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ORIGINAL PAPER

Effect of Key Parameters on Fretting Behaviour of Wire Rope: A Review

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Abstract

Wire ropes are widely used in civil, mechanical and mining engineering. Safety of human life while using wire rope is always been a matter of great concern. Consequently, an efficient and safe performance of wire rope has always been an area of research. Fretting behaviour under repeated cyclic load in practical application is key player in performance of wire rope. Fretting behaviour is affected by a number of parameters viz. wire rope material, its tensile strength, lubrication and coating material and environmental factors like corrosive medium, operating temperature etc. There is a huge potential for further research in the area of fretting behaviour analysis. This paper presents a state-of-the-art review of key variables, their effect as well as remedial solution of fretting behaviour of wire rope.

1 Introduction

Wire ropes found their application in mechanical, mining and civil engineering applications. Wire ropes have been in use since thirteenth century and various modifications have been made over the period of time. The aim of rope making is to combine the strength of individual wires or fibers. There have been many researchers for various improvements in wire rope for inter-wire wear analysis, arrangement of wires in strand and strands in rope [1]. London and Norway were well known centers for research and manufacturing of wire ropes [2]. Wire ropes have different type of structural arrangement, but are regarded as having three basic components viz. wire that forms strands, a core, and multi-wire strands that are helically wrapped around the core. The various components of wire rope are illustrated in Fig. 1. Wire rope uses have been increasing day by day. Recent research toward possibility of use of wire strands as braces of teeth is one such example, power lines having aluminum wire twisted around steel core, wire strand as cords to strengthen the rubber tyres, applications in super conductivity are others.

During the application, wire rope is subjected to axial tensile load, bending load while moving around sheave or drum and sometimes, twisting load too due to rotation of load during its movement and consequently, the failure load reduces considerably [3]. Due to helical structure of wires in wire rope, a radial contact pressure is generated between wires of same strand as well as between inter-strand wires and this radial contact pressure plays an important role along with other variables viz. material and cross-section of wire, co-efficient of friction between wires. This friction makes it possible for broken wires to take their share of load at some distance from the breaking point. The frictional resistance to sliding of wires is directly proportional to tension in wire [4]. Cyclic or fatigue load results from repeated operation of lifting the load or pulling it in horizontal direction as well as repeated bending of wire rope over sheave or drum [5, 6]. The main features of wire rope are high tensile strength, low ductility, high stiffness and flexibility in bending.

2 Materials for Wire Rope

To meet the basic requirement of strength, stiffness, fatigue behaviour for different applications of wire rope, various materials are used for different wire ropes. The very high strength wire ropes are suitable for supporting large tensile load even with smaller diameter pulley. Materials of wire ropes are broadly divided in two segments i.e. metallic wire and non- metallic wires.

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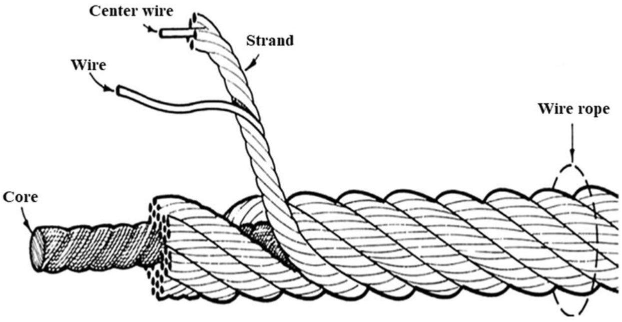

Fig. 1 Components of wire rope

Table 1 Composition of plain carbon steel by mass percentage for wire rope

Constituent	Percentage composition
Silicon (Si)	0.1–0.3
Manganese (Mn)	0.5–0.8
Sulphur (S)	< 0.035
Nickel (Ni)	< 0.20
Chromium (Cr)	< 0.15
Molybdenum (Mo)	< 0.05
Phosphorus (P)	< 0.035
Aluminium (Al)	< 0.01
Copper (Cu)	< 0.25

2.1 Metallic Wire Rope

Metallic wire ropes are mostly used for high strength applications. For high strength wire, steel has been used since a long time. High strength steel wire ropes are made by cold drawing process and are made of non-alloy carbon steel. Mass percentage of carbon in such wire ropes varies from 0.4 to 0.95%. Steel with high carbon content nears 0.86% by mass with eutectoid fine pearlite are preferred for making rope wires. Various common constituents of carbon steel by mass percentage are tabulated in Table 1. Rope wire needs protection against corrosion are coated with Zinc (Zn) or Galfan that is Zinc–Aluminium alloy (95% Zn and 5% Al by mass percentage). In exceptional cases, where wire ropes are to be operated in corrosive environment, wires are made of Stainless Steel [7]. Steel wire ropes are made of steel having mass percentage of carbon ranging from 0.70 to 0.80%, known as Plow Steel [8]. Wire rope has also been made of copper–steel composite to take advantages of both copper and steel [9].

Wire rope with multilayer wires made of Aluminium and layers of one or two metals have been made to take various advantages of different material. Aluminium wires are first coated with Nickel so that zinc coating can be formed easily and advantage of Nickel in Mechanical properties and that of Zinc (Zn) in corrosion resistance can be taken. Some other combinations of Aluminium–Cobalt, Aluminium–Steel were also tested and proposed [10]. Steel wire ropes have been used for hoisting/elevation application. As the number of wire increases; number of wires with smaller diameter makes wire rope better in fatigue bending but also make poor under abrasion as its abrasion resistance decreases [11].

