Wear Mechanisms in a Nonrotating Wire Rope

K.K. Schrems, C.P. Dogan, and J.A. Hawk

A nonrotating wire rope used in mine hoist operations is being examined by the U.S. Bureau of Mines to determine operative wear mechanisms. Typically, bending and loading the ropes during service cause small, localized movements at interwire contacts, leading to material loss through wear. The cumulative effect of both material loss by wear and wire breakage by fatigue failure accelerates rope retirement. If the macroscopic mechanics of wire rope failure are to be understood, microscopic deformation and degradation processes must be identified and quantified. As a first step in this study, interwire wear and deformation were studied using a combination of scanning electron microscopy and hardness measurements. Both fretting and abrasive wear were identified as wear mechanisms. Preferential sites for fretting and abrasive wear were identified and are discussed regarding rope construction and geometry and the tribo-system.

Keywords

abrasive wear, failure, fatigue, fretting, wear, wire rope

1. Introduction

Wire ropes are used in many industries with applications that include mining, off-shore oil production, and towing or mooring ships. Wire ropes are also used extensively in such diverse transportation applications as ski lifts, cable cars, and bridges. Premature failure of ropes can be costly in any application. In mining, the human costs due to the premature failure of a rope can be devastating. Thus a thorough understanding of the characteristics of a wire rope that has become dangerous is a clear and critical necessity. However, developing a rope replacement strategy that is both safe and economical is a complex problem that requires in-depth knowledge of the mechanics of rope degradation and rope failure. U.S. mining regulations currently address this problem by defining rope integrity based on an evaluation of the number and distribution of broken wires, loss of diameter of outside wires, reduction of rope diameter, loss of strength, corrosion, distortion, and heat damage (Ref 1). The U.S. Bureau of Mines, through its interest in the health and safety of mine workers, is studying the failure mechanisms of wire ropes with the goal of more accurately predicting when the end of the useful life of a rope has been reached.

Because of their complexity, wire ropes are generally considered to be machines, and their long-term integrity depends upon their construction, maintenance, and application. As a result, a variety of rope constructions can be selected based upon specific operating requirements. For example, a lang lay rope provides more resistance to abrasion and bending fatigue than a regular lay rope and would, therefore, be found more often in harsh environments where the rope bends frequently over small radii. A nonrotating rope (or a rotation-resistant rope) consists of multiple layers of strands in which the directions of the different layers are alternated to reduce the natural rotation of the rope. This type of rope is frequently used where the end is not constrained, and hence, there is a need for a rope that will not unravel. Seale ropes have large diameter outer wires that can safely tolerate more abrasion than an equivalent diameter rope of filler wire construction. However, the filler wire construction contains a larger number of smaller wires, which gives the rope a longer fatigue life. Minimizing external abrasion, maintaining appropriate lubrication and corrosion protection, and avoiding shock loads can help extend the life of any rope.

In all constructions, the rope is designed so that the failure of several wires will not impair the function of the rope. However, the number and distribution of individual wire breaks will ultimately determine the overall integrity of the rope. In mine hoisting operations, load, speed, bending radii, abrasion, corrosion, fit of the rope on the drum (Ref 2), wear, fatigue (Ref 3), bearing pressure (Ref 4), and Hertzian contact stresses (Ref 5) will all impact the useful life of the rope. Stress analysis models of wire rope constructions have determined that compressive stresses on individual wires due to line and point contacts can be significantly large (Ref 4-10). Thus, the line and point contacts must surely play an important role in determining the overall behavior of the wire rope.

The wear that occurs within ropes used in mine hoisting operations usually occurs as the result of one of three types of con-

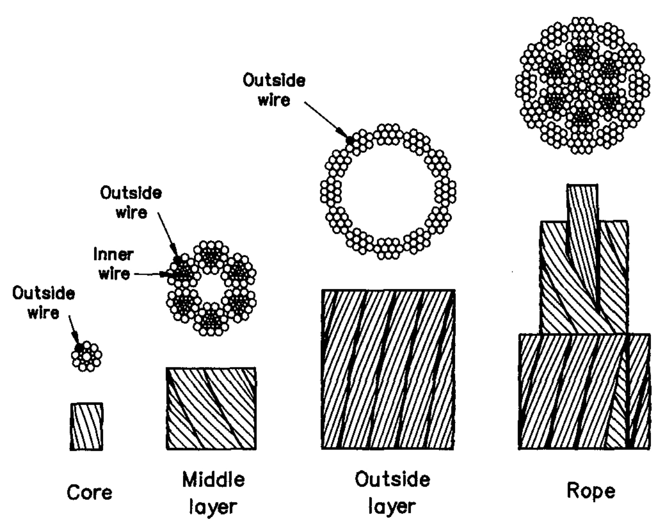

Fig. 1 Detail of the three layers which compose the failed rope. The outside wires from each layer were examined.

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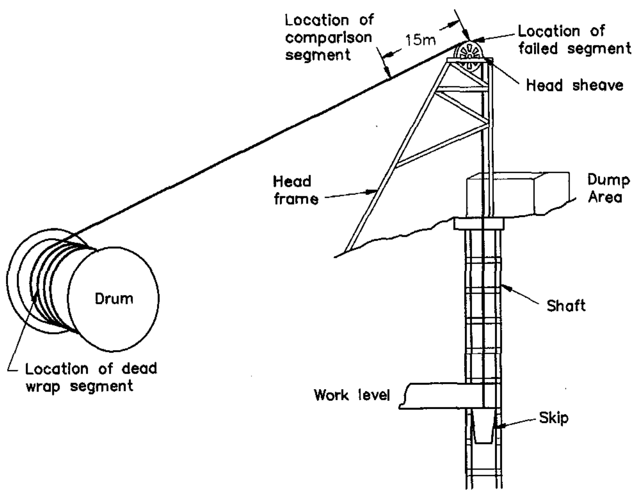


Fig. 2 Schematic of hoisting operation. Locations of failed, comparison, and dead wrap rope segments are indicated.

