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CHAPTER 5

IMPROVING CONDITION MONITORING AND MAINTENANCE FRAMEWORK FOR REFRACTORY LININGS IN INDUCTION MELTING FURNACES THROUGH CONTINUOUS IMPROVEMENT METHODS

ABSTRACT

The service life and reliability of refractory linings in coreless induction crucible furnaces are essential factors influencing the efficiency, safety, and cost-effectiveness of metallurgical melting processes. Premature wear of linings, caused by the combined effects of slag composition, molten metal temperature, crucible geometry, electromagnetic stirring intensity, and cooling conditions, inevitably leads to increased maintenance frequency, unplanned production downtime, and higher operational costs. In the context of the global steel industry's decarbonization strategy and the growing demand for resource-efficient technologies, the issue of extending refractory lining durability in induction melting units gains particular relevance. This study presents an improvement of the lining condition monitoring and maintenance decision-making system through the integration of a continuous improvement methodology and heuristic engineering tools, including TRIZ, morphological analysis, the method of control questions, the method of focal objects, the theory of inventive problem solving, and functional—value analysis. The research incorporates both a review of existing industrial practices and an experimental evaluation of innovative technical solutions. A comparative evaluation of monitoring technologies was carried out, with the criteria including measurement accuracy, implementation complexity, cost, and adaptability to harsh metallurgical environments. This assessment resulted in the selection of laser-based 3D profilometry as the most appropriate solution for high-precision wear assessment and digital surface modelling, providing a reliable basis for predictive maintenance planning. The proposed approach combines technical and organizational measures, including optimization of slag formation processes, adjustment of crucible geometry to reduce thermomechanical stresses, improvement of cooling regimes, and systematic wear tracking supported by digital data analysis. An industrial case study involving EGES-type furnaces at Zaporizhzhia Foundry and Mechanical Plant confirmed the applicability and efficiency of the developed framework under real production conditions, ensuring timely maintenance planning, reducing the risk of emergency lining failure, lowering specific energy consumption, and supporting stable quality of the produced steel. The findings demonstrate the potential of combining continuous improvement principles with modern monitoring technologies to create an integrated refractory lining management strategy that enhances durability, minimizes environmental footprint, and strengthens the competitiveness of electrometallurgical production.

KEYWORDS

Induction crucible melting, refractory wear mechanisms, furnace lining durability, 3D laser scanning systems, automated condition monitoring, continuous improvement methodology, digital profiling technologies, TRIZ methodology, morphological analysis, method of control questions, method of focal objects, theory of inventive problem solving, functional-value analysis, slag formation optimization, crucible geometry adjustment, cooling regime improvement.

One of the approaches to reducing greenhouse gas emissions in the fight against climate change, within the framework of the steel production decarbonization strategy, is the transition to electrometallurgical steelmaking technologies, including the production of steel in induction furnaces [1]. Induction heating as a physical principle is universal for a wide range of metallurgical operations – from melting in crucible furnaces [2, 3] to pre-deformation (pre-forming) billet/blank heating and heat treatment of finished products [2, 4]. The principles of current induction are identical: the electromagnetic field of the inductor induces eddy currents in the conductive material, which, due to the Joule effect, heat its volume, and, under certain conditions, also ensure significant electrodynamic stirring of the molten metal [3]. Such intensive circulation is beneficial for achieving chemical homogeneity, but at the same time imposes additional thermomechanical stresses on the refractory lining.

Given the global decarbonization agenda, increasing the operational efficiency and durability of key components in induction furnaces becomes a critical factor for ensuring the competitiveness and sustainability of metallurgical enterprises. Improving refractory lining management directly contributes to both energy efficiency and production reliability.

One of the main limitations hindering the potential full-scale transition to steelmaking in induction furnaces is the relatively low durability of the refractory lining. At the same time, induction steelmaking units are characterized by high productivity and, as demonstrated in practice, are successfully used for the production of relatively small volumes (from 5 kg to 60 tonnes) of high-quality steels in both industrial (foundry shops) and laboratory conditions. The technical literature reports the use of induction furnaces for melting high-alloy heat-resistant steels [5], structural and low-carbon steels [6], non-ferrous metals [7] and special-purpose alloys [8, 9], as well as widespread examples of combined technologies in which, following melting, processes of severe plastic deformation are implemented to improve the mechanical properties of the final products [10, 11]. Induction melting provides intensive stirring of the melt flows and active slag formation, contributing to metal purification. The effect of reducing segregation and modifying non-metallic inclusions can be further enhanced through the use of special additions based on rare-earth metals [12].

A distinctive feature of the operation of an induction crucible furnace is its similarity to a transformer, where the inductor serves as the primary winding and the metal in the crucible – located at the center of the inductor and powered by a high-frequency alternating current generator – acts as the secondary winding. Due to this design, the molten metal, heated by eddy currents, is subjected to radial forces directed towards the center of the molten bath [13]. These forces cause a circulating motion in the vertical plane, which, on the one hand, facilitates the attainment of chemical homogeneity and the flotation of non-metallic inclusions [14, 15], but, on the other hand, increases the intensity of contact between the molten metal and the refractory lining [13, 16, 17], leading to its accelerated wear.

Active circulation of molten metal positively affects the uniformity of the chemical composition of the produced metals, but has an adverse effect on such a parameter as the durability of the refractory lining in induction furnaces. The lining is located between the molten metal and the inductor (**Fig. 5.1**), and it is evident that the thicker the furnace lining (or its thickening due to build-up deposits), the smaller the magnetic flux penetrating the metal, and consequently the lower the efficiency of electrical energy utilization during melting. Therefore, the lining thickness is subject to certain limitations [18]. The general design of an induction melting furnace is shown in **Fig. 5.1.**

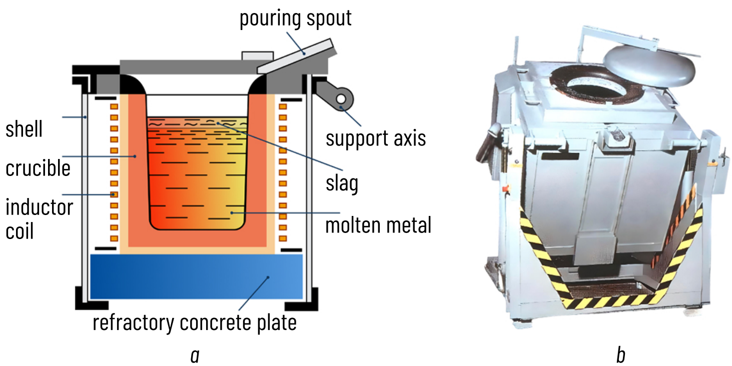

Fig. 5.1 View of a typical coreless induction crucible furnace (modified by the author based on an open-source illustration from KEMA educational resource): *a* – schematic; *b* – general
Source: [17]

The crucible of an induction furnace (**Fig. 5.1**) is manufactured or repaired by ramming or laying with refractory material (bricks). The crucible is positioned directly inside the inductor, which is a water-cooled coil made of copper tubing with a defined number of turns. A rammed crucible made of refractory powder material is fixed in the furnace shell and placed on a base plate made of refractory concrete [17, 18]. The discharge of molten metal is performed through a spout by tilting the furnace together with the shell relative to the support axis. Due to the physical characteristics of heat generation directly within the metal, the maximum melting temperature is mainly limited by the durability of the crucible itself. To increase thermal resistance and reduce thermal stress, water-cooling systems and refractory lining temperature monitoring devices [17, 18] are employed, which may integrate measurement sensors [19] and computer modelling of temperature fields using numerical methods [11, 14]. Such solutions not only extend the crucible's service life but also ensure the stability of the melting process [20]. The crucible is made of refractory materials, which may include ceramics, graphite, or chamotte-graphite [17, 18].

The melting temperatures of steel grades produced in induction furnaces determine the use of three types of crucible linings:

a) acidic;

b) basic;

c) neutral.

Acidic linings (a) are made from refractories based on silicon oxide (90–98% SiO_2), boric acid (1–1.5%), and small amounts of metallic oxides such as Al_2O_3, Fe_2O_3, MnO, and others. The service life of acidic crucibles is typically 80–100 heats. Basic linings (b) are mainly produced from magnesite (up to 85% MgO), water glass, and additives of oxides such as CaO, SiO_2, and others. The durability of such crucibles decreases with increasing furnace capacity and ranges from 20 to 50 heats. Neutral linings (c) are based on Al_2O_3 with magnesite additives. The durability of neutral linings is generally higher than that of the previous two types [17, 18].

