Journal of Chemical Technology and Metallurgy, 59, 2, 2024, 431-438

CONDITION BASED ASSESSMENT FOR PREDICTIVE MAINTENANCE OF METALLURGICAL EQUIPMENT

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Received 09 July 2023
Accepted 20 December 2023
DOI: 10.59957/jctm.v59.i2.2024.23

ABSTRACT

The continuous nature of metallurgical technologies and the intensification of production increase the risk of damage to high-temperature equipment during the technological process. The destruction of the structural integrity of the refractory insulation of this equipment leads to the forced interruption of production and significant costs of emergency response and require measures to be taken to reduce the risk of such situations. An opportunity to solve these problems in the metallurgical industry is the introduction into the production process of sustainable systems for making informed decisions and predictive maintenance of equipment, based on continuous or periodic monitoring of the condition of refractory insulation of high-temperature furnaces and auxiliary equipment.

Predictive maintenance of technological equipment and aggregates, based on an assessment of their current condition, extends their life, reduces downtime, maintains the optimal level of production, and guarantees compliance with the exact delivery time of production (raw materials, materials, energy). A procedure is presented for assessing the real condition of steel ladles based on periodic monitoring results as part of a decision-making system for predictive and safe use of their maximum resource.

Keywords: infrared diagnosis, predictive maintenance, condition-based assessment, metallurgical equipment.

INTRODUCTION

In the process of operation, the refractory insulation of high-temperature units is subjected to the influence of thermal shocks from the successive heat changes and the chemical and physical impact of the liquid metal, leading to its wear or destruction. All this, together with the continuous nature of metallurgical technology and the intensification of production, increases the risk of damage and disruption to the structural integrity of aggregates during the process. Destruction of the structural integrity of the refractory insulation in this equipment led to forced production shutdowns and significant emergency response costs and necessitated measures to mitigate the risk of such situations.

An opportunity to solve these problems in the metallurgical industry is the introduction into the production process of sustainable systems for informed decision making and predictive maintenance of equipment based on continuous or periodic monitoring and diagnosis of the refractory insulation's condition in the high temperature furnaces and auxiliary equipment.

Maintenance of technological equipment and aggregates based on the assessment of their current condition combined with appropriate corrective actions ensures trouble-free operation, prolongs their life, reduces downtime, maintains the optimum level of production and accurate delivery of products, raw materials, energy, etc. [1, 2]. This allows efficient maintenance management of the facilities and reduced material costs for routine and major repairs according to the actual condition of the machines and units.

For the implementation of maintenance procedures based on the actual condition of aggregates and predictive maintenance in the practice of leading manufacturers, computer-based information and diagnostic systems are being developed to monitor the process and collect and classify data on the actual levels of process parameters in order to assess the current state of individual aggregates throughout their life cycle [4 - 12].

This paper presents the results of the development of a system for condition-based assessment and predictive maintenance decision making to extend the life cycle and maximize the resource utilization of steel casting ladles.

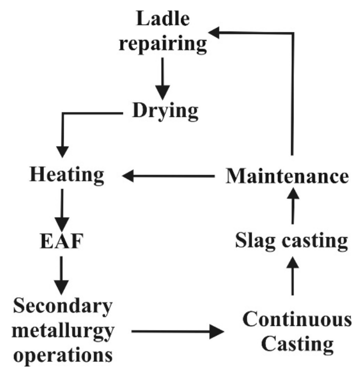

Fig. 1. Scheme of the working cycle of the steel ladle.

EXPERIMENTAL

The realization of the technological process of production of continuously cast steel blocks (Fig. 1) includes the extraction of the steel, its pouring into a steel casting ladle, out-of-oven processing, continuous casting. In carrying out this production, the steel casting ladle is successively and repeatedly passed through the different positions of the technological process, and its refractory insulation is subjected to cyclic thermal loading as a result of the contact with the liquid steel and the planned subsequent maintenance and preparation activities.

The reasons for decommissioning the steel casting ladle and subjecting it to overhaul are the general deterioration of the refractory insulation and the presence of local failures, the successful and permanent repair of which is not always possible by carrying out hot local repair. Either of these two reasons is sufficient justification to stop the ladle from operation.