2.2 Non-metallic Wire Ropes

Wire rope made of nylon and polyester fibers has the advantage of high strength to weight ratio (that is around 10:1) as compared to metallic wire rope but limitation is that these fiber ropes cannot be used at elevated temperature [12]. A combination of steel wire rope with Nylon pulley or sheave for reduced wear of wire rope under repeated applications as compared to metallic drum or sheave in combination with metallic wire rope have been used [13]. Multiple material wire rope have been in trend where Multiple Attribute Decision Making (MADM) model has been used to give a ranking to the candidate material for wire rope, drum or sheave and other mechanical components for various application under given constraints [14]. Under corrosive environment, steel wire rope corrode at quite faster rate and their life is reduced considerably and wire rope made of synthetic plastic material are capable of withstanding substantial load but it undergoes deformation up to 35–50%, so cannot be used in application where deformation is dangerous or undesirable i.e. cranes, elevators, derricks for lifting heavy loads etc. So, another new synthetic plastic material of high tensile strength, aromatic- polyamides, designated as PRD-49 or Kelvar 49 has been used for applications where deformation is undesirable [15]. For a biomedical lead, the conductor cable in the form of twisted wires of composite lead has been used. Conductivity of core is kept low but its mechanical strength is kept high to restrict deformation and wires of periphery are made with material having high conductivity but low mechanical strength [16].

3 Mechanical Properties of Wire Rope

Wire rope is meant to lift or pull load and ensure safety during its application, so its tensile strength is most important parameter. Wire rope is required to have high tensile strength, high stiffness and flexibility in bending. Strength of wire rope relies on a number of parameters and various techniques that are used to measure the strength. Strength of wire rope relies on that of individual wire i.e. wire diameter and its material, angle of twist in strand. Relation of wire

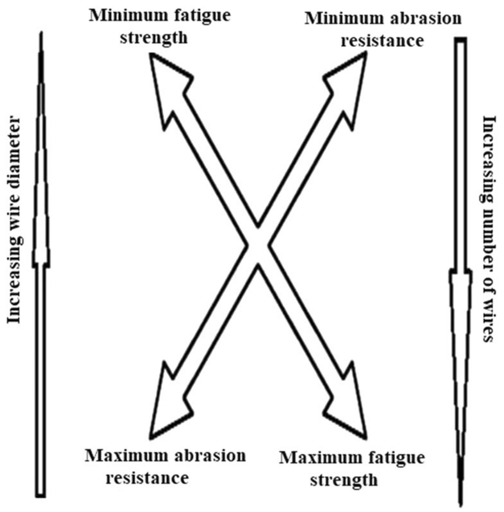

Fig. 2 Relation between wire diameter, number of wire, fatigue resistance and abrasion resistance

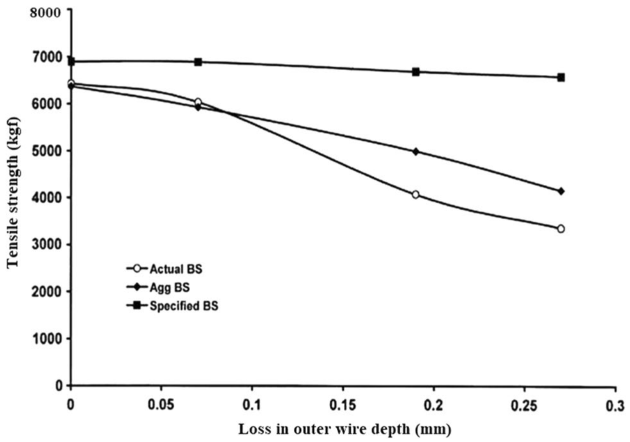

Fig. 3 Effect of wear on tensile strengths of wire rope [18]

diameter and number of wires in wire rope with their performance under fatigue bending and abrasion is illustrated in Fig. 2 [17].

During service, wire rope continuously gets deteriorated under several variables e.g. wear, corrosion, tension, fatigue, and bending. Though all these factors affect strength of wire rope but wear affects most as it results in loss of material. Wear is of *two* types, plastic wear and abrasive wear.

Plastic wear occurs due to high pressure contact between wires of rope and with other items such as sheave wheel. Abrasive wear results from rubbing against various obstructions the rope may come into contact with. Tensile strength of wire rope can be assessed by many ways like loading the wire rope to tensile load can give its actual breaking strength or by analyzing the tensile strength of individual wire and, then multiplying it with number of wires in rope and a rope strength factor, giving its aggregate breaking strength or by multiplying the strength of wire rope material to its cross-section area, can give its specified breaking strength. Wear results in loss of material from wire rope and it results in reduction in strength of it. Effect of loss of material due to wear on various types of strength is shown in Fig. 3 [18]. Strength of wire rope also depends on percentage of carbon and the temperature during wire drawing. Carbon percentage decides the percentage of pearlite in the wire because 0.83% carbon results in 100% pearlite and its percentage decrease with change in carbon percentage on either side of it. Tensile strength of both ferrite and pearlite increases during cold working but increase in strength of pearlite is more than that for ferrite. So, wire rope with carbon percentage near 0.83% carbon with cold working results in wire rope of high tensile strength [19]. The increase in the tensile strength of wire rope is usually co-occur with lowered ductility and increased vulnerability to delayed fracture, called as hydrogen embrittlement. A compromise between strength and ductility is required to be made. In high strength steel wire, strength mainly depends on the size of the pearlite colony and interlamellar spacing i.e. space between layers of cementite and ferrite, and the size and shape of the dislocation cells that are constructed during the process of wire drawing. So, the strength mainly depends on micro-structural behavior. Linear Elastic Fracture Mechanics (LEFM) analysis has been used to get relation between stress field distribution, magnitude of nominal applied stress and stress near crack, shape of crack and size orientation and the material properties. Wire material can tolerate a crack without brittle fracture until the applied stress intensity factor, K_1, is lower than its critical value, the fracture toughness, K_c, which again depends on crack size, shape and orientation, material of wire, metallurgical properties. Fracture toughness describes crack propagation behavior of material. The strain energy density has been used to analyze the deduction into wire toughness caused by environmental degradation. Presence of surface deficiencies acts as stress risers.

