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Studies on metallurgical properties of wire rope for safe operation in mines

This paper describes the different metallurgical properties which define the state of wire rope in mines like wear and corrosion, lubrication, micro examination, galvanization and chemical analysis. Wear and corrosion affects primarily on outer surface and sometime it may penetrate deeper and change the mechanical property. In abrasive wear, wire and strand movement is restricted, therefore the risk of failure by bending fatigue is increased and reduction of wire area can lead to failure under tensile load. Whereas lubrication retards corrosion and therefore proper lubrication helps in preventing premature failure due to abrasion, fatigue and corrosion. Micro structural study of wire rope reveals both manufacturing defects as well as service degradation. Defects like grain distortion, harmful inclusion, decarburization, damage of zinc coating, corrosion pits etc. is clearly visible in microstructural studies. Galvanization of wire rope protects it from corrosion as well as it has a good fatigue resistance.. Chemical testing of wire rope however ensure quality and safety in mining. The importance of these metallurgical parameters has also been highlighted in a case study of failure analysis of wire rope.

Introduction

Metallurgy is the study of the physical and chemical behaviour of metallic elements, their intermetallic compounds, and their mixtures. It is the technology of metals: the way in which science is applied to their practical use. Metallurgical information is gathered from alloys and compounds through its quality testing such as tensile strength, compressive strength, hardness, fatigue, chemical analysis, micro-examination etc. Properties such as hardness, tenacity and ductility are continually being correlated with microstructure, while the numerous defects to which commercial metals and alloys are liable are almost invariably associated with abnormalities of structure. Mining operation is essential to produce coal which is a primary source of energy involving lots of man power. In view of safety of mine and miners regular monitoring of safety of mine appliances is utmost important.

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This paper describes the different metallurgical properties for which the tests are being carried out in Metallurgical Laboratory of CIMFR for wire rope. These tests include wear and corrosion, lubrication, micro examination, galvanization and chemical analysis. Wear and corrosion affects primarily on outer surface and sometime it may penetrate deeper and change the mechanical property. Whereas lubrication retards corrosion and thereby reduces the chances for corrosion failure, abrasive failure and fatigue failure in a wire rope. Micro structural study of wire rope reveals both manufacturing defects as well as service degradation. Defects like grain distortion, harmful inclusion, decarburization, damage of zinc coating, corrosion pits etc. is clearly visible in microstructural studies. On the other hand galvanization of wire rope protects it from corrosion. Chemical testing of wire rope however ensure quality and safety in mines. The importance of these metallurgical parameters has also been highlighted in few case study of failure analysis of wire rope.

Metallurgical parameters considered to ensure quality and safety of wire ropes

1. Wear and corrosion
2. Lubrication
3. Micro examination
4. Galvanization
5. Chemical analysis

Wear and corrosion

General description

Steel wire ropes are critical load-bearing components used in cranes, lifts, mine haulage, etc. deteriorates under several influences like tension, bending, fatigue, wear and corrosion. Wear and corrosion are the two main degradation mechanisms, as wear will remove the protective layer, and increasing corrosion rate thereafter, corrosion will affect internal composition of the material and its mechanical properties and ability to resist wear.

Though wear in materials is known to occur by a variety of mechanisms, in the case of wire rope practically it is usually categorized into two types, plastic and abrasive (Fig. 1a). [1] Plastic wear occurs due to high pressure contact with items

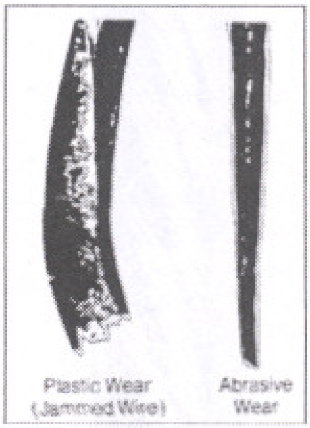

Fig. 1a

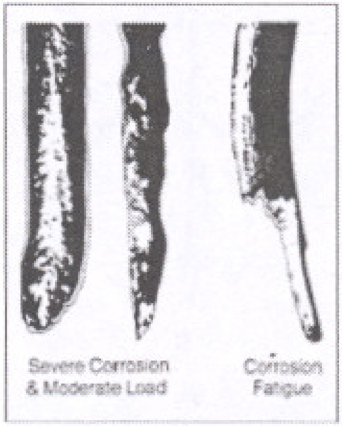

Fig.1b

such as sheave wheels while abrasive wear results from rubbing against rock and other obstructions which come into contact with rope. In addition, wear is classified into external and internal depending on whether it is on the outside of the rope or inner side. Internal wear is due to the contact and movement which occurs between wires.

