

V.V. Kukhar, Doctor of Engineering Sciences, Professor, Vice-Rector for Scientific Research and Development, e-mail: volodymyr.kukhar@mipolytech.education, <https://orcid.org/0000-0002-4863-7233>

K.V. Malii, Candidate of Engineering Sciences (PhD (Engin.)), Head of the Research and Development Department, Associate Professor of the Department of Metallurgy, Materials Science and Production Management, e-mail: kristina.maliy@mipolytech.education, <https://orcid.org/0000-0002-9046-4268>

V.V. Kustikov, Master's Degree Student, e-mail: vladyslav.kustikov@mipolytech.education

“TECHNICAL UNIVERSITY “METINVEST POLYTECHNIC” LLC (Zaporizhzhia, Ukraine)

Methods of Improving the Induction Crucible Melting Furnaces Lining Life and Monitoring its Condition

Introduction. One of the ways to reduce greenhouse gas emissions to combat climate change is to implement electrometallurgical steelmaking processes, including induction furnace melting. However, the short lifespan of the furnace lining is a significant limitation of this method. Induction steelmaking units are efficient for melting small volumes of high-quality steels, but their linings undergo significant wear due to thermal, mechanical, and corrosive impacts.

Methods. The study includes an analysis of scientific and technical literature on induction furnace linings and practical experience from metallurgical enterprises such as “Zaporizhzhia Foundry and Mechanical Plant” LLC. The methodology involves systematizing methods for extending the lifespan of the furnace lining and monitoring its condition. This includes using high-quality materials, cooling systems, automated temperature control systems, and regular maintenance.

Results. The research found that the lifespan of the furnace lining can be extended by optimizing lining materials, using cooling systems, and implementing automated control systems. Practical examples of using induction furnaces in metallurgical enterprises demonstrate the effectiveness of the proposed methods. Specifically, the use of graphite coatings and oxide ceramic materials significantly improves the lining's resistance to high temperatures and chemical wear.

Discussion. The scientific novelty of the work lies in the systematization and classification of methods to extend the lifespan of induction furnace linings. The practical significance of the study is in the potential application of the results to predict lining wear and schedule maintenance work. The proposed methods can be used to improve the reliability and efficiency of induction furnaces in high-quality steel production.

Ключові слова: crucible failure; electrometallurgy; induction furnace; lining wear; methods of lining state control; service life; steel melting.

Introduction. One of the ways to reduce greenhouse gas emissions to combat climate change while implementing the steel industry decarbonisation strategy is to switch to electrometallurgical steelmaking processes, including induction furnace melting [1; 2]. The limitations of induction melting that hinder the transition to induction furnace melting include the short life of their lining. Induction steelmaking units feature significant performance and have been successfully used to smelt relatively small volumes (from 5 kg to 60 tonnes) of high-quality steels both in industrial (foundries) and laboratory environments. The technical literature describes the technologies for smelting high-alloy heat-resistant steels [3–5], construction and low-carbon steels [6–8], non-ferrous metals [9; 10], and special-purpose

alloys [11; 12] in induction furnaces.

The purpose of this research is to systematise the methods of increasing the service life and controlling the state of induction melting furnace linings, which contributes to better anticipation of crucible wear and scheduling of repairs, maintenances and consumables.

In the process of systemic analysis of the problem, it is proposed to solve the following actual research tasks:

- analyze and summarize existing technologies and materials used for induction furnace linings;
- identify and classify the primary causes of crucible failure in induction steelmaking furnaces;
- evaluate and systematize methods for increasing the service life of induction furnace linings based on practical experiences and literature analysis;

- develop recommendations for monitoring and controlling the state of induction furnace linings to enhance operational efficiency and safety.

Analysis of the latest research and publications

An induction crucible furnace features a similarity to the operating principle of a transformer, where the primary winding is an inductor, and the secondary winding is the material in the crucible placed in the centre of the inductor, powered by a high-frequency alternator. Due to this design, the metal melted by the Foucault currents is subject to radial forces directed towards the centre of the molten metal pool [13; 14]. These forces cause the liquid metal to be forced up and down along the vertical axis of the crucible, which promotes electrodynamic mixing of the metal layers, thus ensuring chemical homogeneity of the melt and flotation of non-metallic impurities. Active circulation of liquid metal is beneficial for the chemical homogeneity of the metals being melted but negatively affects the lining life of induction furnaces. The lining is located between the liquid metal and the inductor (Fig. 1), and obviously, the thicker the furnace lining (or thickening due to growths), the lower the magnetic flux penetrates the metal and the lower the efficiency of electricity use during melting, so the lining thickness has certain limitations [15; 16]. The general design of an induction melting furnace is shown in Fig. 1.

