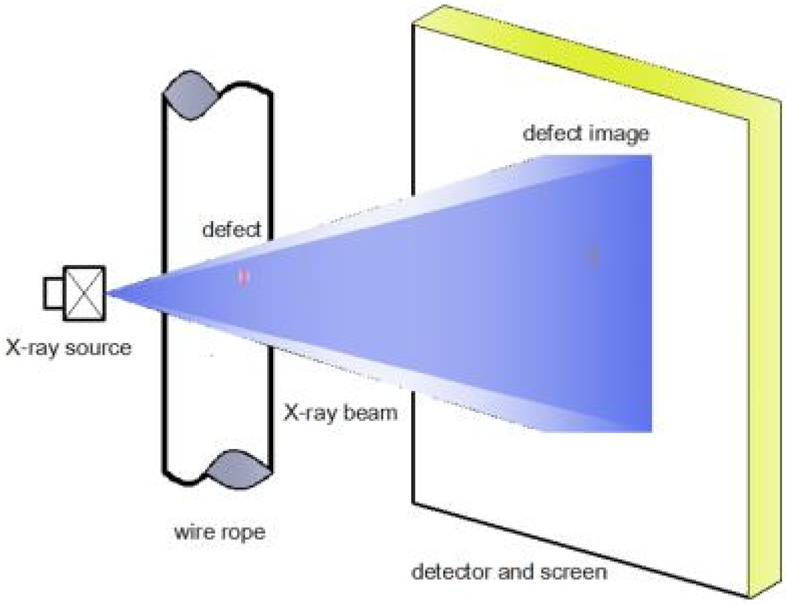



Fig.42: Schematic of X-Ray testing method of wire rope

Owing to the harmful effects of radiation and the sophistication of the radiography equipment there are many challenges in utilising this ,method extensively. The parameters of radiology like the radiation intensity exposure time adjustment and film evaluation are some of the obstacles that are faced as of now.

### 5.1.6 Optical Detection Method

Another non-destructive and effective detection method used is the optical detection method. The underlying principle involves the capture of image followed by damage diagnosis and the working principle is shown in Fig. 43. A high speed camera is used to capture the image of the surface of the wire rope which is the preprocessed and undergoes pattern recognition to diagnose the damage. The situation determines the hardware and software setup of the picture capture system ; the captured images are then processed using pre-treatment techniques like cutting or filtering [72]. The constructed feature datasets are then subjected to dimensionality reduction after features have been extracted using techniques like local binary pattern and gray level co-occurrence matrix. Finally, robust classifiers for state recognition of unidentified images are obtained by training and evaluating machine learning classifiers (such as support vector machines, artificial neural networks, etc.) [72].Vallan et al. studied Vision-Based technique for lay length measurement of metallic wire ropes and proposed a measurement system that is based on a video camera and on an offline processing algorithm. The system is built around a camera that records flowing rope images continually. An algorithm that extracts the rope contour from the rope photos processes the images offline. To extract the basic component, whose period corresponds to an integer fraction of the rope lay length, the contour is analyzed using a fitting technique [106].

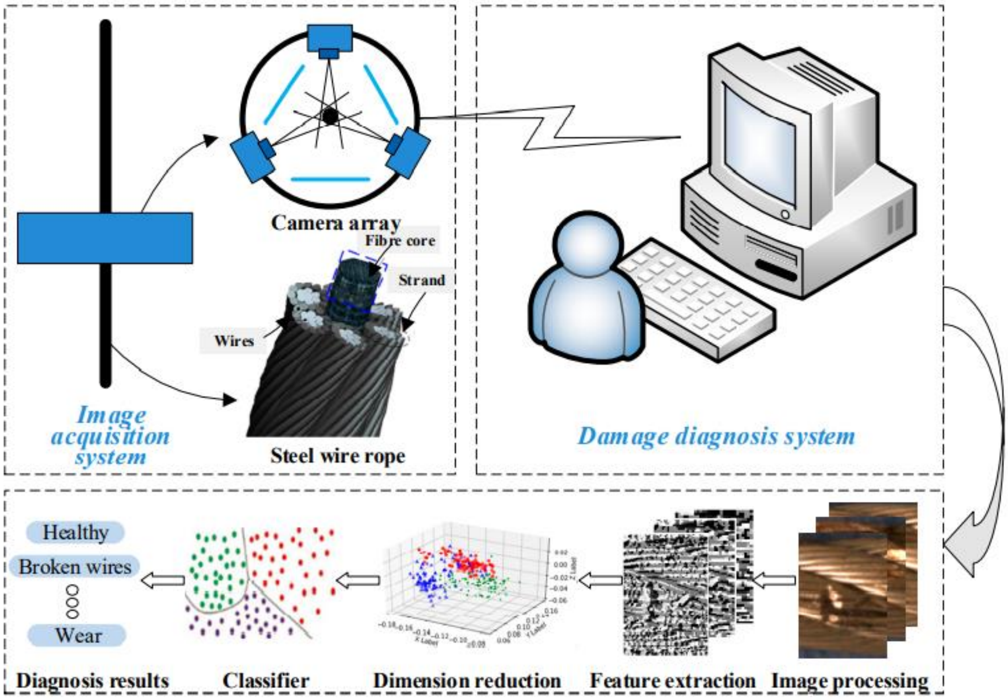



Fig.43: Principle of optical detection method

Yaman and Karakose proposed fault detection approach with image processing for elevator rope monitoring. The suggested approach is based on auto correlation and image processing. The cameras that are fixed to the elevator system are used to take pictures. By removing the margins from the photos, the elevator rope's location is discovered. As a result, the elevator rope is constantly being watched. The grayscale image has a gap where the detected rope should be. Applying auto correlation to the acquired image allows the observation of the elevator rope. With the use of the auto correlation approach, it is transformed into image signals. The resultant auto correlation signal is used to generate the difference signal. Rope fault is discovered when the differential signal has high values [107]. Platzer et al. used a novel approach to employ Hidden Markov models for defect localization in wire ropes and the results depicted a great advance in the field of visual technology [108].

### 5.1.7 Other detection methods

Apart from the methods discussed above, there are some other methods which are currently being developed owing to the advancement of technologies. Magnetic memory inspection and human vision inspection are used in some rare and special cases. machine vision and thermos-vision inspection techniques are becoming more and more popular, thus increasing the level of automation and practicality of operation in wire rope inspection. Robar developed a novel method which utilized the measurement of the resistance in the wire rope after the current is passed to detect defects. The other detection methods are shown in Fig.44

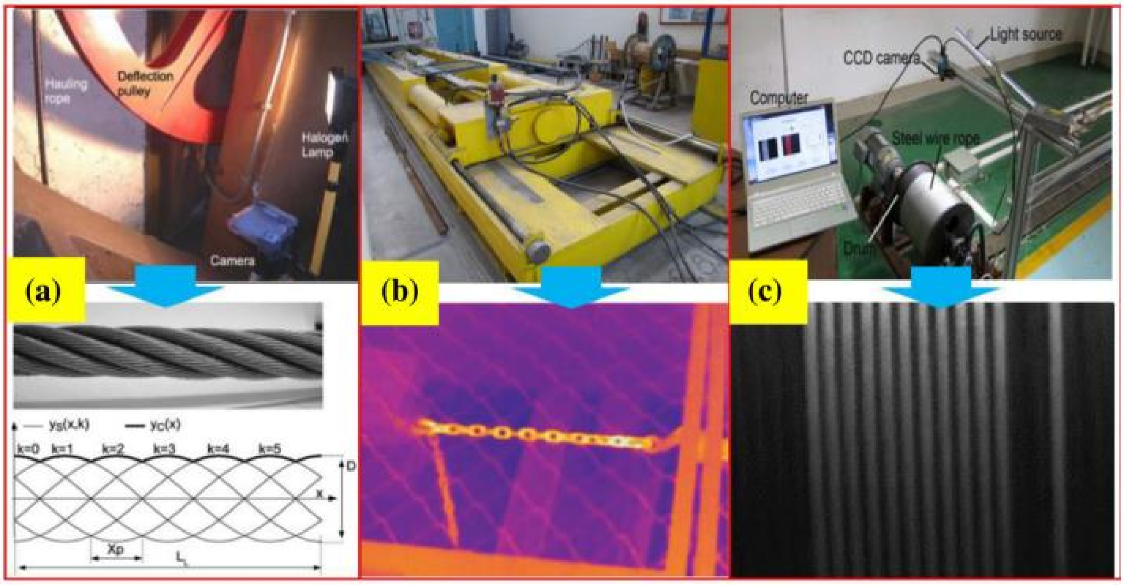



Fig.44: Other testing methods: a) Laser light method b) Thermal Imaging c) Machine vision

## 5.2 Detection Sensors

### 5.2.1 Induction Coil

Coils have been the most widely used electromagnetic sensors to transform magnetic impulses into electric current signals ever since Michael Faraday discovered the law of electromagnetic induction in the eighteenth century. Induction coils are primarily used to sense various magnetic components from many directions, so the flux may be reflected by the output electric current signals from the coils, according to the principles of electromagnetic non-destructive testing . There are various types of induction coils for steel wire rope defect detection, including the planar coil, Rogowski coil, three-axis coil, and flexible printed coil, which significantly increase the detection range for magnetic flux in wire rope inspection due to the requirements for higher sensitivity and accurate detection capability. Some types of induction coils used are shown in Fig.45 [101] [109]. The detecting abilities will also be improved by using varied induction coil connection and distribution types. Additionally, the induction coil has evolved from the conventional solenoid coil to an open magnetization coil, which enhances the coil sensor's overall functionality and detection operating convenience. In response to varied engineering requirements, coil sensors have become increasingly small and light. In the past century, Harmon [68] patented a wire rope flaw detection system that used an oscillator-energized induction coil. Kalwa studied the design of inductive sensors for testing of steel ropes and observed the character of the output signal and the sensitivity depend on the profile of the magnetic concentrators in the sensor [110].They conceived and designed a novel inductive coil for wire rope that had a magnetic concentrator, was more affordable, and required less effort to use during routine inspection.

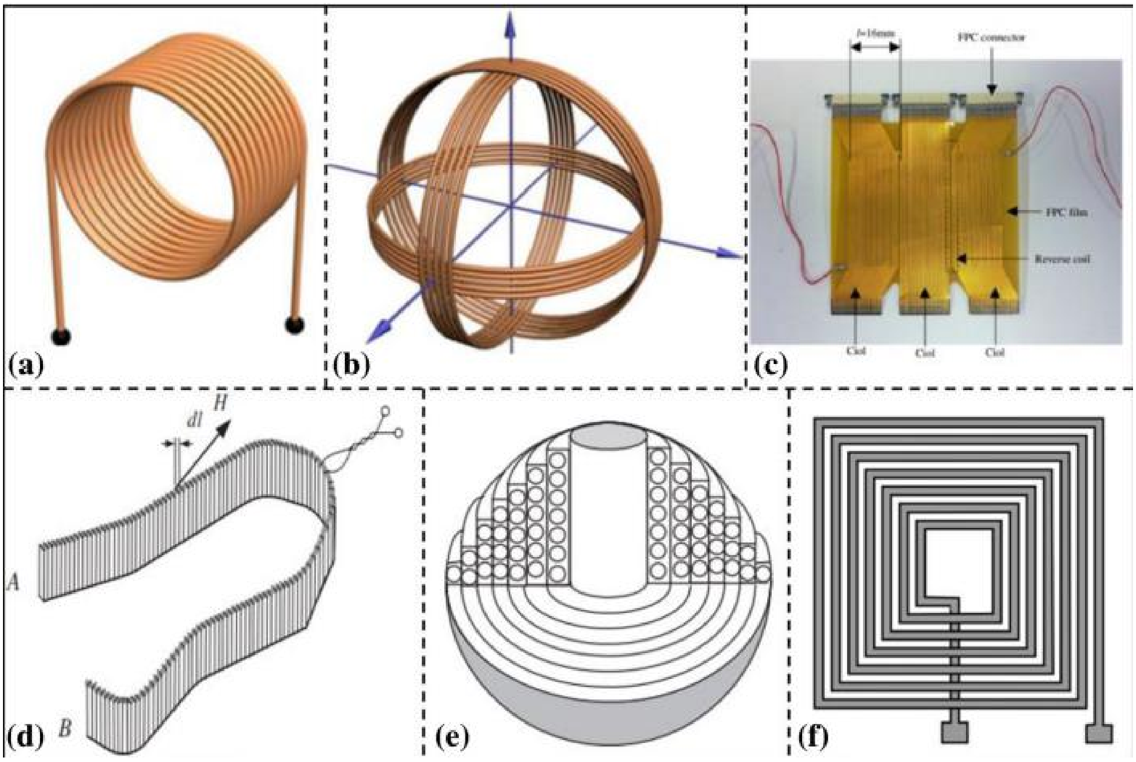



Fig.45: different types of inductive coil sensors. a)The spiral coil, b) three-axis perpendicular coil, c) flexible printed coil, d) Rogowski coil, e) spherical coil, f) Planar thin film coil

When two sensor coils are mutually coaxial and paraxial with the tested wire ropes, a differential triple-coil tester with periodic wire strand effect cancellation by an electrical coil operated by an alternating current was created by Grimson [111]. Zhang et al. also designed a new type of Rogowski air coil sensor to eliminate the signal attenuation and have a sensitive sensor instead of the traditionally used sensors. It eliminated the initial resonance notch frequency and employed adjustable balance impedance to locate high-voltage power cables with greater sensitivity [112]. Tumanski studied the multi coil sensoe for magnetic field investigations utilising numerical and experimental analysis [113].

The complexity of the identification for wire rope defect signals is increased by the induction coil's sensitivity to the strand characteristics and noise signals in on-site wire rope. Additionally, inductive coils are sensitive to how quickly detectors scan, which complicates the components of the output signal. Because working velocities vary, it is difficult to utilize in online wire rope monitoring and inspection. Misron et al studied the effect of inductive coil shape on sensing performance of linear displacement sensors and observed that particular coil shape has its certain advantages and disadvantages. They observed that a caircular shaped inductive coil has a low linear response but high sensitivity. Likewise the square coil has high linearity and medium sensitivity [114]. Devkota et al. proposed a novel approach to increase the sensitivity of inductance coil sensors by creating a sensor core with several soft ferromagnetic microwires as its core. Additionally, due to the advancement of nanotechnology, some wearable, wireless, and RFID sensors are also a new development in the field of non-destructive testing. All these technologies use the induction coil as their primary component and enhance the detection sensitivity and application range.

### 5.2.2 Hall Element

The hall sensor, which primarily relies on the Hall Effect, is another sensor that is widely used. The hall element sensor and the inspection signals are obviously independent of the scanning speed according to the Hall Effect principle, as schematically illustrated in Fig.46. Wire rope testing and defect size identification is made easier, especially in quantitative non-destructive testing. Additionally, because the output signals of the hall element are directly related to the absolute magnetic field strength, the Hall sensor is particularly well suited for the identification of defects that result in a loss of metallic cross-sectional area (LMA), such as abrasion and corrosion.. Hall sensors have been utilised in extreme environments like high temperature and high speed.