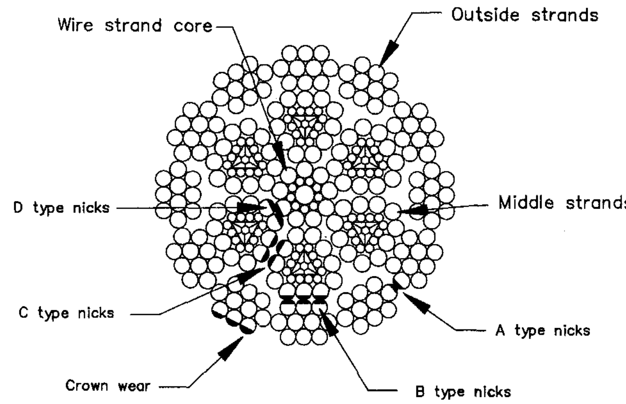


Fig. 3 Locations of interstrand wear sites within rope construction. Type A, interstrand line contact between outside layer strands, was not observed. Types B, C, D and crown wear were easily observed with the naked eye.

tact: (a) contact of the outer strands of the rope with an external member, such as a sheave or drum, frequently called crown wear; (b) line contact between wires within a single strand or between strands; and (c) point contact between wires within a single strand or between strands. Interstrand point and line contacts are also collectively known as "trellis contact" or interstrand nicking. Actual wear of the wires results from the combination of stresses that develop at these contact areas during tensioning of the rope and during localized movement as the rope is bent, loaded, and unloaded. A characteristic pattern forms at each interstrand contact site consisting of one or more wear scars. Each scar has the general form of a hyperbolic paraboloid, with the ratio of the semimajor axis to semiminor axis (elliptical trace in two dimensions) a function of the helix angles of the two wires in contact. Two wires with a large difference in helix angle will produce a small ratio (typically at interstrand point contacts), whereas wires with a small difference in helix angle will produce a large ratio (usually at interstrand line contacts).

Ultimately the wear that occurs within these wires will influence the long-term load carrying capability of the rope as a result of reduction in cross section, creation of nicks that can act as stress concentrators, and production of metallurgical changes in the wire (Ref 11). Recent work on the fatigue failure of a mine hoist rope (Ref 12) identified regions of interstrand nicking as indicator sites of individual wire failures. Although wire ropes are constructed so that the failure of a few wires will not affect the load bearing capacity of the rope, the number, frequency, and distribution of wire breaks will ultimately determine the safe operating life of the rope as a whole.

It is the objective of this study to identify the microscopic deformation and degradation processes that occur within and between the individual wires and strands of a rope that has failed in service, with the ultimate goal of understanding the macroscopic mechanisms of wire rope failure. The wire rope selected for this study is a nonrotating rope that failed prematurely in a mine-hoisting operation. The rope is 50.8 mm in diameter, with a nominal breaking strength of 2000 kN. The 19 strands of the rope are arranged in three layers (Fig. 1). The center layer is a strand core of Seale left lay construction. The middle layer consists of six flattened strands of 29 wires wound in a left lang lay direction. The outside layer consists of 12 ribbon strands wound in a right lang lay direction. The failed segment is that part of the rope which rested on the head sheave when the skip was being loaded at the bottom of the shaft. Of the failed section, the core and middle layers were recovered intact, and 5 of the 12 outside strands were separately recovered.

2. Experimental Procedure

Three segments of the rope were selected for examination (Fig. 2): the failed section, a comparison section some 15 m from the break on the drum side of the head sheave, and a section from the dead wrap region on the drum. The area of study in the failed segment did not include the area of the final rope break in order to minimize confusion with the overload failures created during failure of the rope. During service, the failed segment of the rope experienced cyclic bending stresses from both the head sheave and the drum, as well as cyclic tensile stresses from the weight of the rope and loading of the skip. The comparison segment experienced similar stresses except that it did not pass over the head sheave and thus was exposed to fewer bending cycles. The dead wrap sample experienced some cyclic tensile stress from the loading of the rope.

All three segments were disassembled, and the wires were cleaned in solvent. Since the larger outside wires of the strands are generally considered to be the most important in determining the life of the rope and are designed to carry the majority of the load, this study concentrated on the outside wires, although the small inner wires of the middle strands were by far the most prone to failure.

Wire failures were characterized by their location relative to one of several characteristic wear patterns. Five different wear patterns (also called nicks) were easily identifiable by the naked eye and labeled A through E, based on their location within the rope construction (Fig. 3). Type A nicks occurred at line contacts between strands in the outside layer; type B nicks oc-