The ultimate fracture in wire is a result of two procedures, f*irst*, surface cracks or flaws that commence and *second* one is the propagation of flaws to final fracture. Corrosion pit also make water to enter into the wire and results in hydrogen embrittlement. Crack propagation behavior of the material is a function of fracture toughness, stress condition and metallurgical properties of wire material [20]. Wire rope's strength also gets affected by corrosion. Tensile strength does not get much affected but elongation i.e. ductility, torsional and fatigue strength decreases sharply with increasing corrosion. Corrosion causes corrosion fatigue. Wire rope breaks under the combined effect of high residual stresses, corrosion, cyclic stresses, hydrogen embrittlement and fatigue. During corrosion steel wire absorbs hydrogen and consequently hydrogen embrittlement results. Corrosion

Table 2 Chemical composition by mass percentage for high strength wire rope

C	Mn	S	Si	P
0.86	0.75	0.014	0.84	0.0046

also causes uneven surface and stress concentration, which lead to fracture. Galvanized wire has also been subjected to corrosion but after a longer service life as compared to bare steel wire [21]. Strength of wire rope depends on drawing process and post deformation heat and surface treatment. Cold drawing results in increased tensile strength without significant degrading of ductility. Post annealing at 200–400 °C and/or hot dip-galvanizing at 450 °C improves the anti-corrosion properties of the wire. High temperature annealing i.e. near 400 °C, results in decreased tensile strength by age softening and low temperature annealing i.e. near 200 °C, resulting in increased tensile strength by age hardening. The presence of silicon at the ferrite- cementite interface retards the break-up and spherodization of lamellar cementite to a higher annealing temperature by decreasing the solubility of carbon in ferrite and suppressing the decomposition of lamellar cementite. So, silicon suppresses the age softening during hot-dip galvanizing and is an important alloying element of high strength wires. General chemical composition by mass percentage for a high strength wire is given in Table 2 [22].

Strength of wire rope can also be improved by compaction, mechanically stress relieving and thermal stress relieving. Thermal stress relieving by annealing removes tensile residual stresses. Compaction produces compressive residual stress that improves fatigue strength [23]. For high strength cable, composite fiber material can also be used as these fibers do not deform or buckle under external loads [24].

4 Fretting behavior of Wire Rope

During application, wire ropes are subjected to repeated tensile loading, mechanical vibration and bending loads. Consequently, microscopic relative motion between neighboring wires in the rope takes place. Ultimately this results in fretting wear. The interaction of cyclic load and fretting wear, results in initiation, propagation and consequently, the final fracture of wire rope i.e. fretting fatigue. Fretting fatigue results in loss of material and crack propagation of wire rope. Consequently, wire rope fails. This makes it essential to quantitatively analysis the wear evolution and three-dimensional crack propagation in steel wire during fretting fatigue, to estimate fretting-fatigue life of steel wire and so to get an idea about the fatigue life of wire rope. Surface wear scar and wear depth is evaluated dynamically by using three-dimension white light interferometer. Three-dimensional crack propagation behaviour of steel wires has been presented by using tomography computed by X-ray. A typical fretting observed in wire rope is depicted in Fig. 4a–c [25].

Fretting between contacting surfaces acts as crack initiation site leading to catastrophic failure of the overall structure at very low stresses. Various important fretting parameters are slip amplitude, contact pressure, frequency of applied loads etc. [26]. Properties of wire material have a great effect on its fatigue behavior. For patented and cold drawn wires made of unalloyed carbon steel, the fatigue strength increases by increasing tensile strength with the cross-section reduction being approximately 85% of original area, during drawing. Surface roughness due to fabrication process and surface imperfections such as drawing marks have detrimental effect. Notch sensitivity also increases with increasing strength [27].

There have been various types of test rigs for fretting fatigue experiments and every test rig has its own advantages, disadvantages and limitations. It is hard to compare various types of test rigs. Even after various developments, most advance test rigs that are “state of art test rigs” still have imperfections. Standardization and perfection in test rigs have been still pending and improvements are taking place with advancements [28]. Since fretting originates at surface, so a hard, wear resistant surface layer containing compressive residual stresses would have better resistance

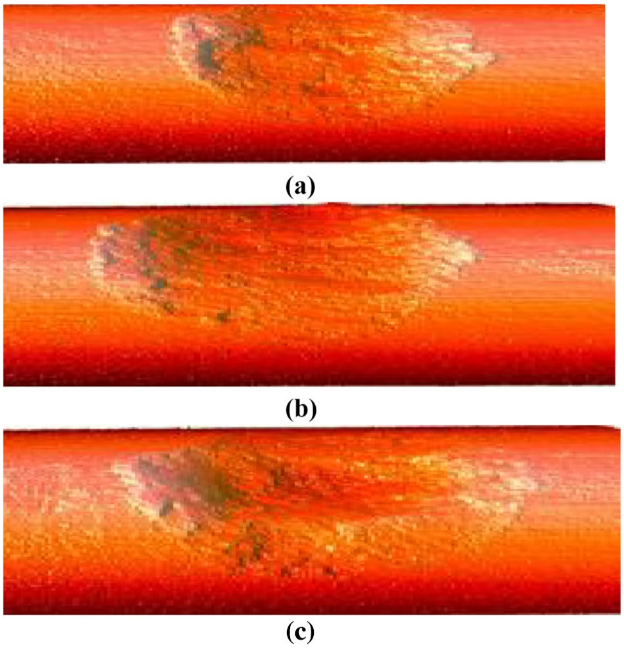

Fig. 4 Wear scar morphologies of tensile steel wires at distinct relative displacements **a** after 5000 cycles, **b** after 10,000 cycles, **c** after 20,000 cycles [25]

to fretting fatigue. In many applications, stainless steel components subjected to wear and fluctuating stresses have been provided with nitriding heat treatment for improving the tribological properties of material [29].

