WIRE

ROPE

Automated Condition Monitoring with Remaining Lifetime Assessment for Wire Ropes in Ladle Cranes

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The hazards and deterioration of operating wire ropes on overhead cranes, which articulate the ladle in the basic oxygen steelmaking process and are subjected to intensive periodic loads and exposure to high temperatures, are discussed. An automated condition monitoring system (ACMS) based on a magnetic flux leakage testing (MFL) flaw detector permanently installed on the rope under test is used. An algorithm of the rope's residual tensile strength assessment is provided. A specially developed software that submits a decision on the rope's condition to the crane operator is described. The practice of combining magnetic rope testing (MRT) and tensile strength analysis for the quantitative assessment of rope condition is reviewed. Practical issues are also discussed, such as how to

...an MFL flaw detector is permanently installed on the rope under test.

Figure 1. A ladle pouring molten pig iron into a converter.

establish the condition monitoring process, set loss thresholds for rope metallic cross-sectional area, and safely prolong the service life of rope.

Introduction

In basic oxygen steelmaking, molten pig iron is transferred using a ladle and then poured into a converter, as can be seen in Figure 1. The steel wire ropes of the overhead cranes, which suspend the ladle, are thus exposed to repeated cyclic loads and intense heat. The corrosive and abrasive wear on the ropes, accompanied by annealing from the heat, degrades the mechanical properties of their component wires.

A statistical analysis on three ladle cranes was carried out during a single shift at the Severstal Mill in Cherepovets, Russia. Figure 2 shows a histogram distribution of loads on the ropes before (gross – P_g) and after (net – P_n) the pig iron was poured into the converter.

The mean net load was P_n = 305.0 tonnes with a standard deviation of σ_{Pn} = 7.7 tonnes and a variation coefficient V_{Pn} = 2.52%. The mean gross load was P_g = 438.0 tonnes, with σ_{Pg} = 11.6 tonnes and V_{Pg} = 2.65%.

In addition to the weight load, the ropes are also exposed to heat radiation of the transported pig iron in the ladle (1250 to 1400 °C) as well as plasma discharges when it is poured into the converter, caused by impurities in the iron and/or the slag. Both of these factors can bring the surface temperature of the wires to more than 200 to 250 °C.

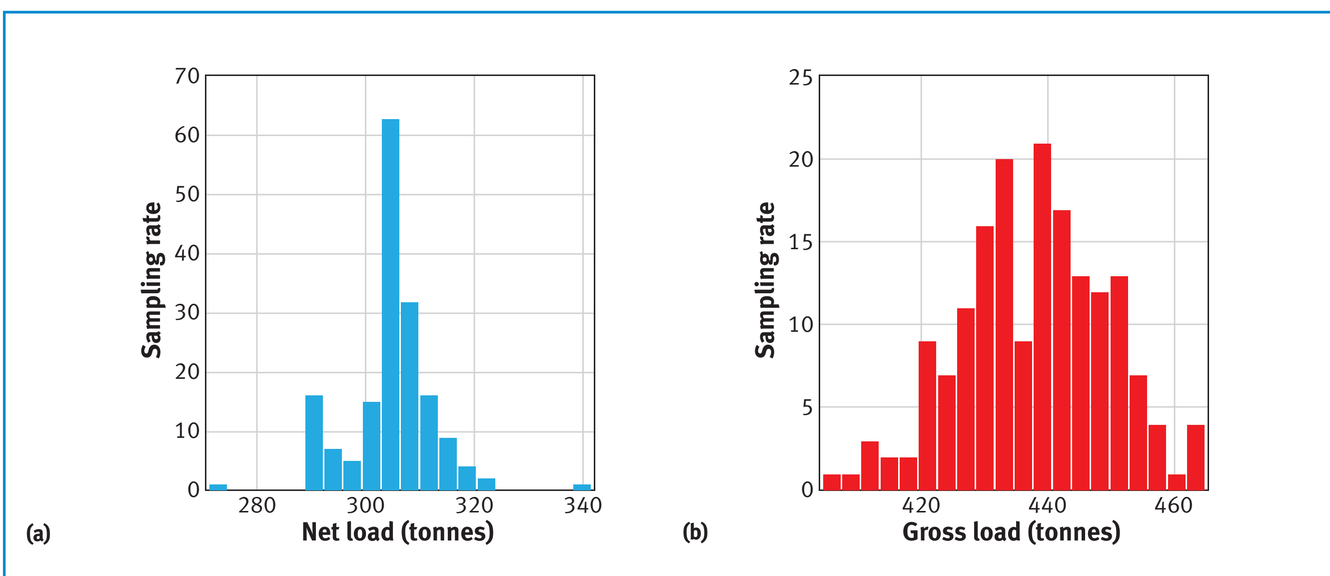

Figure 2. Histograms displaying the loads on ladle ropes: (a) net load; (b) gross load.