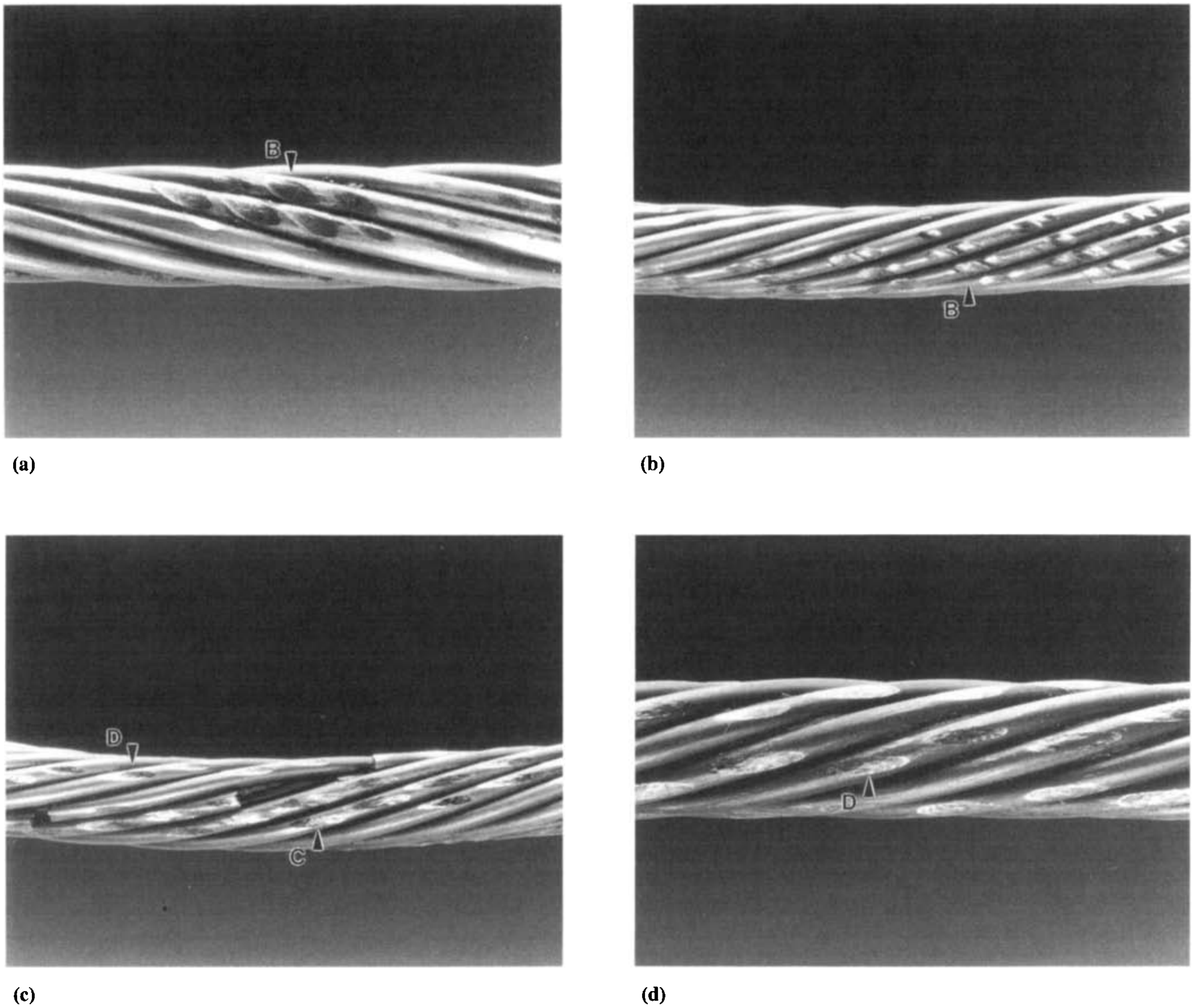


Fig. 4 Appearance of interstrand wear sites: (a) type B pattern on outside layer strand, (b) type B pattern on middle layer strand, (c) types C and D patterns on middle layer strand, and (d) type D pattern on core.

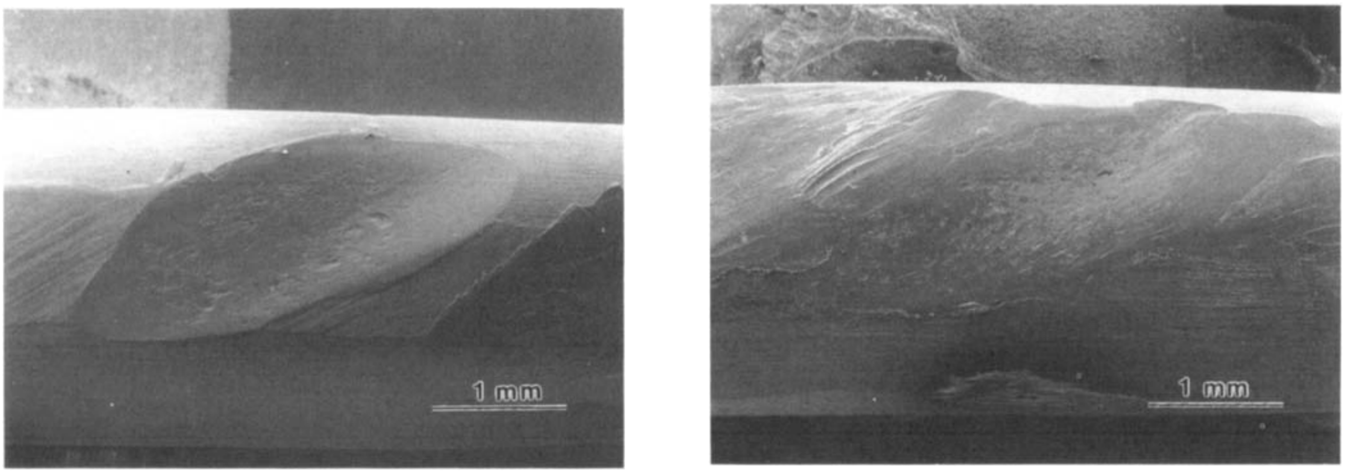
curred at point contacts between strands in the outside layer strand and strands in the middle layer strand; type C nicks occurred at line contacts between strands in the middle layer; type D nicks occurred at line contacts between strands in the middle layer and strands in the core; and type E wear occurred predominantly at sites of crown wear on the outside of the rope. Following optical examination, several examples of each type of wear pattern were examined in more detail using scanning electron microscopy (SEM) in secondary electron imaging mode.

