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Diagnosis of Metallurgical Ladle Refractory Lining Based on Non-Stationary On-Line Data Processing

Venko Petkov[1], *Mincho Hadjiski*[1, 2], *Kosta Boshnakov*[1], *Emil Mihailov*[1]

[1] *University of Chemical Technology and Metallurgy, 1756 Sofia*
[2] *Institute of Information and Communication Technologies, 1113 Sofia*
Emails: venko@uctm.edu hadjiski@uctm.edu kb@uctm.edu emil@uctm.edu

Abstract: *A new method for diagnosis of the remaining thickness of metallurgical ladle refractory lining working in a batch mode is proposed, where directly measured by a thermovision camera data about the amplitude and phase delay of the maximum surface temperature is used. Regression equations are obtained to determine the remaining thickness of the ladle refractory lining depending on the parameters of steady auto oscillations of the maximum surface temperature. It is shown that the data from nonstationary auto oscillations could be used for adaptation of the regression equations, predicting the remaining thickness of the ladle refractory lining in case of a local damage.*

Keywords*: Infrared Thermography, metallurgical ladle, oscillation, regression, refractory lining.*

1. Introduction

The InfraRed Thermography (IRT) is imposed as one of the main methods of diagnosis based on the assessment of features of the surface temperature field [1, 2, 7, 12]. Because of the high resolution of the method, IRT appears to be an efficient tool for the diagnostic information for low temperature [7, 12] and for high temperature plants [5, 8, 14].

A method for assessing the diagnostic state of the metallurgical ladle refractory lining in a batch mode is proposed in this investigation. In the previous works [8, 13, 14] the same diagnosis task, but for steady-state conditions was solved by approximation of the consecutive states of refractory lining, obtained from a direct heat transfer problem solution [8, 9, 10, 14].

As a basic method in the diagnosis of nonstationary plants the model-based methods [3, 4, 6, 11, 15] have been established. In this area there is a large amount of research and results, including industry-oriented applications [6, 11, 15, 16]. Critical in this approach is the creation of an adequate mathematical model of the plant [6, 15]. In the case considered the use of a mathematical model directly in the procedure of diagnosis could be very difficult. This is due to the high complexity of the model of nonstationary heat transfer under varying boundary conditions, which are described by nonlinear partial differential equations [9]. To solve this type of models the most common approach is to use software based on the finite elements method (FEM). Due to the need of large computational load, which is difficult to guarantee in case of sporadic inspections, the present study proposes the use of a Data-based diagnosis approach. Unlike [11, 15, 16], the input data here are derived from IRI thermograms after image processing of the surface temperature of the ladle. These thermograms are nonstationary, but periodic ones. This allows some established parameters of the periodic fluctuations of the individual points of the surface temperatures to be used for diagnosis purposes. They are considered as diagnostic features and used directly in the diagnosis procedure.

2. Problem statement

In this paper the problem of nonstationarity occurs because the metallurgical ladles work in a batch mode with abrupt changes in the boundary conditions. This causes forced oscillations regimes in the refractory lining. A typical operating time schedule for metallurgical ladle is shown in Fig. 1 [9]. The duration of the individual process stages could be considered without significant deviations in various companies. The practical measurements of the ladle surface temperature [5, 9] show that after the fourth cycle from the start of certain ladle work, the temperature has stable oscillations' parameters.