The pyrometry in Figure 3 shows that the temperatures of the ropes during the lowering of the empty ladle were 128 to 160 °C, while the maximum temperature of the crossbeam and heatshield chains were recorded to be 193.5 and 222.6 °C, respectively, and the iron/slag in the ladle was 998.5 °C.

The present international standards do not contain any limitations regarding the maximum temperature at which wire ropes can operate (Gosgortechnadzor 1998; ISO 2017). The North American standard ASME B30.2 only specifies that ropes operating above 82 °C should be of an independent wire rope or strand core design (ASME 2005). The Russian standard RD 10-231-98 states that “the carrying capacity of a steel core wire rope sling is reduced by 25% if the cargo temperature is from 250 to 400 °C. Carriage of cargo with temperature over 400 °C is prohibited” (Gosgortechnadzor 1998). The lack of any tensile limitations on wire ropes due to heat exposure in the existing standards is the reason why most manufacturers specify a limit of 450 °C for all ropes made of carbon steel wires (Bridon 2011; NAI 2008).

The overall work cycle of ladle crane is 25 to 30 pours per day, with an average exposure of the ropes to the heat lasting for 3 min during each pour, making the wear pattern cyclic in character. This leads to deterioration of the wires’ mechanical properties over time (Figure 4) (Chen et al. 2006; Matyunin et al. 2019) and a reduction in the ropes’ load-bearing ability, which can ultimately manifest in rope failure (Malov et al. 1999). Figure 4 shows the relative change in wire tensile strength after different thermal cycles.

It has been observed that most of the operational deterioration in ladle crane ropes is the loss of the metallic cross-sectional area (LMA) due to the corrosive, abrasive, and friction wear on wires (Figure 5), while local faults (LFs), such as broken wires or strands, are rare.

As ladle ropes cannot be repaired, they are discarded once their strength safety factor falls short of the allowed value. This limit is established from the rope’s breaking strength and the degree of risk a rope failure carries. The rope’s breaking strength is determined by the tensile strength of the component wires, the cross-sectional area, the number of wire/strand breaks, and their localization along the rope’s axis.

International standards generally specify the discard criteria of allowable LMA or a number of broken wires/LFs distributed over a unit length (commonly 6D or 30D, where D is the rope diameter) (ISO 2017). These criteria are largely based on theoretical and experimental research on rope mechanics. However, as these studies were carried out when nondestructive testing (NDT) technology was not

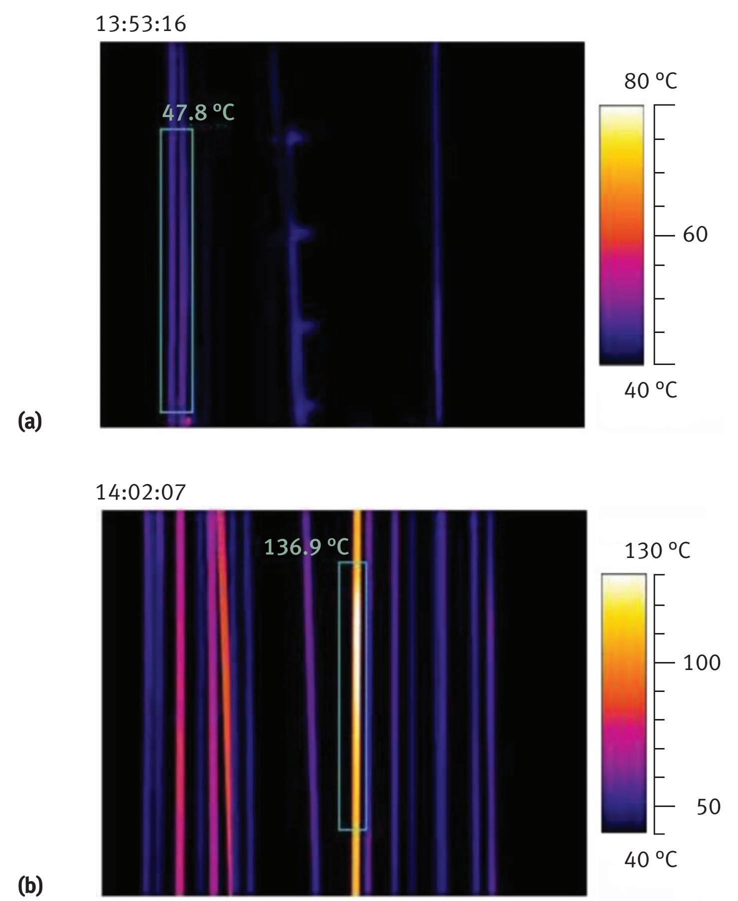

Figure 3. Thermograms of ladle crane ropes: (a) before pouring; (b) after pouring.

