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Hot Metal Crane Ropes: Magnetic NDT, Capacity Simulation, Strength Safety Temperature Criterion

Summary

The problem of hoisting ropes safety operation in metallurgical works is investigated. The experimental and theoretical simulations are performed to reveal the influence of thermal field and wires progressive strength degradation on the rope residual loading capacity. Relying on evaluation of diagnostic indicators derived by magnetic flow non-destructive testing the rope state feature “allowable-caution-prohibited” is submitted. Two-parameter thermal criterion is used to estimate the rope technical condition under supposed foundry rate and to set the rope testing regulations.

1 Introduction

Hot metal crane ropes are usually operating in high temperature environments. In steel mills the ropes may be exposed to flames when the molten metal is being poured from the ladle into converter (Fig.1).

Figure 1: Steel wire ropes operating in a ladle crane at a steel mill.

If converter process is abused the outer wires temperatures of 700÷800°C and even more can easily be reached. During the periodical ladling the ropes are affected by thermal shocks that gradually change a high carbon wires microstructure leading to deterioration of mechanical properties. The structural degradation is going on accompanied with abrasion wear of tensed wires. Such heavy duty leads to a great risk regarding the rope bearing capacity. The rope manufacturers recommend strongly not using the wire ropes for cranes handling hot metal at temperatures above 450°C according to standard regulations [1]. On this point the periodical testing of the ropes technical state in service is of a great importance. So the problem arises to develop the rope monitoring policy that includes the prior thermocyclic safety criterion, the rope NDT schedule and discard requirements.

Several ways should be used to attain this purpose: non-destructive examination of rope health after some of ladlings to reveal the signs of ultimate state coming; the tensile breaking tests of individual wires and entire ropes that have been discarded; the laboratory and in-situ measurements of temperature field at rope cross-section upon enclosing thermal shock and theoretical analysis of rope safety factor under combined power-thermocycling loading.

2 The hot metal crane ropes magnetic testing

The INTRON PLUS company employs for a long time the magnetic tester INTROS for on-line monitoring the ropes of hot metal cranes [2]. Frequent temperature fluctuations cause embrittlement of the wires thus changing the steel magnetic permeability and reducing the mechanical strength. The instrument evaluates the magnetic flow along a rope length and detects the flow alteration caused both by mechanical wear and change of magnetic properties. The rope degradation is specified by generalized diagnostic variable (DV) considered as a signal detected in percents by the loss-of-metallic-area INTROS measuring channel. Magnetic testing is being performed for temporarily cooled ropes in time spans between sequential ladlings.

Figure 2 demonstrates the evolutions of such diagnostic indicator with number of thermocycles (ladlings) for ropes of three hot metal cranes at one of the metallurgical works. Each line relates to different wire rope. The rope construction is 6x25(1+6; 6+12) + 7x7(1+6) D 42 mm.