Microhardness values were determined for areas of general wear as well as wear types B, C, D, and E, using samples metallographically prepared according to conventional techniques, and etched in a 1% nital solution (1 mL HNO_3 + 100 mL methanol). Knoop microhardness tests were performed using a load of 100 grams. In all tests, the long diagonal of the indentor was oriented parallel to a hypothetical tangent to the surface of the wire, at a distance of between 20 and 30 microns from the outside edge of the wire. The resulting microhardness data were analyzed using a multiple linear regression procedure with an initial model that contained indicator variables for all known variations in the rope. Variations in rope segments, strand layers, and wear types were accounted for, as well as changes in microhardness with distance below the surface.

3. Results

3.1 *Microstructural Characteristics*

Optical examination of the wires indicates that in all cases of interstrand contact, the wear scars have a characteristic saddle-



(a) (b)

Fig. 5 Type B nick on middle strand wires from (a) the comparison section of the rope, and (b) the failed section of the rope.

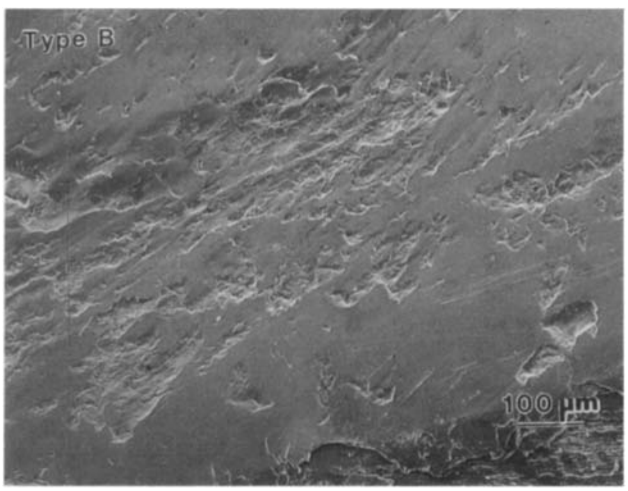


Fig. 6 Detail of the fretting damage present within a type B nick from the failed section of the rope.

shaped appearance and form at an angle to the wire axis, as illustrated in Fig. 4. In addition, all wear nicks show indications of a reddish oxidation by-product that is most likely Fe_2O_3. The strand pictured in Fig. 4a, from the outside layer of the rope, has type B nicks on the inside curvature and evidence of crown wear (type E) on the outside curvature. The lack of readily visible type A nicks on this strand suggests that the outside strands did not contact each other. Strands from the middle layer have type B nicks on the outside curvature (Fig. 4b), type D on the inside curvature, and type C between the outside and inside curvature (Fig. 4c). Because each middle strand contacts another middle strand on each side, there are twice as many type C contact sites as type B or D sites on these strands. The core strand (Fig. 4d) contacts six middle strands, and therefore, has six sets of type D nicks around its circumference. Table 1 summarizes the characteristics of contact sites in the wire rope, such as pattern type, location and type of contact, and the operative wear mechanism.

Closer examination in the SEM of the various types of wear scars present in this rope suggests that fretting is the primary mode of wear in all areas of wire-to-wire contact (i.e., types B, C, and D nicks as well as the intrastrand point and line contacts), whereas abrasive wear is the principal mode of damage in wires that are exposed to external surfaces (i.e., type E, crown wear). Interstrand point contacts between middle and outside strands, type B nicks in Fig. 3, produce the most damage in terms of material displacement and actual material removal. In addition, damage produced by fretting at the type B contact points is more severe in wires from the failed section of the rope than in wires from the comparison section, as is evident by a comparison of Fig. 5(a) and (b). A typical example of the wear surface within a type B nick is provided in Fig. 6. In all type B nicks observed, relative motion between wires occurs along the major axis of the elliptical wear scar, and fracture resulting from subsurface fatigue cracking (delamination) occurs uniformly across the nick. However, although more numerous, the fracture craters created by delamination of the wear surface do not appear as deep as those observed within other types of nicks. At the periphery of the nick, material extrudes out from the area of contact to form a lip that subsequently fractures. Gross movement of strands while the rope is lightly loaded results in abrasive and fretting wear scars in the wire surface between nicks, as is apparent in Fig. 5(a) and (b).

Line contact between strands in the middle layer of the rope, labeled type C contact in Fig. 3, results in a wear scar that appears shallower and that has a much longer major axis than is observed for the B-type nicks. Again fretting corrosion is the principal means of surface degradation, but in this case delamination and fracture are concentrated primarily at the periphery of the nick, suggesting discontinuous contact between the strands. Although it occurs less frequently, delamination results in the formation of much larger fracture craters in the type C nick than observed in the type B nick, as illustrated by a com-

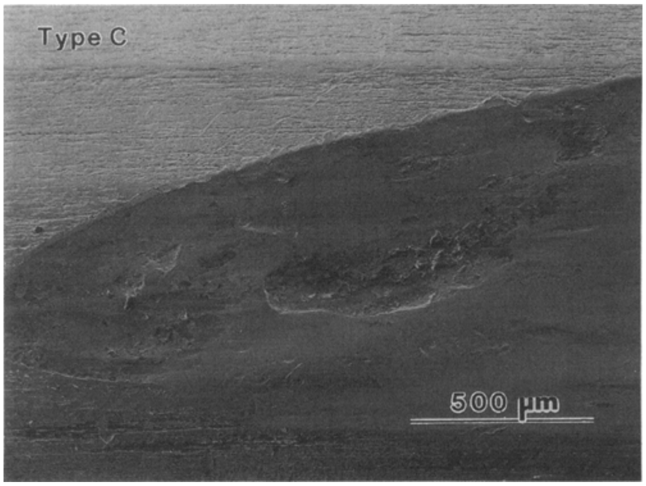


Fig. 7 Portion of a type C nick from the comparison section of the rope.

