Nondestructive testing of mine hoist ropes in the United States of America

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ABSTRACT

The purpose of this paper is to inform the reader about the practical applications and benefits of nondestructive testing (NDT) of mine hoist ropes, The U. S. Department of Labor, Mine Safety and Health Administration (MSHA), utilizes NDT as an effective means to assure that a personnel hoist rope is removed when it meets retirement criteria (discussed later). Mines in the United States incor--porate NDT as an engineering approach to preventive maintenance for personnel and production hoist ropes. The author will describe laboratory tests that determine limitations of the NDT instrumentation, and calibration procedures to assure accurate test results. It will be shown that NDT is a most reliable means to monitor the condition of a rope. Nondestructive testing, incorporated into a preventive maintenance program, reduces costs and enhances safety.

1. INTRODUCTION

The Mine Safety and Health Administration has been actively involved in NDT of mine personnel hoist ropes for about 20 years. NDT does not impair the future usefulness and serviceability of a rope. Through this means, it is possible to determine the type and magnitude of degradation of a rope.

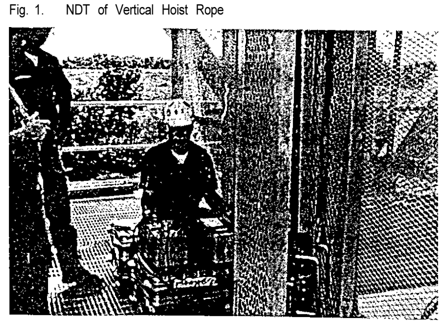
Typical hoists include single/double-drum vertical and slope, emergency-escape, multiple-rope friction, and multiple-rope elevators. MSHA mandates that mine personnel hoist ropes be. calipered for rope diameter or nondestructively-tested every six months. The MSHA regulations for rope retirement address loss of rope diameter, and loss of rope breaking strength as determined by NDT, as well as other criteria.

Conservative rope safety factors are applied to allow for unanticipated and uncalculable occurrences that adversely affect the integrity of a mine hoist rope. Although conservative safety factors are mandatory, there are certain unexpected conditions that adversely affect the integrity of a rope. Consequently, it is impossible to establish a "norm" for a given shaft, portal, or elevator at a given mine. A different rope construction may be used for a given application simply because the rope was available when needed. The construction may have a positive or negative effect on the longevity of the rope. A different construction maybe chosen because it offers better performance for a given application. If the environment is corrosive, a galvanized rope may be chosen to replace a bright (uncoated wires) rope. It is expected that the galvanized rope will last longer. How long? The rope must be monitored in a reliable manner. A visual inspection alone is not always sufficient. Nondestructive testing has proven to be a very effective means to enhance safety and complement a good preventive maintenance program.

2. PRINCIPLE OF NDT OPERATION

The principle of NDT instrument operation is described in the ASTM standard E 1571. Figure 1 illustrates a typical set-up for a vertical hoist rope test. Basically, a magnetic head encircles a rope. A constant flux magnetizes a length of rope as it passes through the head (magnetizing circuit). Variations in a constant magnetic field are sensed and electronically processed to produce an output voltage proportional to the change in metallic cross-sectional area within the region of influence of the magnetizing circuit. Magnetic flux leakage created by a discontinuity in the rope, such as a broken wire or a pit. in a wire from corrosion, is also sensed, processed and displayed. Thus, two channels of information may be displayed: (1) changes in metallic cross-sectional area

Fig. 1. NDT of Vertical Hoist Rope



(referred to as **"LMA",** or "loss of metallic cross-sectional area", because loss is derived from this channel and, (2) localized conditions, or flaws ("LF".) such as broken wires, pits in the wires or inter-strand nicking. This information is commonly displayed on a two-channel strip chart recorder. Recent developments make it possible to store, view, and transcribe data on a portable laptop or notebook computer.