Research shows that the behavior of the refractory lining is determined both by the composition of the refractory material and by the nature of its interaction with the molten metal and non-metallic inclusions [12, 21, 22]. Modelling the processes of interaction between the lining, slag, and metal [11, 14, 17] allows for predicting its wear rate and scheduling maintenance in a timely manner.

In the conditions of the intense electromagnetic field of an induction furnace, safety aspects must be taken into account – including personnel electrical safety, the effects of electromagnetic radiation, and the safe operation of power systems [20, 23]. Addressing these issues involves the implementation of risk control and protection systems based on the principles of industrial safety and occupational health standards.

Sources [24, 25] also highlight, among the advantages of induction crucible furnaces, their broad potential for automation using controllers, as well as the high environmental performance of these units, while citing the low durability of the refractory lining as a disadvantage. According to the author of [26], an important part of maintenance, ensuring equipment efficiency and reliability, and maintaining process safety during melting, is the automated monitoring of lining wear. At the same time, the low durability of the refractory lining once again appears among the main drawbacks, which is why current research focuses on developing methods to improve it, including the application of heuristic approaches, functional value analysis (FVA), and TRIZ tools to optimize the monitoring and maintenance of melting units [27, 28].

Based on the above, the analysis of industrial experience in improving refractory lining durability and the development of recommendations for enhancing the efficiency of lining wear monitoring in induction crucible melting furnaces is a relevant scientific and practical task. The aim of the study is to substantiate and implement a methodological approach to the synthesis and improvement of a condition monitoring and maintenance system for refractory linings in induction melting furnaces, based on continuous improvement methods, in order to enhance the reliability, durability, and operational stability of the induction melting process.

5.1 TECHNICAL BACKGROUND AND METHODS FOR IMPROVING LINING DURABILITY

Induction steelmaking furnaces are widely used in the metallurgical industry, in glass production, and in waste processing. Considering the prospects and the objective necessity for the development of electrometallurgical technologies, the scope and volume of their application are expected to increase. For example, at *Zaporizhzhia Foundry and Mechanical Plant LLC*, an induction steelmaking furnace manufactured by EGES (Turkey) with a capacity of 3.0 tonnes has been installed. **Fig. 5.2** shows the furnace in operation, and **Fig. 5.3** – during tapping. The technical specification s of the furnace equipment are presented in **Table 5.1**.

a *b* *c*

Fig. 5.2 Melting in a 3-tonne induction furnace produced by EGES (Turkey): *a* – overall appearance of the unit; *b* – the crucible is enclosed to minimize heat loss and limit the escape of metal vapors into the work area; *c* – the interior of the furnace visible after tapping

a *b* *c*

Fig. 5.3 Steel casting using a 3-tonne induction melting furnace from EGES (Turkey): *a* – pouring molten metal from the furnace into a ladle; *b* – skimming slag from the surface of the melt; *c* – filling molds during the casting stage

Among the main causes of crucible failure in an induction steelmaking furnace, the following should be highlighted:

– thermal stress: during the steel melting process in the crucible, significant heating and cooling occur. These heating and cooling cycles induce thermal stresses in the crucible material, leading to its damage and wear;

– mechanical impacts: during the charging of the charge material and scrap, impacts occur when the material falls onto the refractory lining. The steel melting process is accompanied by mechanical effects, such as the intensive movement of metal in the crucible. This also causes crucible damage and wear;

– corrosion (erosion): certain constituents of steel or additives used during melting may be corrosively active towards the crucible material, resulting in its wear;

– uneven heating: uneven heat distribution within the crucible during melting also generates thermal stresses, which may cause cracking of the refractory lining;

– contact with metal: direct contact with unmelted metal (at the beginning of melting) and with molten metal during the process leads to mechanical wear of the lining through friction.

Fig. 5.4 shows the process of ramming a 3-tonne crucible of an induction furnace under the operating conditions of *Zaporizhzhia Foundry and Mechanical Plant LLC*.

Table 5.1 Specifications of EGES induction furnaces (Turkey) with crucible capacities of 1 tonne and 3 tonnes

Furnace		**Electric converter**		**Melting rate, kg/h**		**Melting time, min**	
Model	Capacity, kg	Power, kW	Frequency, Hz	Cast iron at 1450°C	Steel at 1600°C	Cast iron at 1450°C	Steel at 1600°C
EGP 1000 SE	1000	600	1000	1137	1043	53	58
EGP 3000 SE	3000	1750	500	3305	3062	54	59

a *b* *c* *d* *e*

Fig. 5.4 Relining of a 3-tonne capacity induction furnace (produced by EGES, Turkey): *a* – inductor workspace prepared for lining; *b* – meconite being readied for application to the furnace lining; *c* – lining the furnace bottom; *d* – placing the furnace lining machine inside the unit using a crane; *e* – charging the furnace for the sintering stage

5.2 METHODS FOR IMPROVING THE DURABILITY OF REFRACTORY LININGS

Improving the durability of the crucible requires a comprehensive approach, which includes both the selection of appropriate materials and the proper management of the operating process. The general methods and strategies used to enhance the durability of the refractory lining in industrial and laboratory induction furnaces, identified as a result of the analysis of literature sources and practical experience, are summarized in **Table 5.2**.

Table 5.2 Systematization of methods for improving the durability of refractory linings in induction steelmaking furnaces

No.	Method for improving durability	Essence of the method
1	**2**	**3**
1	Selection of appropriate crucible material	Use of high-quality materials with high thermal resistance and mechanical strength that meet the requirements of the specific process. Application of special materials, such as silicon carbide or zirconium oxide, which may offer improved thermal and chemical resistance [18, 29]
2	Thermal insulation	Ensuring effective thermal insulation of the refractory lining to prevent heat losses, overheating, and wear under high-temperature conditions. Applied to concentrate heat in the required areas. Thermal insulation coatings are used to reduce heat losses and retain heat within the inner region of the crucible. These materials can help maintain stable temperature conditions and reduce energy consumption [20, 26, 30]
3	Cooling systems	Use of cooling systems to control the temperature of the refractory lining and prevent overheating [18, 31, 32]. This includes lining with integrated channels for water cooling, pumping and circulating a coolant (water), introducing a cooling medium (cold gas) directly into the crucible, and employing additional active cooling methods (e.g., using Peltier elements [33])
4	Temperature regime monitoring and automated control	Installation of temperature monitoring systems for continuous tracking of operating parameters and timely detection of anomalies to avoid sudden temperature changes that may cause thermal shock to the crucible. This includes maintaining a stable temperature regime and ensuring gradual heating and cooling. The method involves installing thermocouples and sensors for continuous crucible temperature monitoring and prompt response to any changes, as well as using automatic temperature control systems capable of adjusting the supply of cooling liquid or gas as required [19, 25, 26, 34]
5	Optimisation of melting processes and crucible design	Analysis and optimization of technological processes to reduce excessive hydrodynamic friction and thermal impact on the refractory lining. This involves studying the hydrodynamics of melting to identify areas where excessive friction occurs, and using computer modelling to analyze and improve hydrodynamic processes and thermal models in order to determine heat distribution and identify zones with excessive thermal impact. Modifications to the shape and configuration of the lining are introduced to reduce frictional resistance. Ensuring proper crucible design takes into account parameters such as wall thickness, shape, and dimensions. The risk of thermal shock is minimized by selecting optimal design parameters [35]

Continuation of Table 5.2

1	2	3
6	Expert assessment, monitoring of wear and deformations	Engagement of specialized experts for systematic assessment of the refractory lining condition and identification of any signs or risks of wear. This includes conducting visual inspections to detect any traces of wear or deformation, as well as using non-destructive testing methods (e.g., ultrasonic inspection) to identify internal defects [13, 18, 26, 36]
7	Regular maintenance and repair	Regular maintenance of the refractory lining to ensure timely detection of wear signs or defects and to maintain its durability. This includes scheduled repairs, refurbishment, or replacement of the crucible [26, 37]
8	Application of protective coatings	Application of protective coatings to reduce the effects of chemical reactions and wear on the crucible surface [30, 38, 39]. Graphite coatings are used to protect the crucible from erosion and oxidation at high temperatures, as graphite is chemically stable and withstands high temperatures, making it an effective material for crucible protection. Ceramic coatings are applied to create a thermally and chemically resistant layer that shields the crucible from aggressive environments (some types of ceramic coatings have high thermal shock resistance). Oxide-ceramic materials, such as aluminum oxide or zirconium oxide, are employed to protect the crucible from oxidation and aggressive reactions at elevated temperatures. Some manufacturers offer specialized coatings designed specifically for metallurgical applications and induction melting, which can be optimized for particular operating conditions. Enamel and ceramic coatings with a low coefficient of friction may also be used to reduce frictional resistance and improve crucible performance
9	Electromagnetic field management	Optimization of crucible design and positioning to reduce the impact of the electromagnetic field on its durability [40, 41]. Transition to innovative electromagnetic cold crucible (EMCC) solutions [40], i.e., the use of a segmented, water-cooled copper crucible for induction melting in a vacuum or controlled atmosphere without the use of refractory materials. EMCC technology is being adopted in two types of industrial applications: (a) as batch crucibles for melt preparation, and (b) as bottomless cylindrical molds for continuous casting. The advantages of EMCC include: reduced friction effects in the forming system (minimized contact between the melt and the crucible), which significantly increases crucible durability; absence of contamination and inclusions in the melt; creation of fluid flow conditions that can control grain structure and accelerate online chemical treatment (resulting in high-quality castings); and reduction of cycle time [41]

The selection of the optimal solution is recommended to be carried out after consultation with manufacturers or specialists in metallurgical equipment.