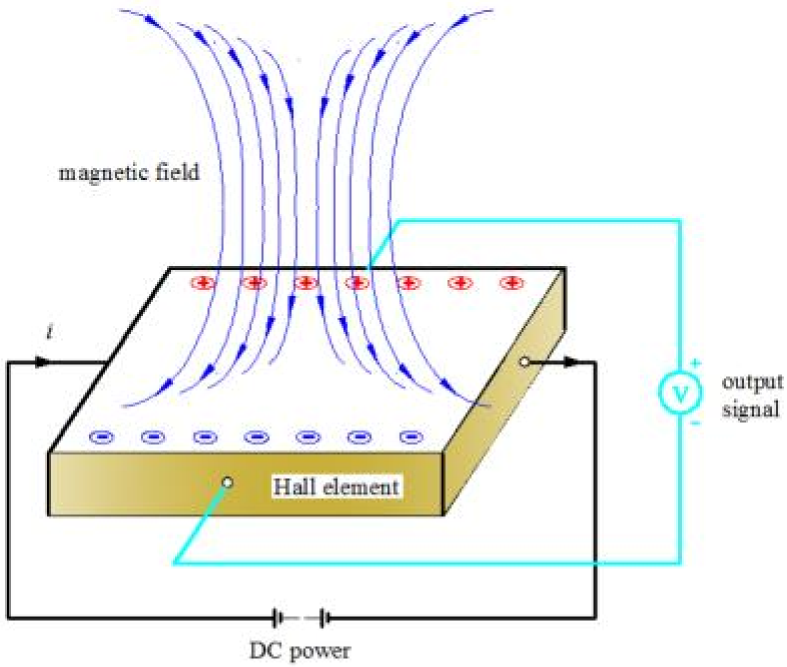



Fig.46: Principle of Hall Effect

Kalwa and Pekaraski presented design and operating principles of four new Hall-effect sensors for magnetic testing of steel ropes and observed that magnetic testing can be enhanced by using magnetic concentrators [115]. Golosiniski studied LMA measure with Hall sensors and observed that the accuracy of measurement depends on type and location of Hall sensors and the sensors positioned centrally on the apparatus head overestimated the measurements by 20% [116].Kim utilised Hall sensors to detect flaws such as abrasion, broken wire, corrosion and deformation for aged wire ropes in elevator. Experimental and field tests proved the efficiency of detection of defects of the sensors to be very high [117] . Lei studied the the detection of broken wire using MFL method and proposed an effective MFL technique for detecting coated steel belt defects utilizing a pair of circumferentially distributed Hall sensors to create a differential signal. They observed that the set up could inspect weak MFL signal at high lift off [118].Dauber et al proposed the fabrication and characterization of ultrasensitive Hall sensor elements based on graphene boron nitride heterostructures and they were able to achieve a sensitivity that outpaced the traditional silicon based sensors [119].

There is no denying the critical role played by hall sensors in electromagnetic non-destructive testing of wire rope. The hall element is another energy-guzzler that needs electricity to function. Additionally, it is still difficult to achieve defect inspection quantitatively and precisely for various types of wire rope and to increase testing sensitivity in a variety of environments

# CHAPTER 6: PERIODIC CONTROL AND MAINTENANCE

As discussed before wire ropes find use in many applications. They not only receive considerable load but are also more often than not subject to extreme working environments like high temperature, heavy loads, moisture etc which leads to considerable mechanical damage throughout their service life. The main causes of wire rope failure are corrosion and excessive deterioration from fatigue, fretting and wear. When the service begins, the individual wires and strands fall into place, increasing the rope's breaking strength. Once it reaches its peak, it quickly decreases as shown in Fig.47.

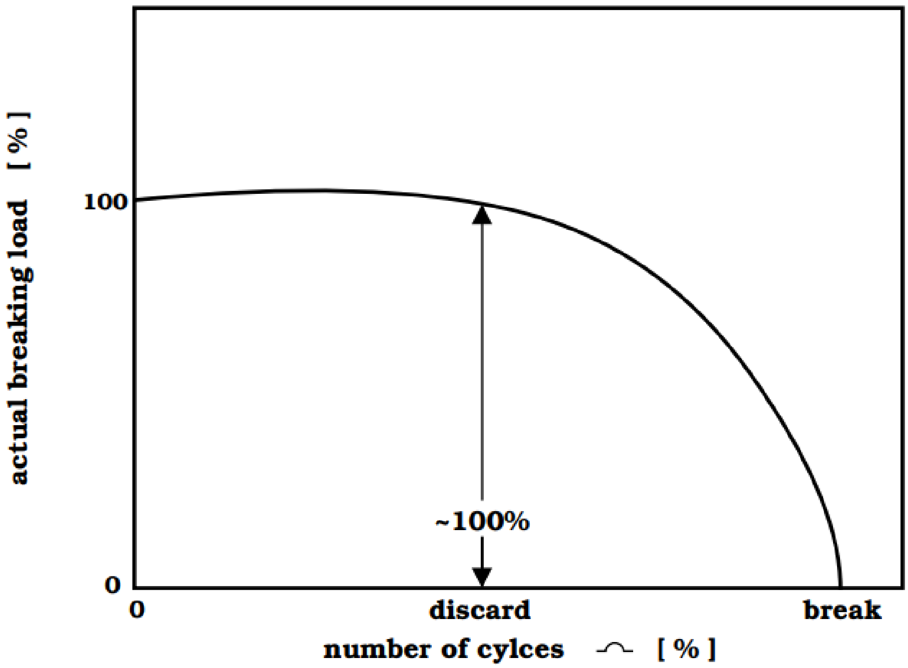



Fig.47: Relation between breaking load and number of cycles

This decline in breaking strength is brought on by wire breakage, changes in rope structure, and the progressive loss of the metallic cross-section from abrasion and corrosion These factors even though unavoidable are extrapolated by wrong usage and lack of proper maintenance and inspection. Wrong usage and lack of maintenance and inspection can lead to early discarding, or even to dangerous consequences like complete failure, which costs dearly not only in economic terms but also sometimes in terms of precious human lives. The damages like surface damage can sometimes be detected easily and sometimes the damage maybe internal which not only requires sophisticated methods but also trained professionals. Regular inspections enable not only high rope performance but also ensures safety of human lives. The aim of control and maintenance is to observe and analyse the deterioration process in order to ensure the removal of rope from the system before it ends as a safety hazard.

Another benefit is the detection of unexpected damage and corrosion. Proper care and maintenance ensure that the rope is discarded before the failure and the precautions taken thereafter owing to the experience of having dealt with a deteriorated wear keep us in a good stead for future purposes. The control and maintenance of wire rope should start even before the installation of wire ropes, as incorrect handling and storage may lead to broken strands, corrosion, crushed wires which can ultimately lead to failure when the rope is in operation.

## 6.1 Handling Wire Ropes

### 6.1.1 Environmental conditions, Receiving, Inspection and Storage

According to the British Standards BS EN 12385-3:2020 limitations due to adverse environmental conditions are the first thing to be taken into consideration. The first and foremost environmental condition is the temperature which plays an important role in the installation of ropes. The maximum temperature that may be reached by the wire rope in service should be given a thorough thought as it can lead to a hazardous situation. The maximum operating temperature for stranded ropes with fibre cores is 100°C. Stranded ropes with steel cores and spiral ropes can work up to 200°C even though attention should be paid to the derating of working load limit. The loss of strength may be assumed to be around 10% for 100-200 temperature range limit. If the wire rope is operating at a temperature around 40°C, the strength of steel wire rope is almost unaffected whereas for temperatures about 200°C special lubricants may be necessary and the loss of strength is greater than the 10% mentioned above. In addition to the limits mentioned above, operating temperatures for different kinds of terminations have to be taken into consideration. The temperatures may range from 80°C for socket filled with a lead based alloy termination to 150°C for turn back eye for aluminium ferrule termination. Hazardous environments in which wire ropes are usually used, like offshore activities, carrying of dangerous loads such as molten metals, corrosive materials and radioactive materials, working load limit should be adjusted accordingly [120].

The optimum time to begin the proper handling and care for wire rope is right away after delivery. To evaluate the rope's identification, quality, and compatibility with the machinery or equipment to which it is to be permanently attached, the rope should be unwrapped and thoroughly checked as soon as it is delivered. The next important thing is the issue of storage which ought to be taken into account. The wire rope needs to be shielded from the weather no matter the time frame of storage. A suitable storage location is a secured area that is not closed or unheated or tightly sealed but is dry and well-ventilated. The aim of such installation is to avoid the condensation that might be formed on the rope, which in turn can lead to corrosion. In case the rope can’t be stored inside, it should be protected by waterproof material. During the process of storage, it should be ensured that the rope is not exposed to any accidental damage. It is to be made sure that the rope isn't exposed to high temperatures, and chemical fumes and moisture and it should be ascertained that the rope doesn't touch the floor. Applying lubricant to each layer when the rope is wound on the drum of idle machinery may be important if the wire rope is to be kept inactive for an extended period. Cleaning, inspection, and re-lubrication should take place before starting up the equipment.

### 6.1.2 Wire Rope Installation

**Pre installation condition:** According to ISO 4309:2017 conditions before the installation are to be considered. The most important condition being the minimum breaking force. It's to be ensured that the minimum breaking force is lower than the one specified by the manufacturer. The condition of the sheaves and drums should be evaluated, and it should be ensured that they are free from any corrugations and the diameter of sheave is 5-10% larger than the nominal rope diameter to have optimum working conditions. If the rope has been in storage time, it should be inspected preferably using MRT. Moreover, diameter of the rope should be measured under the no tension condition. Cleaning, inspection and relubrication should precede start-up of the equipment [121].

**Checking the diameter:** Before installation, it is imperative to measure diameter of the wire rope, so that the rope diameter complies with the specifications set forth for the particular piece of machinery or equipment. If the diameter is less than the recommended dimension, the stress will be higher leading to premature breaking. On the other hand, wires with diameter greater than the recommended value tend to wear out sooner due to the fact that it encounters pinching in sheaves and drums. While checking the diameter, attention should be paid to measure the true diameter. True diameter is the biggest cross-sectional dimension. The correct and incorrect way of measuring the diameter is shown in Fig.48. According to ISO 4344:2004, the diameter to be measured should be measured under two constraints, the first being under no tension and the second being under a tension of 5-10% of breaking force at two positions located 1m apart. Keeping in mind that the measurements are taken at a right angle to the circumscribed circle and the equipment at least covers two strands. It's to be mentioned here that the design diameters are larger than the nominal diameters according to acceptable tolerance limits as shown in Fig.49 adopted from Wire Rope Technical Board [122]

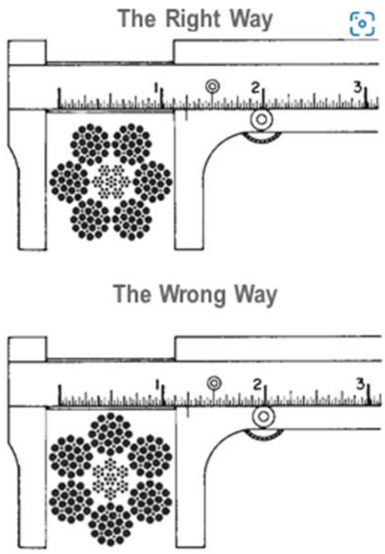



Fig.48: Measurement of wire rope diameter

| Nominal Rope Diameter | Allowable Limits | |
|---|---|---|
| Thru 1/8" | –0 | +8% |
| Over 1/8" thru 3/16" | –0 | +7% |
| Over 3/16" thru 1/4" | –0 | +6% |
| Over 1/4" and larger | –0 | +5% |

Fig.49: Oversize limits of wire rope diameters

**Unreeling and Uncoiling**

Wire ropes are usually supplied as coils or reels, in various cut lengths according to the need and requirement of the installation. Extreme care and great deal of attention should be paid to unwinding and unreeling of the wires as even the smallest damages can be dangerous for the service life of the rope. Improper and forced pulling can cause loops which inturn can cause kinks in the rope as shown in Fig.50

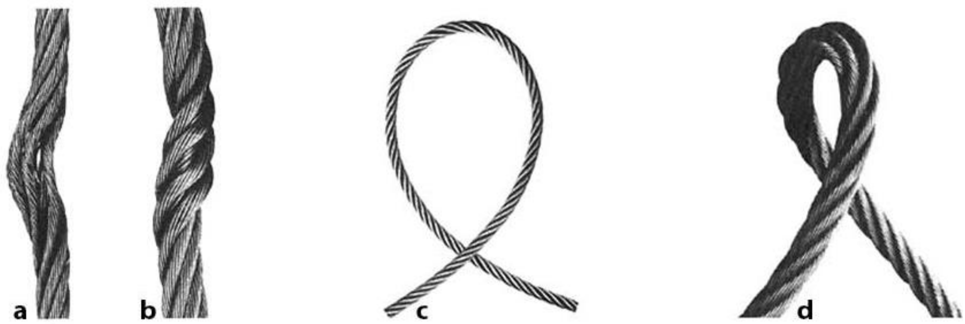



Fig.50: a) Open Kink; b) Closed Kink; c) Starting loop; d) The Kink

ISO 4309 and and BS 12385 give the guidelines for unreeling and uncoiling of wire ropes. During the installation of a wire rope, attention should be paid to avoid turn into, or out of, the rope, which ultimately leads to the formation of loops, kinks or bends in the rope. These defects make the rope unfit for usage. To avoid these defects ropes are paid out in a straight line, with care being taken to keep the slack to minimum as shown in Fig.51 [120] [121]

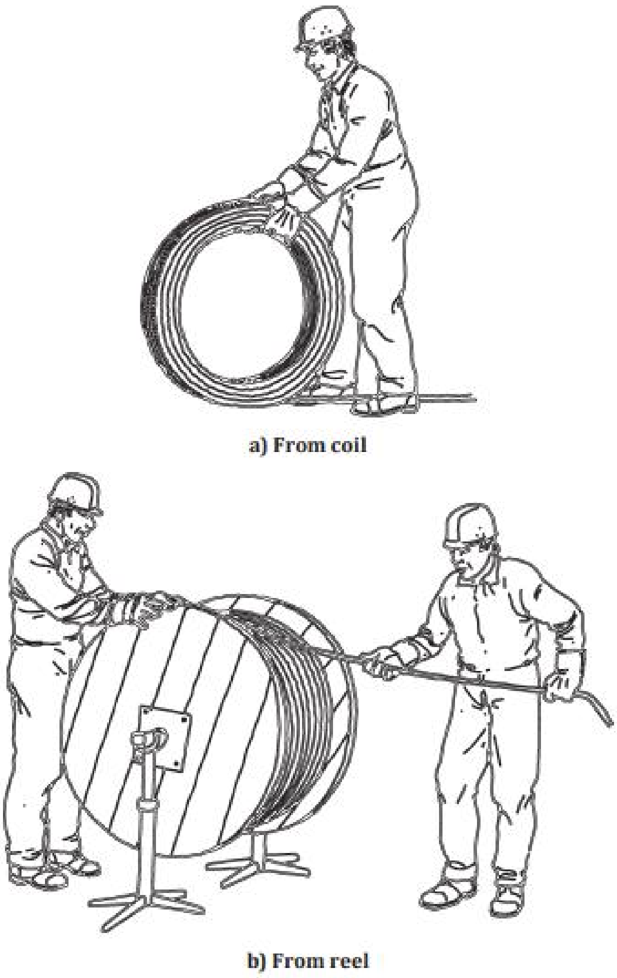



Fig.51: Correct procedures for uncoiling wire rope

The easiest way of uncoiling the rope is placing the coil of rope on the ground and rolling it out straight, but rope contamination with dust, grit, moisture or other harmful materials is to be avoided as much as possible. Pulling away the rope from a stationary coil ought to be avoided, as this leads to formation of kinks in the rope. Sometimes the coil is too large and handling it is extremely difficult; this necessitates the need of a turntable which helps the rope to be paid out as the end is pulled away. Fig.52 shows improper procedures of unreeling and uncoiling which should be avoided come what may; so as to avoid loop formation. When we try to straighten the loops, it invariably result in kinks which lead to damage of wire.