Operation in wet, salty, acid, other chemical etc. conditions produces various degrees of corrosion and pitting and set up stress raisers. Under such conditions, abrasive wear is accelerated; wire and strand movement is restricted, therefore the risk of failure by bending fatigue is increased and reduction of wire area can lead to failure under tensile load (Fig-1b). [1]

Laboratory test procedure

For determining the wear and corrosion of steel wire ropes, in the laboratory, the wire from the wire rope sample separated layer by layer then individual wire was cleaned for assessing any deterioration due to wear and corrosion. Deterioration due to wear and corrosion is first physically examined with the help of a magnifying glass and then it was quantify by measurement of reduction in diameter with the help of dial caliper at three location in the wire viz. most affected surface, least affected surface and not affected surface (original wire dia) of the metals. The percentage reduction is calculated by difference between most affected and not affected surface. In case of shaped wires, the available equivalent round dia (AERD) is calculated. The same procedure is repeated for every layers of the rope. Few examples which are being tested in Metallurgical Laboratory at CIMFR are shown in Table 1 [2].

Lubrication

General description

Wire ropes used in different mining and non-mining operation requires lubrication as it reduces friction between individual wires, between strands, between coils of rope, and between the rope and other surfaces, such as sheaves and drums. The wires and strands must slide in relation to each other to permit stress distribution and equalization. A variety of lubricants are used in wire ropes, depending upon the specific service conditions. Lubricants are made of substances which can be categorized as bituminous and non-bituminous. Additives may be included in these compounds to provide better adherence to wires, increase water repellence, improve heat degradation resistance, and prevent drying and other properties.

It is important to add lubricants during rope assembly, when all strands and individual wires are accessible. Ropes are frequently re-lubricated to replace the material that physically exudes out due to flexure, or is affected by thermal degradation (or) chemical reaction. Rope service in soil and rock are not conducive to adequate perpetual lubrication as dredging will accumulate dirt and wear particulates that enter the rope and cause wear. Rope in this type of service must be replaced frequently.

Lubricant applied during manufacturing and in service should be designed to suit: [3]

1. The construction of the rope, and strands in regards to size and arrangement of the wires: e.g. in coarse rope constructions and large sized ropes using heavy wires with larger valleys and voids between the wires can be effectively lubricated with heavy bodied lubricants which can penetrate such ropes. While finer wire constructions with smaller clearance and voids require lubricants of lighter viscosity.

Table 1

Sample no.	Company	Result	DGMS circular	Remarks
1. Met09/G/3	UCIL, Sunder Nagar, Dist.-Singhbhum (East), Jharkhand	On physical examination, the wire rope sample revealed deep wear and corrosion pitting along with helical indentation marks. Percentage reduction in diameter is 36.67 which is very high in respect to the permissible limit	Maximum loss in depth of the wire should not exceed by 15% of the nominal diameter	Does not confirm
2. Met09/G/6	Dalurband colliery, ECL	On physical examination, the wire rope sample revealed light wear and intermittent corrosion pitting on the surface along with helical indentation mark. Percentage reduction in diameter is 1.92 which reflects good condition and can be reused		Good condition

2. Type of work for which the rope is used: e.g. in mine, winding ropes (i.e. long service ropes) penetrating lubricants is essential.
3. Nature of working conditions of the rope: e.g. water repellent lubricants are recommended for use on fibre cored ropes operating in snow and ice conditions to protect core fibres.

Advantages of lubrication

- To reduce the friction within the rope or between rope and sheave/drum grooving which leads to deterioration.
- Lubrication also retards corrosion of the rope wires, reduces wear on rope and ancillary equipment, inhibits possible rotting of the fibre core.