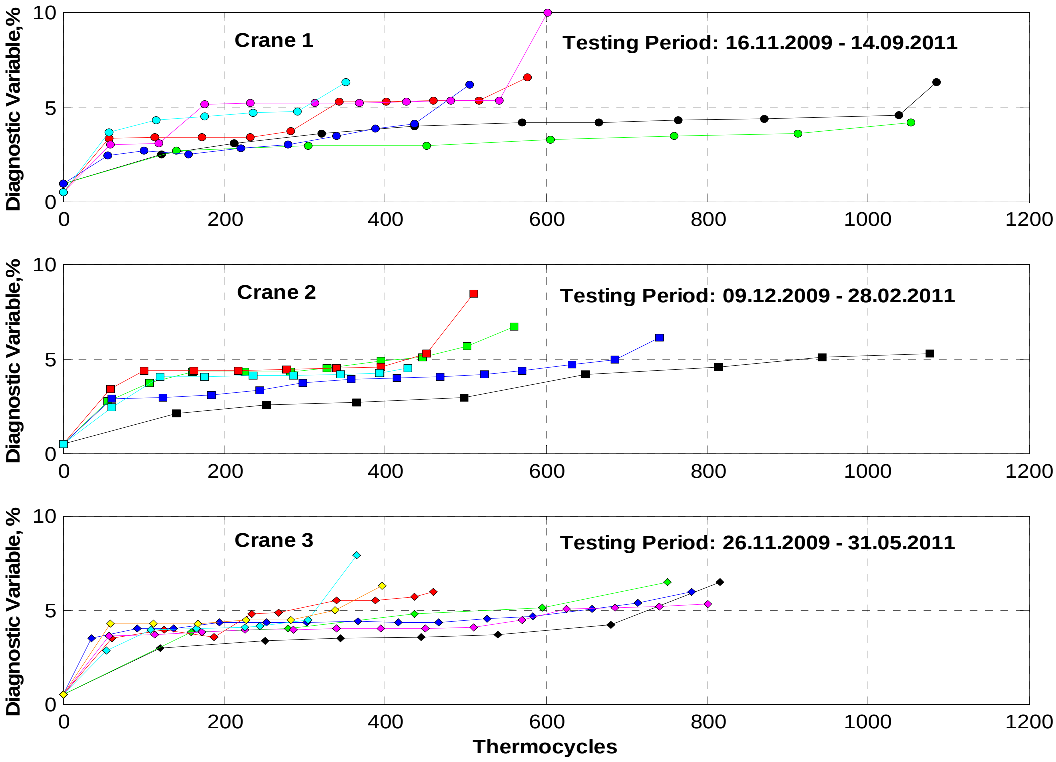

Figure 2: Changing of diagnostic variable of hot crane ropes with thermocycles.

All of dependences exhibit (with slight divergence) three distinctive stages of degradation similar to typical creep curves: initial unsteady, steady and final accelerated. The first stage with high degradation speed is a consequence of initial microstructure transformations at high temperature influences. The steady state is accompanied by gradual increase of thermal embrittlement and by decrease of steel breaking strength. The degradation of all ropes starts to grow dramatically as a diagnostic variable (DV) reaches about 4÷5%. At this situation a certain source of magnetic disturbance appears, common for almost all ropes, which gives rise to diagnostic signal. It happens at different number of thermocycles because the inspected ropes in three cranes were affected generally by various temperatures. A relative breaking strength loss is around 25-30% for cooled ropes with DV 4-5% that was judged by tensile tests. Most probably at this state the microflaw runs up to threshold concentration limit so that the intracrystalline crack extension transforms to intergranular cracking. The corresponding turning points may be noticed on stress-cycle diagrams for metals at elevated temperatures [3]. Last points at the plots in Figure 2 correspond to operating thermocycles when the ropes were discarded because of wires annealed. Table 1 presents an assembly of DV-values related to retirement of all tested ropes at three ladle cranes.

Data entity	**Crane 1**	**Crane 2**	**Crane 3**
Number of tested ropes	44	28	35
Maximum DV-value when retirement, %	11.28	12.75	12.71
Mean DV-value when retirement,%	7.00	6.79	6.81
Mean DV-value when retirement (per all ropes),%	6.87		

Table 1: Estimated diagnostic variables of discarded ropes.

Such a kind of NDT data may give grounds to argue the schedule of rope testing and to formulate the appropriate rope failure criterion.

3 Experimental investigation of discarded ropes residual strength

The thermal influence upon the working rope will be described by two parameters: the top nominal temperature T of outer wires and the number of ladlings (thermocycles) N. The residual strength of the rope having worked at thermal conditions (T,N) may be estimated by safety factor $n(T,N)$ as a relation between the actual breaking load $P_u(T,N)$ and a nominal service tension P :

$$n(T,N)=\frac{P_u(T,N)}{P}. \qquad (1)$$

The alternative parameter is a relative strength loss

$$\chi(T,N)=1-\frac{P_u(T,N)}{P_{u,0}},$$

where $P_{u,0}$ is an actual breaking load of rope in delivery. Its value has been measured for rope D42 mm from tensile tests as $P_{u,0}$ = 1,338 kN.