The crucible of an induction furnace (see Fig. 1) is made by packing or lining it with refractory material (bricks). The crucible is directly located inside the inductor, which is a water-cooled copper tube coil with a certain number of turns. The packed crucible made of refractory powder material is fixed in casing and installed on bottom plate (foundation) made of refractory concrete. The melted metal is released through spout as the furnace along with the casing rotates relative to bearing axis [16]. Due to the physical aspects of heat generation directly in the metal, the increase in the melting temperature is limited mainly by the resistance of the melting crucible itself. The crucible is made of refractory material, which may include ceramics, graphite, or fire clay-graphite [17–19]. Water cooling and temperature control systems are used to increase thermal resistance and reduce thermal stress on the crucible [20; 21].

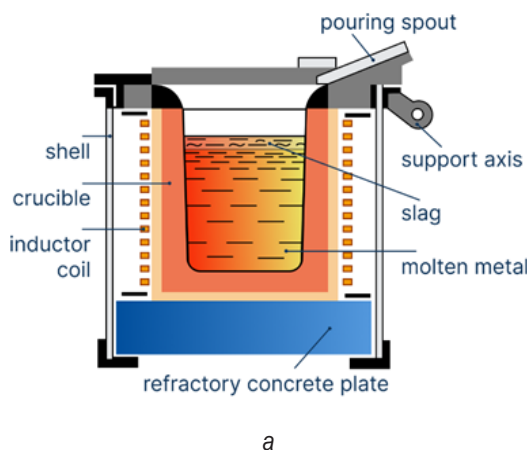
The melting points of steel grades produced in induction furnaces determine the use of three types of crucible linings: (a) acidic, (b) basic, and (c) neutral. Acidic (a) lining involves refractories made of silicon oxide (90...98 % SiO₂), boric acid (1...1.5 %) and a small amount of metal oxides such as Al₂O₃, Fe₂O₃, MnO, etc. The service life of crucibles made of acid lining is 80...100 melts. Basic (b) lining is mainly made of magnesite (up to 85 % MgO), liquid glass with impurities of oxides such as CaO, SiO₂, etc. The life of such crucibles decreases with increasing furnace volume and amounts to 20...50 melts. Neutral (c) linings are made of Al₂O₃-based materials with magnesite additives. The service life of such a lining is higher than that of the two previous options [16; 22].

The authors [23; 24] also point out the wide possibilities for their automation using controllers and the high environmental friendliness of the units as advantages of induction crucible furnaces, while the problem of low lining life is also mentioned as a disadvantage. According to the authors [16; 25], monitoring the lining wear in an automated manner constitutes a vital part of maintenance, ensuring the efficiency and reliability of equipment and the safety of the melting process. Given the above, the relevant scientific and practical task involves analysing production experience in increasing the lining life and developing recommendations to improve the efficiency of lining wear monitoring in an induction crucible melting furnace.

Materials and methods

Induction steel melting furnaces are widely used in the steelmaking industry, in glass production, and in waste processing. Given the prospects and the objective need for the development of electrometallurgical technologies, the scope and volume of their use will grow. For example, "Zaporizhzhia Foundry and Mechanical Plant" LLC has installed induction steel melting furnaces made by EGES (Turkey); the furnace complex includes induction furnaces with 3 ton and 1 ton crucibles capacity. In Fig. 2 shows the 3-ton furnace in operation, and Fig. 3 – during casting process. The technical characteristics of the furnace equipment are given in Table 1.

The main causes of crucible failure in an induction steelmaking furnace include the following:



a



b

Fig. 1.