Proper lubrication helps in preventing premature failure due to abrasion, fatigue and corrosion.

Laboratory test procedure

At first the sample wire rope is cleaned from any visual dirt on the surface, weighed and its length is measured to determine the mass factor. Then each layer of the rope is opened and examined for lubrication condition. The core is taken out in case of fibre core for determination of percentage retention of lubricant in the rope.

The percentage retention of lubricant is determined by taking 10 to 15 gm of lubricated fibre core opened by untwisting and then boiled in moisture free solvent namely toluene or benzene under reflux in Dean and Stark apparatus for four times or more till the sample is completely free of lubricant. Each time fresh 100 cc solvent is taken; the moisture gets condensed as separate layer in the receiver. The fiber core after elutriation is dried in oven at 105-110°C for one hour and then cooled in desiccators. The percentage retention of lubricants has been calculated by difference between the original weight and dried weight of the fibre core. In case of wire rope sample having steel core the lubrication percentage is determined by mass factor (k) i.e. mass per 100m per mm^2 ($kg/100m.mm^2$) according to IS 6594:2001. Few examples of study of retention of lubricants in the wire rope sample at the laboratory is given in Table 2 [4].

Micro structural features of wire ropes

A wire rope is a complex structure that contains many steel wires twisted in a predetermined pattern to achieve the axial

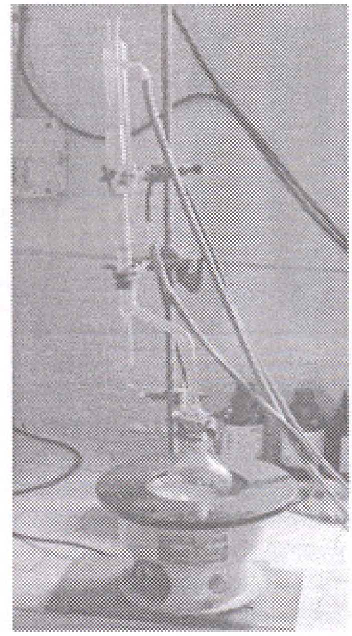

Fig.2a: Dean and Stark Apparatus for Lubrication Test

Fig.2b: Properly lubricated wire rope sample having fibre main core

strength and stiffness and retain flexibility in bending. The strength of steel wires is achieved by using plain carbon steel with high carbon content and a fine microstructure. This wire is then patented and work hardened by successive drawing operation during manufacturing [5]. Any inborn manufacturing defects (micro pipe, inclusions, improper microstructure etc. may interact with service conditions and affect the continual process of degradation and ultimately lead to failure [6]. The process of service degradation (abrasive/plastic wear, pitting corrosion, stress corrosion, martensitic transformation etc.) are reflected in appearance and in characteristics of the rope. Microstructure of both new and used rope plays a very important role in determining the mechanical properties of the rope.

Importance of micro structural examination of wire rope:

- Micro examination of rope wire revealed the micro-cracks from inclusion, fracture and martensitic formation (Fig.3a). These defects can only be examined by micro examination. Further the formation of martensitic structure (Fig.3b) leads to increase in strength of the wire rope but due to

Table 2

Sample no.	Company	Result	IS code	Remarks
1. Met09/J/01	Bejdih colliery ECL	The percentage absorption of lubricant of the winding rope is found to be 6.058% which is below the standard limit according to IS 6594:2001	IS 6594:2001, IS 9182 (Part 1):1993	Frequent lubrication is required to improve the lubrication condition of the rope
2. Met09/E/05	BIS, Bhopal	The percentage retention of lubricant of the FMC steel wire rope is found to be 27.33%		Good lubricant condition (IS 6594:2001)

martensitic character it will become brittle which leads to failure of wire rope.

- Fig 3c revealed decarburization of wire rope which leads to loss of strength of wire rope and resulted in failure.
- Harmful inclusion (Fig 3d) can only be examined by micro examination. The inclusion leads to brittleness of the wire rope resulting in failure of the rope.
- Strength of wire rope may severely affecting by damage of zinc coating, corrosion pitting (Fig 3e), stress corrosion pitting (Fig 3f) etc. The micro examination is the only way which can define these defects.