The American Society for Testing and Materials (ASTM) E1571 "Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope" offers guidance for professionals involved with wire rope. The following paragraphs are included:

1. Scope
2. Referenced Documents
3. Terminology
4. Summary of Practice
5. Significance and Use
6. Basis of Application
7. Limitations
8. Apparatus
9. Examination Procedure
10. Reference Standard
11. Test Agency Qualification
12. Key Words

The standard offers guidelines for the users and testers of ropes, and for enforcement personnel. It may be obtained by contacting ASTM, telephone (610) 832-9500, or FAX (610) 832-9555, or e-mail service@local.astm.org.

3. INCORPORATING NDT WITH U.S. MINE REGULATIONS

It must be stated emphatically that there is no substitute for a thorough visual inspection of a rope. However, when NDT is included, both safety and efficiency can be significantly enhanced. The MSHAwire rope regulations are included in Title 30, Code of Federal Regulations. The regulations address ropes used to hoist persons in shafts or slopes underground or loads in shaft or slope development when persons work below the suspended loads. The regulations do not apply to wire ropes used for elevators; however, an MSHA mine inspector has the means to assure that any rope that adversely affects personnel safety will be removed from service.

The MSHA regulations require baseline (initial) diameter measurements of a new rope after construction stretch has occurred. These measurements are recorded for future reference to determine loss of rope diameter. A baseline NDT is not required, but is useful to determine when and where a rope begins to deteriorate. The baseline may show damage on the new rope. The author has experienced this occurrence. It was necessary to retire the new rope because a vehicle had-run over and damaged a portion of the rope when it was lying on the ground during installation.

Visual examinations of a rope in service are required every 14 calendar days along its entire active length for visible structural damage, corrosion, and improper lubrication or dressing. A visual examination for wear and broken wires must also be made at stress points, including the area near end attachments, where the rope leaves the drum, at drum crossovers, and at change-of-layer regions. When any visible condition that results in a reduction of rope strength is present, the affected portion of the rope must be examined on a daily basis. At least once every six months, nondestructive tests must be conducted of the active length of the rope, or rope diameter measurements must be made wherever wear is evident, where the hoist rope rests on sheaves at regular stopping points, where the hoist rope leaves the drum at regular stopping points, and at drum crossover and change-of-layer regions.

The above paragraph requires daily visual examinations of any part of the rope displaying loss of strength, and rope diameter measurements at stress and wear points at six-month intervals. It will be shown later that visual examinations alone are not always sufficient and may lead to use of an unsafe rope. Nondestructive testing provides a reliable means to locate, or "zero-in," on an anomaly, or flaw.

MSHA regulations for rope retirement address broken wires, loss of rope and crown (outer) wire diameter, corrosion, distortion, heat damage, and loss of rope strength as determined by NDT. Nondestructive testing has a limited ability to detect broken wires. It may not detect heat damage. It does readily identify corrosion, distortion and loss of cross-sectional metallic area, which then aids in determining future use of the rope.

4. LIMITATIONS

The ASTM standard El571 includes a section on wire rope NDT limitations. In general, the practice is limited to the examination of ferromagnetic steel ropes. Flaws at or near rope terminations and ferromagnetic steel connections cannot be detected. Deterioration of a purely metallurgical nature (brittleness, fatigue, etc.) is not easily distinguishable. Another limitation, not yet included in E1571, concerns the magnetic head. A given size magnetic head is limited to a specific range of rope diameters.

NDT instruments, designed to measure changes in metallic cross-sectional area, function by showing changes relative to a section of the rope upon which the instrument is calibrated. The sensitivity of these methods may decrease with the depth of the flaw from the surface of the rope.

It may be impossible to discern relatively small-diameter broken wires, broken wires with small gaps, or individual broken wires within closely-spaced multiple breaks. It may also be impossible to discern broken wires from wires with severe corrosion pits. Because deterioration of a purely metallurgical nature is not easily distinguishable, more frequent examinations may be necessary after broken wires begin to appear to determine when the rope should be retired. A rapid increase in the number of broken wires is indicative of fatigue. Continued use of the rope would be hazardous.

5. REASONS FOR LABORATORY TESTS OF THE NDT INSTRUMENTATION

To assure maximum NDT reliability and accuracy, it is important to know the capabilities and limitations of the NDT instrumentation. The author has gained valuable confidence in the NDT process by having samples of retired ropes autopsied in the laboratory and compared with the NDT results from the same sections of rope.