To make a valid decision on rope condition in terms of structural mechanics it is necessary to establish the dependence between the diagnostic variable and rope strength parameters. So there was carried out a complex investigation of breaking strength for worked-out ropes with known DV-values. The breaking loads $P_u(T,N)$ have been measured for cooled ropes with aid of tensile machine shown in Figure 3.

Figure 3: Tensile testing of discarded ladle crane rope.

Two kinds of tensile tests have been performed: for entire ropes and for individual wire groups. Some results of these tests along with corresponding diagnostic variables are given in Table 2.

Specimen	Actual breaking load of entire rope, kN	Breaking load summarized over all wires, kN	Diagnostic variable, %
1	1,242.64	1,486.80	0.50
2	1,142.56	-	1.60
3	980.00	-	2.70
4	862.40	833.5	4.60
5	815.36	801.00	5.74
6	838.88	843.00	6.12
7	795.76	-	6.40
8	736.96	776.4	8.46
9	529.2	583.57	12.70

Table 2: Comparison of tensile testing data and magnetic testing data for discarded ropes.

More realistic safety assessment requires to know the breaking load parameter $P_{u,T}(T,N)$ that is determined for hot rope put in nearly same working environment, for example in testing machine with a furnace.

The ropes under consideration have been working at tension $P = 174$ kN. The empirical data with Least-Square approximations of strength loss $\chi(T,N)$ and of safety factor $n(T,N)$ as functions of diagnostic variable are presented in Figure 4. Red curves are recalculated from original “cool” data for typical ultimate temperatures T = 300°C and T = 400°C considering the steel strength degradation at high temperatures [4, 5]. It may be seen the real safety is less than that estimated from post factum tensile tests. Safety factor range $3.8 \div 4.0$ at T = 400°C corresponds to beginning of accelerated rope deterioration (see Figure 2). Note the matter concerns a strength of hot rope as a function of diagnostic parameter measured at cool rope.