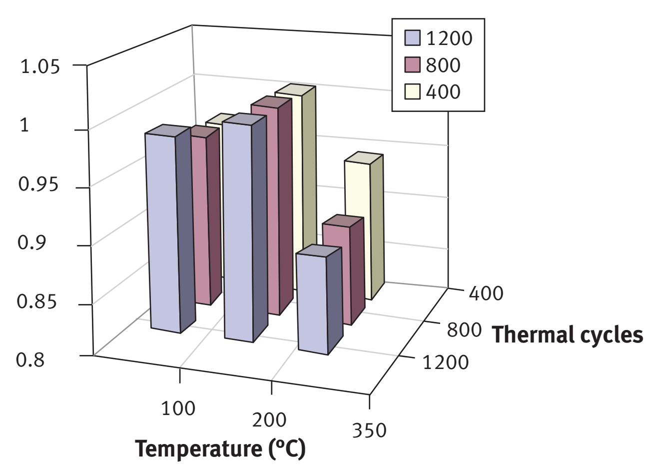

Figure 4. Relative change in wire tensile strength during different thermal cycles.

available, they do not account for internal rope damage, including wire and strand breaks and wear of the core. Because of this, rope tensile strength calculations carry an empirical "unknown coefficient." This approach remains applicable for visual inspection, but its applicability for MRT may be questioned.

Figure 5. A discarded IWRC rope from a ladle crane (D = 42 mm, construction: 6 × 25[1 + 6; 6 + 12] + 7 × 7[1 + 6]).

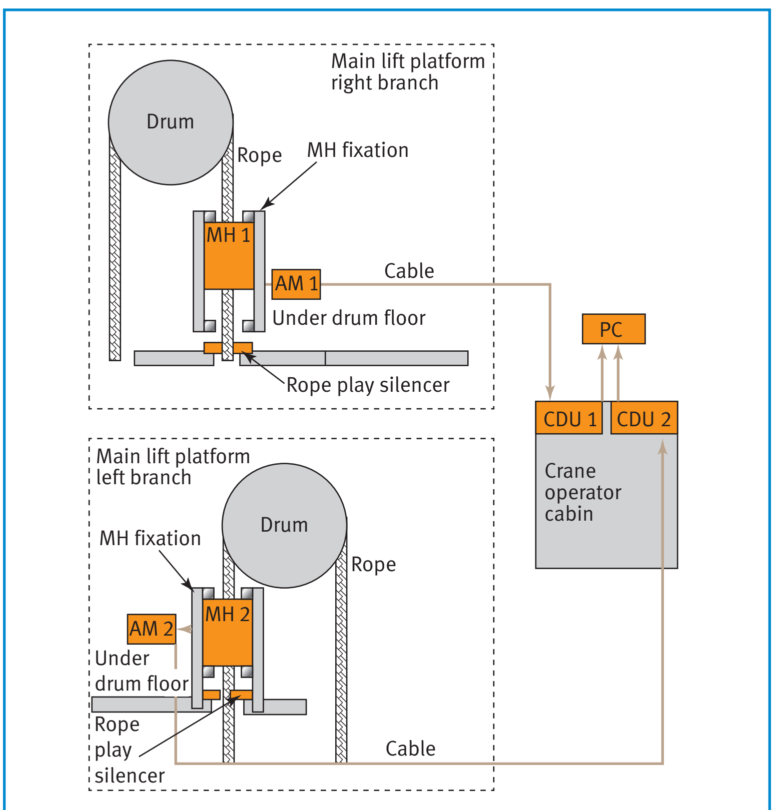

Figure 6. Installation schematic of the automated condition monitoring system for ladle crane ropes (MH = magnetic head; AM = analog module).

Contemporary NDT of wire ropes is done by instruments based on MFL, which registers the respective LMA and LFs from the leakage caused by discontinuities in the ferromagnetic wires (Gronau et al. 2000). MRT has gained wide international practice and recognition.