The laboratory tests described in this paper were conducted with MSHA NDT instrumentation employing coils and integrating circuitry. To conduct certain types of laboratory tests, the author used 3/16 in. (4.8 mm) diam. by 3 ft. (91 m) long drill steel rods. Up to 120 rods may be used to equate to rope diameters up to 2.5 in. (63.5 mm). Three-foot lengths minimize magnetic end-effect errors. Drill steel was chosen because the magnetic characteristics compare closely with those of a ferromagnetic wire rope. The author utilizes two sizes of magnetic heads. The small head accomodates ropes up to 3/4 in. (19.0 mm) diam. (for testing elevator ropes and other small ropes), and the large head accomodates ropes from approximately 13/16 in. (20.6 mm) up to 2.5 in. (63.5 mm) diam. The large head must not be used to test ropes equal to or smaller than approximately 3/4 in. (19.0 mm) diam. (see "LMA Linearity," below). Figure 2 shows a typical laboratory set-up.

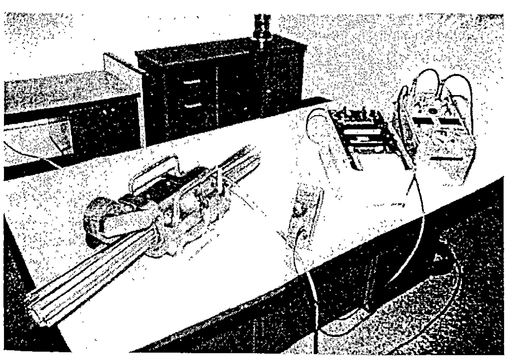
5.1 Drift

Electronic drifting of the LMA circuit may occur, due to extreme temperature variations subjected upon the instrument. For example, taking the instrument from a warm room to a freezing temperature outside. The integrating circuit must be thermally insulated. or the instrument allowed to stabilize to the ambient temperature,

5.2 Droop

Another phenomenon with the integrating circuit was observed. When a positive or negative voltage is produced by a change in metallic mass, the integrating circuit seeks zero. This is called "droop." This is not a desirable occurrence because it may affect the accuracy of the LMA indication. For example, if a significant portion of a rope is deteriorated relative to another portion, droop will reduce the magnitude of the LMA trace. The manufacturer added a potentiometer to the integrating circuit to make it possible to minimize the effects of droop. This is very effective and does not affect the accuracy of the test. It makes it easier to calibrate the LMA signal (described later) because the output voltage remains constant during the short calibration period.

Fig. 2. Laboratory set-up showing (left to right):
Magnetic Head with Calibration Rods, Digital Multimeter, Strip Chart Recorder, Signal Processor



5.3 Magnetic saturation of a rope

A "characteristic curve" of an NDT instrument is instructive because it displays the instrument's behavior to different rope mass, or cross-sectional area. It demonstrates ability of the instrument to magnetically saturate a rope. From a practical standpoint, a magnetic head would be too bulky and weigh too much to contain enough magnets to completely saturate a rope. Less than complete saturation provides satisfactory performance without compromising reliability in locating deterioration inside, as well as on the surface of the rope. The MSHA instrument incorporates "rare earth" magnets in the magnetic heads. Figure 3 shows a plot of LMA gain potentiometer setting vs. rod area. It is seen that the curve is not linear. In fact, it reaches a low point and then rises with increasing area, or mass,

It has been shown that certain things are learned only from controlled laboratory tests. Tests of ropes in-situ have also revealed other factors of instrument behavior and will be described under **FIELD TESTS.**

6. FIELD TESTS

It will be shown how effective NDT is in a preventive maintenance program. To reduce operating costs and insure safety a cost-conscious mine operator will follow recommendations from reports prepared by this agency. However, this is a choice; not a federal government requirement. This agency only requires timely retirement,

Initially, two-channel ink-pen strip chart recorders were used with older-generation NDT instrumentation. Later, when the instrumentation was replaced with state-of-the-art instrumentation (in present use), hot (resistance)-pen recorders were included. Hot pen recorders are convenient, but they are unable to show the complete outline of a broken wire on the LF trace. Also, the traces fade after several years of storage.