Microstructure examination is being carried out at CIMFR to have a better understanding about the condition of the wire rope. The sample is first selected and then it is prepared by proper sizing, cutting, cleaning, mounting and polishing with suitable cloth. It is then thoroughly cleaned and etched avoiding staining of the sample. It is then viewed under microscope. Microstructure examination reveals various defects in the wire rope which otherwise not be able to view physically. Following defects [7] can be easily pointed out in the microstructure examination: [7-9]

Defects reveals in micro examination of wire rope:

- Grain distortion due to overloading which later can leads to failure

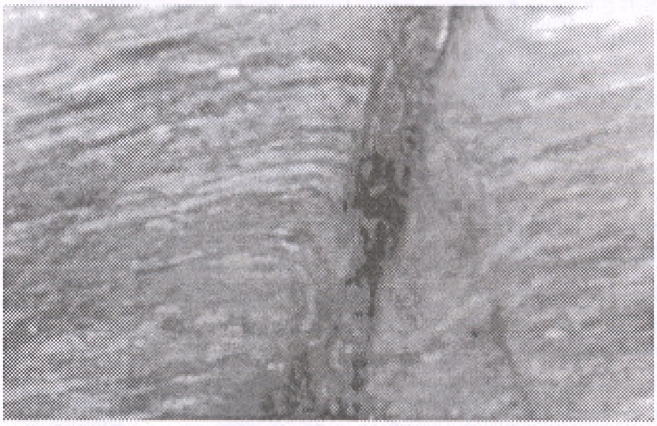

Fig.3a Galvanized round steel rope wire sample revels micro-crack initiated from inclusion, fracture and martensite formation along with damage of zinc coating and distortion of grain along longitudinal direction

- Formation of martensite

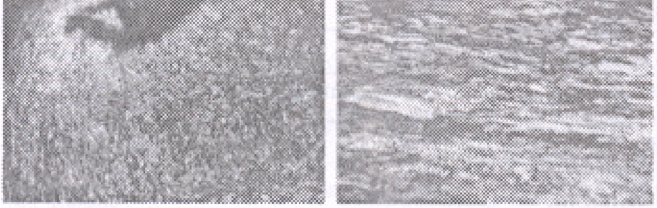

Fig.3b Martensitic formation at the worn out portion of wire rope. (a) Remote end transverse section. (b) Remote end longitudinal section

- Decarburization which leads to loss of strength

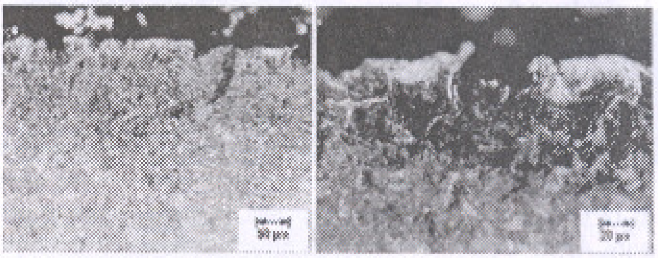

Fig.3c Transverse section of round steel wire sample showing surface and sub-surface decarburization. (a) 200X (b) 500X

- Harmful inclusion
- Damage of zinc coating and corrosion pits

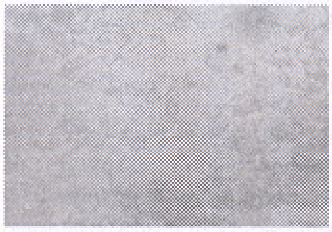

Fig.3d Sample showing impurity inclusion

Fig.3e Wire sample showing crack on zinc coating and corrosion pits

- Stress corrosion pitting

Fig.3f Sample showing stress corrosion pitting in the longitudinal section

GALVANIZING

Galvanized wire rope has a wide variety of uses. In this type of rope, all of the wires are coated with pure zinc, which forms a protection against corrosion. It is called "galvanized wire rope" to distinguish it from bright rope.

Zinc coating protect steel in three ways –

- Zinc weathers at a very slow rate and hence gives a long and predictable life.
- The coating corrodes preferentially to offer sacrificial protection to small regions of steel exposed through drilling, cutting or accidental damage.
- In the case, affected area is larger, sacrificial protection prevents sideways creep that can undermine coatings.