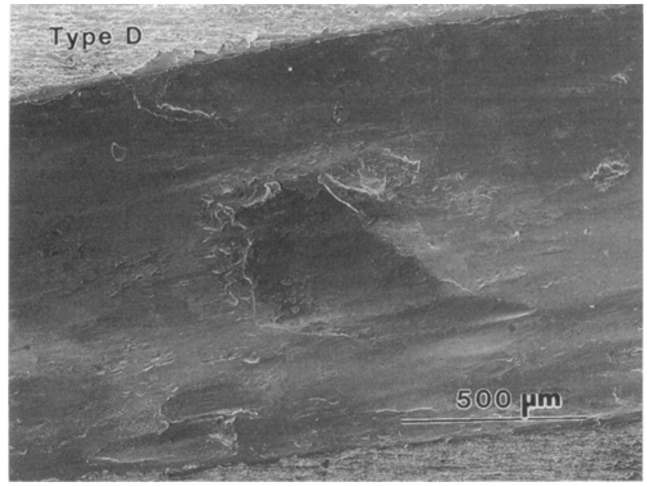


Fig. 8 Portion of a type D nick from the comparison section of the rope.

Table 1 Summary of characteristic wear patterns

Pattern type	Strand location	Type of contact	Wear
A (not observed)	Outside layer	Interstrand line contact within strand layer	...
B	Outside layer and middle layer	Interstrand point contact between strands in adjacent layers	Fretting
C	Middle layer	Interstrand line contact within strand layer	Fretting
D	Middle layer and core	Interstrand line contact between strands in adjacent layers	Fretting
E	Outside layer	Contact with external members (crown wear)	Abrasive
E	Any layer	Causes other than interstrand nicking or crown wear	Variable

parison of Fig. 6 and 7. The central regions of type C nicks are generally smooth, characteristic of the smearing of surfaces that generally precedes fatigue crack initiation from the fretting wear process, leading eventually to material delamination. Qualitatively, slightly more delamination occurs in type C nicks from the failed section of rope than is observed in C-type nicks from the comparison section of rope. However, in all instances, the wire surface is unscarred, or only lightly scarred, in the regions between nicks.

Interstrand line contact between wires in the core and wires in the middle layer of the rope, type D contact in Fig. 3, creates wear scars with characteristics very similar to those observed in the type C nicks. An example of a type D nick is given in Fig. 8. Generally the type D nicks are smooth and relatively featureless except for an occasional region of delamination usually observed at the periphery of the wear scar. However, whereas delamination fracture craters are often uniformly distributed around the edges of the type C nicks, they occur in localized regions in the type D scars, suggesting areas of local increases in pressure and/or relative motion between the strands. Unlike the type B and C nicks, however, there is no significant difference in the appearances of the type D nicks from the failed and comparison sections of the rope. Similarly, the wire surface is undamaged between nicks.

Contact between the outer strands of the rope and external surfaces, creating the type E or crown wear illustrated in Fig. 3, results in wear that is frequently more abrasive in nature and that varies in severity along the length of the rope. Figures 9(a-c) are typical examples of the crown wear scars observed on the dead wrap section, the comparison section, and the failed section of the rope, respectively. Crown wear on the dead wrap section (Fig. 9a) no doubt results from interaction between the outer layer strands and the drum and, while light, has characteristics of both scratching and gouging. After the initial wrap, only minor movement should occur. On the comparison section, crown wear is again minimal and is generally limited to either light abrasive scratching or a smearing of surface asperities as in Fig. 9b. In this case, wear occurs as the rope is wrapped onto and off the drum, and the reason for the reduced wear when compared to other segments is not clear at this time. Crown wear on the failed section of the rope, Fig. 9c, can be quite severe and is the result of contact with the head sheave as well as the drum. Both scratching and gouging of the surface occur as asperities on the surface of the head sheave, and debris particles trapped between sheave and rope move across the wire surface. A fretting wear component may be responsible for the general smearing of the surface and the initiation of what may be fatigue cracks in some areas of the wear scar. There is