Layout (a) and appearance (b) of a typical induction crucible melting furnace

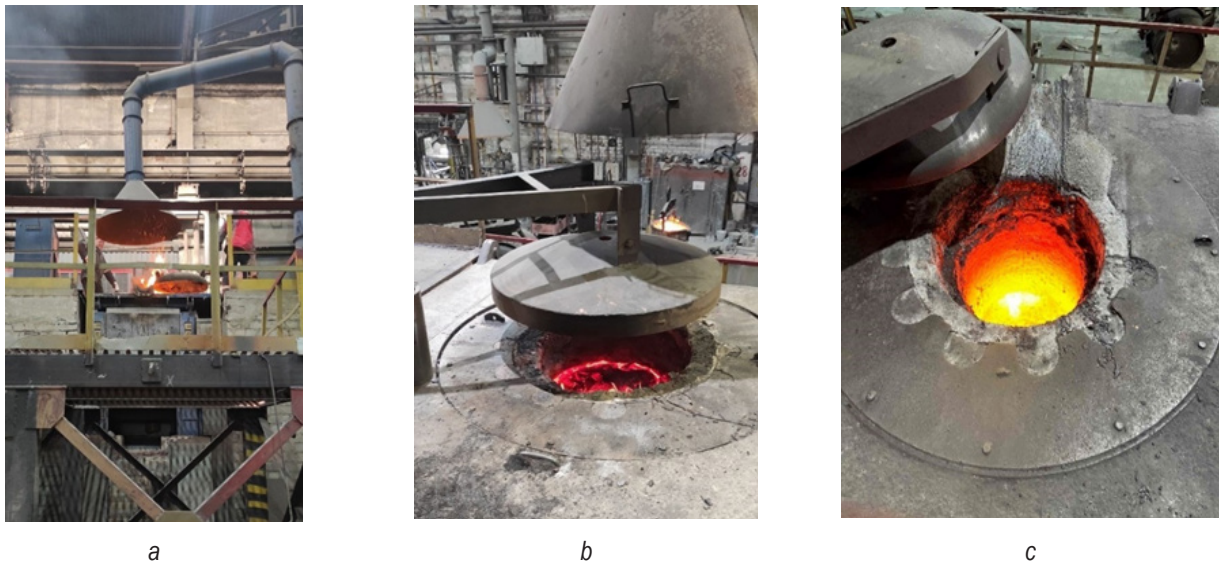


Fig. 2. The melting process in a 3-ton induction furnace (manufactured by EGES, Turkey): (a) general view of the furnace; (b) the crucible is covered to prevent temperature loss and metal emissions from the working space; (c) the furnace working space after metal release

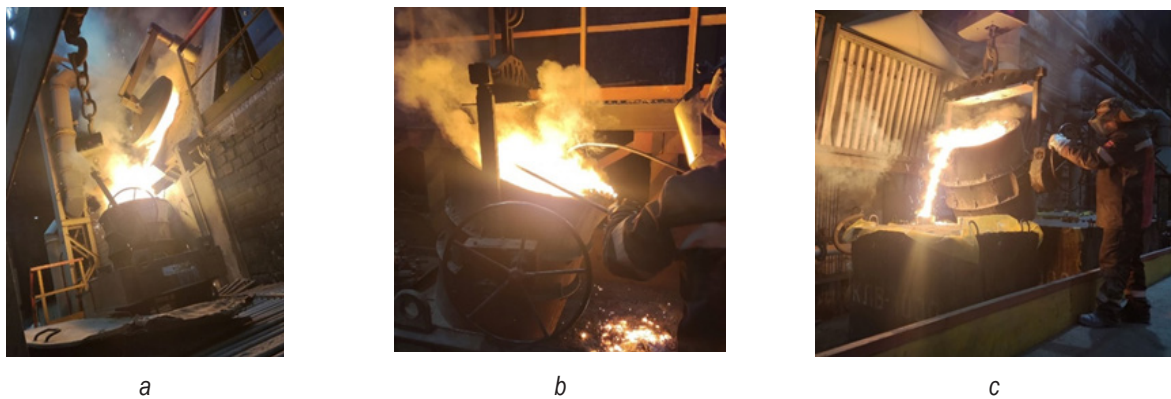


Fig. 3. The casting process at the 3-ton induction steel melting furnace (manufactured by EGES, Turkey): (a) discharge from the furnace into a ladle; (b) slag removal from the metal mirror; (c) casting process into moulds

- Thermal stress. During the steel melting process, the crucible undergoes significant heating and cooling. The heating and cooling cycles cause thermal stresses in the crucible material, which leads to damage and wear.
- Mechanical impact. When charge and scrap are loaded, impacts occur as they fall on the lining. The steel-melting process is accompanied by mechanical impacts, such as the intense movement of metal in the crucible. This also causes damage and wear to the crucible.
- Corrosion (erosion). Certain steel components or additives used during the melting process can be corrosive to the crucible material, causing it to wear away.