Wear behavior of the wire is affected by contact pressure, environmental condition e.g. relative humidity and co-efficient of friction. Fretting wear can be reduced by using different strategies viz. reducing the co-efficient of friction, modifying the environment i.e. relative humidity, changing the material forming the fretting couple, and reducing the fretting amplitude. Reducing the fretting amplitude has not been a suitable technique for wire ropes as the relative movement between wires is required to have flexibility in bending. Material of wire has mostly been of eutectoid carbon steel but its tribological behavior can be changed by using surface coating. Relative humidity can be changed and co-efficient of friction is a function of type of lubricant used. Volumetric wear and the total accumulated dissipated friction energy shares a linear relationship. This energy is a function of the friction force and the sliding amplitude. Increase in relative humidity results in reduced co-efficient of friction by acting as a lubricant [30]. The Magnetic Rope Testing (MRT) also known as Magnetic Flux Leakage (MFL) method is a non-destructive method that has been used for the detection of flaws and cracks in steel wire ropes. It is a portable and reliable diagnostic tool. It can be easily used in operating conditions for the detection of broken wires, wear and corrosion. It uses disturbance in magnetic flux as a parameter to measure crack or flaws [31]. Fretting test of thin cold drawn steel wire of eutectoid composition i.e. 0.8% carbon with tensile strength of 2800 MPa has been carried out by using 90^0 crossed cylinder configuration by varying the stroke, testing time i.e. number of cycles and normal load. Afterwards the volumetric wear is obtained using profilemetry with diamond stylus. Wear rate increases with increase in loads even if crossing angle of wire is kept constant [32]. Fretting in wire ropes, under constant applied load, increases with increase in cross-angle. So, the effect of load and cross-angle is similar in wire ropes [33]. Effect of fretting on reduction in fatigue life of thin steel wires has been done by using frictionally induced multi-axial contact stresses that has been obtained by using finite element wear model. It is based on cyclic material removal due to fretting. Various fatigue coefficient of wire can be estimated by using Modified Universal Slopes, Medians and fatigue S–N curves, Manson's universal slope [34].

Finite element fretting wear simulation model has been used to deal with both circular and elliptical wear scars. Main parameters involved in the simulation are mesh size, simulation wear increments per fretting cycle and cycle jump or number of cycles between two measurements. These parameters can be calibrated to obtain the minimum computational time [35]. Deterioration of rope due to fatigue, corrosion, abrasion and any other mechanical stress results in rope distortion, such as the loss of strands, the "bird-caging" effect, or mechanical damage. Torsional oscillation due to variation in the tensile load increases the length of outer wires as compared to the core wires and makes the rope less efficient and this effect is defined as "bird-caging". It results in very short service life of wire rope [36]. Fretting behavior of material is also a function of its grain size. At high stress level, fine-grained materials have better fatigue properties but at lower stress level, coarse grained material exhibit longer fatigue life. It is due to formation of deformation-induced martensite during cyclic loading and this martensite formation reduces cyclic crack growth and leads to rapid hardening. At high cyclic stresses, formation of martensite was less because deformation-induced martensite is favored after certain amount of cumulative strain is induced in the material that occurs under low cyclic loading and under high cyclic load catastrophic failure takes place. In coarse grained material, around 5% martensite is formed and that, in fine grained material is limited to 1-2%. Effect of grain size on life is illustrated in Fig. 5 [37].

A three dimensional solid geometric model of wire rope can be generated by using Computer Aided Design (CAD) software e.g. cableCAD, solidWorks etc. and analysis for stress, strain etc. under external load through geometric parametric equations and computational modeling procedure. It has been solved by using finite element method (FEM). The finite element analysis (FEA) can be done in many Computer Aided Engineering (CAE) software e.g. Pro/Engineer wildfire 5.0, ANSYS software [38].

Wire rope for applications like aircraft rescue hoist is subjected to vibration during loading and that causes bending stress into it. In such applications, wear takes place in wire rope due to vibrational swinging as wire rope vibrate even under no load condition. It leads to progressive and

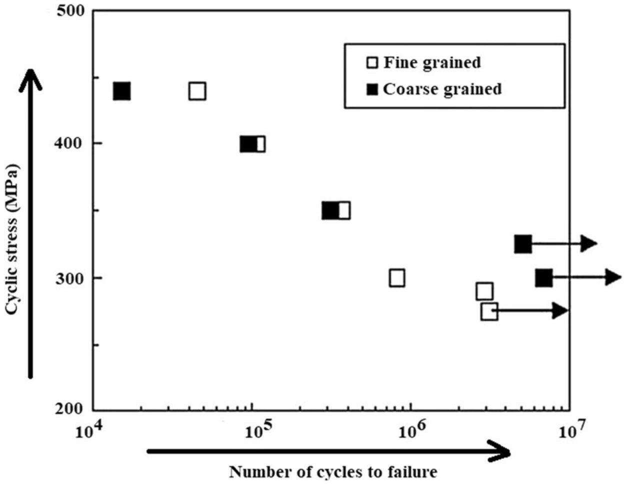

Fig. 5 Effect of grain size on plain fatigue life [37]