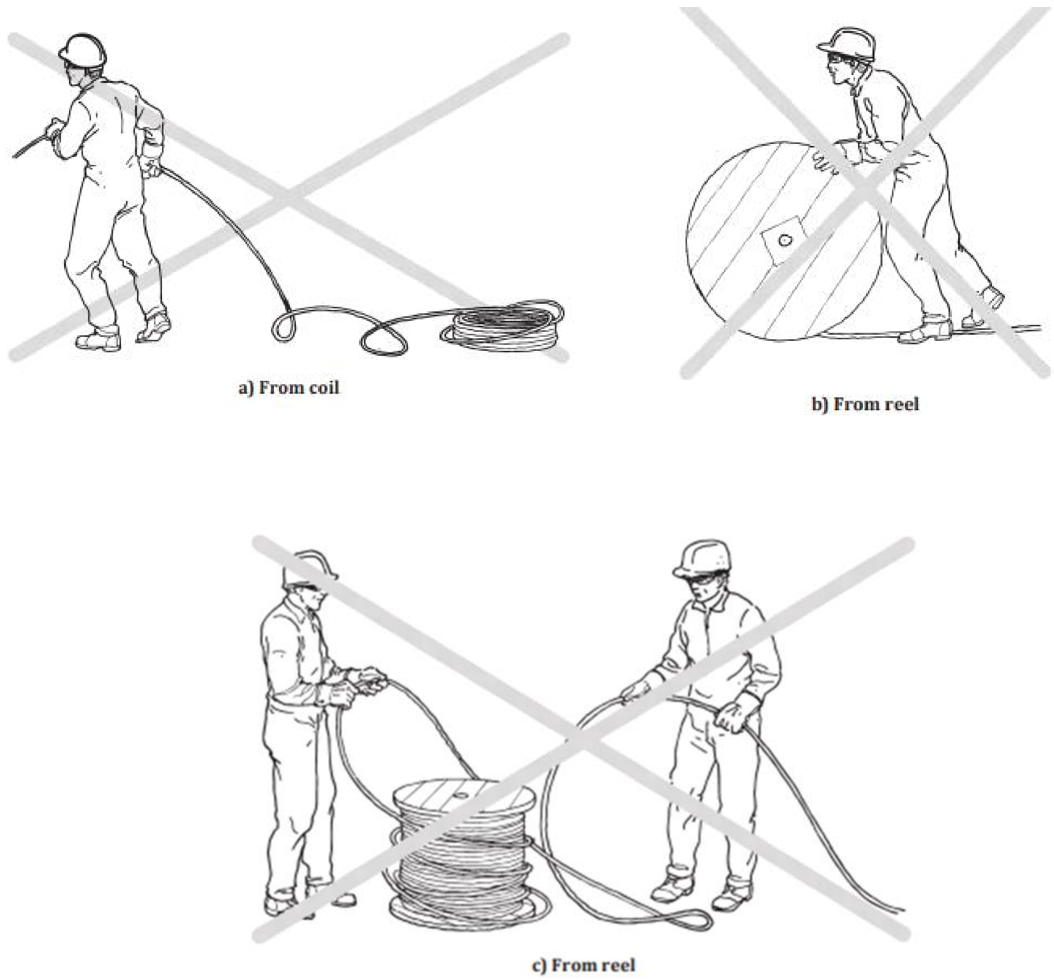



Fig.52: Incorrect Procedures of uncoiling a wire rope

For ropes with reels, the supply reel ought to be as far away from the installation as possible in order to restrain the fleet angle effect and eliminate undesirable rotational effects. Moreover, ropes shall never be allowed to run on the ground directly, instead some covering stuff like mats should be used to eliminate the possible of dirt or ingress of grit or any other contaminants. In case of ropes on reels, inertia of the rope during uncoiling needs to be taken into consideration and it needs to be controlled; brakes are employed to slowly pay out the rope. Also care should be taken that the ropes bend in same direction; that is pay ou of the rope should be either from top of the reel to top of the drum or bottom of the reel to bottom of the drum as shown in Fig.53

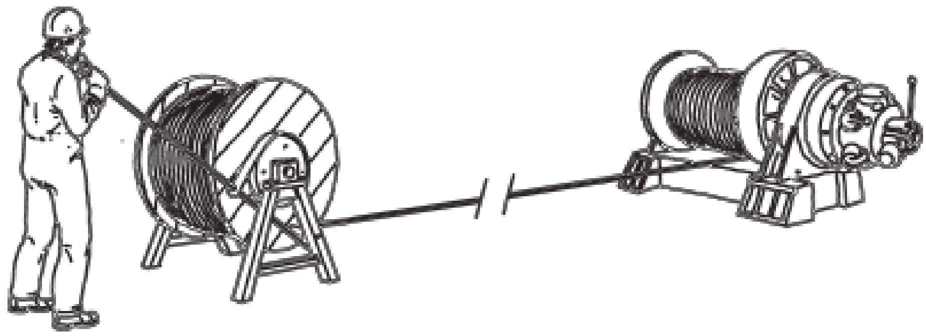


Fig.53: Transfer of rope from bottom of reel to bottom of drum

**Seizing Wire Rope**

Although there are several ways to cut wire rope, specific precautions ought to be taken. The primary and most important precaution is the seizing on both sides of the area, where the cut is to be made. Improper seizing in a wire rope may lead to loosening, deformation and flattening of the strands. These effects can lead to shortened lifespan of the wire rope owing to non-uniform distribution of load on the strands which will ultimately lead to premature failure of the rope. There are two universally accepted methods of seizing. The first method involves placing one end of seizing wire in the trough between two strands, while the other end is wrapped perpendicular to the wire and then the two ends of seizing are twisted together. The second method involves twisting the two ends of the seizing together, twisting until proper tightening has been achieved. The two methods are shown in Fig.54

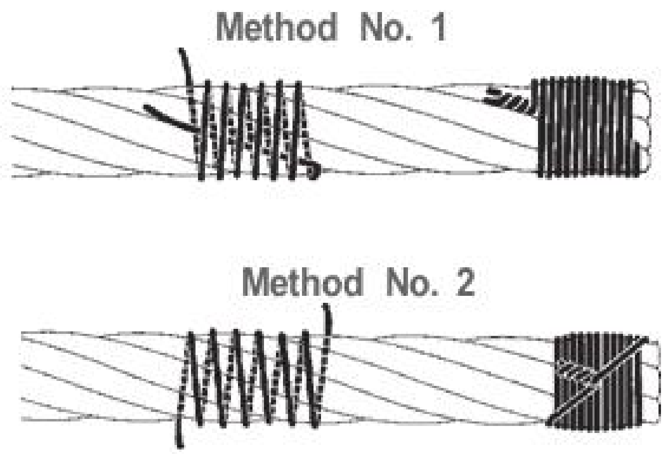



Fig.54: Seizing methods

The seizing wire is usually a soft, annealed wire or strand. The diameter of the wire rope governs the dimensions of the seizing wire and the seize. But the size of the seizing ought to be greater than the rope diameter. Whether a rope is preformed or not determines the number of seizings on each side of the area where the cut is to be made. For preformed ropes one seizing on each side is enough while for non-preformed wires two seizings on each side are to be provided as shown in Fig.55

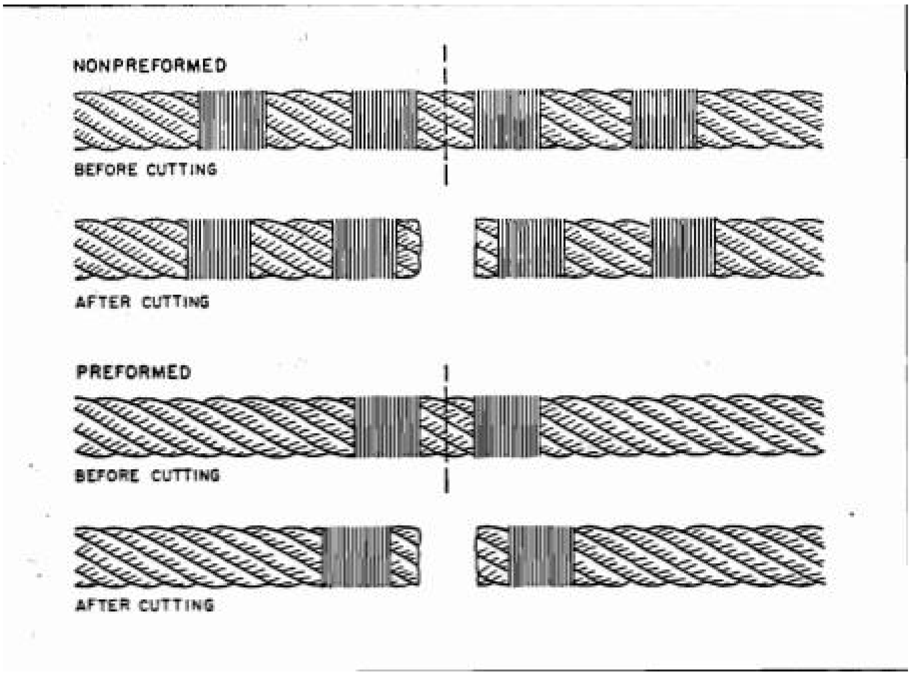



Fig.55: Seizings for non-preformed and preformed wires

**Rope end attachments**

As wire ropes find application in considerable fields, sometimes due to complicated reeving systems, the ends of the rope may need special attachments. These attachments ensure that force and motion are transferred efficiently. It is pertinent to note that each attachment has its own characteristics and are best suited to certain types of installations.The rope end attachments are guide by BS EN 13411 standard.

**Socketing**

Wire rope terminals that are improperly attached create conditions of extreme danger which might lead to catastrophic conditions. As such proper operation is governed by how securely the wire rope components are held in place by the terminals. If the components are not securely held it can lead to the condition where the strands will bear unequal forces leading to early discard of ropes. When preparing a wire rope for socketing, the standards like BS EN 13411 should be followed in spirit to avoid causing damage to the rope.

**Wire Clips**

These are widely used in many applications like haulages, hoists etc and are usually of two types viz. U-bolt and fist grip. Like socketing care should be taken in following the proper procedures given by the standards. Moreover Fig.56 shows the correct and wrong ways of attaching U bolt clips to the ropes.

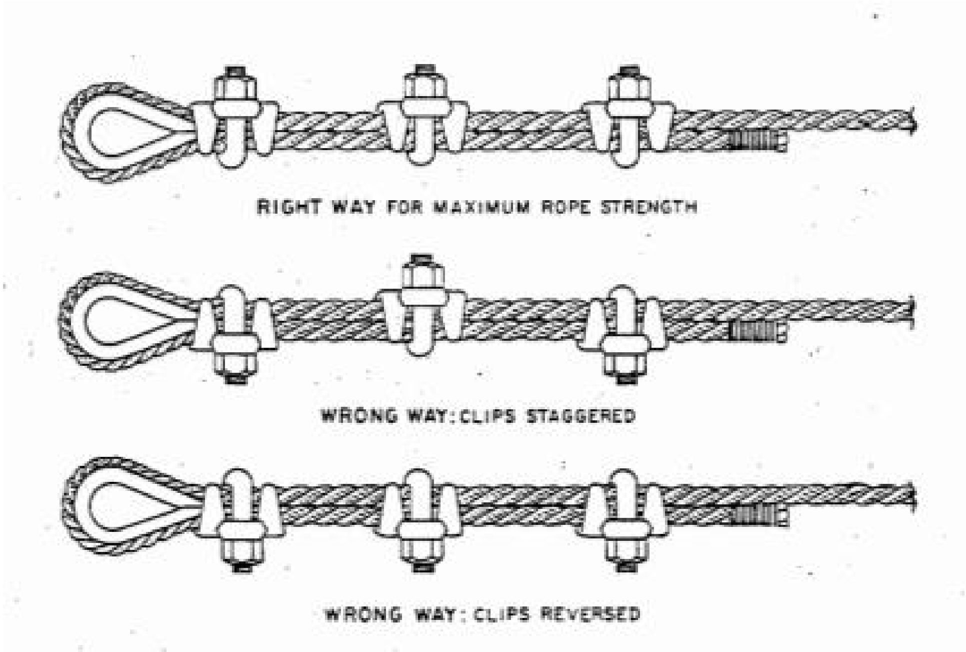



Fig.56: Right and wrong ways of attaching the U-bolt clips

**Drums (Grooved/Smooth)**

Drums are the means of transmission of power to the object. As such for ropes to pick up this power efficiently proper installation is needed. According to ISO 16625, ideally for maximum rope life the drum should hold the rope in one layer, but due to space constraints more than one layers of ropes on a drum are found more often than not. A grooved drum is more adept at furnishing better rope performance and less wear than a smooth drum in case multi-layer spooling is used.

For grooved drum strict adherence to the following recommended procedures is desired: a) the rope end should be attached to the drum in such a way that the end attachment is provided as much strength as desired by the manufacturer, b) winding should proceed under continuous tension, c) the rope must follow the groove in any case, d) Minimum of two dead turns are mandatory according to the codes and standards.

For smooth drums the following points need to be ensured: a) proper attachment of rope to the drum b) winding should proceed under appropriate tension c) ensure there are no gaps between turns d) minimum of two dead turns are mandatory.

The direction of spooling of rope is a critical factor and should be related to lay of rope especially for smooth drums as shown in Fig.57

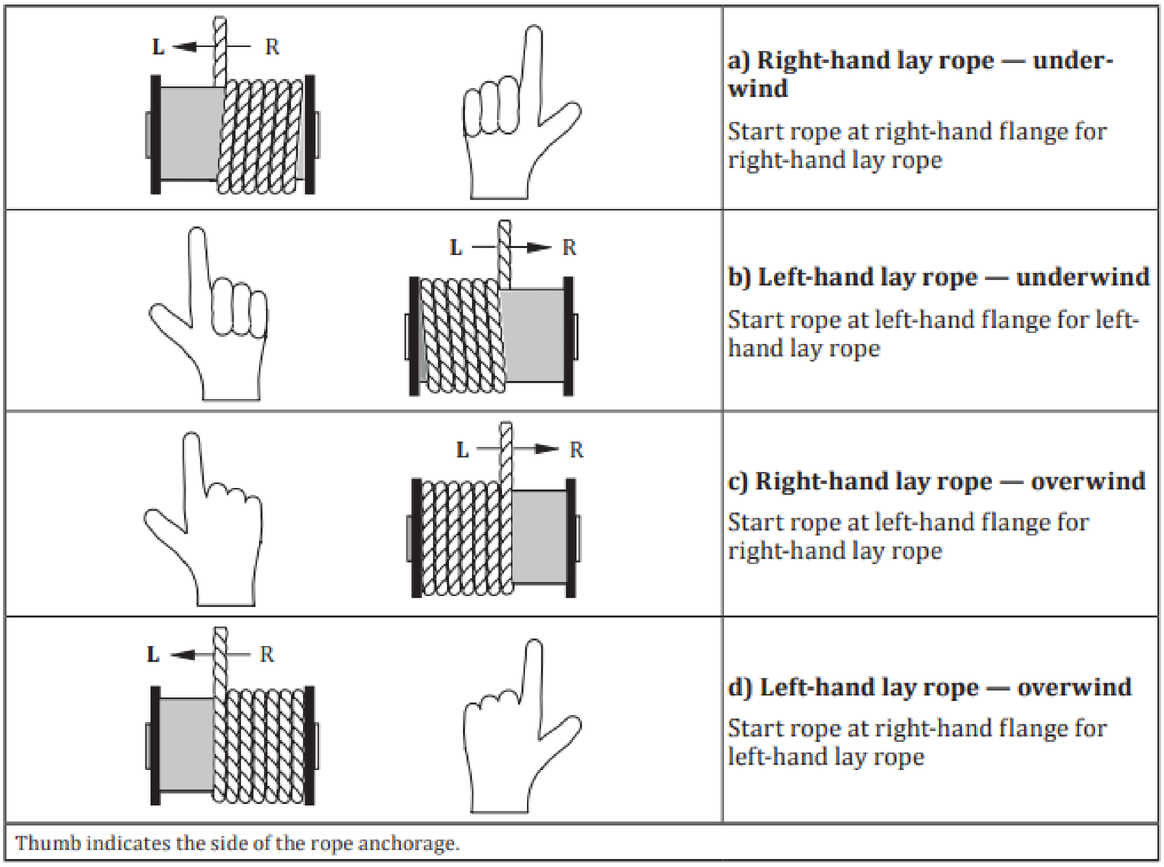



Fig.57: Recommended method for locating rope anchorage point on drum

Multilayer spooling presents many other problems especially for smooth drums, as the first layer is guided by the grooves of grooved drum and provides support to wire but for smooth drum the first should be wound in a close helix by providing appropriate tension. This layer acts as the groove for further layers. As the number of layers grow to two or more than two, crossover is inevitable. These points are susceptible to abrasion and wear and following the above-mentioned methods greatly reduces abrasion and wear.

## 6.2 Operation and Maintenance of Wire Rope

### 6.2.1 Sheaves and Drums

The contact between wire rope and sheaves and drum is the essence of installations and without it the operations involving wire rope won't be possible. As such for the proper functionality of the installation t=all the involved components should be in first class condition.