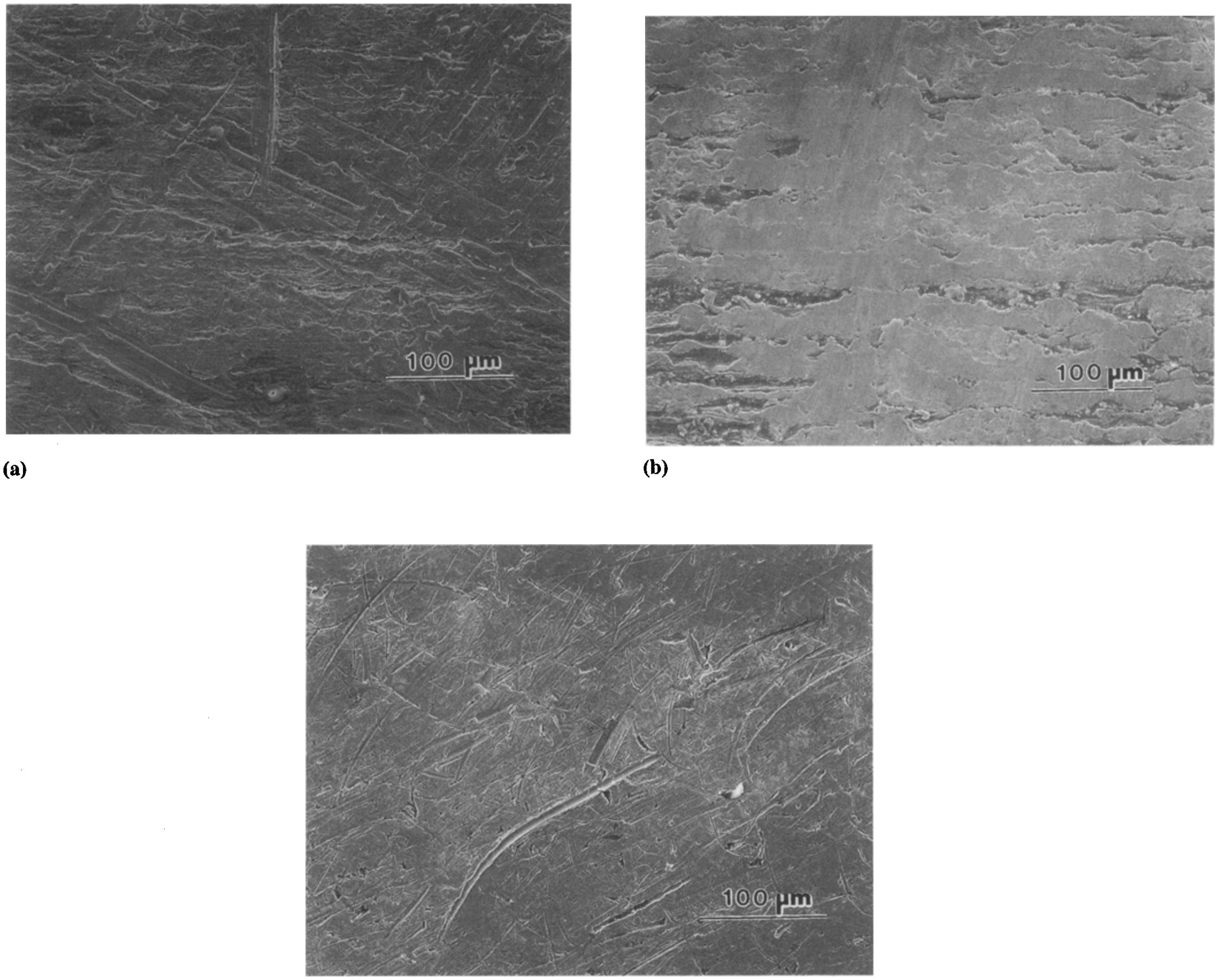
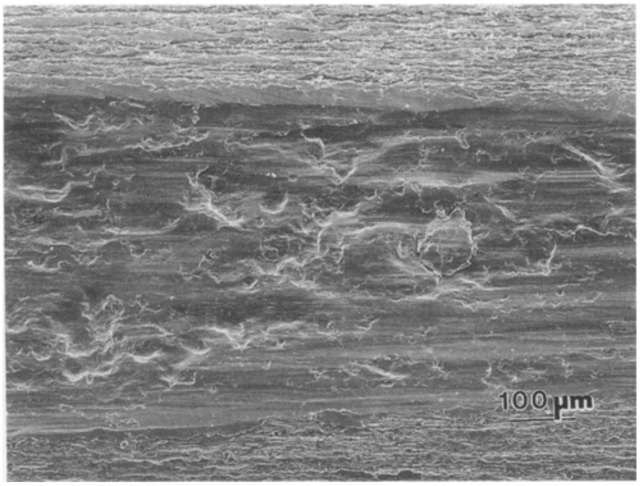


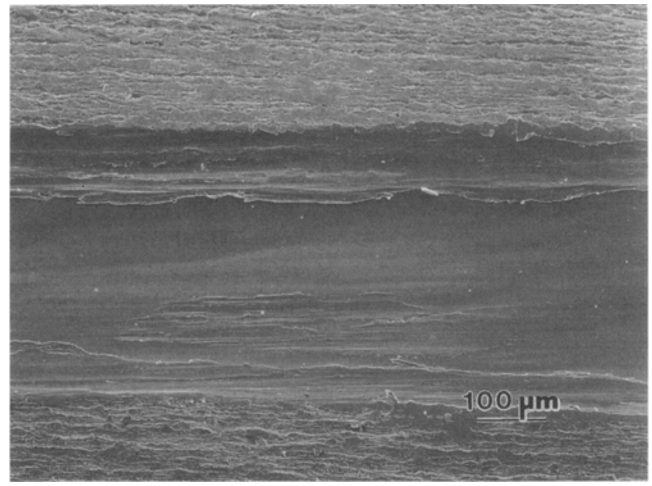
Fig. 9 Crown wear on the outside strands from (a) the dead wrap section, (b) the comparison section, and (c) the failed section of the rope.