When a rope is moving 400 ft. per min. (2 meters per sec.), the pen-movement is too fast to make a complete impression on the paper when a broken wire passes through the magnetic head. Slower rope speeds (400 ft. per min. is the maximum recommended speed) will allow better definition.

This handicap would be more critical for ropes deteriorating strictly from broken wires. A hot pen recorder would not be the best choice. More state-of-the-art recorders with thermal array printheads provide higher frequency response,

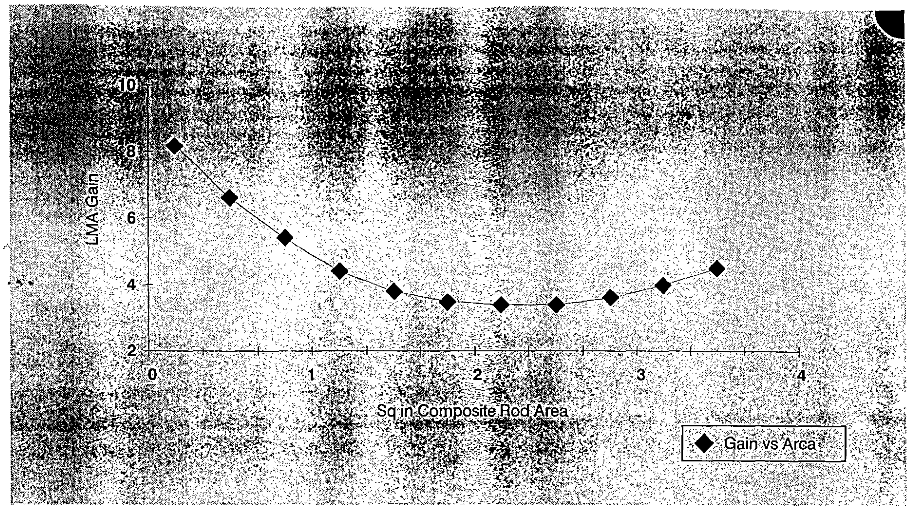


Fig. 3. MSHA DSHTC LMA-250 Characteristic Curve

6.1 Field calibration

The diameter and construction (not classification) of a rope must be known to calibrate the LMA signal. The diameter may be measured with a caliper. However, the area of the rope cannot be measured, and this is necessary to determine loss or gain of metallic cross-sectional area represented by removal or insertion of a calibration rod, respectively. The author refers to tables listing approximate metallic areas for different constructions of wire rope. The tables are supplied by U.S. wire rope manufacturers, The metallic area of a given rope would be equivalent to a smaller-diameter solid steel rod. The more dense a rope, the closer its diameter compares to the diameter of a rod of equal mass, but the rope is still larger in diameter. Listed rope areas may also be referred to as "fill factors." The author measured individual wires from rope samples with a ball micrometer, calculated the areas of the ropes, and compared them with the tabulated approximate areas of equivalent ropes. The differences between actual and approximate were five percent or less. A five percent error would show an actual loss of 10 percent as 9.5 percent or 10.5 percent indicated. It has also been observed that, when the instrumentation is calibrated in the laboratory with three-foot rods, and then calibrated on a rope of approximately equivalent area as the cluster of rods, the LMA gain is nearlythe same. Results of these comparisons add confidence to the accuracy of the test method, the only known reliable method for this instrumentation.

The LF trace does not provide quantitative information as does the LMA trace. The gain is adjusted with a potentiometer, to show a rope "characteristic noise" level equivalent to approximately two minor divisions on the strip chart, as the rope passes through the magnetic head.The rope passes through the test head at hoisting speeds up to 400 ft./min. (2m/sec.) Again, higher rope speeds would affect the resolution of a broken wire indication on the strip chart more adversely. Tests are conducted at slower speeds when necessary because of rope speed limitations and safety. In many cases, more than one set-up is required to test the fully extended length of the rope.