The main reason for wire and groove wear is the stretching of wire rope like a coil spring under the influence of load. The stretch of wire rope causes the rope to rub on the groove and essentially leads to wear of both the wire rope and the groove. As the rope is bent around the sheave or drum, it adjusts due to movement of the wires and strands, which causes additional rubbing within the rope. The wear is connected to the adjusting movement which in turn is dependent on the ratio of sheave diameter to wire diameter (D/d). ISO 16625 prescribes that the diameter of the grooves must be between 5-10 % more than the rope diameter. As an optimum value, the standard specifies a groove diameter of 7.5% more than the rope diameter. If the sheave diameter is too small for the rope, it leads to wire breaks in the inside of the rope caused by so-called arch pressure and excess length of the outer strands in respect of the reduced rope diameter, which is usually shifted to a point and results in strand loosening or even birdcage deformation. A larger diameter leads to reduced contact area which causes increased pressure at the bottom of groove. Increased pressure along with enhanced tension due to rope deformation leads to reduction of service life.The condition of smaller and larger sheave diameter are shown in Fig.58

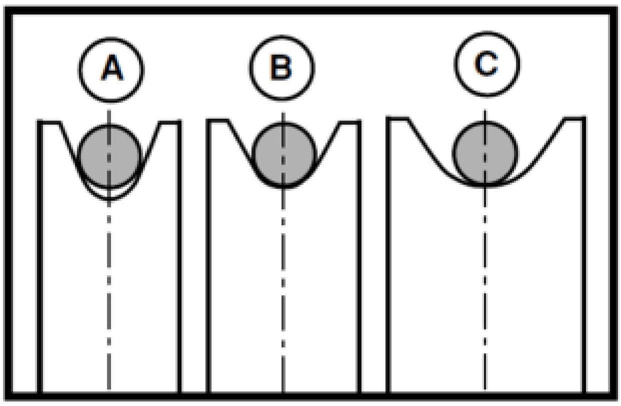



Fig.58: Conditions of small, optimum and large sheave diameter

Smaller D/d ratio escalates the adjusting movement which leads to more rapid wear. The amount of wear is also a function of sheave material and the radial pressure between the ropes and the grooves. In other words, small tread diameter and soft sheave material escalate the rate of wear. The radial pressure is given by the formula

$$p = \frac{2T}{Dd}$$

where p is the unit radial pressure

T is the load on the ropes

D is the tread diameter of sheave or drum

d is the nominal diameter of rope

if the calculated value of p exceeds the allowable radial pressure, it will manifest as undersized or corrugated groove, which will lead to accelerated wear.

### 6.2.2 Bending wire ropes over sheaves and drums

For the best performance of the wire rope system, the sheaves, drums and rollers should be of the optimum design as required by the installation. Owing to the varied application fields of wire rope, one design fits all principle isn't suited for the design of sheaves and drums. The rule of thumb is that the most economical design is the one which satisfies the constraints and parameters imposed by the manufacturer's recommendations and operating conditions. Wires ropes bending over sheaves or drums are inevitably subject to cyclic bending stresses, which ultimately lead to fatigue of wire rope. The main driving factor of these stresses keeping the other variables constant is the D/d ratio as mentioned earlier. The service life curve and its dependence on the D/d ratio is shown in Fig.59

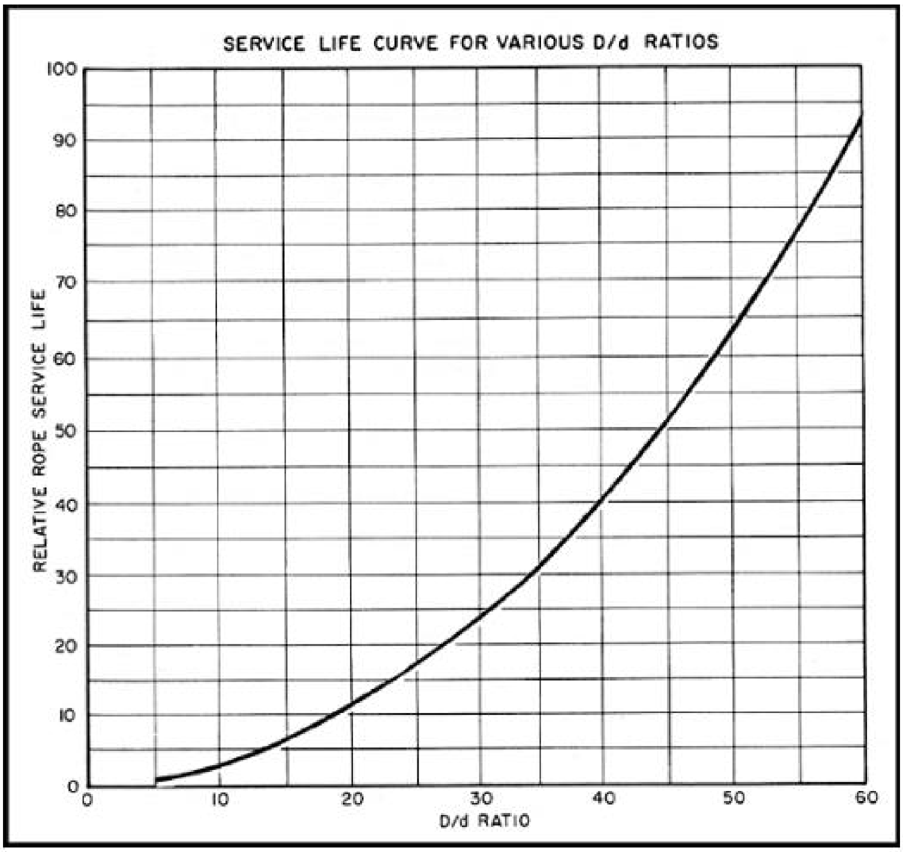



Fig.59: Service life curve of Wire Rope

For bending around the drum or sheave, strands and ropes ought to move relative to each other. This relative movement compensates for the difference in distance between the top side and the bottom side for proper rope action. If the compensation is not optimum service life of the wire rope affected. Also, care should be taken to avoid reverse bending while shifting from one sheave to another.

### 6.2.3 The "X·Chart"

The essence of the engineering design is that you have to make the best possible compromise, as there will always be one parameter or the other can't be satisfied fully. Likewise for ropes sometimes you need to design for less than optimum resistance to abrasion to have more flexibility ( the best example is an overhead crane) and vice versa ( the best example being haulages). The selection of wire ropes is governed by two most important parameters called abrasion resistance and bending fatigue resistance. A balance is to be maintained between these two for the selection of rope and it requires experience and judgement of highest order.This balance is given by the so called X- Chart as shown in Fig.60

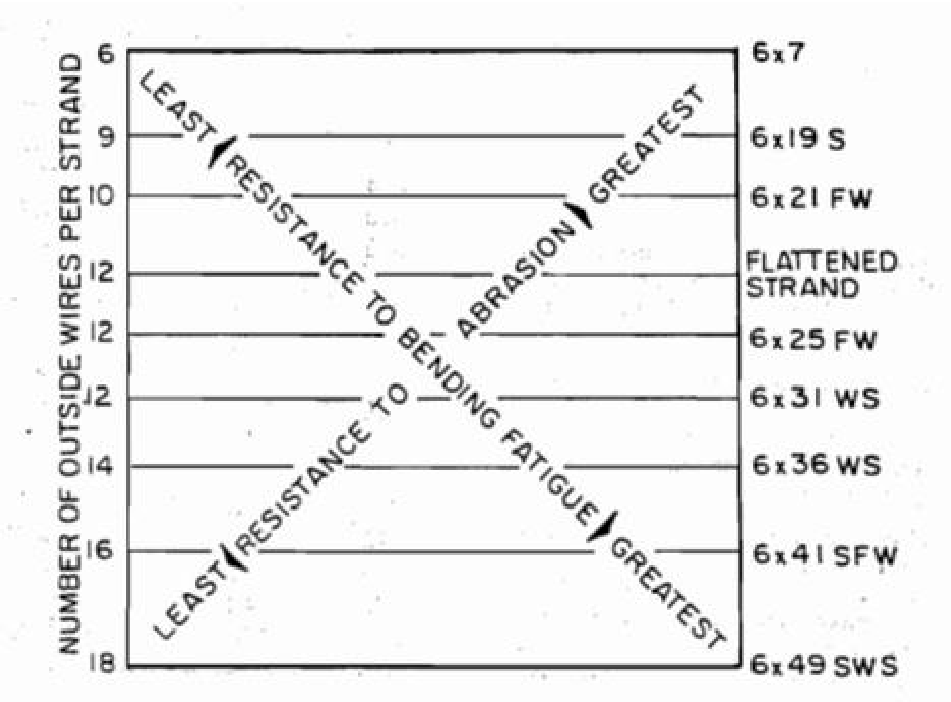



Fig.60: The X-Chart

### 6.2.4 Running in a new rope

According to BS EN 12385-3, if possible, the wire should be allowed to get adjusted gradually to the working conditions by operating the rope with low load for a number of cycles. During this operation care should be taken that all the working parts like sheaves drums and rollers are functioning properly.

### 6.2.5 Fleet Angle

The even winding of rope on a smooth drum is governed by some main parameters viz. the D/ d ratio, the rotation speed, load on the rope, and the fleet angle. Fleet angle is the parameter which exerts the most effect on winding characteristics. Fig.61 shows a helically grooved wide drum with a pitch angle α and a deflection sheave

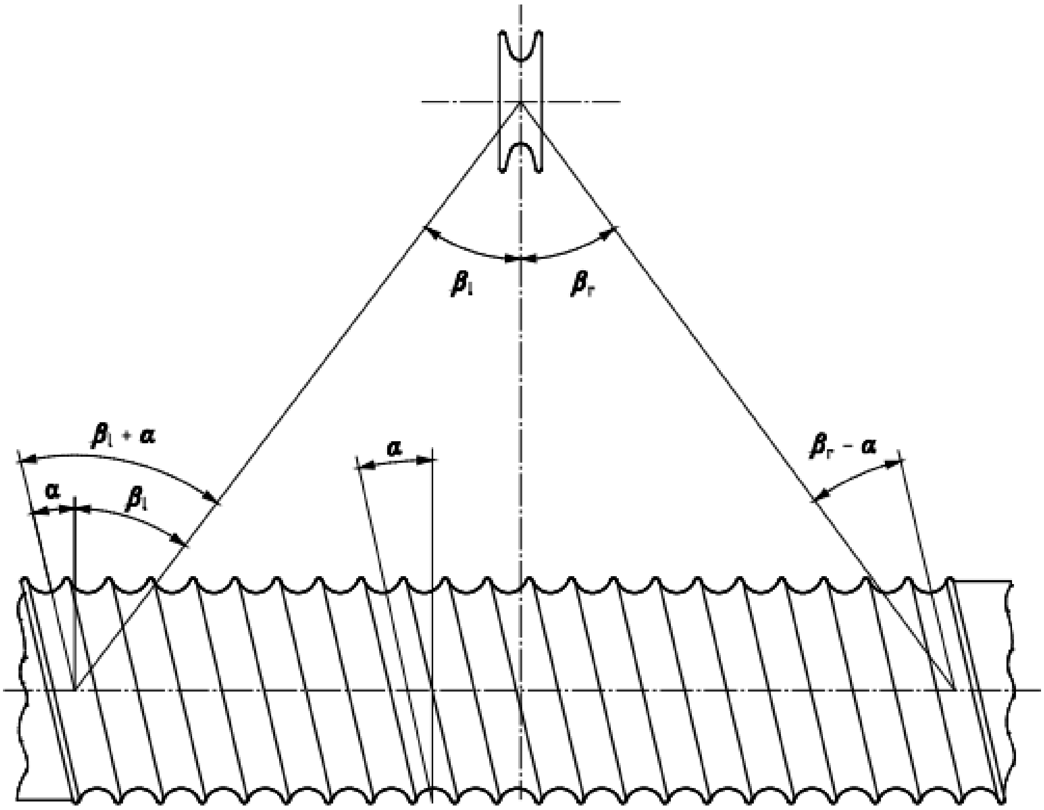



Fig.61: Fleet and Groove Angles

According to BS EN 12385-3 it is necessary to limit the fleet angle to 2° for rotation resistant ropes and to 4° for single layer ropes. Fleet angles can be reduced by increasing the drum diameter or increasing the distance between sheave and drum. Larger fleet angles enhance the problem of abrasion and crushing and rope rubbing against flanges.

### 6.2.6 Maintenance of wire ropes

One of the first steps of maintenance of the rope is relubricating the wire rope. As it is common knowledge during the process production ropes are adequately lubricated which helps in reduction of friction as well as in making them corrosion free. This lubrication never lasts the whole service life of the ropes as such according to ISO 4309 a rope should be lubricated before dryness and corrosion appear. Special attention ought to be paid to high stress areas like the rope areas that run over sheaves and drums. There are various methods of dressing like painting or swabbing, sometimes a continuous drip system is used. But maximum penetration of the lubricant can only be attained by pressure lubricators. The three methods are shown in Fig.62

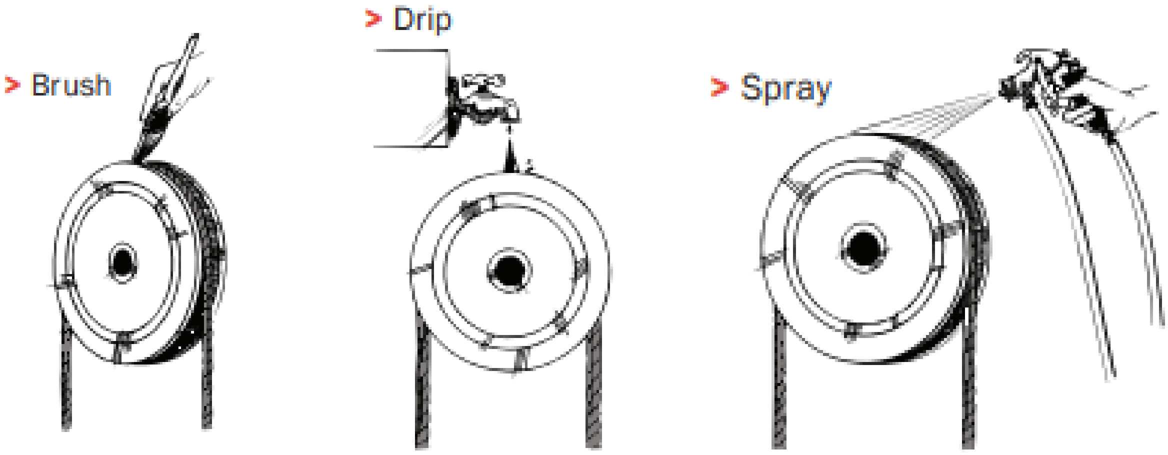



Fig.62: Different types of lubrication

It is of utmost importance to know that the dressing applied should be compatible with the original lubricant.

The next important step of wire rope is cleaning of wire ropes. I the rope is dirty and is contaminated it should be cleaned at regular intervals. This is especially true for ropes operating in chemical and abrasive environments.

Another step of maintenance is to remove broken wires. It is necessary to avoid local deterioration. The protruding end should be grabbed and then bent forward and backward to break it as shown in Fig.63. Also, the location of the broken is to be noted to evaluate it during future inspections.

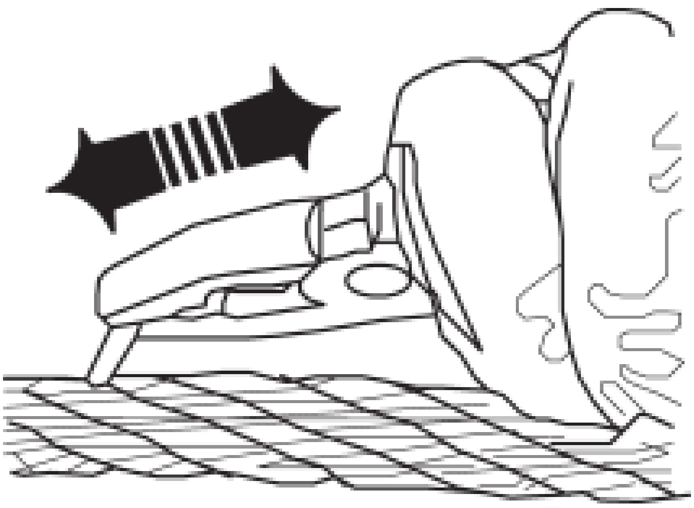


Fig.63: Removal of broken wire

In addition to rope maintenance, sheaves and drum should also be checked periodically to ensure their free rotation.