Assessing the damage and actual condition of the wall requires developing a methodology for applying procedures to assess and classify the damage and actual condition of the refractory insulation and combining these to make a reasoned decision for operating the steel casting ladle as part of a predictive maintenance system. This requires the application of a complex approach, including the combination of results from (i) investigation of the actual operation of the process units, (ii) visual assessment or laser scanning, (iii) measurement of the surface temperature field, and (iv) those from mathematical modelling of the non-steady-state thermal and temperature state of the wall of the steel casting ladle during the different process cycles and at different stages of its operation under different degrees of wear and local damage.

In our previous publications [13 - 15] have been presented the results of:
- study of technological and operational parameters of continuously cast blocks [13];
- determining the optimal time interval for periodic monitoring [13];
- determination of diagnostic parameters for thermographic monitoring [14];
- derivation of approximating dependencies to determine the failure parameters [14].

A defect with the following geometrical feature designations was adopted for the study:
- Residual thickness of the wall Z_1 in the field of the defect;
- Fault height Z_2;
- Degree of wear of the Z_3 wall in the defect-free area;
- Fault width Z_4.

Schematic presentation of the defect and the adopted signs are visualized on Fig. 2 [13, 14].

For the purpose of the study, the joint width of the inner surface of the wall at the base of the defect was assumed to be constant and of the maximum size allowed in practice, Z_4= constant, and the other three parameters were varied at three levels: minimum (-1), mean (0) and maximum (+1), in which a full factorial experiment was planned and implemented, requiring 27 experiments.

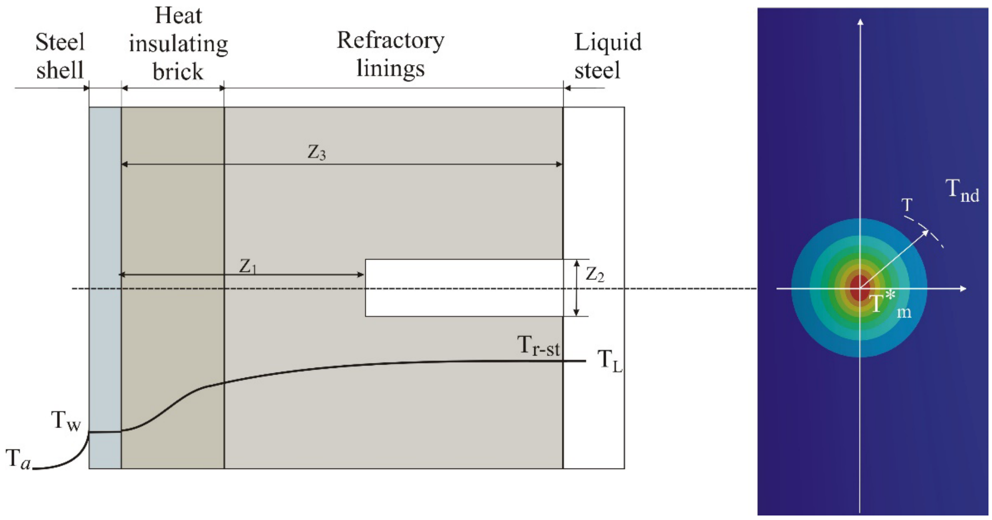

Fig. 2. Schematic presentation of the defect and the adopted signs.

In our previous investigation [13, 14], based on the results of the simulation study, the hot spot parameters have been set (Fig. 3(a), 3(b)), in the defect region, and a temperature contrast analysis was performed representing the difference between the surface temperatures ($T_{p,j}$ - $T_{q,j}$) along the vertical axis in the defect region and those in the defect-free region (Fig. 3(c)). From the derivative of the temperature contrast (Fig. 3(c)) the difference between the projections of the local maximum T'_{max} and the local minimum T'_{min} of the temperature contrast derivative along the vertical axis of the hot spot ($\Delta h_{max} = h_2 - h_1$), the difference $\Delta T'_{max} = T'_{max} - T'_{min}$ of the values of the local maximum and the local minimum, and the ratio $\Delta T'_{max}/\Delta h_{max} = (\Delta T'/\Delta h)_{max}$ between the difference of the values of the local maximum and the local minimum of the temperature contrast derivative and the distance between their projections are reported. These values and relations are assumed to be "temperature contrast derivative parameters". A visualization of the diagnostic features is presented in Fig. 3(c).