5.3 METHODS FOR MONITORING THE CONDITION OF REFRACTORY LININGS

Regular and comprehensive monitoring of the refractory lining condition allows timely detection of any changes and helps to avoid potential accidents or production issues. Based on practical experience and the analysis of information from the sources listed in **Table 5.2**, the methods for monitoring the condition of refractory linings in induction steelmaking furnaces have been systematized. The results of this systematization are presented in **Table 5.3**. It should be noted that the effectiveness of wear monitoring depends on the systematic nature, accuracy, and timeliness of the measurements and inspections performed.

Table 5.3 Methods for monitoring the condition of refractory linings in induction steelmaking furnaces

No.	Monitoring method	Type of work under the monitoring method
1	Visual inspection	Conducting regular inspections of the refractory lining for the presence of cracks, spalling, or any signs of mechanical damage. Checking for uniform wear of the lining and identifying any possible unevenness that could lead to a loss of durability
2	Measurement of crucible thickness and geometric parameters	Carrying out regular measurements of the refractory lining thickness to detect wear (a reduction in crucible wall thickness may indicate the need for replacement). Monitoring other geometric parameters of the crucible (height, diameter) to detect deviations from standard values. The use of appropriate equipment is required to ensure precise measurements
3	Thermal (thermographic) monitoring	Using thermal imaging cameras to identify potential overheating zones or areas of uneven heat distribution, which may indicate problems in the refractory lining. Measuring the temperature on the lining surface and in the contact zone with molten metal when monitoring thermal parameters
4	Tracking of furnace operating parameters	Tracking operating parameters such as operating time, power, and temperature regime to detect anomalies that may indicate problems with the refractory lining. Sudden temperature changes or overheating can accelerate lining wear
5	Non-destructive testing	Using non-destructive testing methods, such as ultrasonic inspection or radiography, to detect internal defects in the refractory lining. Magnetic testing methods can also be effective for identifying cracks and defects in the lining structure
6	Petrographic analysis of refractory lining material composition	Sampling refractory lining material for subsequent petrographic analysis to identify structural changes in the material and determine the degree of ageing, which affects strength and thermal resistance
7	Testing of refractory lining material properties	Measuring the elastic characteristics of the refractory lining material to assess the degree of ageing and durability. Conducting strength tests on the lining to determine its mechanical properties and strength reserve
8	Vibration monitoring	Installing a vibration monitoring system to detect potential vibrations, impacts, or other anomalies that may affect the condition of the refractory lining
9	Scheduled maintenance	Establishing a regular schedule for planned maintenance, including inspection and monitoring of the refractory lining

5.4 HEURISTIC METHODS APPLICATION

To address the problem of improving the durability of the refractory lining of an induction furnace, heuristic methods [42, 43] were used, including:

a) method of control questions (MCQ);

b) morphological analysis / focal objects method (MO/FOM);

c) algorithm for solving inventive problems (ASIP);

d) functional value analysis (FVA).

Heuristic methods are widely used for solving inventive problems and making design decisions. Their essence lies in a set of logical, methodologically justified techniques aimed at achieving a goal under conditions of limited initial data. The solutions obtained are not definitive and require consideration of the specific context and accumulated experience.

5.4.1 METHOD OF CONTROL QUESTIONS (MCQ)

The method of control questions is used to stimulate and verify the understanding of information. The essence of the MCQ lies in creating or using a prepared list of questions that allow the problem to be examined from different perspectives, stimulate critical thinking, systematize the search process, and identify possible solutions to the problem. To ensure a comprehensive exploration of the problem, the questions should be structured to reflect the key aspects of the topic, considered step by step, varied in form and complexity, promote active application of knowledge and creativity, provide feedback to correct misunderstandings, and encourage discussion during collective review (for example, when applied in brainstorming techniques).

At various times, different authors have developed different sets of questions used to stimulate creative thinking within the MCQ framework. These include question lists by authors such as A. Osborn, T. Eiloart, D. Pearson, G. Polya, R. Busch, and others. Below, selected questions (five sample questions) from the lists of A. Osborn and T. Eiloart are presented, with responses based on industrial experience.

Consideration of the problem using A. Osborn's checklist of questions.

"What in the technical object can be changed? What and to what extent can be replaced: using another ingredient, material, process, energy source, arrangement, colour, sound, lighting?"

Answer: As indicated in the literature review, the durability of the refractory lining depends on the lining material. Thus, an increase in durability can be achieved by ensuring the correct selection of refractory material according to the steel grades being produced.

"What in the technical object can be reduced or replaced? Can anything be compressed, condensed, miniaturized, shortened, narrowed, separated, broken down?"

Answer: The thermal resistance of the lining can be increased by performing hot repairs on specific areas of the lining as it wears, namely hot patching in zones of intensive wear — usually in the scrap charging area and near the spout. In such repairs, the hot patch in the form of a briquette is placed on the problem area, where it melts under high temperatures and fills the repaired section. When performed correctly, hot patching can achieve a service life of up to 100 heats.

"What can be transformed in the technical object? Which components can be replaced? Can the model, layout, arrangement, sequence of operations be changed? Can cause and effect be swapped, or can speed, pace, or mode be altered?"

Answer: Instead of briquettes for hot patching, the semi-dry gunning repair method can be used. This method can be applied to repair any zone, and the operation takes less time than hot patching. However, the lining restored by gunning has a lower durability — up to 40 heats — but allows for more selective repairs.

"Is it possible to solve the inventive problem through adaptation, simplification, reduction? What does the technical object resemble? Does the analogy suggest a new idea? Are there similar problematic situations from the past that can be applied? What can be copied? Which technical object needs to be outperformed?"

Answer: A relatively new and advanced method for increasing furnace lining lifetime is the use of laser systems [44–46] (e.g., ZoloSCAN system [47]) to monitor the residual lining thickness. This allows early determination of the need for local repairs and the required amount of repair material, thereby optimizing repair time.

"What modifications to the technical object are possible? Would modification through rotation, bending, twisting, or turning be acceptable? What changes in function, movement, colour, odour, shape, or outline can be applied? Are other changes possible?"

Answer: By controlling slag quality and its chemical composition, the service life of lining materials can be extended. The highest intensity of lining failure is observed during the slag formation period when the basicity CaO/SiO_2 = 1.0–1.5 and oxidation level is high (up to 30% FeO). This indicates the need, in the initial stage of melting, to form a slag with the maximum MgO concentration for the given temperature conditions, as close as possible to saturation.

Consideration of the problem using T. Eiloart's checklist of questions.

"Define the ideal solution, develop possible ones."

Answer: One practical method that can be considered "ideal" for industrial conditions is to increase the durability of the refractory lining through the use of refractories with a longer service life and lower cost. For example, chamotte brick has the highest durability. Although its maximum refractoriness is not as high as that of basic brick (1690–1730°C compared to 2000°C), it withstands temperature fluctuations well and is cheaper.

"Try different types of materials and types of energy."

Answer: From the standpoint of the energy used in induction melting, its utilization is sufficiently efficient. Regarding the use of alternative materials, known methods for improving lining durability include steel melting with slags enriched in MgO, when the slag is formed at MgO saturation levels. Slags of such composition are less aggressive towards the furnace refractory lining.

"Mentally get inside the mechanism."

Answer: When examining the kinetics of slag saturation with magnesium oxide, during the interaction of MgO-C refractory material, modelling the process of adding magnesian flux shows a significant slowdown – by 2–2.5 times – in the rate at which magnesium oxide enters the slag. Industrial trials have made it possible to assess the degree of dissolution of basic refractories in slag depending on its magnesium oxide content, revealing a pattern in which the transition of magnesium oxide from the lining into the slag decreases with increasing MgO saturation.

"Modify the problem solution in terms of time (faster or slower), size, viscosity, etc."