marked weakening of the resistant section [39]. Fatigue life of stranded steel wire rope has been found by using theortical or experimental methods. In theortical approach, the novel theortical bending over Sheave (BoS) fatigue life prediction equation is used that uses least square method of regression analysis. It gives result close to experimental values [40]. In experimental method, wire rope is subjected to repeated bending combined with static tensile load. The experiment is performed for a predefined number of cycles or until the rope fail, to determine the fatigue life [41]. Fretting fatigue mainly depends on normal contact load, bulk cyclic stress and relative slip. Relative slip plays an important role in fretting. Few researchers have found that fretting fatigue strength or life decreases with an increase in amplitude of relative slip. Many researchers have found that fatigue strength or life has been minimum at certain relative slip amplitude, but in general agreement with the literature showed the effect of fretting is more severe for a slip amplitude of about 20-25 µm [42]. Irrespective of process, component fretting largely depends on co-efficient of friction because co-efficient of friction directly affects the amount of shear stress. So, to reduce fretting damage, the key factor is reducing the co-efficient of friction. Various surface coating like Diamond-Like Carbon (DLC) coating is used to produce surface with a low level of friction. Combination of DLC coating and boundary lubrication condition produces very good result of low co-efficient of friction. Other hard coatings used to reduce co-efficient of friction are W–Si–N coating, Ti-based and Cr-based coating [43]. Fretting is also crucial for sea power cables. Dynamic sea power cables i.e. wire ropes, are used for power distribution from offshore wind mills and distribution of electric power to subsea unit for gas and oil production. These cables are subjected to bending and dynamic tension caused by waves and vessel movements. Fretting Fatigue is important for these cables as fretting takes place between wires as well as between wires and water blocking compound [44].

There are various types of fretting palliatives available e.g. shot peening, WC–Co coating, hard chromium coating etc. the objective is to use a fretting palliative that palliate friction, cracking and wear. To select a fretting palliative, there are many approaches but a normalized fretting damage chart approach is one of the fast, quantitative and accurate approaches. A combination of shot peening with any of coating approach can also be used for better palliatives to fretting [45]. As intimated earlier, the white-light interferometer can be used for measurement of wear profile of the wire, surface roughness and co-efficient of friction shares a linear relation with contact pressure. Wear rate remains zero at neutral layer of bended wire rope. For inter-wire wear, contact between wires and relative slippage is essential [46].

Fretting or wear mechanism analysis can also be done by using optical and scanning electron microscopy. In case of high carbon steel wire rope, crack originates from graphite nodules that get stretched by the surface material flow. The deformation tongue, which is formed by a combination of plastic deformation and crack growth, gets oriented along the direction of net sliding motion between the contact pair. High pressure level results in crack growth opposite to the sliding direction. The relative motion between roller or drum and wire rope has three components: rolling contact, slip in the tangential direction of the roller and sliding in the radial direction of the roller [47]. In hoisting application, the wire rope made of strands is used with outer strand having a combination of smaller and larger diameter wires to take advantage of both, flexibility in bending of smaller diameter wires and abrasion resistance of larger diameter wires. Mixing of wires having low and high strength in the outer layer of the outer strand results in different elongation of wires in the specific layer. Consequently, wires with lower strength begun to release from the strand and deform which lead to fracture at weaken places [48].

Cold drawing of steel wire leads to high rise in tensile strength and reduction in ductility. Residual stresses induced during cold drawing result in work hardening and consequently fretting resistance increases. But heavy deformation during cold drawing results in loss of hardening abilities of the material consequently, the plastic strain localizes in tension, necking and failure [49]. Micro-Arc Oxidation (MAO) and Hard Anodizing (HA) are used for coating to improve fretting fatigue and plain fatigue behavior of material. Results of Micro-arc Oxidation (MAO) and Hard Anodizing (HA) coating for Al–Mg–Si alloy (AA6036) samples showed that Micro-arc Oxidation (MAO) coating reduces surface roughness and had better plain and fretting fatigue behavior as compared to Hard Anodizing (HA) coating [50].

Small oscillating motions between contacted surfaces occur due to machine or system vibration and unexpected load in service and consequently, wear debris get accumulated in the contact zone in a wire rope. Wear debris speed up the wear process. Co-efficient of friction is high at initial stage or for fresh wire rope and after some time period of service, it gets decreased and reaches a steady value [51]. Hardness of surfaces has only marginal effect on fretting fatigue of steel. The co-efficient of friction is a function of contact conditions, whether it is gross slip or stick slip [52]. Morphologies of fretted steel wire surface observed by Scanning Electron Microscope (SEM) to analyze fretting wear mechanism showed that fretting regime transform from partial slip regime into mixed fretting regime and then into gross slip regime, also known as slip regime. In partial slip regime, co-efficient of friction remain relatively low and hardly any adhesive wear occurs. Wear increases in mixed fretting regime as wear mechanism become an amalgam of plastic deformation, abrasion and oxidation wear. Then, in gross slip regime more critical degradation occur due to combined effect of abrasive sear due to friction oxidation, wear debris and surface fatigue. In all regimes, fretting wear increases with increase in fretting amplitude [53].

Wear in steel wire undergo through three regimes viz. partial slip regime, mixed fretting regime and gross slip regimes respectively. By using grease, wear rate get reduced to a great extent, especially in partial slip regime as grease reduces coefficient of friction and prevent oxidation to retain hardness [54]. In case of stay cables, high mode of wind induce vibrations due to Von Karman Vortex and consequently fretting fatigue between wires induces [55]. Fretting in any component undergoes partial slip to gross slip phenomenon [56]. In case of hoisting ropes in mines or in some other application, rate of degradation in terms of wire breaks, wear, corrosion etc. increase with service time. Quantitative evaluation helps to evaluate the future rate of degradation and the remaining safe life [57]. To analyze fretting behavior of wire rope, bending over Sheave (BoS) fatigue test and for wear pattern Scanning Electron Microscope (SEM) are used. Reduction in sheave diameter results in a higher wear rate (μm^3/cycle). In various experiments, it was observed that if the D/d ratio (where D = sheave diameter and d = wire rope diameter) is reduced by 25% e.g. 40 to 30, the volumetric wear rate increases approximately 100% and reduction of 50% in the D/d ratio e.g. from 40 to 20, cause approximate increase of 2200% in the volumetric wear rate [58]. For a thin wire, wear test can also be carried out by using “Cross Cylinders” configuration. Further characterization like shape, size of worn surface, crack size etc. can be done by using optical and scanning electron microscope, and a diamond stylus [59]. A steel wire consist of core filament, a first layer of intermediate steel filaments twisted around the core and a second layer of second steel filaments twisted around the first layer. Fretting wear can be effectively reduced even if filaments of intermediate layer are coated with polymer as shown in Fig. 6 with a thickness around 0.10 mm or 0.15 mm or 0.25 mm. Preference should be given to hard polymer having good mechanical and fretting resistance properties.