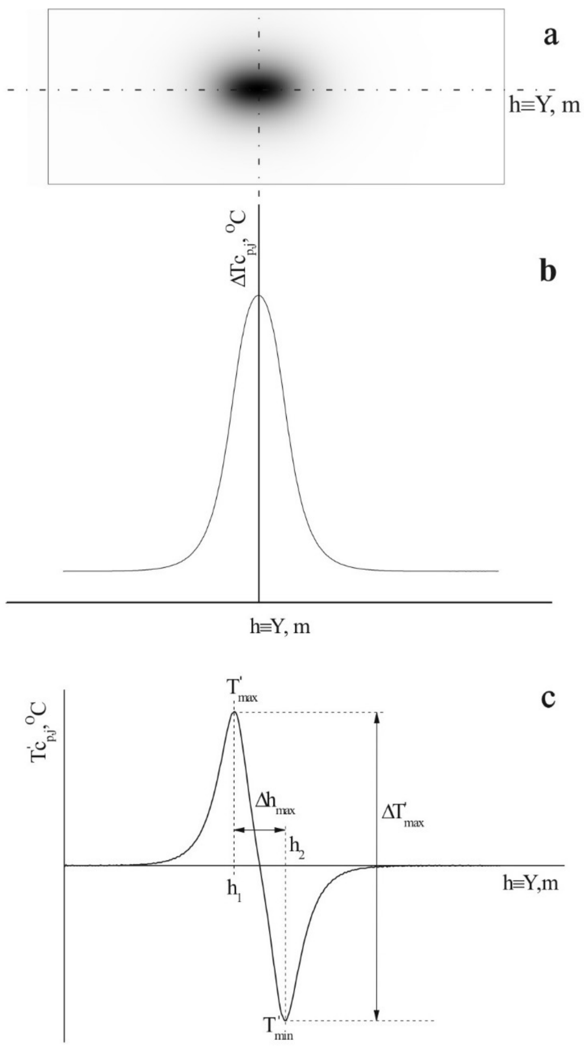

Fig. 3. Temperature change, temperature contrast and diagnostic signs.

RESULTS AND DISCUSSION

As a result of the study, the background temperature T_f (the surface temperature in the defect-free region), the maximum hot spot temperature T_{max}, and the parameters of the temperature contrast derivative ($\Delta h_{max} = h_2 - h_1$, $\Delta T'_{max} = T'_{max} - T'_{min}$, $(\Delta T'/\Delta h)_{max} = \Delta T'_{max}/\Delta h_{max}$) were assumed to be diagnostic features, based on which approximating relationships were derived.

When using the results of thermographic monitoring to estimate the actual condition of the steel casting ladle wall, the derived approximating relationships of [14] can be used:

- The total wear on the Z_3 ladle wall from the measured background temperature in the defect-free region, which can be represented as:
  $Z_3=f(T^*_f)$ (1)
- The height of the defect Z_2 from the total wall wear Z_3, the residual wall thickness infront of the defect Z_1 and the distance Δh^*_{max} between the projections of the local maximum and the local minimum of the derivative of the thermographically determined temperature contrast along the vertical axis of the hot spot which can be represented in summary by:
  $Z_2 = f(\Delta h^*_{max}, Z_1, Z_3)$. (2)
- The residual wall thickness in front of the defect Z_1 of the total wall wear Z_3, the defect height Z_2 and the maximum measured hot spot temperature T^*_{max}, which can be summarized as:
  $Z_1=f(T^*_{max}, Z_2, Z_3)$. (3)
- The residual wall thickness Z_1 in front of the defect from the total wall wear Z_3, the defect height Z_2 and the difference $\Delta T'_{max} = T'_{max} - T'_{min}$ of the values of the local maximum and local minimum of the thermographically determined temperature contrast by hot spot height, which can be represented as:
  $Z_1=f(\Delta T'^*_{max}, Z_2, Z_3)$ (4)
- The residual wall thickness in front of the defect Z_1 of the total wall wear Z_3, the height of the defect Z_2 and the ratio $(\Delta T'/\Delta h)^*_{max}$ between the difference of the values of the local maximum and local minimum of the derivative of the thermographically determined temperature contrast by hot spot height and the distance between their projections, which can be summarized by:
  $Z_1=f((\Delta T'_{max}/\Delta h)^*_{max}, Z_2, Z_3)$ (5)