## 6.3 Inspection of Wire Ropes

Periodic inspections are critical as all wire ropes will ultimately wear out. There are many international standards that focus on the wire inspection like ASME B30.2, BS ISO 4309, BS EN 12927, BS EN 1709. Wire rope inspection is important because the rope is literally used up while in use and loses its strength. The purpose of inspevtion is to ascertain if the rope is viable for future operations or it needs to be discarded. According to BS EN 12927 each rope should be inspected for a) surface defects b) internal defects c) structural defects d) geometrical defects.

### 6.3.1 How often should the inspections take place

**Daily Visual Inspection:** In the absence of recommendation by the manufacturer, inspections should be carried according to ISO 4309. ISO 4309 recommended daily visual inspection of the rope section in work to detect any damage or deterioration especially at the point of attachments of the rope to the crane. The position of rope on sheave should also be checked and it should be ensured that it has not slipped**.**

**Periodic Inspection:** Periodic inspections are very critical and should be carried out by a trained professional. Periodic inspection determines whether a rope can remain in service or should be discarded immediately or after a certain time frame. The severity shall be expressed either as a percentage or as a grade. List of common modes of deterioration and assessment methods are shown in Fig.64

| Mode of deterioration | Assessment method |
|---|---|
| Number of visible broken wires (including those which are randomly distributed, localized groupings, valley wire breaks and those that are at, or in the vicinity of, the termination) | By counting |
| Loss of metallic area caused by broken wires | Visual, MRT |
| Decrease in rope diameter (resulting from external wear/abrasion, internal wear and core deterioration) | By measurement |
| Loss of metallic area caused by mechanism other than broken wires e.g. corrosion, wear, etc. | Visual, MRT |
| Fracture of strand(s) | Visual |
| Corrosion (external, internal and fretting) | Visual, MRT |
| Deformation | Visual and by measurement (wave only) |
| Mechanical damage | Visual |
| Heat damage (including electric arcing) | Visual |

Fig.64: Modes of deterioration and assessment methods

The frequency of periodic inspections is determined by various factors which are enlisted by ISO 4309 as:

a) Statutory requirements of the country
b) Type of installation and the environmental conditions
c) Type of mechanism

d) Result of previous inspections
e) Service life elapsed
f) Frequency of use

Usually the length of the inspection involves the whole rope. But in special cases it can be left on the discretion of the checking authority but still the working length along with at least 5 turns on the drum are to be considered.

Thorough attention should be paid to high stress areas like anchorage, rope length passing through sheaves, vicinity of terminations and other areas mentioned in section 5.3.3 of ISO 4309. Sometimes special inspections need to be carried out called the inspection after incidents, which are undertaken right after any untoward happening. Sometimes MRT is used in case there are doubts that some damages may have been missed by the visual inspection.

### 6.3.2 Types of Inspection

The two main types employed are the visual inspection and MRT (MRT was already discussed in the previous chapter). The first step of visual inspection involves detection of deformation. Steel wire rope distortions are usually obvious in most cases and can be easily identified by the inspector. The main reason of these distortions is shock loading or swift induction of torque. Usual types of wire rope deformation are Wave distortion, Bird-caging, Core rope displacement or fracture, Kinking (that can develop in “dog-leg” deformation), Swelling / constriction. The second step involves cloth rag testing, in this step the inspector runs a rag around the rope to try to find a broken wire if the rag gets snapped by the broken wire, a careful inspection is to be followed. But this method is highly unreliable for obvious reasons. The third step involves the measurement of rope diameter. Wear or damage cause the reduction of diameter and if care is not taken can lead to rope failure. The fourth step involves abrasion corrosion and lubrication check.

### 6.3.3 Inspection of Sheaves and Drums

Even though during periodic inspection all parts are inspected, but as an additional measure all the working parts related to rope are inspected again prior to the installation of new rope. The primary check is the evaluation of groove condition, and the check is performed by groove gage as shown in Fig 65 and Fig.66 . The groove gage evaluates the size contour and the wear, for optimal condition the gage and groove contact should be of 150°. Mainly two types of gages are used. For new grooves the gage is nominal plus the full oversize percentage while for old groves nominal plus half oversize percentage is used. The gage for old grooves is the one that’s more commonly used and it is a no go gage, any diameter smaller than this will damage the ropes.

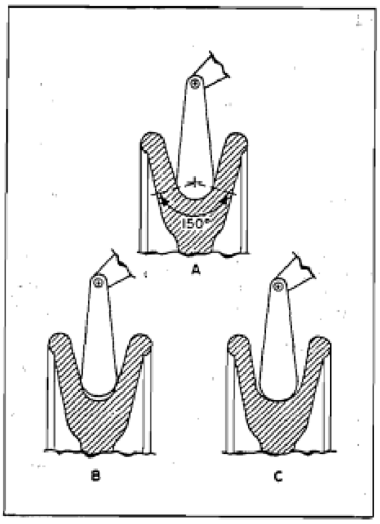



Fig.65: Schematic of gage groove contact, A is the optimum condition, B is small sheave diameter and C is large sheave diameter

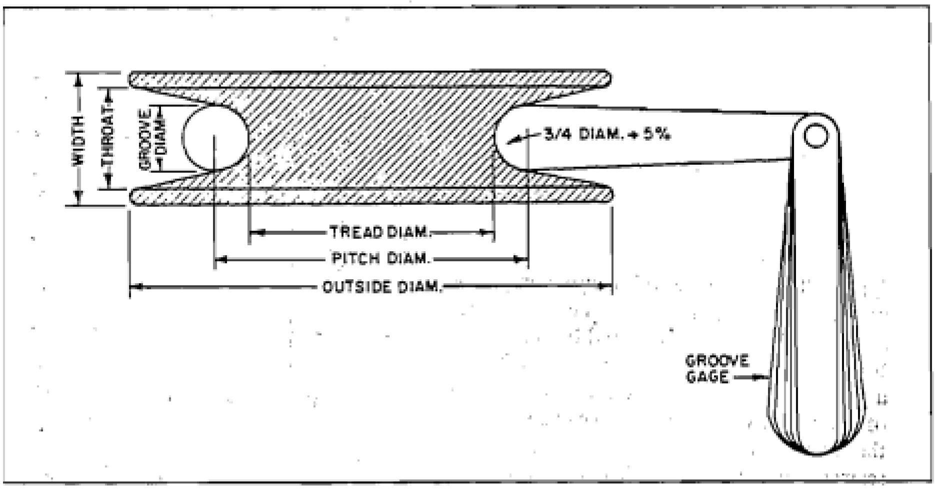



Fig.66: Schematic of sheave dimensions and gage usage

### 6.3.4 Wire Rope Inspection

Some critical inspection parameters of Wire Rope are listed below:

a) **Abrasion:** Movement over drums and sheaves is the main reason of abrasion. Most standards recommend discarding of rope if the wear is more than one third of the rope diameter.

b) **Rope Stretch:** Application of load causes the stretch and it is divide into three phases. The stretch curve is shown in Fig.67 and it depicts the three phases. Phase I is the initial stretch when the rope adjusts to installation. Phase II is a quasi-horizontal line depicting service life and phase III is an upper inclined line which denotes rapid deterioration.

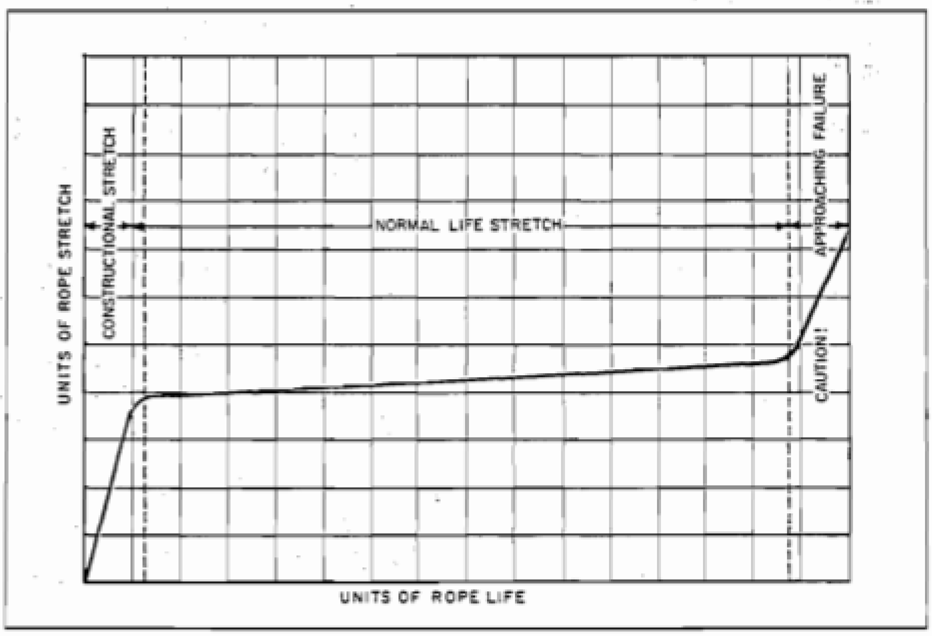



Fig.67: Stretch Curve of wire rope

c) **Diameter reduction:** Any reduction in rope diameter is bad news and points to damage of rope.
d) **Corrosion:** It is more dangerous than abrasion. Usually, it occurs internally first then its visible externally, It can lead to pitting which renders the rope unsafe and may even lead to fatigue
e) **Kinks:** Permanent distortions which demand discard of rope
f) **Bird Caging:** Caused due to mistreatments like sudden stops and demands rope discard unless it can be removed.
g) **Heat Damage:** Due to elevated temperatures the rope maybe damaged the rope need to be replaced
h) **Protruding Core:** If the rope core protrudes from the rope strands, the rope ought to be discarded
i) **Damaged end attachments:** Damaged end fittings must be removed.
j) **Scrubbing:** Displacement of wires and strands owing to contact with other objects. Enhances wear and remedial actions are to be taken
k) **Broken wires:** the number of broken wires is the indicator of condition of the wire ropes and demands inspection and usually replacement of rope

# CHAPTER 7: FAILURE OR FRACTURE

## 7.1 Fracture and its types

According to Anderson "Fracture may be defined as rupture in tension or rapid propagation of a crack, leading to large deformation, loss of function or serviceability of the structural element, complete separation of the component" [123].One of the primary concerns of the wire rope installation is fracture performance, owing to high level and varied types of stresses and many times under extremely harsh environments. Fracture has four main mechanisms viz. Ductile Fracture, Cleavage or Brittle Fracture, Trans granular Fracture and Fatigue Fracture. The first three mechanisms are shown in Fig.68

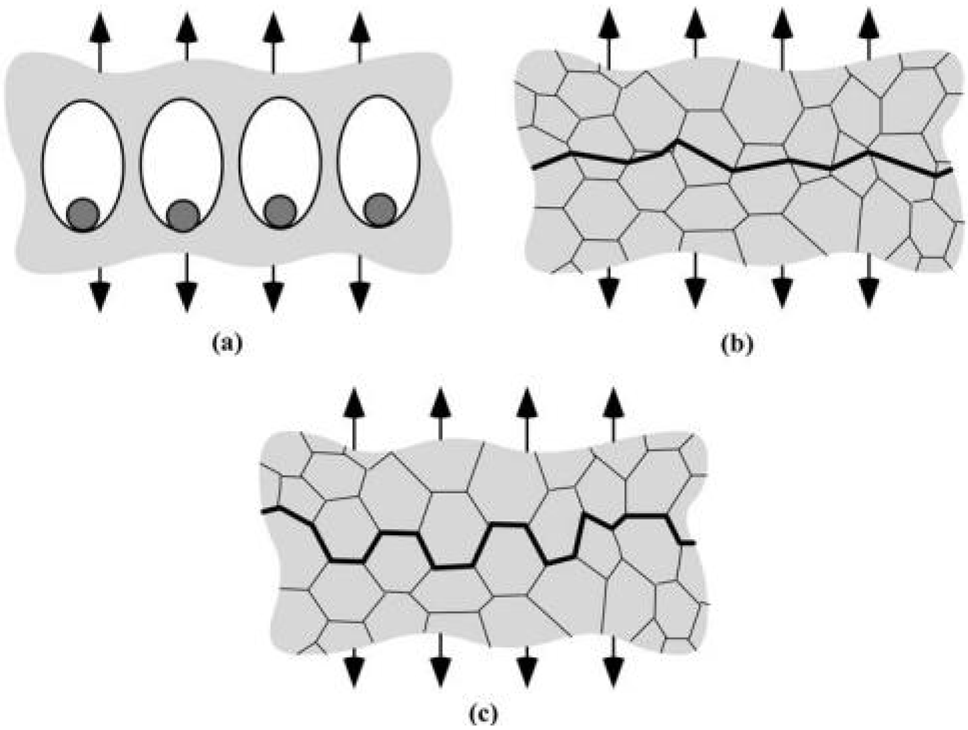



Fig.68: Mechanisms of Fracture a) Ductile, b) Cleavage, c) Intergranular [123]

**Ductile Fracture:** In metallic alloys and metals, a ductile fracture often results from the growth, initiation, and coalescence of microscopic voids during plastic deformation. The interfaces of second-phase particles are where the void nucleation typically occurs. Disassociation is thought to be the primary mechanism of void nucleation at these contacts. After void nucleation, there is further plastic deformation, which is known as "void growth," leading to an increase in the size of the voids and a distortion in their shape. The characteristic of ductile fracture is large plastic strain occurring at macroscopic level. Due to the localisation of the plastic strain in the inter void matrix, which creates the final fracture surface, adjacent voids link up with one another as these voids significantly enlarge and deform through plastic deformation. The fractograph is shown in Fig.69

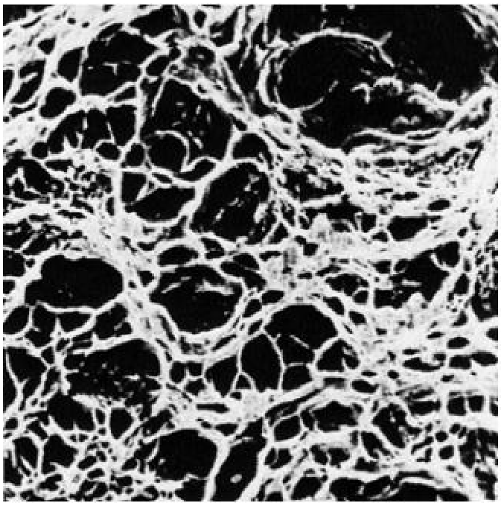


Fig.69: Dimpled ductile fracture [124]

**Cleavage Fracture/Brittle Fracture:** The propagation of a crack along a certain crystallographic plane is known as cleavage fracture. Even though cleavage is brittle, it can be preceded by extensive plastic flow and the growth of ductile cracks. Since fewer bonds need to be broken and there is more space between planes, the lowest packing density cleavage planes are preferable. In this kind of fracture, a brittle crack develops along specific crystallographic planes at rates that are comparable to the rates at which elastic vibrations cause waves to propagate. The "100" plane in the crystalline lattice (body-centred cubic) of "alpha-iron" is the crystallographic plane in question. As can be seen in the fractograph in Fig.70, there are many uniform but isolated regions.

Fig.70: Cleavage fracture specimen of a carbon steel [124]

These regions are referred to as Cleavage facets; with each region corresponding to one grain. Just as adjacent grains have different orientations, so do adjacent facets. The direction of fracture is dependent on the so-called river pattern. It is pertinent to mention that the direction of crack propagation need not be the same the direction of fracture it can sometimes be even in the opposite direction. The main driving forces of the cleavage fracture are low temperatures, strain hardening and unfavourable microstructure. [124].