Further galvanized coatings have good fatigue resistance.

Laboratory test procedure

Firstly the sample of galvanized wire of any length over 300mm preferably 600mm is taken and cleaned. The clean test piece is then weighed and immersed in the test solution of antimony trichloride either by bending or coiling the wire if it is too long for complete immersion. The test piece is then taken out, washed in running water and wipe off well. The test piece is again weighed and diameter is measured and mass of zinc coating is calculated in g/m^2.

For uniformity of zinc coating the sample is cleaned and dipped on testing solution i.e, copper sulphate solution kept at 18°C. The time of dipping depends on the diameter of the wire. After dipping the sample is rinsed immediately in clean running water and remove any black deposit including holes and pockets by suitable brush. Then it is wiped and dry.

The material passes this test if at the end of the specified number of dips do not show any adherent of red deposit of copper upon the base metal. Some of the test samples results are indicated in Table 3 [10].

Chemical analysis

Chemical analysis is an important parameter for determination of metal properties. The percentage of elements present in the materials used in mine appliances play an important role in enhancing the safety in mines. Chemical analysis does however ensure quality, productivity, safety, consistency, control and many other factors.

Improper chemical composition will lead to premature failure of the rope.

Laboratory test procedure

The chemical analysis at CIMFR Metallurgical Laboratory has been carried out as per IS:228-1959 IS: 1835-1976 and renowned text book on chemical analysis for carbon, silicon, manganese, sulphur, phosphorous, copper, nickel and chromium by gravimetric method except carbon which is carried out in Strolein apparatus. Few examples of chemical analysis carried at the laboratory are as shown in Table 4 [11].

Failure analysis of wire rope considering metallurgical parameters (a case study)

Laboratory investigation was carried out to assess the causes of premature failure of the 26 mm diameter, 6×7 construction haulage rope of SRP (P) area of the Singareni Collieries Company Ltd. The investigation was carried out in light of following parameters:

Visual examination

The outer surface of the rope was heavily corroded. The rope was found devoid of lubricant dressing on the surface. On examining individual wires it was found that the wires which were exposed to the surface revealed severe corrosion, pitting, wear, nicks, and plastic indentation. Whereas the inner layer of wire rope particularly in contact with the fibre core was found generally free from such defects.

The overall condition of the wires in the rope is defined as:

(i) eighteen wires revealed 19%-26.92% reduction in diameter due to wear and corrosion

(ii) sixteen wires revealed 11.53%-19% reduction in diameter due to wear and corrosion

(iii) twenty seven wires out of forty two revealed fatigue fracture aided/initiated by corrosion, bending tensile, mechanical damage, wear etc.

(iv) rest fifteen wires is tensile shear and brittle type fracture associated with wear and corrosion and mechanical damage (Fig.4a & 4b).

Table 3

Sample no.	Company	Result	IS code	Remarks
1. Met010/B/9	BIS, Bhopal	After testing and calculation, the mass of zinc coating of 0.63mm diameter galvanized wire rope sample is found to be above 85.72 g/m^2 Further there was no red deposit on the sample which indicates uniformity of the zinc coating	IS: 1835-1976, IS: 4826-1979 (Reaffirmed 1992) minimum mass required for steel wire rope of dia. (0.60-0.80) mm- 85 g/m^2 (0.80-0.90)mm dia. - 75 g/m^2	Good condition, fulfilling the requirement
2. Met09/I/06	Nangalwala Impex (P) Ltd.	Seven number of 0.85 diameter wire sample of trailing cable has been tested for mass of zinc coating. The mass of zinc coating found to be in the range of (42.18-62.98) g/m^2 The wires also revealed red deposit on the base metal		Not confirming

Table 4

Sample no.	Company	Result				IS Code	Remarks
1. Met010/F/7	BIS, Bhopal	Carbon Manganese Silicon Sulphur	0.46 0.60 0.15 0.025	Phosphorus Chromium Copper Nickel	0.027 Traces Traces Traces	Method – IS 228-1959, and IS: 1835-1976	Fulfilling the standard requirement
2. Met010/D/2	BIS, Bangalore	Carbon Manganese Silicon Sulphur	0.62 0.59 0.18 0.013	Phosphorus Chromium Copper Nickel	0.018 0.15 Traces Traces		Fulfilling the standard requirement

Fig.4a

Fig.4b

LUBRICATION CONDITION

The rope suffered from lack of lubricant dressing on the surface. The inner wires were well lubricated. Fibre main core was in good condition. Retention of lubricant in FMC was 16.50% and acidity of the lubricated fibre core is 0.39 mg of KOH/g of FMC.