Answer: The geometry of the crucible and compliance with dimensional tolerances during lining installation have an additional impact on lining durability. The crucible may undergo pre-assembly at the facility manufacturing the refractory structures, which can also contribute to increasing the number of heats.

"Identify alternative problems and systems that remove a specific link from the chain, thus creating something entirely different and leading to the desired solution."

Answer: It is evident that the refractory lining undergoes the most severe wear (softening and slag build-up) in zones with elevated temperatures. Therefore, one approach aimed at extending lining service life is targeted cooling in these zones.

5.4.2 FOCAL OBJECTS METHOD (FOM)

The focal objects method is intended for improving a selected object – called the focal object (because it is the focus of attention) – by transferring the characteristics of randomly chosen objects onto the focal object [48]. This is a method for generating new ideas, notable for its simplicity and potential for repeated application. With the goal of improving the durability of the refractory lining of an induction furnace, which average service life is around 50 heats, the system for monitoring the residual lining thickness was chosen as the focal object. The selection of random objects and their defined properties is presented in **Fig. 5.5**.

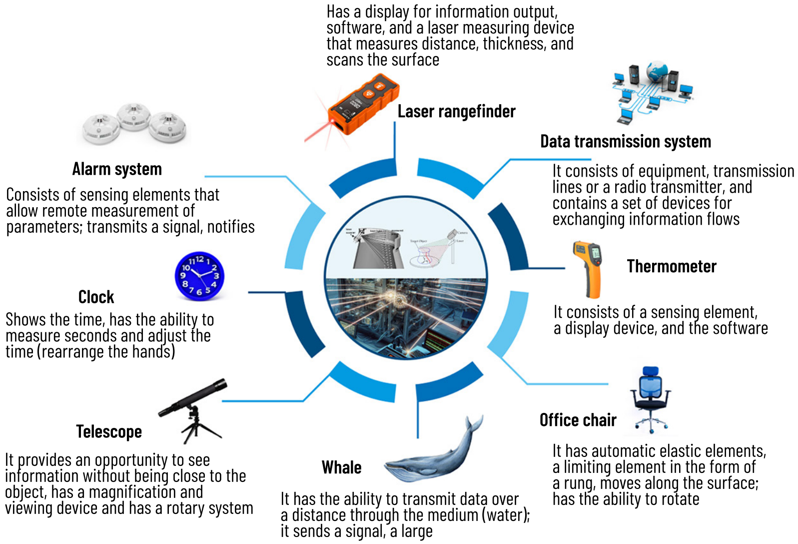

Fig. 5.5 Improvement of the system for monitoring the residual refractory lining thickness using the focal objects method: analysis of the properties of randomly selected objects

By generating ideas through the addition of variable properties from randomly selected objects (**Fig. 5.4**) to the focal object, the feasibility of implementing laser systems was determined.

The experience in developing and successfully applying a laser system for monitoring the condition of an induction furnace crucible is presented in [49]; in [46], a similar laser system was implemented for measuring the wear of a blast furnace lining.

Notable manufacturers of laser systems with the required functions include: DELTA (Sensors and Systems for the Steel Industry), SAVEWAY, Luoyang Songdao Induction Heating Technology Co., Ltd, MTI Corporation, and Acuity, among others.

For practical industrial application, the LR 2000 Delta CCS laser scanning unit was selected for implementation to monitor the residual thickness of the refractory lining. The system is based on the principle of a 3D scanner for constructing the lining profile [49], which enables the determination of residual dimensions. This allows early identification of the need for local repairs, optimization of repair time, and calculation of the required amount of lining materials.

5.4.3 ALGORITHM FOR SOLVING INVENTIVE PROBLEMS (ASIP)

The ASIP is a sequence of systematically executed actions (steps, stages) aimed at solving an inventive problem, which, in the context of this work, is improving the efficiency of monitoring the condition of an induction furnace refractory lining. The application of ASIP is reduced to the rational search for new technical solutions within a given system, achieving effective problem resolution with minimal cost, minimal modification of the original technical system, and economically justified expenses when implementing the developed solution.

The creation of a new technical solution is based on a technical contradiction within the system, which must be resolved during the implementation of ASIP. The essence of ASIP lies in comparing the ideal and actual states of the object, identifying a specific technical contradiction or its root cause – a physical contradiction. The algorithm involves determining the specific parameters that are in conflict, translating them into standardized general parameters, and using G. S. Altshuller's contradiction matrix to search for standard solutions (inventive principles) to eliminate the identified contradiction. This is followed by selecting a rational option and returning from standardized to specific parameters, with a description of the developed solution [42, 43].

Below is the solution to an inventive problem related to the implementation of a modern laser monitoring system (adopted from the results obtained using the focal objects method) for assessing the lining condition. In this context, new promising ideas are proposed, the feasibility of which will depend on the state of development of science and technology. **Fig. 5.6** presents the algorithm applied for solving the inventive problem using G. S. Altshuller's matrix (tables). **Fig. 5.7** contains information on the formulation of the technical contradiction using the "If – Then – But" formula (I, **Fig. 5.6**), with the identification of which specific parameters (II, **Fig. 5.6**) are improved and which are worsened when using a laser system for measuring lining thickness.

The transition from specific to generalized parameters (III, **Fig. 5.6**) listed in G. S. Altshuller's matrix [42, 43] may include the options (with the corresponding matrix number) given in **Table 5.4**: **F** – parameters to be improved (generalized: 27, 28, 33, 36, 38, 39), **G** – parameters to be worsened (generalized: 19, 22).

The contradictions (IV, **Fig. 5.6**) between generalized parameters according to G. S. Altshuller's matrix make it possible to determine the numbers of generalized inventive principles **H** (VI, **Fig. 5.6**), the names of which are provided in the note to **Table 5.4**.

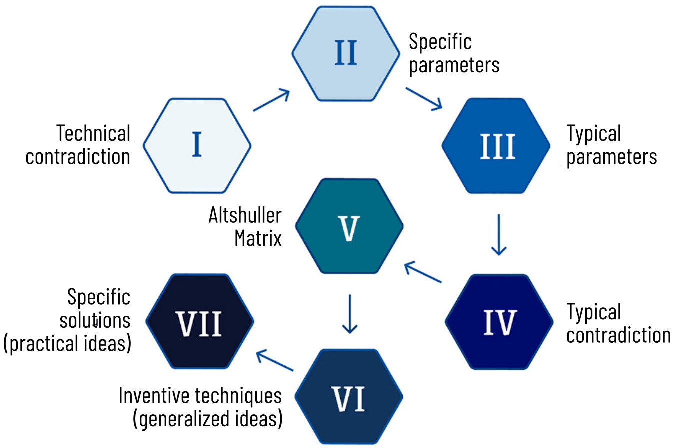

Fig. 5.6 Procedure for solving an inventive problem using G. S. Altshuller's matrix (ASIP)

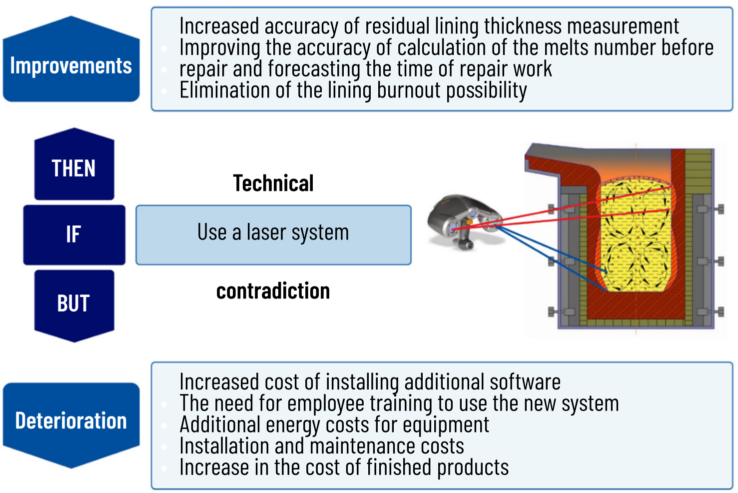

Fig. 5.7 Formulation of the technical contradiction using the "If – Then – But" formula when applying a laser system for measuring the thickness (3D scanning of the condition) of the refractory lining

Table 5.4 Application of ASIP to the use of a laser system for determining the lining thickness of an induction steelmaking furnace