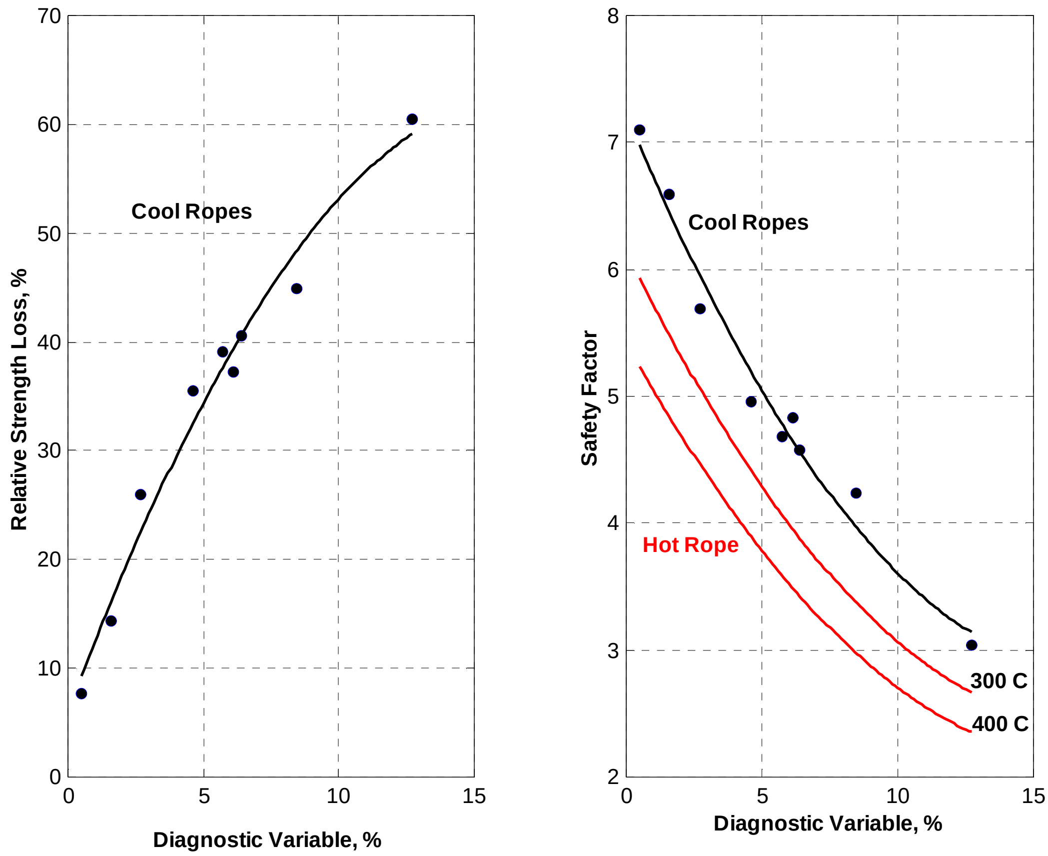

Figure 4: Strength parameters of hot metal crane ropes as functions of diagnostic variable.

4 Theoretical analysis of rope mechanical state in hot environment

Assume the rope to be an axially loaded statically indeterminate system of two parallel bars with common elongation. Bar 1 represents the outer strands wire group (for short - “outer wires”), bar 2 – the core wire group. The rope failure in ultimate state will be treated as a fail of one of these structural components. Denote by $\Delta T = T_1 - T_2 > 0$ the average temperature drop between outer wires and core wires during the hot metal pouring into converter. Experiments with rapid heating the ropes immerged in molten plumbum and FEM thermal analysis indicates ΔT is around 200°C. Let the outer wires temperature T_1 is not above the allowable level 400°C so the steel modulus of elasticity E and the coefficient of thermal expansion α may be considered approximately constant. Denote by $\sigma_{u,T}(T,N)$ the tensile strength of wire that has been heated to temperature T within pouring duration of $5 \div 7$ minutes over N ladlings (thermocycles). This mechanical parameter is assigned from wires “hot” tensile testing [4]. It is less than the corresponding “cool” parameter $\sigma_u(T,N)$ by $(25 \div 35)$ % in range $(200 \div 400)$°C gradually decreasing with number of cycles N. The test rig is shown in Figure 5.

Figure 5: Tensile testing of hot wires.

The combined power/thermal mean stresses in outer wires σ_1 and in core wires σ_2 are

$$\sigma_1 = \frac{P}{A} - \frac{E\alpha\Delta T A_2}{A}, \quad \sigma_2 = \frac{P}{A} + \frac{E\alpha\Delta T A_1}{A}.$$

Here A_1 and A_2 are the total squares of outer wires metal cross-section and core wires cross-section respectively, $A = A_1 + A_2$. The following relation holds true in actual ladling process:

$$\sigma_{u,T}(T_2,N) - \sigma_2 \le \sigma_{u,T}(T_1,N) - \sigma_1.$$

Therefore, the core fail is coming first as powered tension increases and respective ultimate load $P_{u,bar}$ of rope bar model may be estimated by expression

$$P_{u,bar} = \sigma_{u,T}(T_2,N)A_2 + \left(\sigma_{u,T}(T_2,N) - E\alpha\Delta T\right)A_1.$$

The breaking load value $P_{u,T}(T,N)$ for “hot” rope interpreted as an entire helical structure is less than ultimate load $P_{u,bar}$:

$$P_{u,T} = kP_{u,bar}.$$

Here k = 0.90÷0.92 is an empirical factor evaluated by comparing the tensile test data of entire ropes and of single wires.

Mechanical model gives possible to predict the rope safety factor $n(T, N)$ by equation (1) with limit load $P_{u,T}$ for prescribed thermal operating conditions (T, N). An illustrative example on this point is cited below for following parameters: $T_1 = 300°C$, $T_2 = 100°C$, $N = 1$, $E = 2{\cdot}10^5$ MPa, $\alpha = 12{\cdot}10^{-6}$ °C^{-1}, $A_1 = 750$ mm^2, $A_2 = 110$ mm^2, $P = 174$ kN, $\sigma_{u,T}(T_1, N) = 1{,}312$ MPa, $\sigma_{u,T}(T_2, N) = 1{,}757$ MPa. The mean operating stresses in outer wires and core wires are $\sigma_1 = 141$ MPa, $\sigma_2 = 621$ MPa; the hot rope breaking load is $P_{u,T} = 958$ kN i.e. 28.4% less than 1,338 kN for healthy rope in supply; the operating safety factor is $n = 958/174 = 5.5$ instead of $n_0 = 1{,}338/174 = 7.7$ for new rope.