Commonly used hard polymers for coating are Polyethylene Terephtalate (PET), Polybutylene Terephtalate (PBT) and Polyethylene Naphtenate (PEN) [60]. Torsional fretting in wire ropes strongly depends on normal contact force, angular displacement amplitude, and number of cycles. Damage increases from partial slip regime to gross slip regimes and wear results from combination of abrasive wear, the oxidation wear, and the delamination, plastic deformation [61]. In wire ropes, tangential force and relative slip increases with increase in strain amplitude under load and/or vibration, consequently the fretting life decreases. Endurance limit of smooth, galvanized and lubricated wires in fretting process are 100 MPa, 170 MPa, and 250 MPa respectively [62].

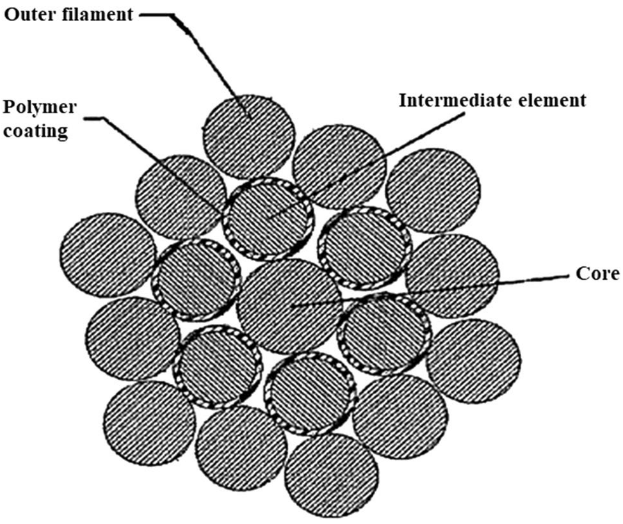

Fig. 6 Wire rope with coated intermediate filaments

Fretting regimes start from partial slip regime, followed by mixed fretting regime and then gross slip regimes. The fretting strongly depends on the tangential force and the stress state [63]. Various kinematic factors such as variable mass of the system, stiffness of the rope, acceleration and deceleration inertial load, flexible impact etc. plays a strong role in fretting behavior of wire rope, especially in vertical loading. Kinematic parameters affect the fretting behavior by affecting the contact load and relative displacement [64]. For wire ropes used in coal mines, fretting is dominated by Mixed Fretting Regime (MFR) i.e. combined effect of wear and cracking. Increase in contact load, promotes the adhesive wear and fretting wear, a rougher fracture surface topography. It results in accelerated wear and consequently crack initiate, propagate. This results formation of brittle cleavage and longitudinal splitting [65]. For analyzing fretting behaviour of wire rope, elastic–plastic finite element analysis has been used. For axial strain of 0.005 ring-shaped stress region is generated around the centre of contact zone. Combined stress i.e. Shear stress, normal stress is induced near the contact region. Shear stress distributes uniformly but the normal stress distribution is non-uniform [66]. Quantitative analysis of fretting–fatigue damage using modified Archard’s wear co-efficient in different corrosive media show that the wear co-efficient of steel wire decreases with increase in pH value of corrosive medium i.e. in the order of acidic solution, neutral solution and alkaline solution. The worst and best anti-wear properties of steel wires occur in acidic and alkaline solutions respectively [67]. In case of hoisting wire rope used in coal mine, fretting and fatigue parameters like wire break, wear etc. are a function of terminal mass or mass that is to be lifted. Increase in terminal mass results in increased tension as a combined effect of weight and acceleration during lifting operation [68].

In case of double-helix wire under axial tensile load, effect of torsional shear stress in wire rope can be neglected while analyzing fretting parameters [69]. When a wire rope coated with solid lubricant e.g. Molybdenum Disulfide (MoS_2) coating, graphite coating, and Polytetrafluoroethylene (PTFE) or Teflon coating, and its fretting behavior is analyzed under Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD); the results show that bonded solid lubricant coating has excellent anti-friction and wear resistant performance under fretting condition and strongly modifies fretting regime behavior [70]. When the wire rope is operated in acidic medium, the relative slip between wires increases and co-efficient of friction between wires decreases. Wear mechanism in acidic medium was mainly abrasive wear and corrosive wear in place of delamination and oxidation wear of dry friction environment [71]. Broken wires in wire ropes, hidden parts (anchoring) can be detected by using acoustic emission. Acoustic emission uses vibration to detect broken wires and main parameters of vibration that are used in acoustic emission technique are amplitude of bending and frequency. Acoustic emission technique is able to distinguish damaged and healthy cables [72].