The data on presence, parameters, and localization of discontinuities as well as their growth dynamics may be used for the assessment using specialized software, which calculates the tensile properties of the ropes, including their residual breaking strength.

Thus, there is a possibility of using two independent methods for evaluating rope condition: via existing discrete discard criteria (based on LMA values and quantity and location of LFs) and using tensile strength parameters. An example of a product that utilizes both of these approaches is an automated MRT condition monitoring system for wire ropes (Slesarev et al. 2017). The philosophy of the system was discussed in an earlier paper (Sukhorukov 2021).

Condition Monitoring of Ladle Crane Wire Ropes

The Severstal steel mill has used conventional MRT flaw detectors for more than 20 years (Kotelnikov and Sukhorukov 2003). The instrument works by axial rope magnetization using permanent magnets up to magnetic saturation and subsequent MFL recording by hall sensors and/or induction coils (Sukhorukov 2013; Sukhorukov et al. 2014). The hall sensors are temperature-compensated to decrease environmental temperature variability influence on the LMA channel signal.

Severstal internal guidelines set the inspection timelines and discard criteria for the ladle crane wire ropes. The former recommends inspection every 50 to 60 pouring cycles, while the latter has two discard parameters: when the LMA exceeds 6%, or after the ropes complete 1200 pouring cycles. These standard values (LMA = 6% and N = 1200 pouring cycles) were determined from aggregate strength experimental studies and safety factor calculations for previously used ropes, which were subjected to intense thermal and mechanical loads during operation. The results and accompanying discussion of using standard MRT flaw detectors for monitoring rope wear in steel mills have been covered previously (Sukhorukov 2007; Vorontsov et al. 2013). These guidelines have been in use since 2009. A new system has now been installed for hot air expulsion from the ladling zone and a different type of rope is used. Large-scale statistics on discarded ropes show they were discarded before their full lifetime.

When values from at least one of the channels approach the allowed threshold, the operator is warned by a light...

In March 2017, as part of a pilot project, one of the cranes had an ACMS installed for trial operation. An overall schematic is shown in Figure 6, where two magnetic heads (Figure 7a) are permanently installed on each of the crane ropes under the drum, above the crane's girder. This way, they can inspect the sections of the ropes that are most exposed to drum crushing and heat exposure. In the cabin of the crane operator is a control and display unit (CDU) (Figure 7b).

The most important component of the ACMS is the internal software within the CDU. LMA and LF raw data are read from hall sensors and induction coils in the magnetic head. A special filtering algorithm distinguishes the wire break signals from the noise. A continuous summation is in place to measure the number of breaks per unit length (6, 30, or 500 D), and this number is cross-referenced against the allowable discard criteria. LMA data is processed similarly and when values from at least one of the channels approach the allowed threshold, the operator is first warned with an amber light and then informed with a red light that the condition of the rope is past discard. This saves a considerable amount of time required for setting up the equipment and analyzing the trace data, as well as reducing the potential human error.

The crane operators log the monitoring results at the end of every shift (see Table 1). All measurements are stored and may be uploaded to a PC for analysis using conventional software, just like in a standard MRT inspection.

(a) (b)

Figure 7. Components of the automated condition monitoring system: (a) magnetic head permanently installed on the rope; (b) control and display unit in the cabin of the crane's operator.

TABLE 1
Monitoring results of ladle cranes

Crane	No. of pouring cycles by 19:00	16 January 2020			16–17 January 2020 (overnight)		
		Monitoring results					
		Pouring cycle number	% wear (left branch)	% wear (right branch)	Pouring cycle number	% wear (left branch)	% wear (right branch)
8	364	369	2%	2%	377	3%	2%
8a	932	936	2%	2%	946	2%	2%
10	705	720	2%	1%	731	2%	2%

To illustrate, Figure 8 shows LMA traces on a rope's working section on crane 10 recorded within two weeks. The blue curve was recorded shortly after the rope was loaded, and its average LMA value is approximately 0%. The visible slow fluctuations on the LMA curve (within ±0.5%) are caused by rope vibrations during testing. Further tests were carried out after the rope was discarded. The brown curve conforms to about 50 pouring cycles, and the average value is 0.8% LMA. The green and purple traces were recorded after about 220 and 300 pouring cycles relative to the first trace, respectively, and the average values correspond to 0.9 and 1.2% LMA.