Parameter	**What is improved, F**	**What is worsened, G**	**Typical contradiction (IV, Fig. 5.6), F – G**	**Numbers of generalized inventive principles, H (VI, Fig. 5.6)***	**Frequency of occurrence of the generalized inventive principle, N (times)**	**Numbers of generalized inventive principles, H (VI, Fig. 5.6)***
Specific (II, **Fig. 5.6**)	Accuracy, reliability of prediction	Costs, energy consumption, and expenditure	27–19	11, 19, 21, 27	5	2
Generalized (III, **Fig. 5.6**)	27 – reliability; 28 – measurement accuracy; 33 – ease of operation; 36 – device complexity; 38 – degree of automation; 39 – productivity	19 – energy consumption by a stationary object; 22 – energy losses	27–22	10, 11, 35	4	10, 13, 35
			28–19	3, 6, 32	3	19, 27, 28, 32
			28–22	26, 27, 32	2	3, 11, 29
			33 – 19	1, 13, 24	1	1, 6, 21, 24, 26, 38
			33 – 22	2, 13, 19		
			36 – 19	2, 27, 28, 29		
			36 – 22	2, 10, 13, 35		
			38 – 19	2, 13, 32		
			38 – 22	2, 3, 28		
			39 – 19	10, 19, 35, 38		
			39 – 22	10, 28, 29, 35		

*Note: *names of the generalized inventive principles (H) according to their numbers in G. S. Altshuller's classification. Principles: 1 – "Segmentation"; 2 – "Extraction"; 3 – "Local quality"; 6 – "Universality"; 10 – "Preliminary action"; 11 – "Cushion in advance"; 13 – "The other way round"; 19 – "Periodic action"; 21 – "Skipping"; 24 – "Intermediary"; 26 – "Copying"; 27 – "Cheap short-life instead of expensive long-life"; 28 – "Replacement of a mechanical system"; 29 – "Use of pneumatic and hydraulic structures"; 32 – "Change of colour"; 35 – "Change of physical and chemical parameters of the object"; 38 – "Use of strong oxidizing agents"*
Source: [42, 43]

Each contradiction corresponds to a certain set of generalized inventive principle numbers, and from the full list, those occurring with a frequency of one to five times were selected (**Table 5.4**). It can be assumed that the inventive principles that occur most frequently should be given more attention, as they address a relatively larger number of technical contradictions – the higher the frequency of occurrence of a generalized inventive principle, the greater its relevance.

From the generalized inventive principles, we then proceed to specific solutions (VII, **Fig. 5.6**) in the form of practical and promising ideas, considering each case in the order of decreasing frequency of occurrence (**Table 5.4**). The results of the analysis are presented in **Table 5.5**.

Table 5.5 Numbers and names of inventive principles and proposed solutions

No.	Name of Principle	Solution (Idea) (VII, Fig. 5.4)
1	2	3
		N = 5
2	Extraction	a) establishment of a dedicated service (outsourcing [50]) or training one or several specialists to operate the laser system and maintain several furnaces (possibly not only induction furnaces but also basic oxygen converters, blast furnaces, electric arc furnaces, etc.); b) relocation of the laser system outside the unit (furnace), ensuring mobility of the measuring device
		N = 4
10	Preliminary action	a) focus the sensors and laser scanning on areas of maximum wear and dimensional changes in the refractory lining, as identified from operational experience; b) perform measurements only in areas subject to maximum wear, deformation, and changes; c) take measurements several heats before the known critical number that characterizes the minimum durability of the lining; d) pre-scan the initial shape of the lining (crucible) or its critical shape and periodically compare with the actual condition to determine wear
13	Inversion (reverse, the other way round)	Reorient the sensors and embed them "in the armor" outside the refractory lining, directing the laser (or an acoustic system, ultrasonic testing [51], etc.) not from the outside onto the lining, but rather from beneath the lining outward
35	Parameter changes (changing the physical or chemical parameters)	a) controlling slag build-up on the refractory lining [52] by adding fluxes during the melting process; b) modifying the crucible shape during repairs, taking into account slag build-up ("freezing-on"), in combination with Principle 10 (*Preliminary action*); c) adjusting the relative position of the inductor coil and the crucible to anticipate slag deposits; d) in the case of acidic linings, avoiding the use of fluorspar (CaF_2) and borax ($Na_2B_4O_7$) in the slag to prevent a sharp decrease in lining durability; e) reducing the porosity of the lining and selecting appropriate raw materials, e.g., using high-quality quartzite linings with boron anhydride for alternating melting of cast iron and alloyed (corrosion-resistant, chromium–nickel) steels
		N = 3
19	Periodic action	a) operating the sensors (laser system) not in a continuous mode, but only when measurements are required, for example, before the predicted critical heat corresponding to the minimum durability of the lining; b) effective when applied in combination with Principle 13 (*Reverse – The other way round*); c) alternating melting of cast iron and alloyed steels
27	Cheap short-living instead of expensive long-living	The use of inexpensive laser sensors is hardly feasible. Replacing the laser system with mechanical measurement is unproductive, unsafe, outdated, and contradicts the task requirements

Continuation of Table 5.5

1	2	3
28	Replacement of a mechanical system (with an optical or acoustic one)	In certain cases, it is reasonable to consider replacing a costly laser system with a more affordable ultrasonic system [51] for measuring the lining thickness
32	Change of colour	Changing the color of the laser beam depending on the lining thickness (the color changes together with the thickness). This is possible when using an ionic liquid (molten salts, sodium chloride at 800°C) [53] and controlling the state of the ionic liquid via feedback ("laser – lining thickness – laser")
		N = 2
3	Local quality	Differentiated gunning during repairs
11	Cushion in Advance	Disabling or preventing the start-up of a furnace, which lining thickness is below or above the critical value
29	Use of pneumatics and hydraulics	Application of gas, liquid, and other types of lasers [53, 54]. Liquid lasers enable continuous adjustment of emission wavelengths, i.e., beam color (used in conjunction with Principle 32 – color change)
		N = 1
1	Segmentation	a) perform measurements not in a continuous mode, but at specific time intervals (see also Principle 19 – Periodic Action); b) since the lining thickness changes unevenly, more detailed measurements should be taken in areas of intensive thickness variation (see also Principle 10 – preliminary action)
6	Universality	Use lasers capable of varying their power over a wide range, both for scanning the lining profile as its thickness changes and for performing repair work such as overlaying a protective glaze on worn areas and/or selectively melting slag deposits. In the future, apply laser melting for metal processing ("laser furnaces"), considering current developments in laser sintering and casting [55]
21	Skipping	Following earlier proposals, use a high-power laser for both repair [56] and scanning [57] of the lining condition in a "skip" mode, allowing much shorter measurement times
24	Intermediary	Apply a controllable laser amplifier [58] to enable seamless switching between "scanning-measuring" and "repair-modification" modes
26	Copying	Study lining wear using photocopies and scanned images. Create a holographic model of the crucible for further analysis
38	Use of strong oxidants	Employ laser ionization methods [59]. Although oxidation is harmful to both the metal and the lining (crucible material), future laser technology could ionize the layer between the lining and the molten metal [60], preventing direct contact. Combining this with Principle 6 – Universality, one can envision melting units based on variable-power lasers that can: a) scan the lining condition; b) repair and modify the lining; c) ionize the contact layer; d) melt metal

It should be noted that some of the ideas presented in **Table 5.5** are formulated with consideration for the innovative development of science and technology, demonstrating the prospects of using laser systems for monitoring the thickness of the lining and expanding their technological capabilities.

5.5 FUNCTIONAL VALUE ANALYSIS

Functional Value Analysis (FVA or ABC-Method) is a method for evaluating the efficiency of a technical system in terms of its functionality and cost. In order to optimize the expenses for the technology of repairing worn-out linings of induction crucible furnaces, FVA is expedient to apply for determining the relationship between the functionality of cost components (materials) used for repair and their price. The main stages of FVA for evaluating the effectiveness of materials for repairing the worn lining of an induction crucible furnace are given in **Table 5.6**.

Table 5.6 Main stages of FVA in evaluating the effectiveness of materials for repairing the lining of an induction crucible furnace

No.	FVA stage	Description of the FVA stage
1	Identification of the functions of the repair materials	See **Table 5.7**
2	Evaluation of the importance of functions	Determining the degree of importance of each function for restoring the lining and ensuring the efficient operation of the induction crucible furnace, using the ABC principle. Assessing the impact of each function on furnace productivity and operational safety
3	Cost analysis of functions	Considering the costs of materials, their manufacturing, and installation. Evaluating the efficiency of different materials in terms of service life extension, resistance to aggressive environments, and lining cost
4	Identification of alternatives	Reviewing various types of thermal insulation, structural, and heat-resistant materials that may be used for lining repairs. Comparing their technical characteristics and cost
5	Selection of the optimal option	Selecting the material that ensures the highest efficiency at an affordable cost
6	Optimization and continuous improvement	Implementation of the selected material. Monitoring the material's performance. Adjusting the material specification if necessary

The wear of the crucible lining in an induction furnace is influenced by the severe operating conditions it is subjected to: thermal, erosive, and corrosive impact of the hot molten metal; the chemical corrosion processes caused by slag; the effect of the static pressure of the molten metal column (up to 40–80 kPa [18]); the effect of dynamic friction during molten metal stirring; mechanical impacts during charging of scrap and alloying elements; as well as during the collapse of bridges formed during melting.