**Inter granular fracture**: In rare cases and special circumstances like precipitation of brittle phase on the grain boundary, inter granular corrosion, grain boundary cavitation cracks can form and propagate along grain boundaries. There is decohesion at the grain boundaries and this fracture is related specific microstructure. The fractograph is shown in Fig.71

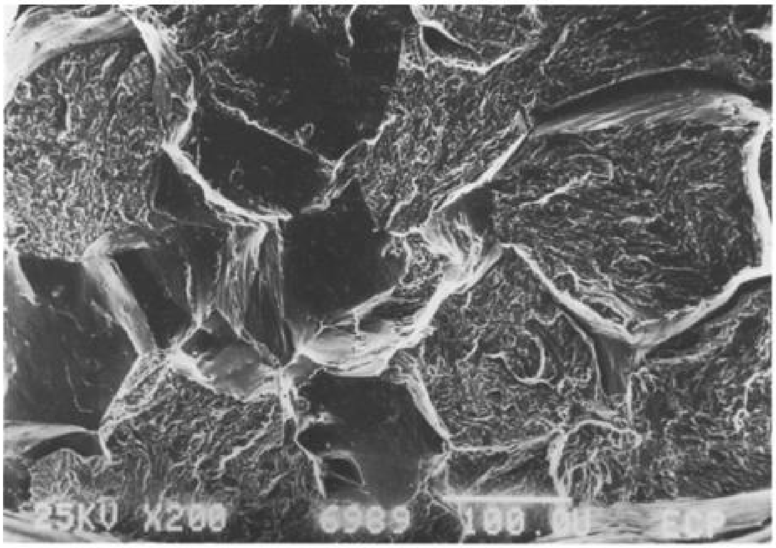



Fig.71: Intergranular fracture of steel

**Fatigue Fracture:** It's also called progressive fracture. This fracture is characterised by cyclic loading and the failure is usually way below the ultimate strength of the material. Fatigue failure inevitably starts from irregularities on metal surfaces or from points of high stress concentration. The fatigue fracture has three main stages called the crack initiation, crack propagation and final rupture. During crack initiation there is nucleation of crack and small crack growth. The cracks initiate surface defects or locations of high stress concentrations. The propagation of the persistent slip planes along the maximum shear plane is the culmination of crack nucleation. During crack propagation growth of micro cracks starts after the critical size of cracks has been attained. The size of crack transverse nearly three grain boundaries. Plastic stresses are induced at the crack tip due to the stress concentration. The orientation of cyclic plastic stress perpendicular to principal stress leads to the growth of micro crack. When the crack is two big the material ultimately fractures.

## 7.2 Failure and Fracture of Steel Wire Ropes

The wire rope failure has been studied extensively owing to the importance of wire ropes across diverse fields. Toribio et al. studied the role of non-metallic inclusions on the fracture of pearlitic steel wire and observed that in case of heavily drawn pearlitic steels, the fractograph as shown in Fig.72 corresponds to anisotropic fracture behaviour with frequent local deflections. This behaviour is due to the presence of multiple micro cracks aligned along the drawing direction and triaxial stress state generated after necking [125].

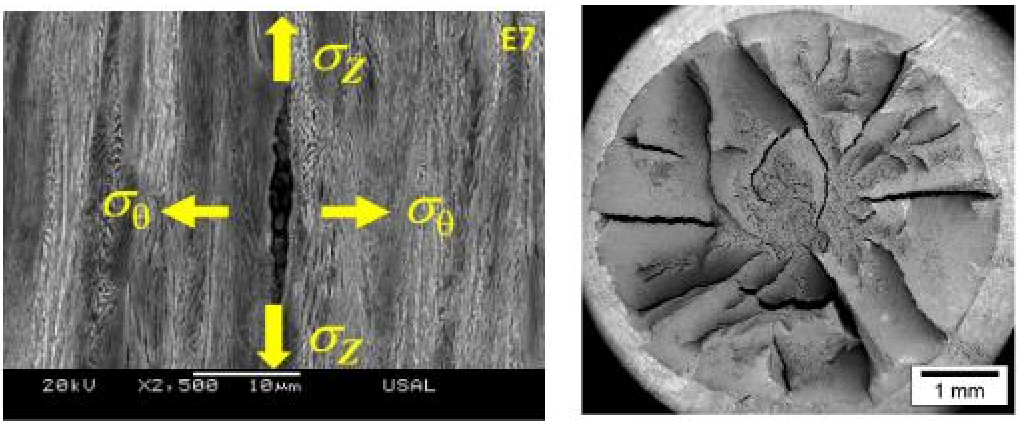



Fig.72: Anisotropic fracture behaviour in cold drawn pearlitic steel

Zhang et al. studied fatigue and fracture behaviour due to the fretting wear of steel wire in hoisting rope and observed that that as fretting cycles and contact stresses grew, so did the steel wires' fretting wear depth. Inversely correlated with wear depth, fretting cycles, and contact loads were the fatigue lives of steel wires with fretted damage [126]. Lambrighs proposed a fracture mechanics approach to fatigue of heavily drawn steel wires and observed that only a small portion of filaments failed due to surface defects caused by cold drawing process and concluded that past crack initiation mechanisms of thicker wires are not valid for more heavily drawn thinner wires. Moreover, not only surface stress concentrations but the fatigue cracks also initiated at internal non-metallic inclusions [127]. Li et al. performed an experimental study on the fatigue behaviour of corroded steel wire and observed four kinds of fatigue fracture viz. conical shaped, oblique shaped, cup shaped, stepped shaped and concluded that fatigue fracture is dependent on the corrosion degree. They also concluded that lower the stress amplitude the higher the corrosion degree as such more significant is the degradation [128]. Yilmaz studied failures during the production and usage of steel wires and concluded that non-metallic inclusions during wire drawing or service are the main cause of failure [129].Roffey performed extensive test programme which included metallographic wire examination, tensile testing and cyclic fatigue testing to study fracture mechanism of cable wires. He observed that fractures were connected to perpendicular cracks of varying depths originating from surface corrosion in every case. Final fracture zones tended to have sloping crystalline features or cup and cone features, respectively, and were either brittle or ductile in nature. On many of the fractures, a common feature was a change in propagation direction near the crack tip before overload failure, though. The crack branched out longitudinally to form a "T"-shaped crack tip as a result of the shift in direction as can be seen in Fig.73. He concluded that the main reason for tensile strength reduction is localised corrosion which propagates perpendicular cracks within individual wires and there was no direct relation to general corrosion severity as was previously assumed [130].

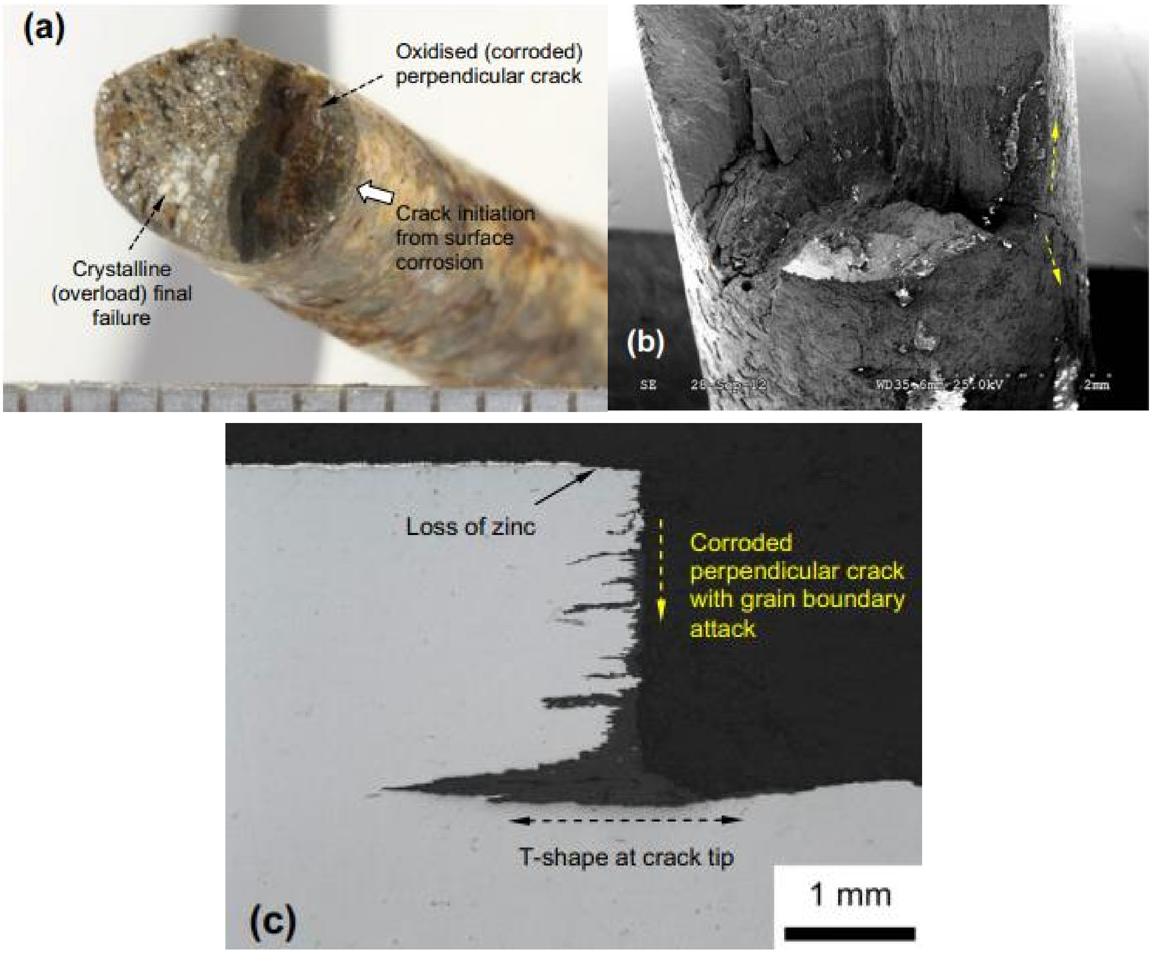



Fig.73: Broken wire removed from the cable a) corrode crack initiation b) change in crack propagation direction c) grain boundary attack [130]

Morgado et al. performed a case study on failure analysis of prestressed steel cable, the observed some wires had undergone cup and cone type ductile fracture while some wires showed brittle fracture. Two fracture modes viz. void coalescence and secondary cracking and intergranular failure mode are shown in Fig.74.

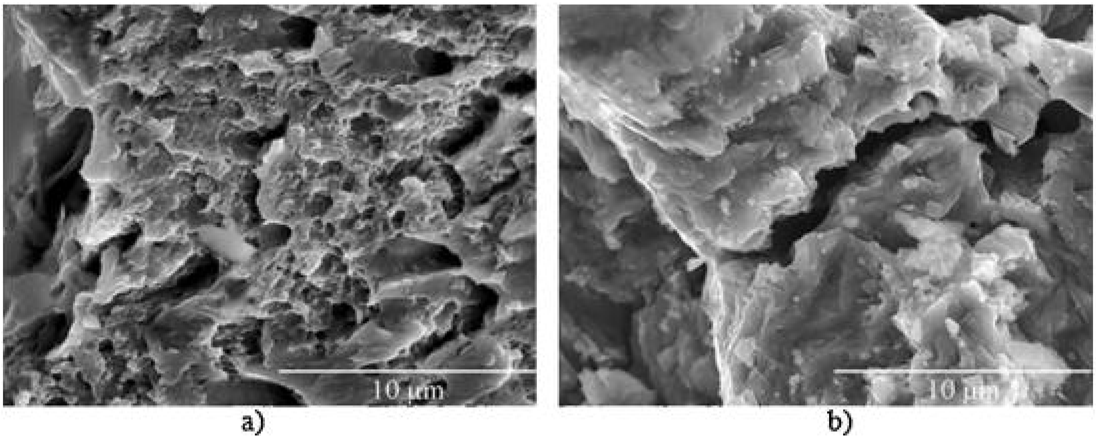



Fig.74: a) void coalescence and secondary cracking; b) Intergranular failure

They conclude that a small variation in the applied stress causes a great variation in the fatigue cycle, and the fractographic analysis revealed that the cable failed in two stages: first, the rods were attacked by stress corrosion, which seriously affected more than 50% of the rods and gradually caused them to fracture; second, when the number of remaining rods could no longer support the applied force, the remaining rods broke by ductile fracture [131]. Chang et al. studied the breaking failure characteristics of hoist ropes with different wear scars by the breaking tensile test. They found that in the wear scar region, there is considerable plastic deformation and a clear temperature increase. The quantity and the order of the fractured strands can be inferred from the temperature rise graphs during the breaking tensile test. The wires with irregular wear scars always fracture along the sliding wear direction at the region with the greatest wear depth, and the internal wires fracture earlier than the worn-out exterior wires [132]. In other experimental investigation Chang et al. studied the fracture failure behaviour of wire rope with different surface wear. They analysed , the effects of the wear scars caused by sliding friction under different crossing angles and cross directions on the mechanical response of wire rope. They used scanning electron microscopy to comprehend wear evolution as can be seen in Fig.75. It is obvious that the wear debris resembles thin slices, and the debris particles have a variety of shapes. Additionally, the surface's complex structure and a variety of damage characteristics, primarily plastic deformation, micro-cutting, and cracking, are present. Right cross contact with a crossing angle of 7 degrees results in minimal wear depth and a smooth wear surface . The surface has a light scratch and deformation, and the shape of the debris is more standardized. For left cross contact presence of galvanizing material can be seen which renders the debris crisp and hard, which in turn makes them more fragile.

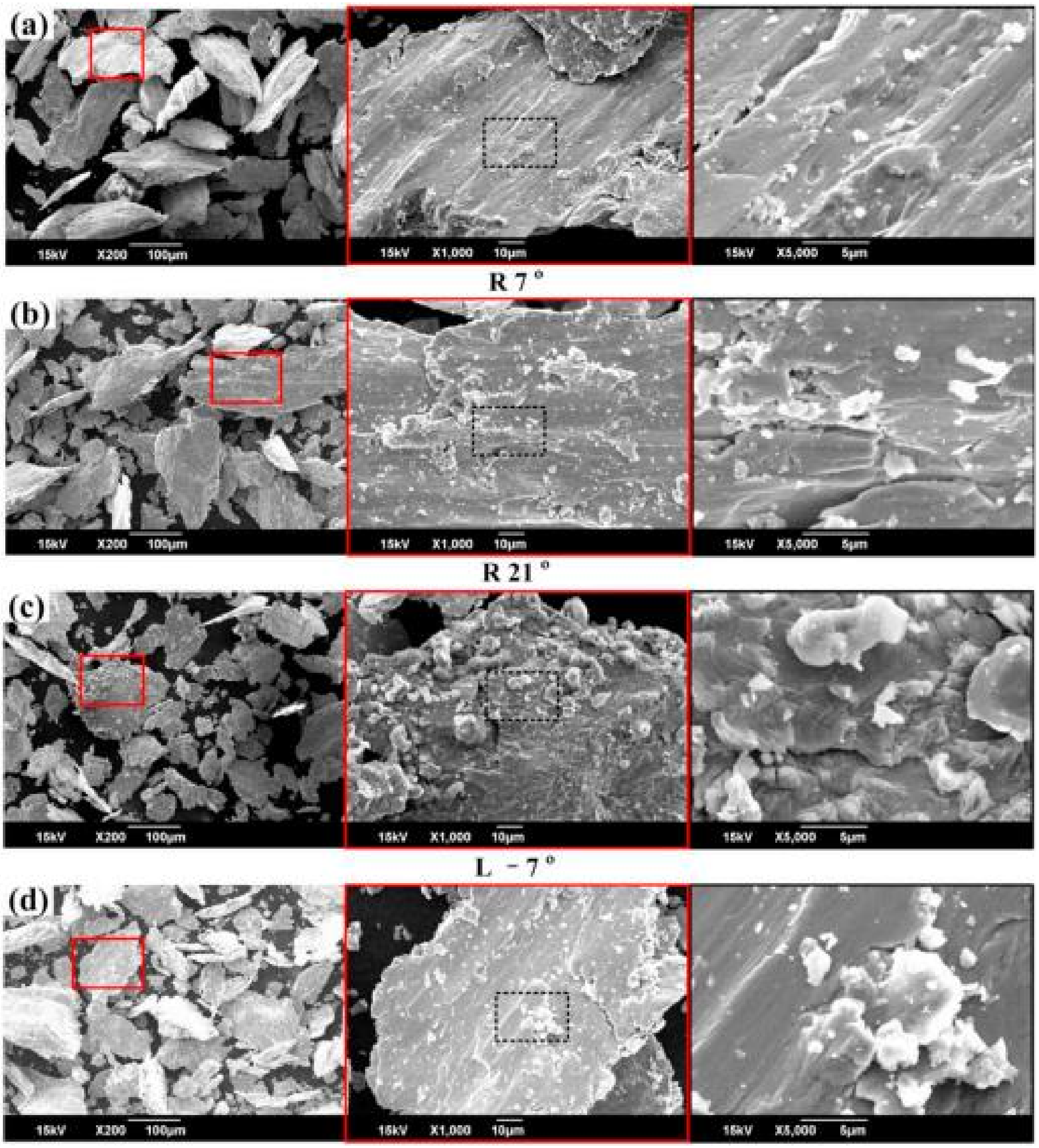



Fig.75: SEM micrograph of debris a)and b) right cross contact; c) and d) left cross contact [133]

The observed that for a rope with wear scars, the range of the breaking force variation is greater when it slides under right cross contact, and the damage is more severe when it slides under left cross contact. Before the rope breaks, there is a clear plastic deformation and temperature increase close to the wear scar. Ductile fracture with surface dimples and necking is the fracture failure mechanism [133]. Shamsuddin et al. studied failure analysis of crane rope. The fractography with the description of images can be seen in Fig.76. In a the point of origin can be seen and it is the cross over point and the ratchet and beach marks confirm the fatigue fracture. They observed that the outside strand wires of the wire rope were subjected to cyclic torsional stress, which led to its failure. The wires become fatigued because during services, as the rope was continuously pulled up and down over small diameter sheaves. The core wire eventually fractured in a ductile overload way as a result of being continuously overloaded and being unable to support the load any longer [134].