By March 2019, the installed system had successfully endured over 600 shifts (more than 15 000 pouring cycles). The equipment has fully withstood the adverse operational conditions, and the trial operation was deemed successful. By October 2019, five more systems had been installed on all three ladle cranes.

Analysis of Condition Monitoring Results on Rope Operability

Rope operability can be defined as the condition of the rope, wherein the parameters characterizing its ability to withstand thermal and mechanic loads are within the allowed specification. For the ladle crane ropes, these

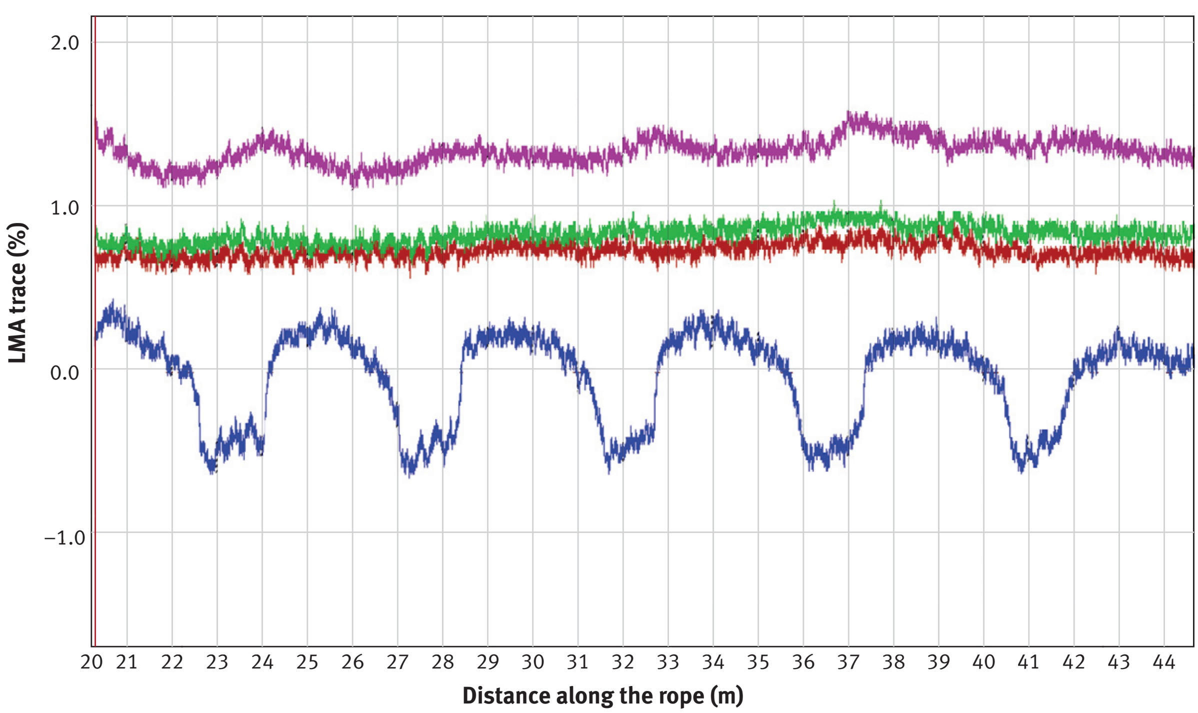

Figure 8. LMA traces from the working section of a rope installed on crane 10 recorded from 1–12 March 2020.

parameters are the maximum working tension, ambient temperature during pouring, running time, and the condition wear parameter (for example, LMA). The running time is defined as the number of pouring cycles into the converter (also called thermocycles).

As mentioned previously, the ACMS stores the test results and can upload them to a PC via cable or wirelessly. After an analysis of the trace data, an assessment of the residual tensile strength of the rope is possible using special software (Vorontsov et al. 2013). The algorithm is explained as follows.

Three tensile calculations are carried out: (a) for a defect-free rope; (b) for a rope with LMA; and (c) for a rope with LFs. In each case, first the deformations and strains are deduced for stretching, bending, and twisting in the wires. Then, the maximum equivalent stresses (max σ_{eqv}) are calculated for the most strained wire, and the safety factor $n = \sigma$ / max σ_{eqv} is obtained, where σ is the maximum tensile strength of the wire material (carbon steel). Relative indicators of a reduction in rope strength, indicated by the loss of metallic cross-sectional area ΔF and wire breaks A, are parameters $\chi_{\Delta F}$ and χ_A, where: $\chi_{\Delta F} = 1 - n_{\Delta F} / n_0$; $\chi_A = 1 - n_A / n_0$, where $n_{\Delta F}$ and n_A are rope strength safety coefficients for LMA and LF, respectively, and n_0 is the safety strength coefficient for an undamaged rope. Although $\chi_{\Delta F}$ and χ_A are calculated independently, the resulting rope strength loss is a superposition of $\chi = \chi_{\Delta F} + \chi_A$. The residual strength safety factor of rope is given as $\tilde{n} = n_0(1 - \chi)$.