Acoustic signature of inter-wire friction is a function of lubrication conditions of the cable. Inter-wire fretting makes wires to break and consequently, during bending, vibration is induced in wire repeat the location of break in wire. This vibration has been used to detect the presence and the location of broken wire in anchorage [73]. Fretting behavior of wire rope is also affected by the presence of corrosive medium during the operation or application of wire rope. Effects of corrosive medium are similar to that of acidic medium as co-efficient of friction decrease and wear loss increase, wear occur by abrasive wear and electrochemical corrosive wear. Effect of corrosive medium depends on pH value of corrosive medium [74]. Fatigue life of wire rope while working around nylon pulley is two times longer than that is while working around steel pulley. Working around nylon pulley delays the fracture onset and wear. Wear and fracture to external wires are relatively less. Growth rate of accumulated fracture amounts are also relatively less. Fractures in the rope working around the steel pulley occur by wear. With nylon pulley crack propagation zone remain very narrow [75].

Fretting fatigue behavior of wire rope also gets affected by strain ratio. As strain ratio decreases, the fretting regimes changes from partial slip regime to mixed slip regimes. Shorter fretting fatigue life and higher wear co-efficient induce at lower strain ratio [76]. A wire rope made of coated wires with coating of bonded Molybdenum Disulfide (MoS_2) had excellent radial fretting damage resistance. Damage of coated wires strongly depends upon the applied maximum load and inclined angle under composite fretting condition of delamination and oxidation [77]. For wire rope made of Inconel 690, used in under water applications, failure is caused by oxidation, deformation, fatigue, and delamination cracks on worn subsurface [78]. For polymer cables that are used in applications like fully constrained cable driven parallel robots are subjected to bending cycles while transmitting large force over long distance. Polymer fibers have superior strength to weight ratio and higher flexibility. Fretting behaviour of polymer cable can be analysed by using bending cycle analysis [79]. Co-efficient of friction of Polymer like Polytetrafluoroethylene (PTFE) and R-11 acrylic polymer has been tested using micro-tribometer, shows function of relative sliding motion i.e. magnitude and speed [80]. Fretting behaviour of wire mainly depends on friction; wear through relative tangential slip, crack initiation and propagation, grease lubrication condition viz. retention or replenishment of grease, applied load [81]. Wire ropes generally fail due to fretting fatigue. Fatigue life of the wire rope has been investigated using finite element modeling technique and geometric model can be developed using ABAQUS/CAE software [82]. Various failure mode of wire rope are fracture under single load, alternating load, environmental medium i.e. low stress brittle fracture, wear viz. mechanical wear, plastic wear etc. and corrosion [83]. Torsion angle also affect fretting fatigue behaviour of steel wire and with increasing torsion angle; deflection angle, wear scar size, co-efficient of friction etc. increases and fretting fatigue accelerates [84].

Fatigue life of steel wires has also been affected by crossing angle as it varies contact area and contact stress. A crossing angle near 18° results in larger contact area and weaker contact stress, consequently low co-efficient of friction [85]. During application, a wire rope can be subjected to torsional fretting, longitudinal fretting or a combined longitudinal and torsional fretting. Wear scar developed under all of these fretting. Wear scar has been quantitatively analysed by using three dimensional white light interferometer and the wear mechanism can be observed by using Scanning Electron Microscope (SEM). Combined longitudinal and torsional fretting results in larger relative slip and area of hysteresis loop, wear scar size and co-efficient of friction also have largest value under combined fretting [86].

Dynamic response of wire rope has been analysed using co-simulation method that is based on multi-body dynamic and finite element method. Finite element analysis can be done by using ABAQUS software [87]. Finite Element Method (FEM) has been used to get contact stress and relative slip between spiral strands and between the ropes and the friction lining. Contact stress has been maximum along contact path and it also depends on speed at which load is being lifted or moved [88]. Under dry condition, co-efficient of friction between wires increases with increase in load and stabilizes at approximately 0.73. It decreases with increasing sliding velocity. Under lubrication condition, co-efficient of friction is almost independent of contact load and sliding velocity. It stabilizes at a value near 0.35 [89]. Wear or fretting results in degradation of wire ropes. Wear scar affect mechanical properties of wire rope viz. necking and dimples on the surface and temperature rises near wear scar before the rope breaks. Breaking load decreases with increase in wear depth [90].

4.1 Effects of Fretting Performance of Wire Rope

Fretting results in wear and consequently material loss from wire surface due to inter-wire friction. Load carrying capacity of wire rope gets reduced. Other parameters that are adversely affected by fretting or wearing of wires are strength, service life, safety and reliability.

4.2 Remedies for Wire Rope Fretting

There have been a number of ways to reduce fretting of wire ropes. All these factors reduce fretting and consequently improve fretting life to a great extent.

4.2.1 Wire Rope Lubrication and Coating

Wire rope lubricants have two main functions, viz. to reduce friction as the individual wires move over each other during service or application and to provide protection against corrosion; lubricate the core and inside wires as well as on the exterior surfaces. There have been two types of lubricants that are used in wire ropes viz. penetrating and coating.

Penetrating lubricants penetrates into the core of the wire rope and a heavy lubricating film is formed to lubricate and protect each strand. There have been a number of penetrating lubricants such as grease, plastics and other polymers. Coating lubricants penetrate slightly and provide sealing to the outside of the cable from moisture and also reduce the fretting corrosion and wear from contact with external body surfaces [91]. In wire rope strands are wound about central axis. A foraminous conduit is formed along the central axis that permits radial flow of lubricant. The lubricating compound injected into the channel defined by the conduit and migrates radially outward through orifices formed in foraminous wall of it.