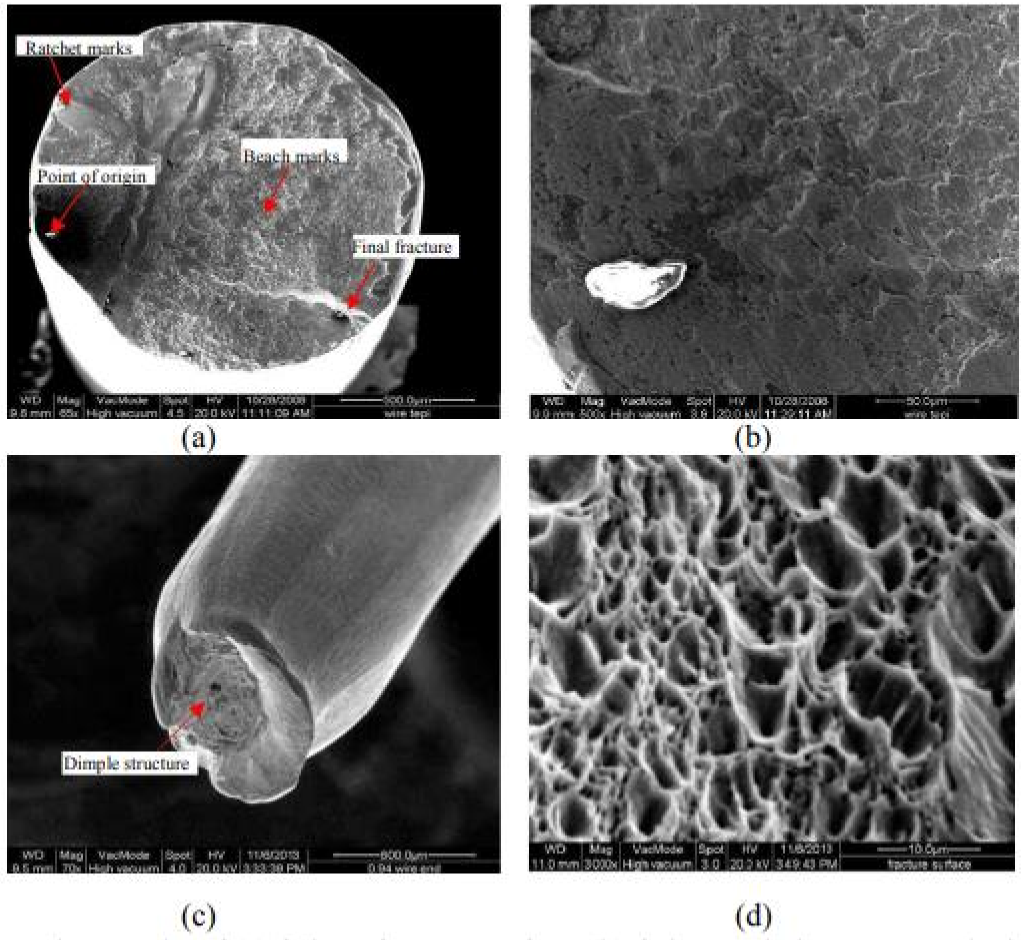



Fig.76: a) fatigue fracture surface; b) fatigue striations; c) cup of cup and cone fracture; d) zoomed in image showing dimple morphology [134]

Fuentes et al. performed the failure analysis of steel wire rope used in overhead crane system. The analytical techniques employed were visual examination, fractographic analysis, hardness analysis and SEM analysis. Scanning Electron Microscopy was used to examine the fractures in detail, and Fig.77(a, c, and e) demonstrates how the wire and core fractures are fragile . There are three stages to the failure mechanism in these fractures: crack initiation zone "A," crack propagation zone "B," and failure zone "C." (Fig. 77c). The wear zones are visible in Fig. 77 (b, c), and the arrows pointing to them demonstrate that the wire rope's core and exterior both experienced wear. They observed a primary deformation wear mechanism in outer part of the rope which ended in rupture several external wires alongwith degradation of lubricant. The rupture of wires lead to increased work stress which inturn gave rise to deformation hardening and finally to fragile fractures. The remaining wires fail due to the loss of tensile strength during cyclic loading [135].

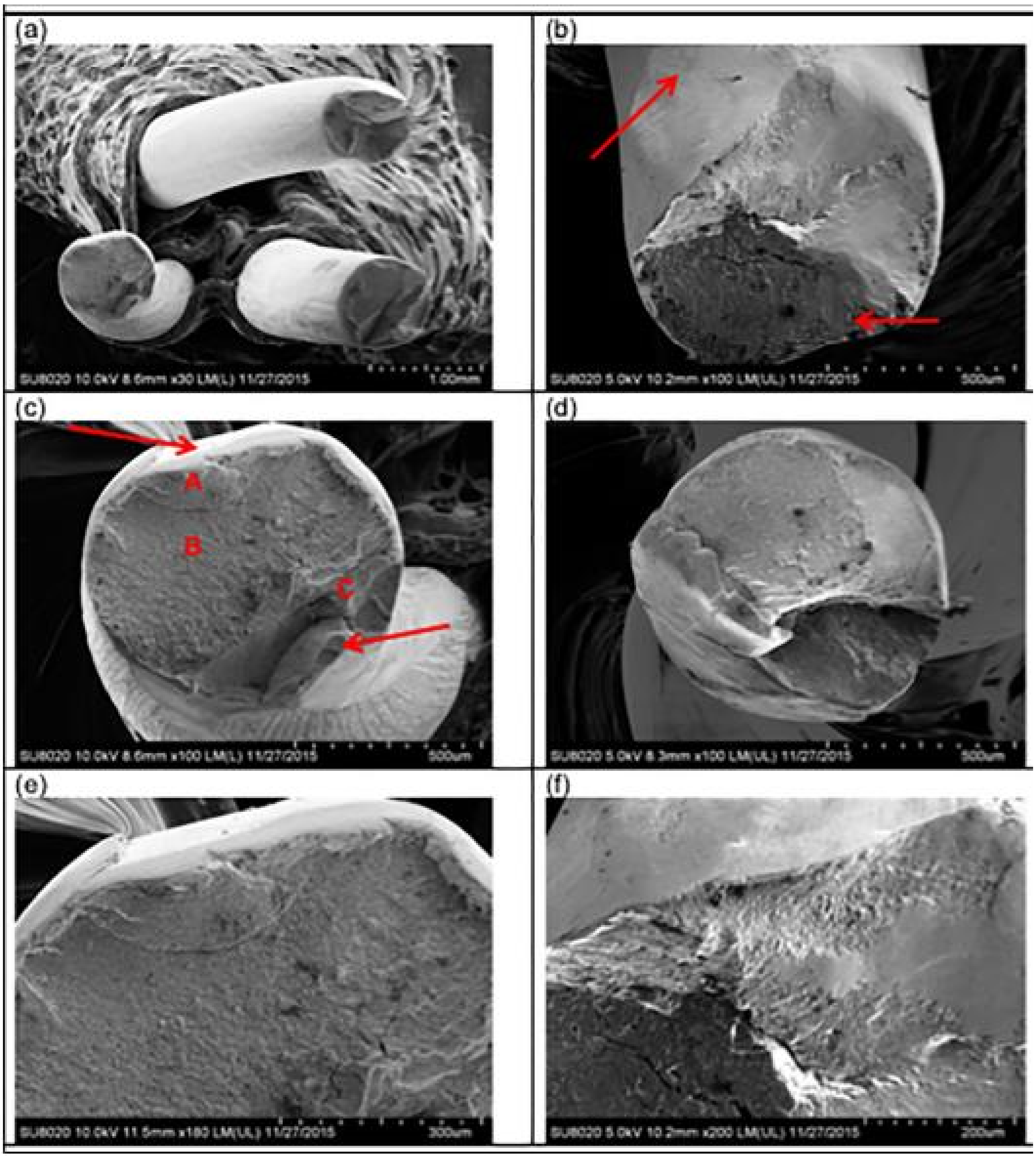
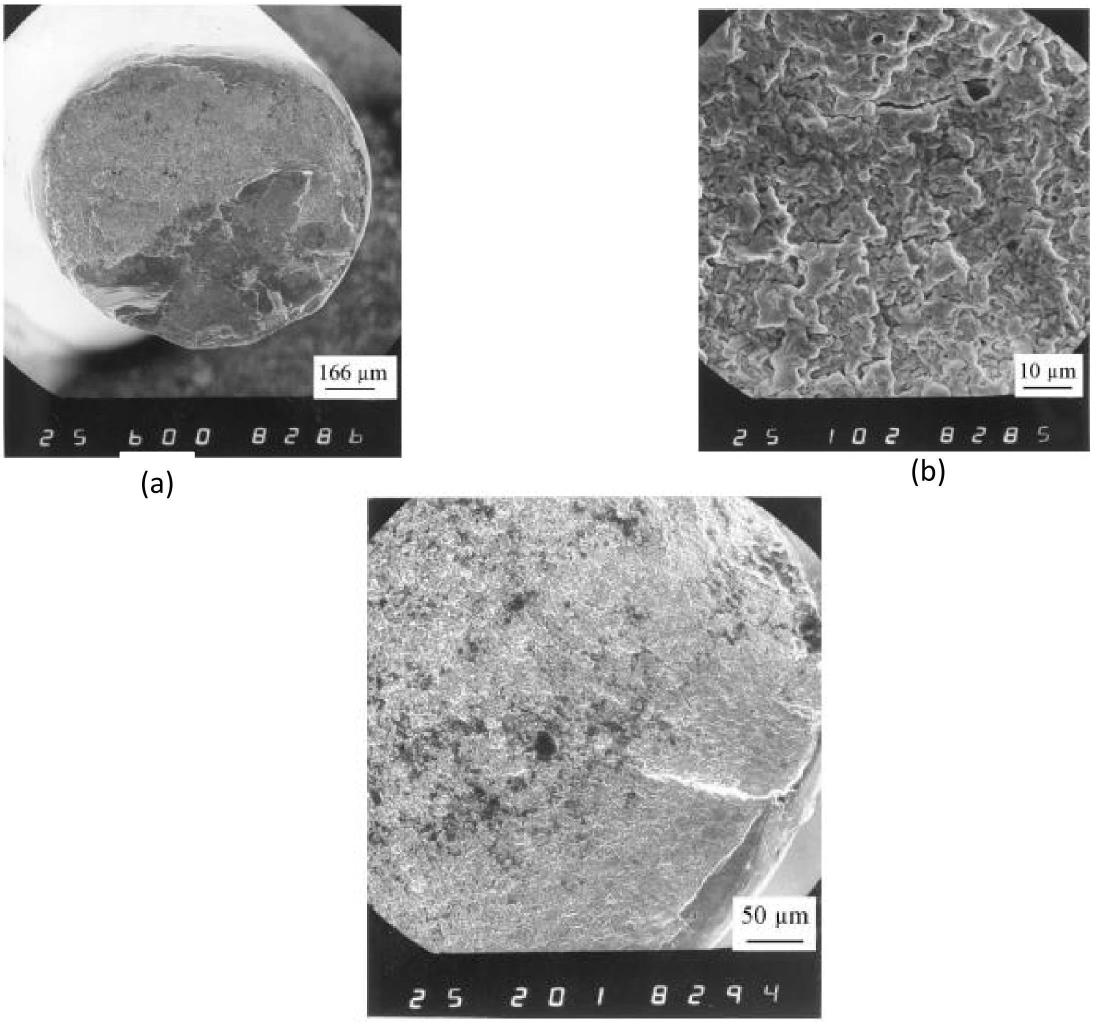


Fig.77: (a, c, e) Representative wires of the core, (b, d, f) representative wires of the external part [135]

Singh et al. studied failure of cold drawn steel wires and observed a white coloured layer having a fine structure near the wire edges at locations where failures occurred. This white layer has greater hardness and was identified as untempered martensite. They proposed the failure of wire rope was due to the brittle nature of this untempered martensite. They presence of martensite was inferred to be the result of generation of large amount of localised heat due to sliding conditions; this heat raised the temperature to austenitising temperature and then rapidly cooled to transform a harder microstructure called friction-martensite [136].

Torkar et al. studied the failure of crane wire rope. The SEM fractography indicated that the broken wire fracture surfaces display characteristics of fatigue, Fig78. Moreover, the fracture started from on the surface and the fatigue crack grows until final fracture. Also a crack was observed which might have been the initiation point (Fig.78 c).




(a) (b)

(c)

Fig.78: Fatigue Fracture with a) damaged edges b) micro-cracks c) Initial Crack [137]

They concluded that the fracture was a result of accelerated fatigue as well as lack of proper inspection and timely maintenance. The fatigue crack growth initiated from the surface defects. Ultimately the rope failed due to decreased load capacity which was brought about by increasing number of broken wires [137]. Moradi et al. analysed the failure of a drilling wire rope using metallurgical inspections and finite element method of computational analysis. While studying the morphologies of fractured surfaces they observed the wires mainly failed in shear and tensile modes confirming tensile overload. While the finite element analysis indicated to small sheave diameter and highest maximum principal stress was found in the core [138]. Islam et al. studied elevator rope under vibration and concluded that increasing the natural frequency of hoist ropes increases the chances of fatigue and the natural frequency. They also observed that the natural frequency can be reduced by increasing rope length and number of hoisting ropes, and decreasing modes of vibration

[139]. Erene et al. analysed fatigue and fracture of seven strand steel wire under axial and bending loads. They performed various tests using different combinations of tensile and bending loads. They deduced if failure near  to clamps is avoided then the failure is mainly a function of global stresses. Moreover the boundary conditions of strands are vital to fatigue life [140].Palit et al. assessed life cycle of wire rope used in crane application in a steel plant. The SEM fractograph is shown in Fig.79 and we can see the fatigue and ductile are visible in fractograph.