6.2 Influence of a moving metallic mass during emergency - escape hoist rope test

Emergency escape hoist ropes were tested in a shaft that also carried an ore skip which was in continuous operation. Four ropes supported the escape cage. Each rope showed unusual indications on the LMA trace. There were no corresponding indications on the LF trace. It was noticed that the skip was traveling up and down the same shaft at regular intervals of time, causing the even spacing between indications. The indications always showed increases in metallic cross-sectional area, which correlated to the mass of the skip. This was an important occurrence to observe and understand. It was learned through this experience that metallic masses near the magnetic head influence the total metallic mass sensed by the LMA circuit. The LF trace was not affected. If there is something legitimately wrong with the rope, both traces will show something. Also, a repeat test can be done to check for repeatability. The spacing between skip occurrences is constant, but the location of the occurrence with respect to the rope would be different between tests,

This brings up another important point about metal in close proximity to the magnetic head. 'if the metal is close enough and remains stationary, it will influence the LMA calibration. The LMA potentiometer setting is a function of total metallic mass affecting the LMA circuit, and this includes the combined mass of the rope and other metallic mass within close proximity. Thus, if more than one set-up is required to test the fully extended length of the rope, the LMA gain potentiometer settings may be different for each location. Also, magnetic influence in the general area may be different or absent at a later date. If, during the test, the magnetic head moves with respect to the stationary metallic mass, the LMA trace may show the movement, but nothing unusual is indicated on the LF trace.

6.3 LMA averaging

LMA averaging occurs with instruments designed to sense changes in metallic cross-sectional area (or, more appropriately, mass). Slight error from averaging occurs because the sensor(s) in the magnetic head is a short distance away from the flaw in the rope. For example, if one of the wires in a rope contains a corrosion pit, the LMA sensor will average the magnetic influence of that pit over a certain distance along the rope. The influence from the pit will not show up on the LMA trace. Eventually, there will be enough pits in not only one wire, but in several wires that a loss will be shown on the LMA trace with corresponding "hash" indications on the LF trace. The true loss will still be slightly greater than the indicated loss. When wire deterioration from corrosion eventually reaches a certain extent and affects a greater length, the true loss of metallic cross-sectional area will equal the indicated loss on the LMA trace. The LMA averaging error is inversely proportional to the extent of the degradation (from corrosion or inter-strand nicking, for example). Error is greatest when degradation is slight over a rather short rope length, but there is little or no error with significant degradation. Fortunately, there is minimal error when 10 percent LMA makes rope retirement imminent. Personal experience from testing ropes and performing laboratory analyses on retired rope samples has indicated that the error is negligible when there is more than 10 percent LMA from corrosion (most common occurrence in the mining environment). The effect of averaging with the MSHA instrumentation is small. Correction factors are not applied. Consideration for rope retirement is based on the direct determination made from the strip chart record. Operators of instruments incorporating flux gate sensors and hall semiconductors apply conservative LMA correction factors to assure timely retirement of a rope. As a result, many ropes may be retired somewhat prematurely. Laboratory testing needs to be done to determine the effects of averaging with all LMA-type instruments.

6.4 Mismatched elevator suspension ropes

A set of suspension ropes was tested on an elevator used to transport personnel into a coal mine. The car was supported by seven 5/8 in. diam. 8x25 fiber core, alternating right/left regular lay ropes. The NDT indicated 5.0 percent LMA on one of the ropes; the other six ropes showed no loss. The ropes were less than three years old, relatively new for elevator ropes. It was learned that there had not been enough galvanized rope on a reel to make seven individual ropes. Consequently, six ropes were galvanized and one was bright (uncoated). The bright rope had already lost 5 percent of its cross-section from corrosion. The American Society of Mechanical Engineers (ASME) A17.2 standards requires all of the suspension ropes to be from the same manufacturer and of the same material, grade, construction, and diameter - preferably cut from the same reel. Consequently, the mine had to replace all of the suspension ropes. Without NDT, the ability to determine that one rope was corroded would have been uncertain. The galvanized ropes demonstrated, dramatically, the ability of the zinc-coated wires to resist a corrosive environment. Eventually, zinc-coated wires corrode too, but this process is delayed considerably. Thus, a cost comparison between zinc-coated and bright wire ropes must also consider useful life of a rope or set of ropes,