5 Thermal interval criterion of rope safe operation

To predetermine the rope reliability under specified operating process it is desirable to have the rope safety factor parametric diagrams in variables (T, N) where T is a temperature of outer wires and N is a number of thermocycles (ladlings). Such diagrams may be obtained arranging empirical information from rope magnetic testing and tensile testing with safety factors evaluated in hot-working situations. Because of general uncertainties of thermal ladle regimes and of wires magnetic/mechanical properties, there might be not the strict distinction between the feasible and prohibited areas. So it seems reasonable to get the interval criterion with a peculiar “caution” buffer zone separated the acceptable and intolerable working conditions.

The graphical representation of rope state areas is shown in Figure 6.

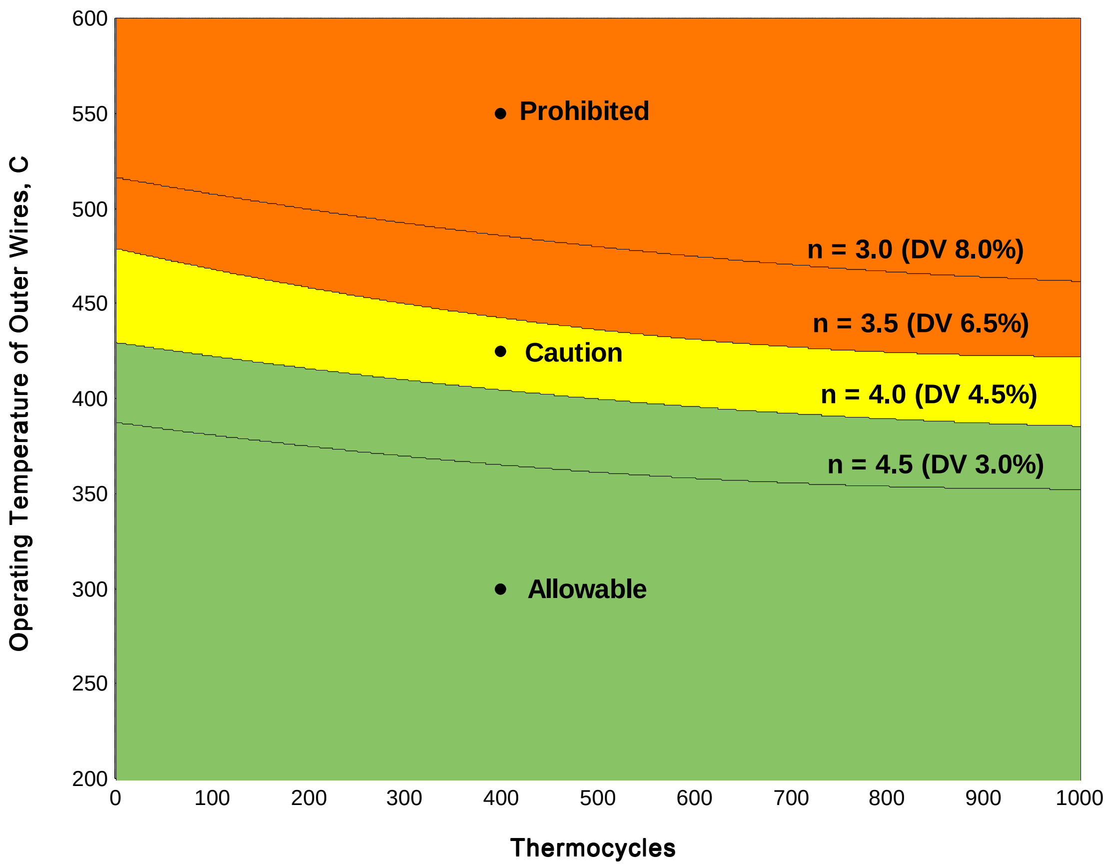

Figure 6: Specific working conditions of wire ropes for ladle cranes at a steel mill.