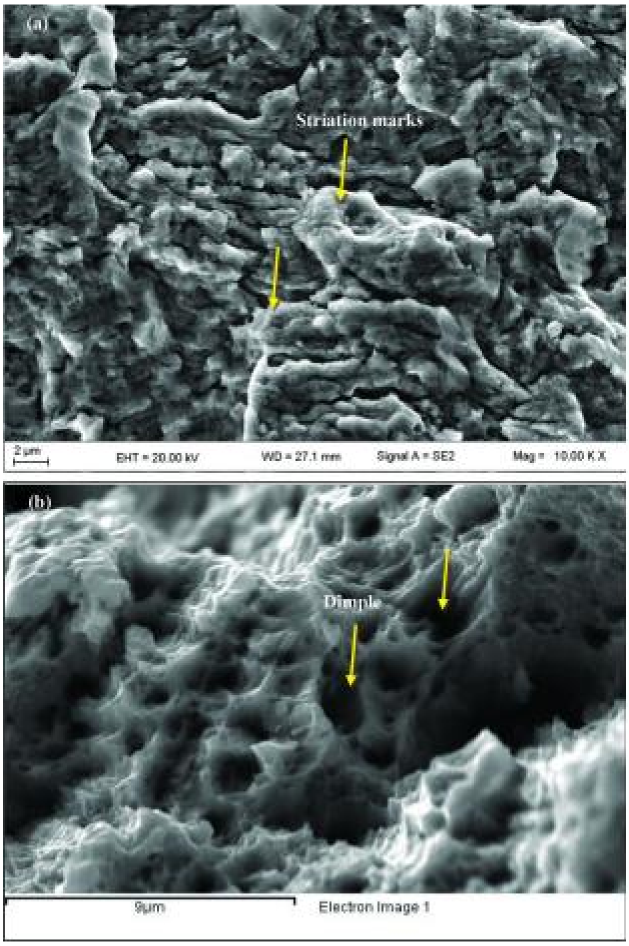



Fig.79: a) striation indicating fatigue; b) dimples indicating ductile fracture [141]

They observed The slab yard crane wire rope failed in two pieces. Failure took place during slab movement, and wire ropes slipped out of the sheave. Also damage marks on sheave indicated fouling of ropes. They concluded that main failure mechanism was fatigue, and that fatigue cracks were started from the abraded area that was caused by constant contact between the wire surface and the sheave guard [141]. Kishore et al. proposed a novel degradation mechanism of a structural wire rope. The observation of microfractography using SEM shows striation marks for wires who encounter square break indicating fatigue failure and fine dimples were observed in some wires which displayed cup and cone fracture surfaces as shown in Fig.80

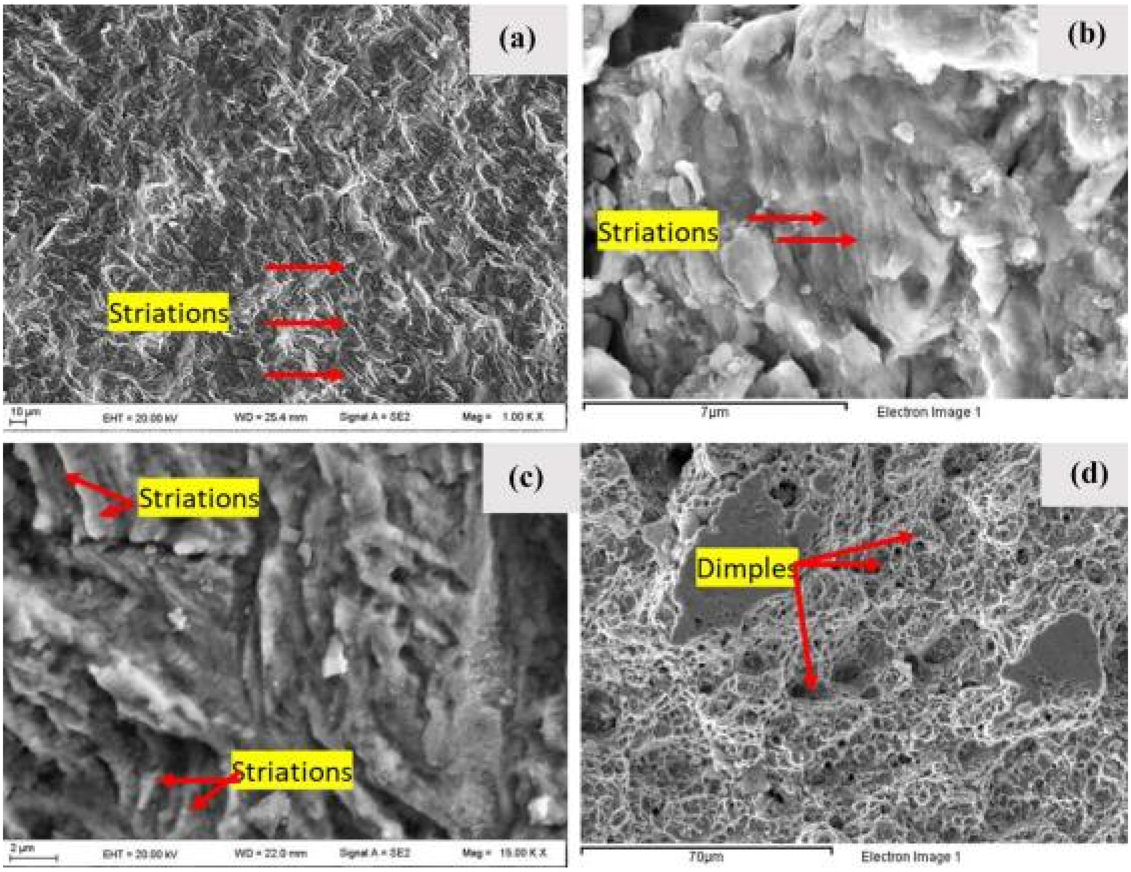



Fig.80: SEM microfractography a), b), c) showing fatigue striations; d) cup and cone fracture showing dimples

The novelty of this study was in the number of mechanisms that contributed to failure. The main cause of premature damage was inappropriate lubrication which was a given due to the abrasion marks, discoloration, and dry rope core. The majority of wire breaks displayed square shaped surface fracture with striations indicating fatigue and the remaining wires displayed cup and cone fracture indicating ductile fracture which is an after effect. As can be seen there is also the presence of white layer of harder microstructure of frictional martensite, which was formed during the service life owing to improper lubrication. Moreover, fusion zones were also discovered which acted as the point of initiation of cracks [142]. These failure contributing mechanisms can be see in the microfractography as shown in Fig.81

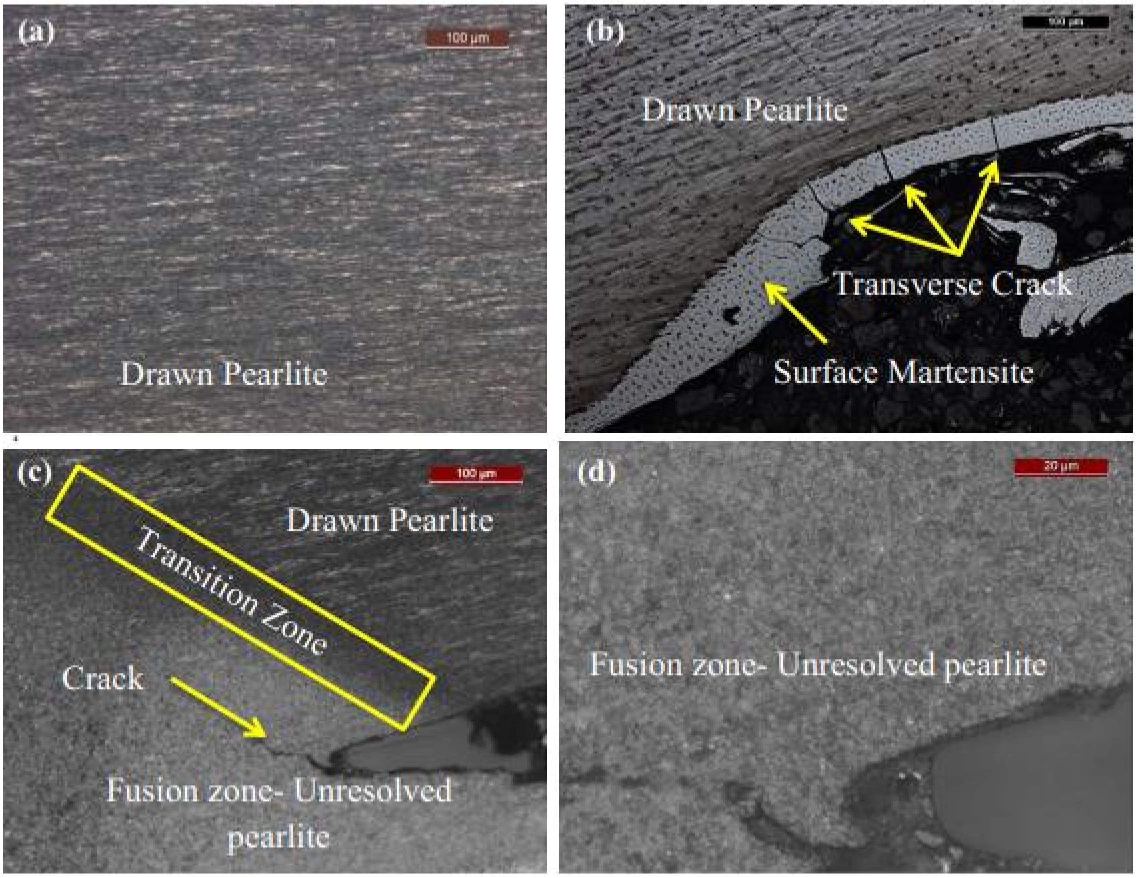



Fig.81: Optical microfractography of damaged ropes a) away from damaged zone; b) abraded region; c) and d) fusion zones at different magnifications [142]

Hu et al. studied origin and mechanism of torsion fracture in cold drawn pearlitic steel wires. They observed two types of torsion fracture viz. flat and cleavage fracture as can be seen in Fig.82. The flat fracture indicates excellent torsional property as the fracture was flat, while cleavage fracture displays unstable deformation pattern poor torsional tolerance. Due to sudden torque drop crack extends at an acute angle to axial direction [143].

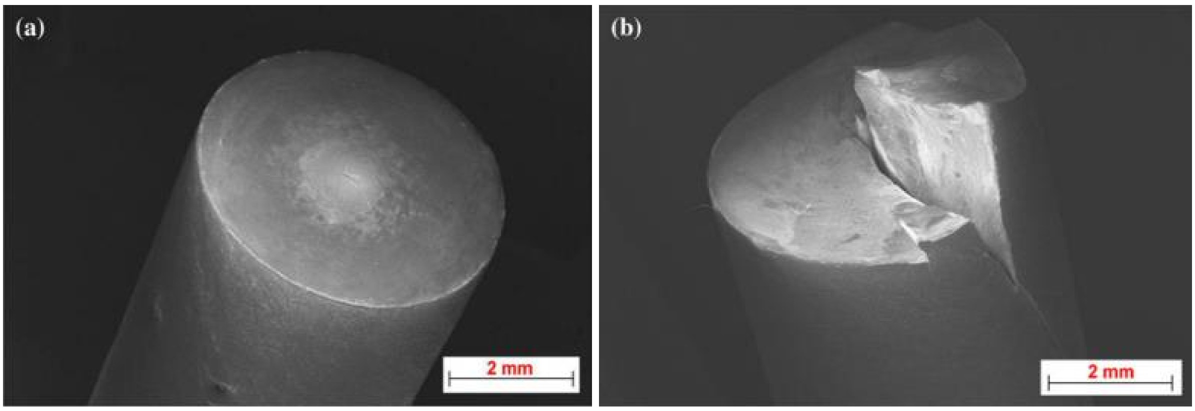



Fig.82: Torsion fracture of steel wire a) Flat fracture; b) Cleavage fracture [143]

The crack initiated at the interface between ferrite and cementite in coarse pearlite and the interface acted as the pathway of propagation because of its weak strength as can be shown in Fig. 83 [143]

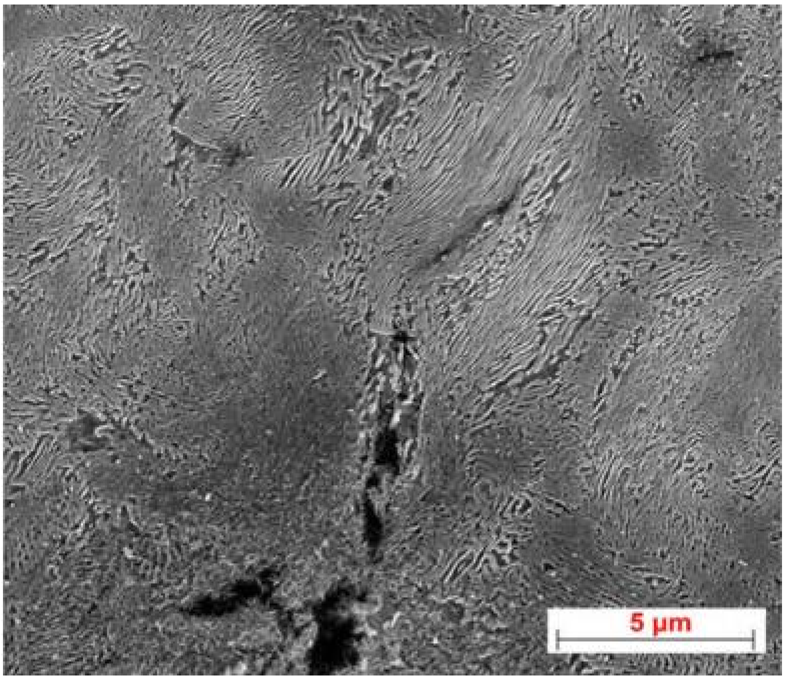



Fig.83: SEM microfractography showing torsion cracks in pearlite [143]

Zhang et al. studied tribo-fatigue behaviours of steel wire rope under bending fatigue with the variable tension. They made a novel bending fatigue test apparatus that could provide variable tension. They observed that fractures of steel wires at wear scars are attributed to the combined effects of fatigue, bending and contact stresses [144].

# CHAPTER 8: CONCLUSION

The aim of this thesis was to provide a literature review of all the mechanisms right from production and metallurgy to the final failure of steel wire ropes. The first chapter was dedicated to get to know, what the need was, of studying the fatigue and fracture mechanisms. We came across how devastating and catastrophic results could be, if fatigue and fracture mechanisms were not paid attention to. The second chapter was all about knowing the ins and outs of the wire rope. Right from why we need a wire rope to its constituent elements and components; everything was dealt with in detail. The strength and ruggedness of the wire rope make it a wonder machine, and how its utility varies from the dry and arid deserts to the vast oceans was discussed. We also came across the rope terminations that need to be utilised to obtain the functionality that's desired. The know how of the constructional arrangement of the rope and different types of Lays of rope was also dealt with. The third chapter dealt with microstructure and production of the steel wire rope. The composition of steel along with the classification of steel and the phases and different structures were discussed. Moving ahead, the iron carbon diagram including the eutectoid transformation was also touched upon. The structure and kinetic transformation of pearlite was thoroughly canvassed owing to it being one of the most structure of wire ropes. The metallurgical and production processes were dealt with in detail as they are what provide the characteristics of the steel wire rope. The fourth chapter is of special importance as it discusses the mechanisms of degradation in general and the wire rope in particular. The various degradation mechanisms like tension-tension fatigue, bending over sheaves fatigue, bending fatigue, fretting, wear and corrosion were all discussed keeping in mind their causes and the various research that have been done so far. The factors, both intrinsic and extrinsic like the environment, the medium, the material defects, the contaminants etc. responsible were discussed according to the available literature. The fifth chapter focussed on various testing methods like the magnetic flux leakage method, radiography method, acoustic emission methods. The mechanisms of the methods along with various developments and the introduction of new technologies were discussed. Light was also shed upon the sensors, like Hall sensor and induction coil and their working mechanisms. The shortcomings and the advancement of the technology as out forth by various researchers and scientists were thoroughly discussed. The sixth chapter discussed A-to-Z of the care and maintenance of wire ropes, and it is of critical importance for the service life of wire rope. The care and maintenance according to international standards was deliberated. The topics covered were storage and handling of rope, the consideration of environment, the installation of the wire rope, the operation and the maintenance of rope. Right from the moment the wire rope is received to the moment it is about fail, everything was discussed. The proper and improper ways of care and maintenance were evaluated and recommendations for the better practices were made. The final chapter dealt with the final fracture or failure of the wire rope. The fracture mechanisms along with the enhancing factors and parameters were discussed. All the types of fracture like ductile brittle, torsion, intergranular etc. were discussed. The history and the present understanding of the fractures was provided in line with the literature available.

Going through all the research papers and literature utilised for this thesis, it is safe to say that the prevention of accidents begins right from the production stage as many times the point of initiation of cracks were the stress concentration areas produced due to the processes. Also, other causes of accident was improper handling, maintenance and inspection. In many case studies it was found that the reason of failure was the improper lubrication or lack of inspection. Also new techniques need to be developed for the testing of the wear and fatigue as the current technologies are limited by the shortcomings. Last but not the least, expert supervision right from the beginning of production to the installation and discard of ropes is of critical importance

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