The rope's lifetime is simply the running time from its installation to reaching a maximum allowed value N^* or if its wear exceeds the discard criteria.

A generalized indication of the rope as a mechanical unit is the load safety factor "when hot." Vorontsov et al. (2013) list a method of calculating the residual safety strength of ladle ropes with MRT results accounting for these thermal and mechanical factors.

Figure 9 shows the monitoring results of EN 12385-4-2000 type ropes, which were installed on ladle crane 10, from October 2017 to October 2019. The numeration follows the sequence of the ropes after their discard. Numerical estimates of the corresponding probability characteristics of all three cranes are given in Table 2.

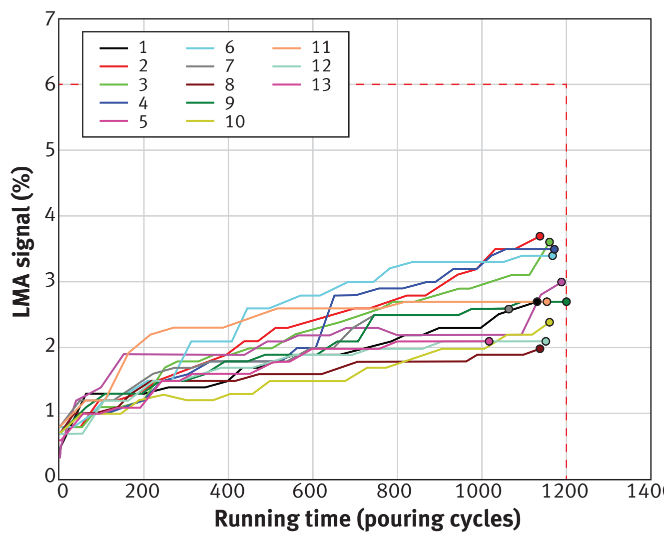

Figure 9. LMA based on running time of EN 12385-4-2000 ropes on crane 10, from 18 October 2017 to 20 October 2019.

TABLE 2
Ladle crane rope operability from 2017 until 2019

		Crane 8	Crane 8a	Crane 10
		Monitoring period		
		21 October 2017 to 16 November 2019	20 September 2017 to 28 October 2019	18 October 2017 to 20 October 2019
Number of ropes changed		17	18	13
Individual lifetime (number of pouring cycles)	Maximum	1200	1200	1200
	Minimum	936	1097	1017
	Average	1136	1146	1142
	Standard deviation	62	28	49
Rope LMA at discard (%)	Maximum	4.5	4.0	3.7
	Minimum	2.0	2.0	2.0
	Average	3.28	3.19	2.81
	Standard deviation	0.64	0.71	0.59

All of the ropes were discarded at a running time close to $N^* = 1200$ pouring cycles, with mean values of 1136, 1146, and 1142 for cranes 8, 8a, and 10, respectively. The mean LMA and its compact deviation at $N^* = 1200$ shows that EN 12385-4-2000 ropes have very consistent and stable operability at the end of their running time, which opens the possibility of safely prolonging the EN 12385-4-2000 ropes' lifetime to the design standard of 6% or even higher.

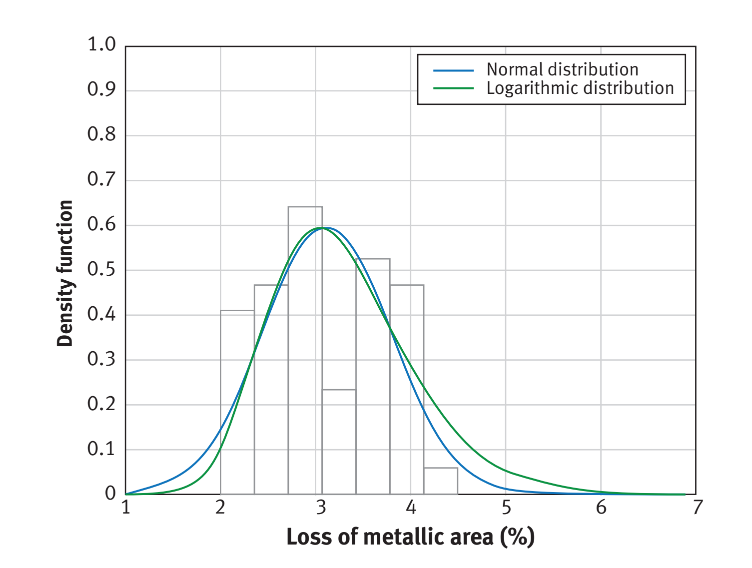

Figure 10. Histogram of the LMA value at rope discard and its approximations.