Also, approximating relationships between the maximum value of the hot spot at the values for the selected study levels of the residual wall thickness in front of the defect Z_1 and the values of the damage height Z_2 and the total wall wear Z_3 in the undamaged section of the species are derived:

$T_{max}(Z_1) = f(Z_2, Z_3)$. (6)

After the steel casting ladle has passed through the process stages and the continuous casting of steel has been completed, the empty ladle enters the section for maintenance work including replacement of worn refractory fittings, visual inspection of the condition of the internal surface of the thermal insulation, the external surface of the steelwork and the wall as a whole. In this period, the height of the Z_2 defect can be determined as a result of visual assessment or laser scanning of the inner surface.

This allows the application of a complex assessment approach, involving the combination of results from visual assessment, thermographic measurement of the surface temperature field and those from mathematical modelling of the non-steady-state thermal and temperature state of the steel casting bucket wall during individual duty cycles and at different stages of its service life under varying degrees of wear and local damage.

To implement this comprehensive approach, the following procedures were developed to assess the failure maintain and plan the thermographic monitoring to maximize the utilization of the available resource and make a reasoned decision to remove the steel casting ladle for repair:

- Procedure for assessing overall wall wear

Using relation (1) to determine the average insulation thickness Z_3 based on the measured external surface temperature in the defect-free region T^*_f, an estimate of the total wall wear can be made. During the first half of the operational campaign, thermographic monitoring can be the result of regular measurements. During the inspection and maintenance period of the steel casting ladle, if local damage is identified, monitoring should be scheduled to assess the size of the defect and the severity of the damage. Depending on the results of the local damage assessment, thermographic measurements may be continued as routine or the period between diagnostic procedures may be reduced. In parallel, if feasible, a hot repair application of the local fault is scheduled. Since $Z_1 \leq Z_3$, equality is only possible in the absence of local insulation damage. In the procedures and failure classification, an additional level is introduced when the wear is within 5 mm of the maximum allowable value ($e \leq 0.005$ m) and the assessment should be carried out before each subsequent duty cycle in order to safely use the maximum service life of the steel casting ladle. As wear enters the zone ($-1+e < Z_3 < 0$), diagnostic procedures are performed at smaller time intervals depending on the specific results in order to assess the failure and predict the remaining life of the facility. Irrespective of the number of operating cycles, when residual thickness in the range $-1 < Z_3 \leq -1+e$ is detected, monitoring should be carried out at each subsequent operating cycle in order to assess the actual condition and make a decision to stop the ladle from operation when critical values of residual wall thickness $Z_3 \leq -1$ are reached. Reaching the critical value is grounds for decommissioning regardless of the presence of a local defect and the assessment of its severity (at values of $Z_1 > 0$), because based on the value of Z_3 the failure is categorized as serious.