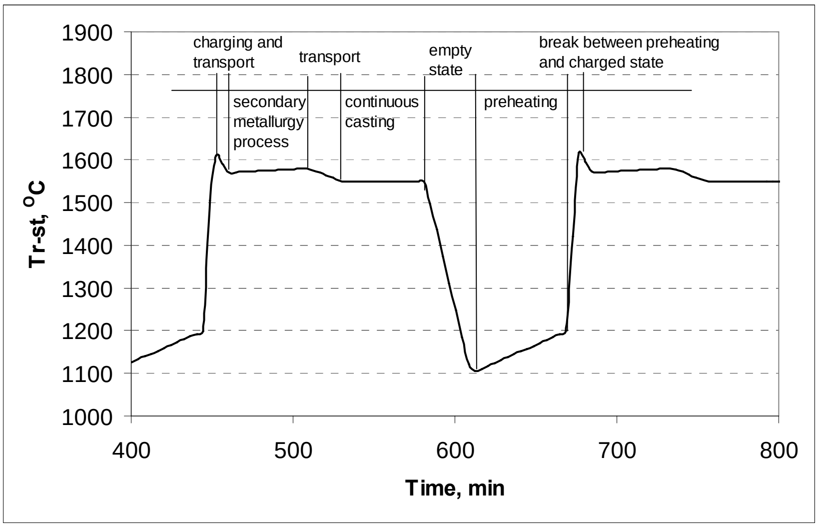


Fig. 1. Temperature variation during the technological cycle

Consider the process of nonstationary heat transfer, which is described by the following mathematical model:

$$\rho . c\frac{\partial T}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda\frac{\partial T}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right), \tag{1}$$

where T is the temperature, °C; λ is the heat conductivity, W/(m.K); c is the specific heat, kJ/(kg.K); ρ is the density, kg/m^3; r is a radius, m; z, r and φ are coordinates; τ is the time, s.

The transient thermal model has been developed using two boundary conditions.

1. For the inner lining wall:

$$T(z,\varphi,\tau)\big|_{r=r_1}=T_{\text{r-st}}(\tau) \tag{2}$$

where $T_{\text{r–st}} = f(\tau)$ is the temperature of the contact area between the inner wall of the refractory lining and liquid steel, °C; r_1 is the radius of the inner lining area, m.

2. For the outer wall to the environment:

$$\lambda(T)\,\text{grad}T(z,\varphi)\big|_{r=r_2}=\alpha_\Sigma\left(T_w-T_{\mathbf{a}}\right), \tag{3}$$

$$\alpha_\Sigma=\alpha_{\text{c}}+\alpha_r \tag{4}$$

where r_2 is the radius of the outer surface, m; T_{a} is the temperature of the environment, °C; α_Σ is the heat transfer coefficient from the outer surface to the environment, W/(m^2.K); α_{c} and αr are the convective and radiant components of the heat transfer coefficient, $\alpha_r = q_r/(T_{\text{w}}-T_{\text{a}})$, q_r is the resultant heat flow from the outer surface to the environment, W/m^2.

The following tasks appear:

1. To develop a method for determining the current thickness of the ladle (z_3) (Fig. 2) based on measuring the surface temperature field in a dynamic mode.

2. To use the data from direct thermovision measurements for fine adjustment of the coefficients in the regression equations, defining the diagnosis features performance z_1, z_2, z_3, obtained in [8, 13, 14].

3. To assess whether it is necessary to make corrections to the results, obtained from the static regression models [8, 13] to evaluate the refractory lining damages in the ladle.

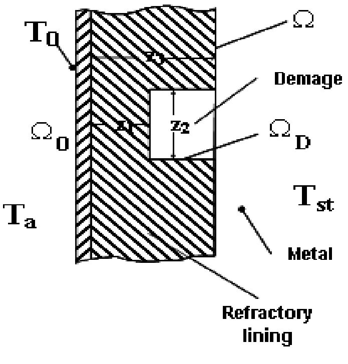
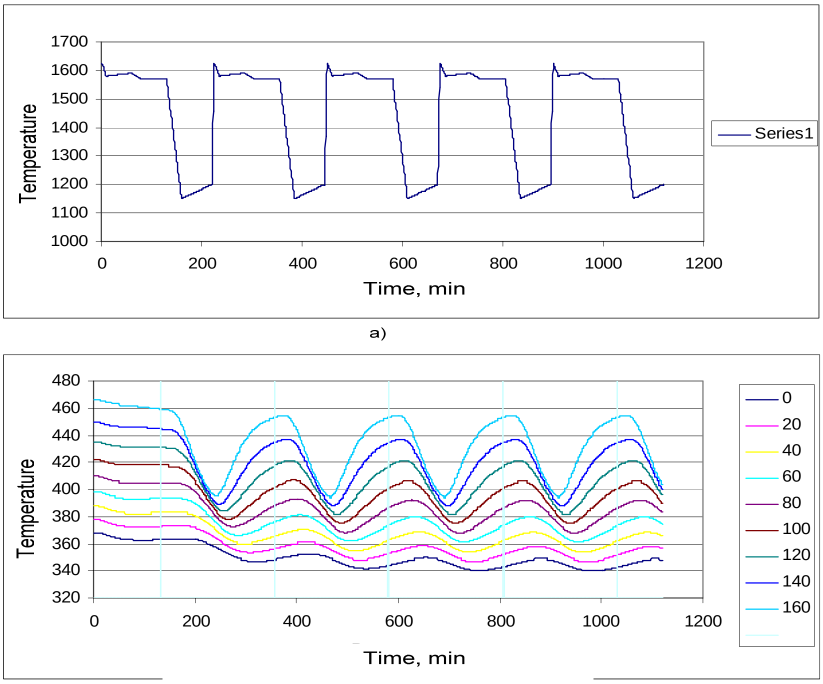