The object of improvement considered is a 3t induction crucible furnace operated in the melting department of the foundry shop of *Zaporizhzhia Foundry and Mechanical Plant LLC*.

Thus, FVA makes it possible to select the optimal material for repairing worn lining, ensuring process efficiency and economic feasibility in resource utilization. The furnace lining must typically be replaced on a monthly basis. The following components are required for the repair: refractory mass, refractory concrete, ramming mass, a mold for furnace ramming, and a crucible (which has its own service life and requires replacement after wear).

The functionality of the materials was assessed in terms of their significance for achieving the goal (effect) of extending the intervals between repairs. An expert assessment method was applied to evaluate the functionality of the elements. Following the Eisenhower-Pareto principle, functions (see item 1 in **Tables 5.6** and **5.7**) were categorised by their contribution to achieving the goal, assigned to specific ABC classes, denoted as follows: **A** – main functions, **B** – secondary functions, **C** – unnecessary or redundant functions.

Table 5.7 Distribution of repair material functions for furnace lining (as per item 1 in **Table 5.6**) according to the ABC principle for the target objective of extending the inter-repair period

No.	Components	Functions						
		F1	F2	F3	F4	F5	F6	Total by components
1	Crucible	B	A	A	A	A	B	4A–2B
2	Refractory mass	B	B	–	A	–	B	A–3B
3	Refractory concrete	–	B	B	A	–	C	A–2B–C
4	Ramming mass[1]	A	C	–	C	–	–	A–2C
5	Furnace ramming mould[2]	A	–	–	–	–	–	A

Note: [1]mineralizers and binding agents; [2]welded from sheet material.
F1 – restoration of the lining's dimensions and shape; F2 – recovery of the lining's thermal insulation properties operating across the entire working temperature range (200...1650°C); F3 – provision of mechanical strength to retain the melt and withstand impacts; F4 – ensuring resistance to high-temperature exposure; F5 – protection against erosion, aggressive media, and wear caused by hydrodynamic stirring of the molten metal; F6 – restoration of heat-reflective characteristics
Source: [61]

Thus, the materials are considered according to the expenditure incurred for furnace repair. Owing to fluctuating prices, nondisclosure policies, and the likelihood of trade secrecy affecting the repair cost, **Table 5.8** presents the distribution of repair expenditures as resulting percentage values. The costs for items 2–3 in **Table 5.8** are given per tonne of material. In addition, the materials used for furnace repair were evaluated in terms of their functional significance for achieving maximum lining durability. The evaluation was performed on a tenpoint scale. A survey was conducted among employees of various shop departments, namely: the section foreman, representatives of the procurement department, and repair crews. The average expert scores for significance are provided in **Table 5.8**. Based on the obtained results, a significance coefficient was calculated for the constituent materials used to repair the induction crucible furnace (**Table 5.8**). The data obtained are presented graphically in **Fig. 5.8** as a functional-value diagram.

Table 5.8 Calculation of cost coefficients for constituent materials used to repair an induction crucible furnace

No.	Components	Repair costs		Expert assessment of the significance		Cost ratio
		Share in total costs, STC (%)	Class	Average score (10-point scale)	Significance, SIG (%)	Cost coefficient, CC = STC/SIG
1	Crucible	81	A	7.6	21	3.85
2	Refractory mass	6.2	A	8.3	24	0.25
3	Refractory concrete	3.5	B	7	20	0.17
4	Ramming mass	5	A	7.6	21	0.20
5	Furnace ramming mold	4.3	C	5	14	0.30
Total		100	–	35.5	100	–

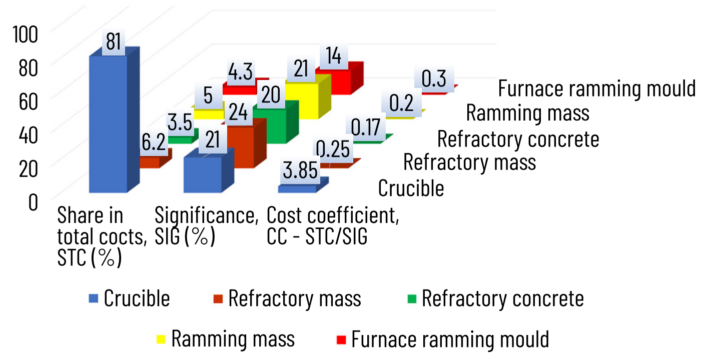

Fig. 5.8 Functional-value diagram for the repair of an induction crucible furnace

For an optimal technical system, the ratio of the specific weight in total costs to the significance of each individual parameter (component) should not exceed 1.0. Based on the obtained results, it was established that the cost coefficient (CC) for crucible replacement is 3.85, which indicates the need to search for alternative crucible suppliers with lower prices. It should be noted that crucible replacement does not take place during every repair. Therefore, in the future, it is advisable to refine the above-mentioned FVA methodology to recalculate costs per tonne of steel produced.

As an organizational optimization measure, recommendations have been developed to ensure compliance with crucible operating rules to extend the intervals between repairs and to carry out maintenance by re-ramming the furnace without crucible replacement. The cost coefficient for other components is considered favorable (<1.0).

CONCLUSIONS

In the context of global decarbonization, this study addresses the improvement of electrometallurgical steelmaking processes, particularly the operation and reliability of induction melting furnaces used for high-quality steel and alloy production. These units combine high productivity with stable process control and lower environmental impact, yet the durability of the refractory lining remains a limiting factor for operational efficiency and reliability.

The improvement of induction furnace performance primarily depends on optimizing the crucible design and refractory lining properties, including resistance to thermal shocks, slag corrosion, and mechanical stresses, as well as maintaining minimal wear during melting. Based on the operational experience of *Zaporizhzhia Foundry and Mechanical Plant LLC*, a methodological framework for systematic condition monitoring and maintenance decision-making of refractory linings was developed and tested. This framework integrates engineering practice with heuristic analysis and continuous improvement principles to identify actionable measures for enhancing lining durability and stability of melting processes.

The application of the method of control questions (MCQ) enabled identification of critical operational and design factors affecting refractory wear. These findings formed the basis for the monitoring logic, linking observed wear symptoms with preventive and corrective actions — selection of optimal refractory materials, implementation of local hot repairs, control of slag quality and chemical composition, and optimization of crucible geometry and cooling zones. Using the focal objects method (FOM), innovative technical concepts were generated, particularly the feasibility of introducing a laser-based system for real-time monitoring of the residual lining thickness. This system, functioning as a diagnostic element of the proposed monitoring framework, allows continuous tracking of the lining profile and thickness, enabling early detection of critical wear areas and precise scheduling of maintenance operations.

The TRIZ/ARIZ methodology contributed to the synthesis of the overall monitoring and maintenance framework by connecting heuristic problem-solving with the structural definition of decision-support stages — data acquisition, condition assessment, and corrective planning — within a continuous improvement loop. In turn, the Functional–Value Analysis (FVA) enabled the evaluation of the cost-efficiency of maintenance and repair operations for a 3-tonne induction crucible furnace, identifying cost drivers and establishing decision criteria for supplier selection, resource allocation, and maintenance optimization.

Organizational improvements were also proposed, focusing on standardized maintenance protocols and adherence to operational parameters to extend crucible service life. These measures facilitate the transition from reactive to predictive maintenance strategies, improving process stability and the overall efficiency of the equipment.

The integration of the developed condition monitoring and maintenance decision-making framework, grounded in continuous improvement principles, enables a systematic increase in process reliability, reduction of unplanned downtime, and improvement of refractory lining durability. The obtained results confirm the effectiveness of combining analytical, heuristic, and managerial methods in advancing electrometallurgical process control systems and serve as a practical foundation for further development of decision support tools for maintenance planning and optimization of refractory management in induction melting furnaces.