6.5 "Finger prints" of each corroded elevator suspension rope

Another set of elevator suspension ropes was tested. All five ropes showed extensive corrosion. The greatest loss of metallic cross-sectional area was 29 percent. Because the loss was greater than 10 percent LMA, and there were corrosion pits in the wires, the ropes were retired. Even when only one rope meets retirement criteria, all must be retired (ASME Al 7.2). One rope was shipped to the author for a laboratory analysis to compare measurements of loss with the NDT indication. The rope was pulled through the magnetic head. Comparison of the strip chart record with the records from the on-site tests indicated that this rope was designated "Rope No. 3". All of the ropes displayed losses at the same locations. However, each rope also contained a unique "finger print." The influence of magnetic "end-effects" near each end of the open (unattached) rope was observed on the strip chart. Macro- and micro-photographs from the laboratory analysis showed the effects of significant corrosion pitting and erosion. It was concluded from the analysis that there was an average LMA of 33 percent, compared with the 27.5 percent LMA from the NDT of this particular rope. These ropes were overdue for retirement. This was the first NDT conducted on these ropes. Regular NDTs conducted every six months would have made it possible to retire the ropes in a timely manner.

It has been learned from other NDTs of elevator suspension ropes that, not only can the location of the corrosion be determined, but the source can also be located. During a test of coal preparation plant elevator suspension ropes, it was observed that water was dripping onto the ropes directly over the driving sheave. It was relatively easy for the water to penetrate to the core of each rope while the elevator was idle, because the individual strands separate slightly while the ropes are bent around the sheave. The extent of the corrosion was great enough on these five-year-old ropes to make retirement necessary. An identical coal preparation plant elevator included a shield over the driving sheave. These 10-year-old ropes showed negligible loss. Effective preventive maintenance is the key to safety and economy!

During the wash down procedure at some coal preparation plants, water contacts. the elevator suspension ropes: It has been learned from NDTfollow-up visual observations, that the corroded portions of the ropes are concentrated where they contact the sheaves mounted on top of the car and counterweight (2:1 single-wrap traction). The concentration is very localized and would. be virtually impossible to find from a visual inspection, if it was not known where to look. While the elevator is idle and the car is parked at the same location when not in use, water migrates down the ropes and 'collects under the sheaves. Good preventive maintenance may consider operating the elevator after a wash to remove water from the ropes, and park the elevator at different landings to distribute water concentration rather than concentrating it at the same location all the time.

6.6 Continuous haulage ropes and ropes, the ends of which,have been reversed

Wire rope NDT is a relative-type of test. The strip chart record of the LMA trace is studied to compare the worst section of the tested rope with the best section. The best section is assumed to be equivalent to a new, unused rope. In reality, the best section may also be deteriorated. The ends of the rope may have been reversed to place a deteriorated portion onto the drum. This is not recommended because the safety factor may be less than it was prior to reversal. Now, when the rope is fully extended, the deteriorated portion on the drum supports more load than when it was near the conveyance. Shock loading would have a more adverse effect. Continuous haulage ropes wear evenly. It is important to caliper a rope and compare the measurements with a baseline. It is also important to observe the LF trace and visually examine questionable points on the rope. An effective rope test includes more than just a nondestructive test. It requires physical measurements and close visual examination by knowledgeable person.

7. CONCLUSIONS

1. The importance of laboratory tests to gain a better understanding of the NDT instrumentation and its limitations is evident. It has been shown that field tests of ropes have revealed other important points about the instrumentation. The results of the NDTs have made it possible to determine the safety status of a rope and establish preventive maintenance procedures to extend the useful life of a rope.

2. Instrument averaging exists with all LMA-type of instruments. Research should be undertaken to determine appropriate correction factors, for a given instrument, for different indicated LMA losses.

3. Wire rope nondestructive testing provides a useful and reliable means to determine the remaining life of a rope. It affords the knowledgeable inspector the ability to determine the structural integrity of the rope, even though it is not possible or even necessary to determine the remaining breaking strength of the rope.

4. ASTM E 1571 “Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope” refers strictly to loss of metal because loss of breaking strength cannot be measured from a nondestructive test. The standard offers useful information on instrument capabilities and limitations, and the test procedure.