- Procedure for local failure assessment

After the value of Z_3 has been determined by equation (1) and the value of the defect height Z_2 has been determined by visual inspection, the value of the insulation thickness in front of the defect Z_1 can be determined by equations of the type (3) using the maximum temperature T^*_{max} of the hot spot measured by thermographic monitoring. The combination of equations of the form (2), (4) and (2), (5) represent two systems of two equations with two unknowns in which the value of Z_3 is uniquely determined by equation (1) and they can be used to determine the values of Z_1 and Z_2 based on the temperature contrast parameters along the vertical axis of the hot spot calculated from the surface temperature field measured with the thermographic camera. The determined values of Z_2 can also be used to determine the value of Z_1 by equation (3). In this case, a complex estimation of the wall wear in front of the defect Z_1 is applied using the approximating dependencies of type (4) and (5). Different degrees of Z_1 damage severity are considered in the evaluation, depending on which the corresponding measurement frequency is also applied for IR diagnostic evaluation purposes. In parallel, if feasible, a hot repair application of the local fault is scheduled. When the value is outside the zone of attention and the fault is categorized as permissible ($0 < Z_1 \leq +1$), regular measurements are carried out and the monitoring interval is determined depending on the specific value of Z_3. On entering the zone of attention ($-1 < Z_1 \leq 0$), when the failure is categorized as moderate and as the critical value is approached ($Z_1 = -1$), and/or the residual thickness and total wear $-1+e < Z_3$ the diagnostic measurements are carried out at shorter intervals and when the wear is close to the critical ($-1 < Z_1 \leq -1+e$) the measurements are carried out on each subsequent cycle until the ladle is stopped for repair when $Z_1 \leq -1$ is reached. The failure is then categorized as serious (requiring immediate action) and the ladle must be taken out of service. The use of the thermograms from the periodic monitoring in the process of infrared diagnostics allows a detailed determination of the temperature fields in the defect area and the background temperature, which is a prerequisite for the precise measurement of the values at each point in the temperature field, and hence the necessary temperatures to determine the values of the diagnostic parameters, which can be used to determine the size of the defect and assess its severity.

- Procedure for local failure *express* assessment

Equations of the type (6) allow the determination of the theoretical maximum temperature $T_{max}(Z_1)$ that would be obtained in the hot spot at different levels of Z_1 ($Z_1 = -1$; $Z_1 = 0$; $Z_1 = +1$) depending on the values of Z_2 and Z_3. This allows the maximum hot spot temperature T^*_{max} measured with the infrared camera to be compared with the determined theoretical $T_{max}(Z_1)$ and at the corresponding values of Z_2 and Z_3, and a check to be performed using the boundary value method. Using the measured maximum hot spot temperature T^*_{max} and equation (6), it can be determined whether the value of Z_1 is in the range of regular measurements with an expected allowable defect severity or in the interval of caution when the failure is categorized as moderate and is gradually approaching the critical value of size at which to rate it as severe. For values of $T^*_{max} \leq T_{max}(Z_1 = -1)$, it is assumed that the value of $Z_1 \leq -1$ and the failure is categorized as serious. According to the developed approach, thermographic monitoring of the external surface of the steel casting ladle should be implemented before the continuous casting process, with duration of ~60 min. During this period, based on the established maximum hot spot temperature and the results and evaluations of the previous diagnostic procedures, a decision on further operation should be made. When information on the categorization of the fault is available and in monitoring mode of each process cycle, the establishment of the critical value of $T^*_{max} \leq T_{max}(Z_1 = -1)$ is considered a sufficient condition for decommissioning.

Thus, the described procedures in combination with the results of real thermographic measurements allow the determination of:

- the residual wall thickness Z_3 in the defect-free region by the measured surface temperature T^*_f;
- the height of the defect Z_2 when using:
- the results of visual inspections and
- the results of thermal imaging monitoring in determining the distance Δh^*_{max} between the projections of the local maximum and local minimum of the temperature contrast derivative along the hot spot height (vertical axis of the hot spot),
- the value of the insulation thickness in front of the defect Z_1 based on:
- the measured maximum hot spot temperature T^*_{max} and
- the difference $\Delta T'^*_{max}=T'^*_{max}-T'^*_{min}$ of the values of the local maximum and local minimum of the derivative of the thermographically monitored temperature contrast by hot spot height, or the ratio $(\Delta T'/\Delta h)^*_{max}$ of this difference and the distance between their projections;
- the severity of the failure based on the measured maximum hot spot temperature T^*_{max}

Thus, by applying the results of the thermographic measurements together with those of the visual inspection to the derived approximating relationships, the dimensions of the overall wear and the local defect can be determined, based on which an assessment of the severity of the failure can be made and a decision on further service can be taken.

Using the functionalities provided by the thermal imaging camera software, the values of the measured maximum temperature and that along a set line coinciding with the vertical axis of the hot spot and parallel to it in the defect-free area can be automatically read. When setting the actual values of the conditions under which the measurement is performed (ambient temperature, air humidity, distance to the surveyed object, degree of blackness of the surface) required to adjust the infrared camera, the system software determines the exact values of the recorded temperatures, which are available in digital form and in combination with the derived approximating dependencies can be used directly to implement the diagnostic procedures.