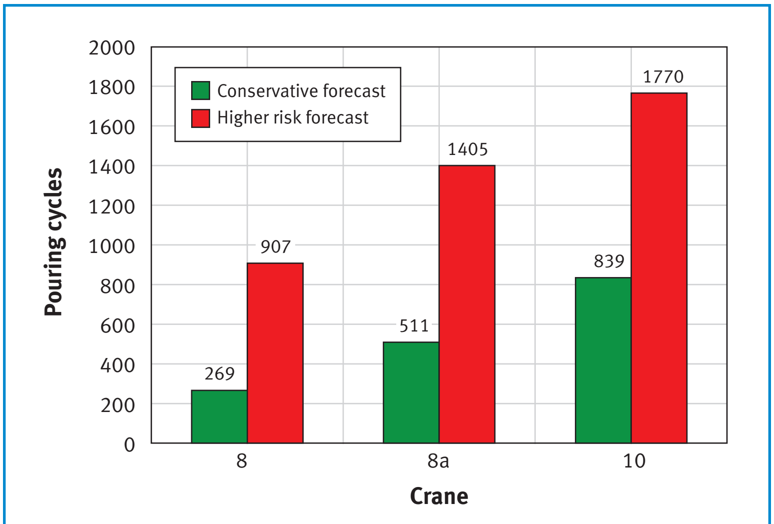

Figure 11. Potential extended lifetime of the ropes, provided that the LMA growth is extrapolated from the last three inspections.

Risk Assessment and Recommendations on Extending Rope Lifetime

Table 2 shows that the discarded ropes at $N^* = 1200$ cycles can be further operated without compromising safety. LMA is, to all intents, a random value. As a risk indicator of rope's critical condition, it is possible to take the statistical probability of the LMA value to be 6% at $N^* = 1200$ cycles. A histogram of measured LMA values for discarded rope at three cranes, along with normal and logarithmic normal approximations, is shown in Figure 10. The logarithmic normal distribution is subjective to the amount of loading and temperature cycles to failure (Bolotin 1999).

The safety function $S(N)$ is given as a probability **P**{A} of a random event A, in that when $N = N^*$, no failure occurs (that is, the LMA remains under the threshold value), such that $S(N^*) = \mathbf{P}\{\text{LMA}(N^*)\} \leq \text{LMA} = 6\%$. Function $Q(N^*) = 1 - S(N^*)$ will thus determine the sought probability (risk) of exceeding the allowed LMA at N^*. In our case we have the following:

$$(1)\quad \begin{aligned} &\mathbf{P}\left\{1 < \text{LMA} \leq \text{LMA}^*\right\} = 0.999199 \\ &Q\left(N^*\right) = \mathbf{P}\left\{\text{LMA} > \text{LMA}^*\right\} = 8.01144 \times 10^{-4} \end{aligned}$$

assuming normal distribution, and:

$$(2)\quad \begin{aligned} &\mathbf{P}\left\{1 < \text{LMA} \leq \text{LMA}^*\right\} = 0.998673 \\ &Q\left(N^*\right) = \mathbf{P}\left\{\text{LMA} > \text{LMA}^*\right\} = 13.2697 \times 10^{-4} \end{aligned}$$

assuming logarithmic normal distribution.

When monitoring the ropes with the ACMS with the output discretization set at 1% LMA, the amber and red indicator lights are 4% and 5%, respectively. In this case it is important to consider N as a random value of either of the two indicators. Then, for both risk indicators, we can state the statistical probability of random events that occur when N becomes $N^* = 1200$ cycles with LMA being 4% and/or 5%:

$$(3)\quad \begin{aligned} &Q_1\left(N^*\right) = \mathbf{P}\left\{N > N^*, \text{LMA} > 4\%\right\} \\ &Q_2\left(N^*\right) = \mathbf{P}\left\{N > N^*, \text{LMA} > 5\%\right\} \end{aligned}$$

Determining Q_1 and Q_2 requires sufficient statistical data, which will enable the building of histograms of N with the occurrence of these events.