Table 2 Average microhardness values according to category

Site	None	Line	Point	B	C	D	General	Crown wear
Dead Wrap								
Core	459	...	...	N/A	N/A	...	493	N/A
Middle (outside wire)	490	...	502	...	...	...	479	N/A
Outside	452	...	448	...	N/A	N/A	...	455
Comparison								
Core	462	461	467	N/A	N/A	488	...	N/A
Middle (outside wire)	463	501	502	530	508	508	...	N/A
Outside	464	478	456	509	N/A	N/A	...	476
Failure								
Core	452	...	500	N/A	N/A	498	499	N/A
Middle (outside wire)	463	499	487	543	501	520	423	N/A



(a)



(b)

Fig. 10 Damage resulting from intrastrand point contact in the middle strand of the failed section of rope: (a) material removal through delamination of the surface in some regions, and (b) smearing of the surface in other areas of the scar.

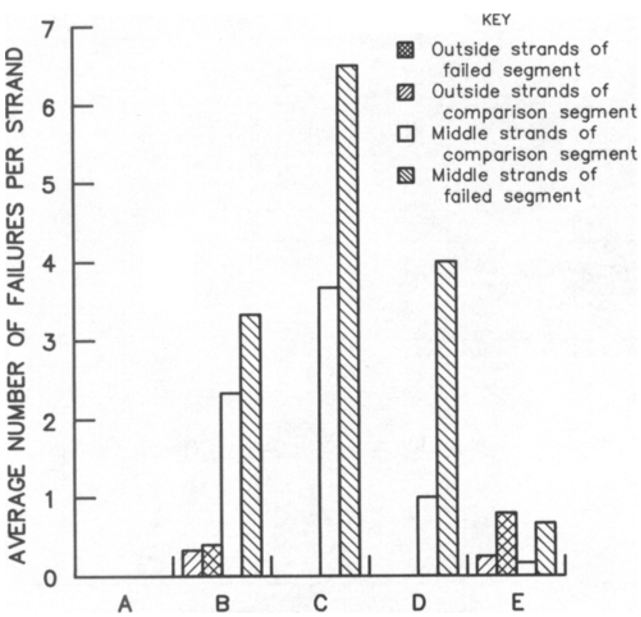


Fig. 11 Average number of wire breaks at characteristic wear sites.

evidence of corrosion (to be distinguished from oxidation, which occurs in all sections of the rope) in this region as well.

Intrastrand point and line contacts display many of the fretting wear characteristics described previously for types B, C, and D interstrand nicks, except that wear is rarely uniform across the length of the scar, varying from that severe enough to cause delamination (Fig. 10a) to that resulting only in minor surface smearing (Fig. 10b). In all cases of intrastrand contact, however, actual material removal is minimal.

3.2 *Microhardness*

Average microhardness values for each of the different contact sites, as well as for the unworn surface, are listed in Table 2. Microhardness values have a strong dependence on distance below the surface, which is accounted for in the linear regression model, but does not allow for accurate comparisons between categories in Table 2. In the multiple linear regression model used for analysis, the outside wire of the middle layer is the comparison site and is predicted to have a microhardness value of 470 HK_{100} at 28 micrometers below the surface. The outside wires from the core are 10 HK_{100} softer than at the comparison site. Even before accounting for wear sites, a general progression of hardening is found between the rope segments. Wires from the outside layer are 25 HK_{100} softer in the dead wrap segment and 25 HK_{100} harder in the failed segment.

Introducing contact between wires results in an increase in the hardness of the contact regions when compared to unworn regions of the same wire, with one exception. Regions of crown wear (type E) exhibit no significant difference in microhardness with respect to the as-drawn surface. The largest increase in hardness, 70 HK_{100}, occurs at the type B nicks. This is compared to an increase of 50 HK_{100} at the type C nicks and 25 HK_{100} and 45 HK_{100}, respectively, at type D nicks in the comparison and failed rope segments. Intrastrand line contacts are 30 HK_{100} harder, whereas intrastrand point contacts are about 35 HK_{100} harder. General wear scars found between nicks in the types B, C, and D wear patterns cause an increase in hardness of 20 HK_{100}.

As expected, differences are found among the three segments of rope. In the dead wrap segment, wires from the outside layer are found to be softer than those in the comparison segment. Furthermore, the wires from the outside layer of the failed segment are harder than those found in the comparison segment. However, only the type D nick from the failed rope

Table 3 Relative values of contact stresses for various nick sites

Wear pattern	Length of semimajor axis, b, mm	Ratio of semimajor and semiminor axes, b/a	Maximum normal contact stress, P_0	Ratio of stresses (normalized to C contact stress)
B	5	3/1	$P/17$	2.1
C	10	6/1	$P/35$	1.0
D (comparison)	9	5/1	$P/34$	1.0
D (failed)	8	5/1	$P/27$	1.3

segment shows a different amount of hardening over that found in the comparison rope segment.

3.3 *Failure Sites*

A histogram illustrating the relative number of observed failures at each contact site is presented in Fig. 11. For outside wires in the outside strands of both the comparison and failed rope segments, failure usually occurs either at type B contact sites or at regions of crown wear (type E sites). The average number of failures per strand is 1.2 for the failed segment, and 0.58 for the comparison segment, with the difference between them residing primarily in the larger number of crown wear failures in the failed segment. This is expected since crown wear in the failed segment is much more severe than that observed in the comparison section.

Failure of the outside wires in the middle strands can occur at one of the four types of contact sites (Fig. 11); however, failure predominates at the type C nicks, especially in the failed segment of the rope. A significant number of failures also occur at the type B and C contact regions. The failed segment averages about 15 failures per strand compared to 7 per strand in the comparison segment. In addition, the middle strands have approximately 10 times more failures than the outside strands. The core strand did not contain any failures in either the comparison rope segment or the failed rope segment.