Fig. 2. Scheme of local damage geometry

3. Numerical experiments

Searching parameters of the steady oscillations of the surface temperature of the ladle in solving problem (1)-(4) under the following conditions:

- The boundary conditions are nonstationary, periodic and correspond to a typical steel plant (Fig. 1).
- The oscillations of the surface temperature at various thicknesses of wear (from 0 to 160 mm) are considered.
- All temperature registrations are made after the fourth cycle, when steady state of the oscillations is established.
- The current wear of the lining of the ladle during the cycle (which averaged 3.2 mm per one cycle) is neglected, i.e., the damage is modeled with constant geometry for each of the cases considered.
- The cases of symmetrical axial and radial wear of the wall without any other defects are considered.



a)

b)

Fig. 3. Input disturbances (a) and output surface temperature (b)

Fig. 3 shows the input impacts by the liquid metal (a) and the maximum temperatures of the surface of the ladle (b) with thicknesses of the wear δ: 0, 20, 40, 60, 80, 100, 120, 140 and 160 mm as functions of time. Separately the background surface temperature of the ladle $T_{\text{fon}} = f(\delta)$ is registered, depending on the thickness of the wear.

Processing of the oscillations curves is made in respect of two features for any wear of the refractory lining (Fig. 4):

amplitude difference

$$A(\delta) = \Delta T_{\text{av}}, \tag{5}$$

$$\Delta T_{\mathbf{av}} = \frac{1}{3}\sum_{i=1}^{3}\left(T_{\max i} - T_{\min i}\right); \tag{6}$$

phase difference

$$\varphi(\delta) = \frac{\Delta t}{T}, \tag{7}$$

where Δt and T are averaged from three values of each case by formulae, analogous to (6).

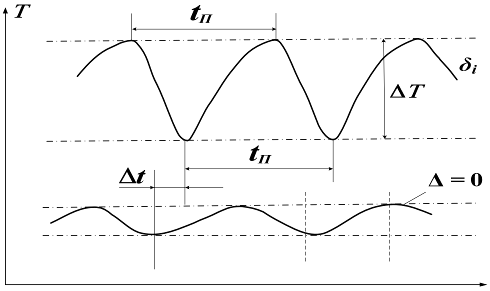
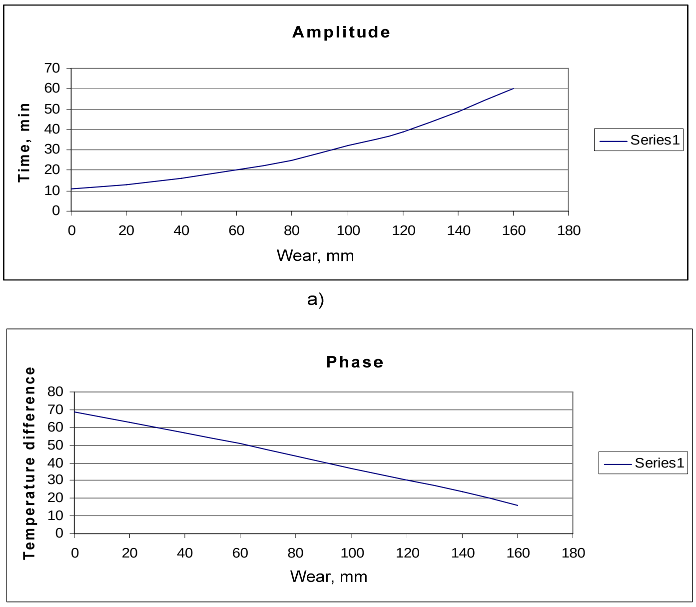