REFERENCES

1. Zhang, J., Guo, H., Yang, G., Wang, Y., Chen, W. (2025). Sustainable Transition Pathways for Steel Manufacturing: Low-Carbon Steelmaking Technologies in Enterprises. Sustainability, 17 (12), 5329. https://doi.org/10.3390/su17125329
2. Mariani, A., Malucelli, G. (2023). Insights into Induction Heating Processes for Polymeric Materials: An Overview of the Mechanisms and Current Applications. Energies, 16 (11), 4535. https://doi.org/10.3390/en16114535
3. Hauck, A., Schmitz, W. (2018). The basic properties of the coreless induction furnace and its application in recycling production scrap. World of Metallurgy – ERZMETALL, 71 (6), 309–317.
4. Kukhar, V., Prysiazhnyi, A., Balalayeva, E., Anishchenko, O. (2017). Designing of induction heaters for the edges of pre-rolled wide ultrafine sheets and strips correlated with the chilling end-effect. 2017 International Conference on Modern Electrical and Energy Systems (MEES), 404–407. https://doi.org/10.1109/mees.2017.8248945
5. Ren, W., Wang, L. (2022). Precipitation behavior of M23C6 in high nitrogen austenitic heat-resistant steel. Journal of Alloys and Compounds, 905, 164013. https://doi.org/10.1016/j.jallcom.2022.164013
6. Wang, B., Zhang, Y., Qiu, F., Cai, G., Cui, W., Hu, Z. et al. (2022). Role of trace nanoparticles in manipulating the widmanstatten structure of low carbon steel. Materials Letters, 306, 130853. https://doi.org/10.1016/j.matlet.2021.130853
7. Chelariu, R. G., Cimpoeșu, N., Birnoveanu, T. I., Istrate, B., Baciu, C., Bejinariu, C. (2022). Obtaining and Analysis of a New Aluminium Bronze Material Using Induction Furnace. Archives of Metallurgy and Materials, 67 (4), 1251–1257. https://doi.org/10.24425/amm.2022.141049
8. Li, H., Wang, A., Liu, T., Chen, P., He, A., Li, Q. et al. (2021). Design of Fe-based nanocrystalline alloys with superior magnetization and manufacturability. Materials Today, 42, 49–56. https://doi.org/10.1016/j.mattod.2020.09.030
9. Aikin, M., Shalomeev, V., Kukhar, V., Kostryzhev, A., Kuziev, I., Kulynych, V. et al. (2025). Recent Advances in Biodegradable Magnesium Alloys for Medical Implants: Evolution, Innovations, and Clinical Translation. Crystals, 15 (8), 671. https://doi.org/10.3390/cryst15080671
10. Markov, O. E., Khvashchynskyi, A. S., Musorin, A. V., Markova, M. A., Shapoval, A. A., Hrudkina, N. S. (2022). Investigation of new method of large ingots forging based on upsetting of workpieces with ledges. The International Journal of Advanced Manufacturing Technology, 122 (3-4), 1383–1394. https://doi.org/10.1007/s00170-022-09989-1
11. Kukhar, V., Balalayeva, E., Hurkovska, S., Sahirov, Y., Markov, O., Prysiazhnyi, A., Anishchenko, O. (2019). The Selection of Options for Closed-Die Forging of Complex Parts Using Computer Simulation by the Criteria of Material Savings and Minimum Forging Force. Intelligent Communication, Control and Devices. Singapore: Springer, 325–331. https://doi.org/10.1007/978-981-13-8618-3_35
12. Kalisz, D., Żak, P. L., Semiryagin, S., Gerasin, S. (2021). Evolution of Chemical Composition and Modeling of Growth Nonmetallic Inclusions in Steel Containing Yttrium. Materials, 14 (23), 7113. https://doi.org/10.3390/ma14237113

13. Patil, D. D., Ghatge, D. A. (2017). Parametric Evaluation of Melting Practice on Induction Furnace to Improve Efficiency and System Productivity of CI and SGI Foundry- A Review. International Advanced Research Journal in Science, Engineering and Technology, 4 (1), 159–163. https://doi.org/10.17148/iarjset/ncdmete.2017.36
14. Sinelnikov, V., Szucki, M., Merder, T., Pieprzyca, J., Kalisz, D. (2021). Physical and Numerical Modeling of the Slag Splashing Process. Materials, 14 (9), 2289. https://doi.org/10.3390/ma14092289
15. Dou, W., Yang, Z., Wang, Z., Yue, Q. (2021). Molten Steel Flow, Heat Transfer and Inclusion Distribution in a Single-Strand Continuous Casting Tundish with Induction Heating. Metals, 11 (10), 1536. https://doi.org/10.3390/met11101536
16. Liang, X., Li, M., Cheng, B., Wu, F., Luo, X. (2023). Effects of induction furnace conditions on lining refractory via multi-physics field simulation. Applied Physics A, 129 (8). https://doi.org/10.1007/s00339-023-06808-6
17. Kozlov, H. O., Topolov, V. L., Kozlov, O. H. (2025). Konstruktsiia elektrometalurhiinykh ahrehativ. Nikopol Professional College of the Ukrainian State University of Science and Technology. Available at: https://kema.at.ua/book1.html#fig73
18. Shiqi, L., Weili, L.; Kuangdi, X. (Ed.) (2024). Induction Furnace Melting. The ECPH Encyclopedia of Mining and Metallurgy. Singapore: Springer, 929–931. https://doi.org/10.1007/978-981-99-2086-0_967
19. Khrebtova, O., Shapoval, O., Markov, O., Kukhar, V., Hrudkina, N., Rudych, M. (2022). Control Systems for the Temperature Field During Drawing, Taking into Account the Dynamic Modes of the Technological Installation. 2022 IEEE 4th International Conference on Modern Electrical and Energy System (MEES). IEEE, 1–6. https://doi.org/10.1109/mees58014.2022.10005724
20. Savchenko, I. V., Shapoval, O., Kuziev, I. (2022). Modeling of High Module Power Sources Systems Safety Processes. Materials Science Forum, 1052, 399–404. https://doi.org/10.4028/p-24y9ae
21. Artiukh, V., Mazur, V., Kukhar, V., Vershinin, V., Shulzhenko, N. (2019). Study of polymer adhesion to steel. E3S Web of Conferences, 110, 01048. https://doi.org/10.1051/e3sconf/201911001048
22. Shapoval, A., Kantemyrova, R., Markov, O., Chernysh, A., Vakulenko, R., Savchenko, I. (2020). Technology of Production of Refractory Composites for Plasma Technologies. 2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP). IEEE, 1–4. https://doi.org/10.1109/paep49887.2020.9240830
23. Kruzhilko, O., Volodchenkova, N., Maystrenko, V., Bolibrukh, B., Kalinchyk, V., Zakora, A. et al. (2021). Mathematical modelling of professional risk at Ukrainian metallurgical industry enterprises. Journal of Achievements in Materials and Manufacturing Engineering, 1 (108), 35–41. https://doi.org/10.5604/01.3001.0015.4797
24. Pachkolin, Y., Bondarenko, A., Levchenko, S. (2018). Practical application of mathematical models of electro-thermo-mechanical processes in industrial induction furnaces with the aim of increasing their energy efficiency. Technology Audit and Production Reserves, 5 (1 (43)), 28–33. https://doi.org/10.15587/2312-8372.2018.146484
25. Razzhivin, O., Markov, O., Subotin, O. (2022). Automated Melt Temperature Control System In Induction Furnace. 2022 IEEE 4th International Conference on Modern Electrical and Energy System (MEES). IEEE, 1–4. https://doi.org/10.1109/mees58014.2022.10005650