The upper bound of allowable area ($n = 4.0$, DV 4.5%) relates to beginning of rapid degradation of wires material (see Figure 2). The caution band refers to intensive high carbon wires deterioration. The low bound of prohibited area ($n = 3.5$, DV 6.5%) corresponds to events when the worked ropes have been retired by reason of “over anneal”. The ultimate value of diagnostic variable may be set as $DV_u = 7\%$ with tolerance of 0.5%. Two additional typical curves – one of allowable states and the other of inadmissible states – are presented for comparison with probable DV-values.

Such a diagram may be used to make a tentative diagnosis on rope safety operation if the ladling regime is known. For this purpose one needs to get the continuous information about the temperature T of outer wires. This parameter should be detected exclusively by contact methods because of too large errors when using infrared measure technology. Two conditions must be satisfied to be sure on rope safety duty: thermal parameters (T, N) are within an admissible area and the magnetic diagnostic variable (DV) is less than limit level $DV_u = 7\%$. The rope must be retired if one of these requirements is disturbed. The rope keeps working in caution (T, N)-area but the more frequent magnetic testing is necessary to make sure that condition $DV \leq DV_u$ is satisfied.

The interval criterion was applied to set magnetic testing schedule of ladle crane ropes at one of metallurgical plants in Russian Federation.

To have more diagnostic information the magnetic testing might be as well added by hardness testing of outer wires. Figure 7 represents two instruments that have been employed to determine the mechanical parameters of wires metal on polished microsections and directly on the rope.

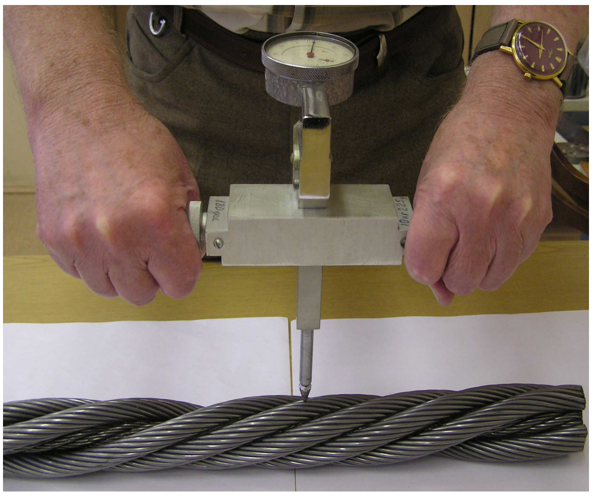

Figure 7: Hardness testing of worked-out ladle crane rope.

The conventional yield strength and limit tensile strength of wires were evaluated from measured Brinell hardness. The results are in good agreement with those obtained by tensile testing [4]. This technique may also be used straight in foundry by pressing the indenter with diameter 0.4 mm under load around 50 N in hanging rope wires.

6 Conclusions

To make the valid decisions on operating endurance of ropes in ladle cranes it is necessary to perform the complex investigations of working conditions and their influence on rope mechanical and physical properties. The presented procedure allows to get a practical guide for maintaining the reliability of steel ropes working in hot environments.

The rope health must be controlled periodically to reveal the dangerous situation coming. Two methods proved to be used: 1) magnetic control that detects an evolution of rope generalised state due to mechanic wear and microstructure change and 2) the hardness testing that permits to estimate the on-line residual tensile strength of outer wires.

The most important is to measure the outer wires temperature and to reveal the temperature slope over rope cross-section that greatly affects on stresses in wires. The rope should not be used if its surface temperature lasts above 400 °C during several ladlings. In this case the described principles of rope safe duty are unsuitable.

Theoretical analysis based on NDT and tensile testing data (especially in hot state of rope or wires) gives a proper account of rope-in-service safety factor thus reducing the operational risk of ladle crane.

Reference

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