METALLOGRAPHIC EXAMINATION

Samples in polished condition revealed no harmful defects like inclusion, segregation etc. One of the samples revealed stress corrosion cracking in transverse section originating from one periphery travelled in lateral direction to another periphery. Number of corrosion pits were revealed on metal surface on both side of the crack. Corrosion pits are more in the root area than on the propagated area due to time lag in the propagation of crack (Fig.4c).

After etching the sample with 1% natal it has been observed under the microscope and found stress corrosion cracking from a corrosion pit on one periphery travelling to other periphery in transverse section (as revealed in polished condition is not accompanied by any micro-structural change (Fig.4d). The micro-structure is typically patented structure of high carbon steel of 0.74% which is conforming IS: 1835-1976 comprises sorbitic-pearlitic structure (Fig.4e). The longitudinal section revealed good cold drawn structure with internal corrosion initiated from periphery towards the direction of the drawn (Fig.4f). In another case martensitic structure along with minute multiple cracks is revealed. This suggests generation of high heat due to rubbing followed by abrupt cooling (Fig.4g).

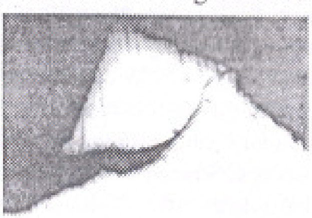

Fig.4c

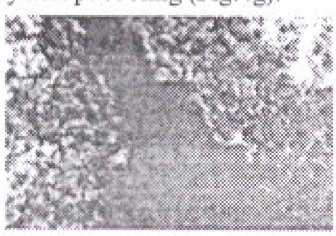

Fig.4d

RESULT AND DISCUSSION

The wire rope suffered from lack of lubricant dressing on its surface though internal lubrication was good. Severe corrosion and wear caused reduction in diameter of wire (18 wires 19% to 26.92% reduction, 16 wires 11.53% to 19% reduction). These seriously lowered the fatigue strength and reduced the load bearing capacity of the rope. Fourteen of the wires revealed mechanical damage similar to appearance of chisel cut in the fracture area or adjacent to that. These might be due to severe abrasion against some sharp object in service. All these tribological defects lowered the load bearing cross section of failure zone leading to premature failure of the rope. The failure also attributed due to reduction of metallic cross section of the rope during its use.

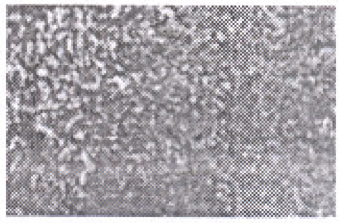

Fig.4e

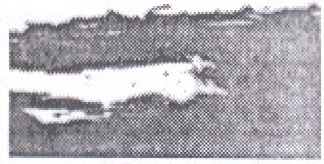

Fig.4f

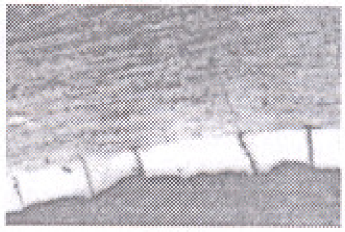

Fig.4g

Conclusion

It is evident from the study that the metallurgical properties like wear and corrosion, lubrication, micro examination, chemical analysis and galvanized test play a vital role to assess the condition of the wire rope time to time. Further it has been observed that the wire rope qualify the mechanical parameters but at the same time they may fail to qualify the metallurgical tests which lead to failure of the wire ropes. Wire rope should be tested thoroughly before putting into operation so that it can last long during operation. Adequate lubrication of the rope can enhance the life of rope further increasing the safety of mining personnel. The metallurgical test may be carried out time to time as per DGMS guideline for safe operation of the mine.

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