26. Dötsch, E.; Rudnev, V. T., Totten, G. E. (Eds.) (2014). Operation of Induction Furnaces in Iron Foundries. Induction Heating and Heat Treatment. ASM International, 491–520. https://doi.org/10.31399/asm.hb.v04c.a0005904
27. Achkan, V. V., Vlasenko, K. V., Chumak, O. O., Sitak, I. V., Kovalenko, D. A. (2022). A model of learning the online course "Creative Thinking through Learning Elementary Maths." Journal of Physics: Conference Series, 2288 (1), 012020. https://doi.org/10.1088/1742-6596/2288/1/012020
28. Hsia, T.-C., Huang, S.-C. (2011). Using the Theory of Inventive Problem-Solving (TRIZ) to Implement Safety Improvements in Foundry Engineering Pouring Procedures. 2011 International Conference on Management and Service Science. IEEE, 1–4. https://doi.org/10.1109/icmss.2011.5999352
29. Refractory lining materials for induction furnaces (2024). Refractories Materials. Available at: https://refractoriesmaterials.com/refractory-lining-materials-for-induction-furnaces
30. Park, H.-S., Dang, X.-P. (2013). Reduction of heat losses for the in-line induction heating system by optimization of thermal insulation. International Journal of Precision Engineering and Manufacturing, 14 (6), 903–909. https://doi.org/10.1007/s12541-013-0119-6
31. Umbrasko, A., Baake, E., Nacke, B., Jakovics, A. (2008). Numerical studies of the melting process in the induction furnace with cold crucible. COMPEL – The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, 27 (2), 359–368. https://doi.org/10.1108/03321640810847643
32. Dötsch, E., Nacke, B.; Rudnev, V. T., Totten, G. E. (Eds.) (2014). Components and Design of Induction Crucible Furnaces. Induction Heating and Heat Treatment. ASM International, 447–461. https://doi.org/10.31399/asm.hb.v04c.a0005899
33. Nesarajah, M., Frey, G. (2016). Thermoelectric power generation: Peltier element versus thermoelectric generator. IECON 2016 – 42nd Annual Conference of the IEEE Industrial Electronics Society. IEEE, 4252–4257. https://doi.org/10.1109/iecon.2016.7793029
34. Demin, D. (2020). Constructing the parametric failure function of the temperature control system of induction crucible furnaces. EUREKA: Physics and Engineering, 6, 19–32. https://doi.org/10.21303/2461-4262.2020.001489
35. Przyłucki, R., Golak, S., Oleksiak, B., Blacha, L. (2011). Influence of the geometry of the arrangement inductor – crucible to the velocity of the transport of mass in the liquid metallic phase mixed inductive. Archives of Civil and Mechanical Engineering, 11 (1), 171–179. https://doi.org/10.1016/s1644-9665(12)60181-2
36. Sadri, A., Ying, W. L., Erskine, J., Macrosty, R. (2016). Smelting furnace non-destructive testing (NDT) and monitoring. 19th World Conference on Nondestructive Testing. Munich, 1–12. Available at: https://www.ndt.net/article/wcndt2016/papers/th4e5.pdf
37. Ung, D. (2023). Enhancing crucible performance in non-ferrous applications. Foundry Practice, 272, 13–17. Available at: https://27097971.fs1.hubspotusercontent-eu1.net/hubfs/27097971/FP%20272%20en.pdf
38. Tamura, S., Ochiai, T., Matsui, T., Goto, K. (2008). Technological philosophy and perspective of nanotech refractories. Nippon Steel Technical Report, 98, 18–28. Available at: https://www.nipponsteel.com/en/tech/report/nsc/pdf/n9804.pdf

39. Prstić, A., Aćimović-Pavlović, Z., Terzić, A., Pavlović, L. (2014). Synthesis and Characterization of New Refractory Coatings Based on Talc, Cordierite, Zircon and Mullite Fillers for Lost Foam Casting Process. Archives of Metallurgy and Materials, 59 (1), 89–95. https://doi.org/10.2478/amm-2014-0015
40. Buliński, P., Smolka, J., Golak, S., Przyłucki, R., Palacz, M., Siwiec, G. et al. (2017). Numerical and experimental investigation of heat transfer process in electromagnetically driven flow within a vacuum induction furnace. Applied Thermal Engineering, 124, 1003–1013. https://doi.org/10.1016/j.applthermaleng.2017.06.099
41. Durand, F. (2005). The electromagnetic cold crucible as a tool for melt preparation and continuous casting. International Journal of Cast Metals Research, 18 (2), 93–107. https://doi.org/10.1179/136404605225022883
42. Savransky, S. D. (2000). Engineering of creativity: Introduction to TRIZ methodology of inventive problem solving. CRC Press, 408. https://doi.org/10.1201/9781420038958
43. Altshuller, G. S. (1984). Creativity as an exact science. CRC Press, 320. https://doi.org/10.1201/9781466593442
44. Wu, X., Ma, J., Wang, J., Song, H., Xu, J. (2025). Mobile Tunnel Lining Measurable Image Scanning Assisted by Collimated Lasers. Sensors, 25 (13), 4177. https://doi.org/10.3390/s25134177
45. Tucci, G., Conti, A., Fiorini, L.; Parente, C., Troisi, S., Vettore, A. (Eds.) (2020). Refractory Brick Lining Measurement and Monitoring in a Rotary Kiln with Terrestrial Laser Scanning. R3 in Geomatics: Research, Results and Review. Springer, 296–310. https://doi.org/10.1007/978-3-030-62800-0_23
46. Kuo, S.-K., Lee, W.-C., Du, S.-W. (2008). Measurement of Blast Furnace Refractory Lining Thickness with a 3D Laser Scanning Device and Image Registration Method. ISIJ International, 48 (10), 1354–1358. https://doi.org/10.2355/isijinternational.48.1354
47. Andrade, J., Viale, M., De los Santos, C., Butler, R., Kan, M., Rambo, M., Corbari, R. (2015). EAF application of SmartFurnace and ZoloSCAN laser off gas measurement technology at Vallourec Star (Tech. Rep. No. PPMS001_2018). AMI. Available at: https://www.amiautomation.com/PPMS001_2018
48. Angelova, D. (2021). Experimental application of the method of focal objects in design education. Innovation in Woodworking Industry and Engineering Design, 2 (20), 82–87. Available at: https://www.cabidigitallibrary.org/doi/pdf/10.5555/20220215904
49. Schmitz, W., Donsbach, F., Henrik, H. (2006). Development and use of a new optical sensor system for induction furnace crucible monitoring. Proceedings of the 67th World Foundry Congress: "Casting the Future". Institute of Cast Metals Engineers. Curran Associates, Inc., 653–662. Available at: https://www.iftabira.org/pdfs/15%20W.Schmitz_441168101.pdf
50. Pererva, P., Kuchynskyi, V., Kobielieva, T., Kosenko, A., Maslak, O. (2021). Economic substantiation of outsourcing the information technologies and logistic services in the intellectual and innovative activities of an enterprise. Eastern-European Journal of Enterprise Technologies, 4 (13 (112)), 6–14. https://doi.org/10.15587/1729-4061.2021.239164
51. Sadri, A., Ying, W. L., Erskine, J., Macrosty, R. (2016). Smelting furnace non-destructive testing (NDT) and monitoring. 19th World Conference on Nondestructive Testing. Munich, 1–12. Available at: https://www.ndt.net/article/wcndt2016/papers/th4e5.pdf

52. Prijanovič Tonkovič, M., Lamut, J. (2020). Build-up formation in an induction channel furnace. Materiali in Tehnologije, 54 (2), 167–171. https://doi.org/10.17222/mit.2019.233
53. Zhang, H., Zhang, C., Vaziri, S., Kenarangi, F., Sun, Y. (2021). Microfluidic Ionic Liquid Dye Laser. IEEE Photonics Journal, 13 (1), 1–8. https://doi.org/10.1109/jphot.2020.3044861
54. Biswas, D. J. (2023). Molecular Gas Lasers. A Beginner's Guide to Lasers and Their Applications. Cham: Springer, 261–285. https://doi.org/10.1007/978-3-031-24330-1_11
55. Yang, L., Tang, S., Fan, Z., Jiang, W., Liu, X. (2021). Rapid casting technology based on selective laser sintering. China Foundry, 18 (4), 296–306. https://doi.org/10.1007/s41230-021-1099-2
56. Mudge, R. P., Wald, N. R. (2007). Laser engineered net shaping advances additive manufacturing and repair. Welding Journal, 86 (1), 44–48. Available at: https://www.researchgate.net/publication/285913676_Laser_engineered_net_shaping_advances_additive_manufacturing_and_repair
57. Chang, K.-S., Lu, S.-T., Wu, Y.-P., Chou, C. (1992). Correction algorithms in a laser scanning dimension measurement system. IEE Proceedings A Science, Measurement and Technology, 139 (2), 57–60. https://doi.org/10.1049/ip-a-3.1992.0011
58. Zuo, J., Lin, X. (2022). High-Power Laser Systems. Laser & Photonics Reviews, 16 (5). https://doi.org/10.1002/lpor.202100741
59. Hu, S., Huang, K., Zhu, F., Gai, B., Li, J., Tan, Y., Guo, J. (2023). Temporal evolution of laser-induced ionization and recombination processes in argon-helium mixture. Optics Continuum, 2 (12), 2516. https://doi.org/10.1364/optcon.506849
60. Oukach, S., Pateyron, B., Pawłowski, L. (2019). Physical and chemical phenomena occurring between solid ceramics and liquid metals and alloys at laser and plasma composite coatings formation: A review. Surface Science Reports, 74 (3), 213–241. https://doi.org/10.1016/j.surfrep.2019.06.001
61. Gorokhovskii, A. V., Meshcheryakov, D. V., Burmistrov, I. N., Sevryugin, A. V. (2019). Heat-Reflecting Ceramic Materials Based on Potassium Polytitanate and Silicon Oxide. Refractories and Industrial Ceramics, 59 (6), 663–666. https://doi.org/10.1007/s11148-019-00292-3