This allows to summarize that the described model-based diagnostic approach, including the complex use of the mathematical modeling of the thermal and temperature state of the refractory insulation and statistical processing of the obtained results to derive approximating functions for the failure parameters, in combination with results from thermal imaging surface temperature measurements and those from visual inspection is fully applicable for on-line diagnostics.

Simulation results, operational rules and expert experience allow to defining a system for classifying (presented in Table 1) the failure into some of the following classes:

- **A** - The ladle is serviceable, with a low number of duty cycles, initial wear is present, categorised as safe, no local damage ($Z_1 = Z_3$) and regular measurements are recommended to assess wear due to contact with the liquid steel.
- **B** (admissible) - Wear is present ($0 < Z_3 \leq +1$) as a result of contact with the liquid steel with or without a local defect ($0 < Z_1 \leq +1$) with a low risk of failure and categorising the failure as admissible - it is recommended that operation continues with regular thermographic inspections carried out.
- **C** (moderate) - Wear is present as a result of contact with the liquid steel ($-1+e < Z_3 \leq 0$) with or without a local defect ($-1+e < Z_1 \leq 0$) with an increasing risk of failure and categorising the failure as moderate - operation may continue with more frequent thermographic inspections and application of local repairs to the area of local failure (if present).
- **D** (moderate + risk) - Wear is present as a result of contact with the liquid steel ($-1 < Z_3 \leq -1+e$) with or without a local defect ($-1 < Z_1 \leq -1+e$) with the failure categorised as moderate, but there is a risk of failure (due to approaching the permissible limit by $e \leq 0,005$ m) and measurements should be carried out every subsequent cycle until shutdown at the critical value, accompanied by local repair in the area of the local fault (if present).

E(dangerous) - Wear is present as a result of contact with the liquid steel ($-1 \leq Z_3$) with or without a local defect ($-1 \leq Z_1$) and categorising the failure as serious with an extremely high risk of failure - the ladle should be sent for overhaul.

The failure categorization depending on the value of the residual wall thickness Z_3 and that in front of the defect Z_1 are presented in Table 1.

The procedures described and the evaluation system formulated represent a comprehensive approach to conducting diagnostic procedures based on the combined use of the results of thermographic surface temperature

Table 1. Failure categorization depending on the failure parameter values.

Z_1 / Z_3	$Z_1(\approx+1) = Z_3$	$(0) < Z_1 \leq (+1)$	$(1+\varepsilon) < Z_1 \leq (0)$	$(-1) < Z_1 \leq (-1+\varepsilon)$	$Z_1 \leq (-1)$
$Z_3(\approx+1) = Z_1$	A	B	C	D	E
$(0) < Z_3 \leq (+1)$	B	B	C	D	E
$(-1+\varepsilon) < Z_3 \leq \div(0)$	C	C	C	D	E
$(-1) < Z_3 \leq (-1+\varepsilon)$	D	D	D	D	E
$Z_3 \leq (-1)$	E	E	E	E	E

measurement, visual assessment and the application of approximating dependencies involving the assessment of the condition of the steel casting ladle insulation, failure classification and decision making for further operation, maintenance or repair.

CONCLUSIONS

Based on simulation results obtained from a full factorial experiment and derived approximating relationships describing the relationship between the failure parameter values and the formulated diagnostic signs, diagnostic procedures based on the combined use of surface temperature measurement results with an IR camera and visual assessment are developed.

Based on the results of the diagnostic procedures, operating rules and expertise, a system has been defined for classifying and assessing the actual state of the damage and making a decision on monitoring, maintenance and further operation of the steel bucket.

The developed rules allow using the results of thermographic monitoring of the surface temperature field, to assess the actual condition of the steel casting ladle and make a reasoned decision on its decommissioning.

The described procedures and the formulated system for classifying and evaluating the actual condition represent a complex approach for evaluation based on the current condition as part of a system for predictive maintenance of steel ladles.

Acknowledgements

This study is funded by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No BG-RRP-2.004-0002, "BiOrgaMCT".

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