Fig. 4. Amplitude and phase differences

The averaged results of the numerical experiments are shown in Fig. 5, depending on the wear of the refractory lining.



a)

b)

Fig. 5. Wear as a function of the amplitude (a) and phase (b)

4. Determination of the residual refractory lining

The curves of Fig. 5 are approximated by two different regression equations with respect to the degree of wear of the refractory lining:

$$\delta_A = R_A(A) = -62.8 + 6.83A - 0.053A^2, \tag{8}$$

$$\delta_\varphi = R_\varphi(\varphi) = 204 - 2.63\varphi - 0.0046\varphi^2. \tag{9}$$

In the case of numerical experiments, the results (8) and (9) are identical:

$$\delta_A = \delta_\varphi = \delta. \tag{10}$$

However, in the real measurements from the thermogram, the experimentally obtained values of δ_A and δ_φ will be different because of measurement errors and measurement noise. Because of that it is useful the obtained two different values for wear δ_A and δ_φ to be processed by weighted averaging:

$$\delta^E = \gamma\delta_A + (1-\gamma)\delta_\varphi. \tag{11}$$

The weight coefficient γ is determined empirically, but its initial value could be set at a level $\gamma = 0.6 \div 0.7$, because the amplitude differences A_i are measured more precisely than the differences in phases φ_i. Because of this A_i and φ_i, $i = 1, 2, 3$, must be determined in areas with maximal sensitivity.

5. Adaptation of the regression model

According to the results obtained in [8, 13], the total remaining thickness of the refractory lining of the ladle is uniquely determined by the background temperature T_{fon} (Fig. 2) by a regression equation:

$$Z_3^R = \beta_{30} + \beta_{31}T_{\text{fon}} + \beta_{32}T_{\text{fon}}^2 + \beta_{33}T_{\text{fon}}^3, \tag{12}$$

where β_{3i} are coefficients that depend on the thermo-physical characteristics of the heat conducting process: heat exchange coefficient λ, heat transfer coefficient α and emissivity ε. The generalized regression equation (12) can be written in the form:

$$z_3^R = R_3(T_{\text{fon}}, \beta_3), \tag{13}$$

where the regression coefficients $R_3(*)$ are summarized in the vector β_3 and depend on the values of the thermo-physical characteristics λ, ε, α.

The remaining thickness of the refractory lining z_3 (Fig. 2) can be presented by the result obtained in equation (11):

$$z_3^E = z_3^0 - \delta^E \tag{14}$$

Since z_3^E gets independent information about A and φ, the two results obtained for the remaining thickness of the refractory lining z_3^R and z_3^E could be used as a base for adapting the coefficients β_3 of the regressor $R_3(*)$. This is shown in the scheme of Fig. 6. The correction of the coefficients β_3 is performed by an optimization procedure.

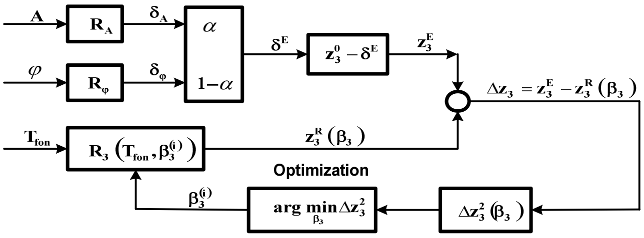


Fig. 6. Iterative correction of the regressor R_3

The overall algorithm for determining the thickness of the remaining lining z_3 with correction of the base regression equations R_i is shown in Fig. 7.