This opens the possibility of prolonging the service life of the EN 12385-4-2000 ropes on ladle cranes. As shown in Table 2, many ropes were discarded before their lifetime reached $N^* = 1200$ pouring cycles, while the measured LMA values at discard were about half of the allowed 6%, with negligible risk of exceeding it. Economically, this can be viewed as a premature discard of a rope, which, as a consumable, can be safely operated beyond the $N^* = 1200$ cycles limit.

In the first approximation, the extended lifetime of a working rope may be evaluated by a linear extrapolation of the measured LMA up to the 6% value, taking into account the rate of LMA growth. A conservative calculation of extended lifetime corresponds to the maximum LMA growth rate, determined by the selection of LMA values over the whole lifetime. A riskier assessment assumes average LMA growth on the current selection.

The forecast values of an extended lifetime up to LMA = 6% measurements are given in Figure 11. Based on these assessments, one can conclude that it is possible to safely extend N^* from 1200 up to 1500–1600 cycles.

For this, it is important to address the procedure of rope monitoring. Based on the current inspection data and research into the tensile strength of wire ropes under temperature loads (see Vorontsov et al. 2013), an interval criterion is suggested of allowable rope condition based on the temperature (thermal cycle parameters). The allowable and not-allowable temperature regimes are separated from each other by a relative transitional (buffer) zone. At the interface between the transitional and non-allowable zone, the maximum LMA will be 6.5%. Therefore, provided all precautions are taken, it is thus possible to increase the allowed LMA threshold from 6% to 7% and correspondingly raise N^* to 1600 to 1700 pouring cycles.

It is recommended that the rope be monitored every $\Delta N = 30$ to 40 pouring cycles for the first 300 cycles on a new rope, and then carry out monitoring every $\Delta N = 50$ to 60 cycles, until $N = 1200$. Once this threshold is passed, monitoring should be done again to every $\Delta N = 30$ to 40 pouring cycles until $N^* = 1500$. If the results show a growth of ΔLMA > 1%, then the monitoring rate is to be additionally reduced after every $\Delta N = 20$ pouring cycles. If, during any time of the rope's lifetime, a high-temperature surge is recorded on the ropes at 200 °C, then N^* is reverted to the 1200 cycles, and the rope is discarded if it has surpassed it. If the surge results in overheating (more than 250 °C), then the rope is to be immediately discarded, regardless of its lifetime.

It should be noted that MRT must be augmented with a periodic risk assessment of increasing the ropes' service life. The methodological approach and results described in this paper allow confidence in the ropes' load-bearing ability when the specified thresholds are attained.

At the beginning of this project, in 2009–2011, Severstal recorded a rapid surge in LMA and a drop in the ropes' tensile strength due to plasma ejections upon the pig iron's pouring into the converter. These conditions had objectively higher risks for exceeding the threshold LMA values along with an accompanying decrease in tensile strength (Vorontsov et al. 2013). In this period, risks were not assessed due to the lack of failure statistics, and the task of increasing service life was not specified.

The introduction of a hot gas venting system made the pouring cycle "calmer," which was marked by a gradual LMA increase, and, correspondingly, slower mechanical degradation of the ropes. Acquired operational statistics confirm this. Quantitatively, the risks of nonpermissible LMA turned out to be so low that a safe increase of the operational lifetime is now permissible, as opposed to the rough operating conditions of yesteryear.

Conclusions

An ACMS for the magnetic NDT of steel rope designed to improve the safety of ladle cranes was deployed in a large basic oxygen steelmaking mill. The case study described in this paper used the system to monitor ladle crane ropes, which were subjected to intensive periodic loads and high-temperature exposures. The system's deployment for hazardous machinery resulted in a reduction of labor and time for NDT inspection (which is now more correctly denoted as taking "measurements") and removal of the human factor for more accurate interpretation of NDT data. This alone brings considerable risk mitigation and economic benefits.

The corresponding statistical analysis of the accumulated condition monitoring data and tensile strength calculations allow for a review of the present standards, which define the discard criteria and can be used to validate an extension of their service life without compromising safety, thus bringing a greater economic benefit.

ACKNOWLEDGMENTS

The authors express their gratitude to the Severstal Co. and its senior managers, Anatoly Chernayev and Sergey Buryanin, and NDT specialist, Igor Ponomarev.

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CITATION

Materials Evaluation 79 (11): 1050–1060
https://doi.org/10.32548/2021.me-04226
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