4. Discussion

The damage observed within this rope was a result of thousands of cycles of loading and unloading, bending and unbending, as a skip was hoisted out of a mine shaft and then returned for another load. Damage created at points of interstrand wire-to-wire contact is visibly and measurably (through microhardness measurements) the most severe, and failure site analyses confirm that these are frequently the sites of wire failure. In all cases of wire-to-wire contact, fretting wear is the primary mechanism of surface degradation, although abrasive wear and wear-corrosion resulting from contact with external bodies is also observed. Given the service requirements of a wire rope, these wear mechanisms are essentially unavoidable and their effect can only be mitigated through judicious selection of raw materials, optimization of rope construction, and proper lubrication during service.

Fretting damage occurs when loaded surfaces in contact undergo relative tangential oscillatory movement as a result of vibration or cyclic stressing (Ref. 13). The degree of damage created as a result of fretting depends upon both the amplitude of oscillation and the load at contact points. Gibson, in an analysis of wire failure within a six-strand filler wire construction rope (Ref 9), found that the amplitude of oscillation between adjacent wires is a function of strand location (adjacent strands within a layer having larger relative motion), bending (smaller bends producing larger relative motion) and internal friction. Internal friction reduces the relative strand motion and alters the load distribution within the rope, causing some strands to carry a greater proportion of the load and others a smaller proportion. If it is assumed that the same criteria apply to the rope construction examined in this study, then type C contacts can generally be expected to experience the largest amplitude of oscillation, with type C contacts in the failed segment of the rope (that which repeatedly passed over the head sheave) experiencing a still larger amplitude of oscillation. Unfortunately, it is impossible to make a direct correlation between amplitude of oscillation and the characteristic damage observed after the fact within the wear scar, since contact stresses are also variable. However, wire breaks are found to concentrate in the middle layer strands and to occur most frequently at the C-type nicks, indicating that these may be regions of relatively larger oscillations and therefore more damage. In addition, the fracture craters resulting from delamination within the type C contact areas are inhomogeneously distributed around the periphery of the wear scar and are relatively deep, suggesting that slip across the contact area may be discontinuous and that subsurface fatigue cracks (which precede delamination) have propagated deeper below the wire surface.

The degree of surface and sub-surface damage imparted by fretting wear is also a strong function of both the level of stress at the region of contact and how it is distributed over the contact area. Contact stress is a non-linear function of the force exerted between the wires, the area of contact, the radii of curvature of the wires, the contact angle between the wires, Poisson's ratio and modulus of elasticity for the two wires (Ref. 14). A rough comparison of the contact stresses present at each of the characteristic nicks can be made using the Hertzian theory of elastic contact. In the case of a purely elastic contact, the maximum contact pressure, P_0, can be calculated using the equation:

$$P_0 = \frac{3P}{2\pi ab} \qquad \text{(Eq 1)}$$

where P is the total load, and a and b are the semiminor and semimajor axes, respectively, of an ellipse of constant separation (Ref. 15). The total load at the contact point, P, is a function of the axial force in the wire, the external radius of curvature of the rope, and the helix radii (Ref 16), and in this case, is assumed to be constant for each type of contact. Values for a and b are measured from the wear scars on the rope. Results of these calculations, listed in Table 3, suggest that the contact stress at type B contact points is twice as high as that at either type C or D contact points and that the stress at type D contacts is slightly higher in the failed segment of the rope than in the comparison segment. Note, however, that these results are qualitative at best since they are based on the assumption that contact between wires is purely elastic whereas experimental evidence indicates that, in each case, contact between wires involves a significant amount of plastic deformation. Similarly, the total load is not constant at every point within the wire. Nonetheless, fretting wear between strands in type B contact is clearly the most damaging to the wire surface, as is apparent both by SEM observations and microhardness measurements, and supports the calculation that contact stresses within these regions are relatively high.

As expected, therefore, wires frequently fail at type B contacts, which are determined to be regions of relatively high stress, and at type C contacts, which are believed to be regions of relatively larger amplitude oscillation. But they also often fail at type D contacts, where neither contact stress nor oscillation are predicted to be extreme. Further, in the failed segment of the rope, wire failure at type D contacts is more frequent than at type B contacts. Visual examination of the type D wear scars provides no conclusive reason for the increase in wire breakage at these sites, although evidence does suggest that subsurface fatigue cracking may be more extensive in these regions. However, Gibson (Ref 9) did determine that the region of maximum bending stress in a six-strand filler wire construction rope occurs at a position analogous to the type D sites in the rope of this study. Thus the extra stress created as a result of repeated bending over the head sheave may accelerate the material removal from delamination as a result of fretting wear, resulting in increased wire breakage at these sites in the failed segment of rope. Calculation of an increased contact stress (Table 3) and measurement of greater work hardening at type D sites in the failed segment relative to analogous positions in the comparison segment support this conclusion.

5. Summary and Conclusion

The results of this study indicate that contact between wires within a wire rope leads to surface and subsurface degradation through fretting wear that accelerates the process of wire breakage and ultimately leads to failure of the entire rope. Interstrand wire-to-wire contact is by far the most severe, resulting in a majority of the wire breaks. Type B point contact between outside and middle strands results in the most visibly severe wear of the wire surface; however, type C and D line contacts, between middle layer strands and strands in the middle layer and core, respectively, are the most likely to lead to wire failure in the failed segment of the rope. The wear scars produced at both sites are similar, with an increased tendency for more extensive subsurface cracking when compared to B-type scars. Type C contacts occur twice as often as other types, and this no doubt contributes to their prevalence as a fracture origin. Type D contacts occur at regions of relatively large bending stress. Although much less common, abrasive wear at type E sites, resulting from contact with external surfaces, can also lead to wire failure, particularly in the failed segment of rope.

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