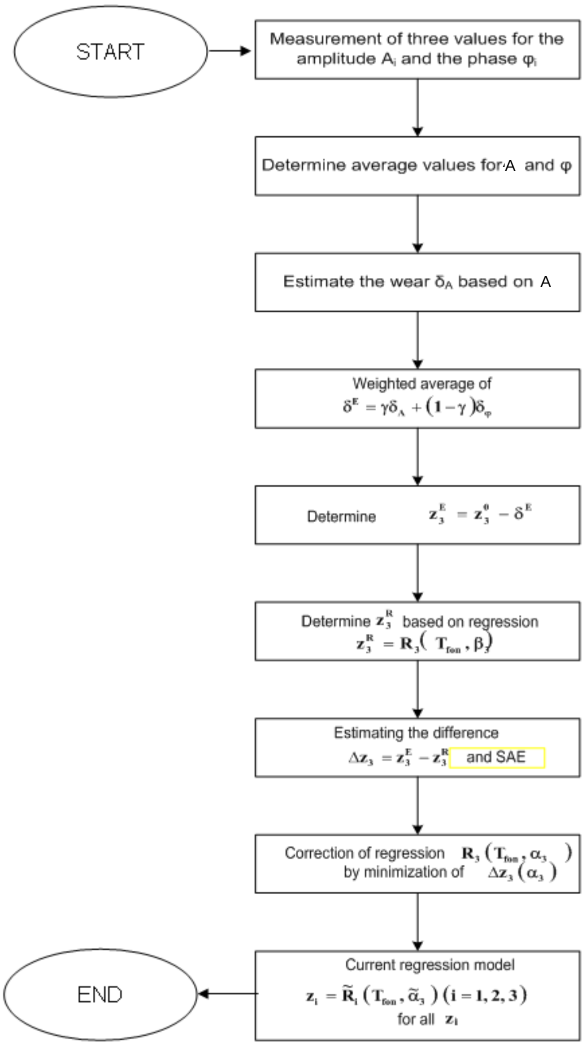


Fig. 7. Generalized scheme of successive diagnosis

6. Admissibility of using static adapted regressions

Additional investigation of the frequency characteristics of refractory lining shown in Fig. 8 indicates that the base frequency of the periodic behaviour $\omega_c = \frac{\pi}{t_c}$ (see Fig. 4) is infra low and the fall of amplitude-frequency characteristic of the ladle refractory lining at this frequency is neglectable.

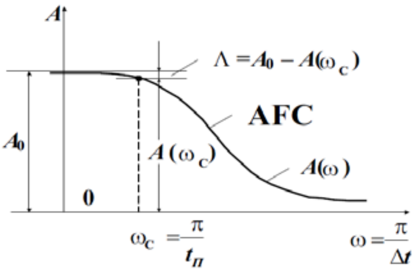


Fig. 8. Frequency characteristics

The result from Fig. 8 gave a reason to state that in case of periodic processes in a metallurgical ladle, in order to determine the extent of the damage of refractory lining, the regression equations obtained for the static models could be used [8, 13].

The numerical experiments for independent determining the degree of wear of the refractory lining, based on data from stationary and nonstationary measurements of the surface temperature of the ladle give different, but converging results. This confirmed the assumptions made and their practical usefulness.

7. Conclusions

The developed method allows reliable estimation of the remaining average thickness of the refractory lining of metallurgical ladle in a dynamic mode to be done.

Using the data about the amplitude and phase differences by two independent sources of information improves the accuracy of the method proposed in case of high level of measurement noises and noncoherency in measurement.

The proposed method for determining the total thickness of refractory lining using independent measurement of the amplitude A and phase φ allows the iterative correction of the underlying regression equations, for improving the accuracy in determining the main diagnosis parameters z_i.

The study shows that in case of a small or medium degree of wear of the ladle refractory lining as first approximation, the static, but adaptive regression equations could be used.

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