Lubrication promotes unrestricted movement of the wires in the rope with minimum fatigue and frictional resistance. Wire ropes are lubricated by dripping oil into it or pulling rope through oil bath. In recent trend, solid core is made of porous polymer with lubricant absorbed into it. When the core is stressed, lubricating material squeezed from solid core. More lubricant can be poured into it during service [92]. Provision can be made for more than one conduit for injecting the lubricant as well as the other performance enhancing material [93]. An internal and external lubrication will also prevent or reduce corrosion to a great extent. Lubrication along with slight rope rotation helps to avoid the formation of negative imprints on the surface. Good wire rope lubrication and re-lubrication during its service life, reduces the friction between the rope elements and consequently fatigue resistance of the steel wire rope get improved [60]. Fibers, such as polypropylene, nylon, polyesters, polyvinylchloride, and other thermoplastics and thermoset materials and high modulus materials have been added to the rope construction, typically in the core. The fibers have typically been used to carry lubricants in an attempt to increase the abrasion resistance of wire ropes and for corrosion resistance [94].

Coating provides hard protecting layer over wire rope that performs functions of resistance to corrosion and fretting wear resistance. For applications under high fretting, it needs a hard coating layer and material like chromium, molybdenum. Table 3 shows the performance assessment of various key variables that affect the fretting behaviour of wire rope.

More than one material layer is also used to get benefit of various characteristics of different material. For application of wire rope in corrosive environment like sea water, zinc coating have been used to improve corrosion resistance and so the service life duration of steel wire ropes. Longevity of the zinc coating and hence the service life of the rope depends on mass of the zinc that has been coated over the wires and its rate of degradation [95]. For application in sea water, wire cables have been getting replaced successfully by synthetic ropes that are manufactured from high modulus synthetic fibers. Theses ropes have the advantage of corrosion resistance along with benefits of light weight, high strength, and durability [96]. Polyethylene Naphtalate (PEN) or Polyethylene Terephtalate (PET) filament in wire rope core gives good lubrication during service life. A core comprising one or more high performance polyethylene fibers have been very suitable [97]. Steel wires with pre-extruded polymer around all intermediate steel filaments provide polymer coating [98].

5 Conclusions

Fretting behaviour of wire rope depends on a number of variables and most prominent variables are briefly described from the review of work done by various researchers on wire ropes as follows:

- Basic properties of wire rope material are high tensile strength, rigidity under tension and flexibility under bending.
- Strength of metallic as well as fiber ropes is quite high but metallic rope found superior in practical application at elevated temperature. Most prominent reason of wire rope failure is fretting fatigue.

Table 3 Performance assessment of key variables in fretting behaviour of wire

Variable	Findings	References
1. Material		
Fiber of Nylon, polyester, poly-propylene as wire	Polymer gives high strength to weight ratio	Foster [12]
PVC, Polyurethane as sheave material	Wear rate reduces	Hambin and Stachowiak [13]
2. Strength		
Steel wire rope	Strength reduces with abrasive wear	De Silva and Fong [18]
Cold drawn high carbon steel	Strength increase in cold drawing, surface crack, corrosion acts as stress riser	Shiota et al. [19], Mahmoud [20] and Nakamura [21]
3. Fretting fatigue		
Dynamic wear and crack propagation	Fretting fatigue decrease with increased wear and crack	Wang et al. [25]
Fatigue in steel cable	Cold drawing improve fatigue behaviour	Nuruberger [27]
Fretting	Reduce fatigue strength	Allen et al. [29]
Contact pressure, lubrication and relative humidity	Reduced contact pressure, increased lubrication and relative humidity reduces wear	Urchegui [30], Cruzado [32] and Xu et al. [70]
Crossing angle	18° crossing angle gives maximum contact area	Cruzado [33] and Zhang et al. [85]
Grain size	Coarse grain gives better fatigue life	Jayaprakash [37]
Sheave diameter	Larger sheave diameter gives better fatigue life	Onur and Imrak [40]
Diamond like coating (DLC), Shot peening, hard chromium and WC–Co, MoS_2, Coating	Improved fatigue life	Kalin and Vizitin [43] and Kubiak et al. [45]
Vibration, contact load	Reduces fretting life	Siegert and Brevert [55] and Wang et al. [63]
Corrosive media	Increased pH results in increased anti-wear properties	Wang et al. [65], Wang et al. [67] and Xu et al. [71]
Pure water as operating media	Oxidation and delamination, consequently reduced fretting life	Li et al. [78]
Torsion angle	Increased torsion angle results in reduced fretting life	Wang et al. [84]

- Lubrication of wire rope with grease and graphite increases service life by 40%.
- Fretting regime changes from partial slip regime to mixed fretting-slip regime followed by gross slip regime and is a function of normal load and displacement. Co-efficient of friction increases in partial slip regimes with displacement reaches to maximum value in mixed fretting slip regime then decreases in gross slip regime.
- Most suitable parameter to characterize the wear behaviour is scar depth and volumetric loss of material in wear.
- In fretting fatigue, Archard's wear coefficient increases in order of alkaline solution, neutral solution and acidic solution respectively.
- Coating of various materials like graphite, Poly tetra fluro ethylene, Molybdenum Disulfide, Diamond like Carbon, hard Chromium and sprayed Tungsten Carbide-Cobalt coating improves fretting behaviour of steel wire ropes. Various combinations of solid lubrication coating and wear resistant coating of hard material can be tested.
- Fatigue life of steel wire rope working around nylon pulley is about twice that is with working around metallic pulley.
- Fretting fatigue depends on environmental factor viz. relative humidity, corrosive media along with vibration, contact pressure, grain size, and type of loading, sheave diameter and material.
- Online and real time fretting and wear analysis can make things easier and consequently damage control approach can be implemented. So, research can be directed accordingly.
- Online and real time load carrying capacity of wire rope will make it safer and more useful.
- Fretting can be analysed using a number of method or test rig viz. scanning electron microscope (SEM), X-ray diffraction, Elastic–plastic finite element analysis, Bending over Sheave (BoS) fatigue life prediction equation, Magnetic Flux Leakage (MFL) method, Linear Elastic Fracture Mechanics (LEFM) analysis etc.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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