- Uneven heating. If the heat is not evenly distributed over the crucible during the melting process, thermal stresses also occur, which can cause the lining to crack.
- Contact with metal. Direct contact with the unmolten metal (at the beginning of the melting process) and the melt during the melting process causes mechanical wear of the lining due to friction.

Fig. 4 shows the process of lining repair packing for the crucible of 3-ton capacity induction furnace at "Zaporizhzhia Foundry and Mechanical Plant" LLC.

Results and discussion

Increasing crucible life requires a comprehensive

Table 1
Technical characteristics of EGES induction furnaces (Turkey), 1-ton and 3-ton crucible capacity

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

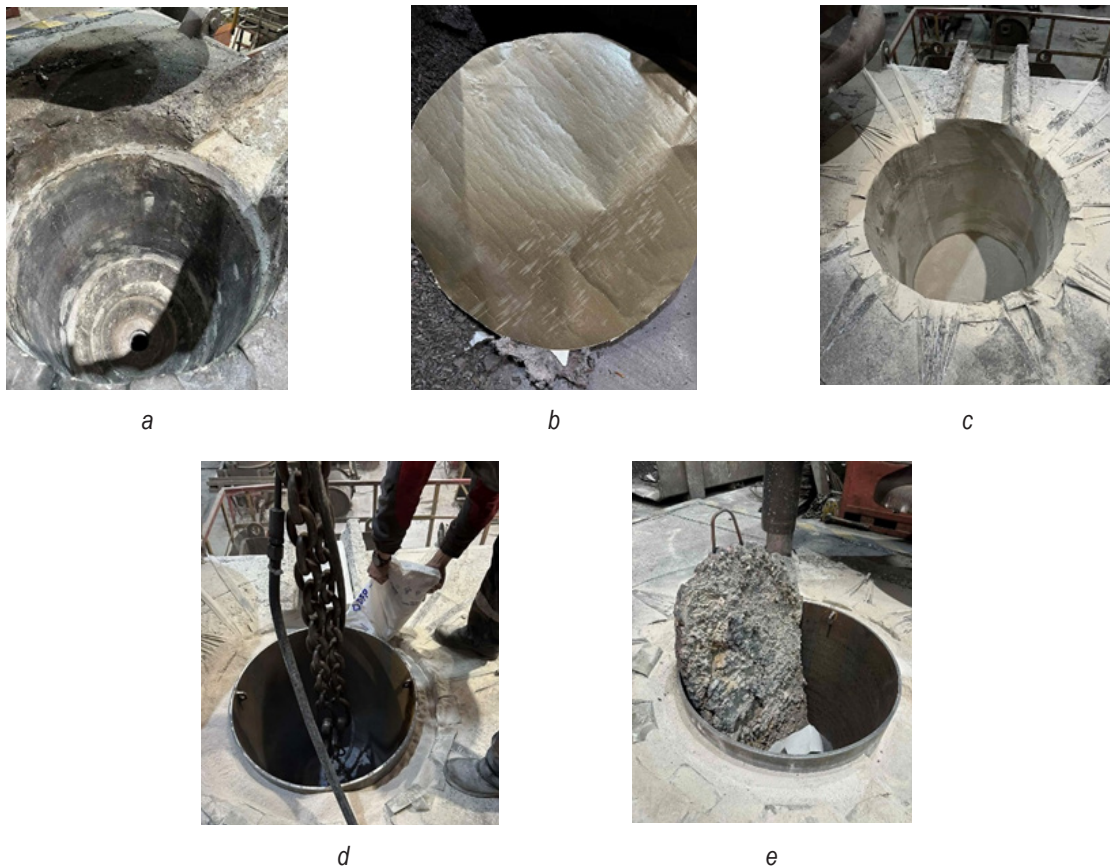


Fig. 4. Lining of the induction furnace with a capacity of 3-ton (manufactured by EGES, Turkey): (a) working space of the inductor for lining; (b) preparation of meconite for lining the furnace lining; (c) the process of lining the furnace bottom; (d) loading the furnace lining machine into the furnace by crane; (e) loading the furnace for sintering

approach that includes both the selection of appropriate materials and the proper management of the operation process. The general methods and strategies used to increase the lining life in industrial and laboratory induction furnaces and identified through the analysis of literature and practical experience are shown in Table 2.

It is recommended to choose the optimal solution in consultation with manufacturers or metallurgical equipment specialists.

Regular and comprehensive monitoring of the lining allows for the timely detection of any changes in its state and the avoidance of possible accidents or problems in production. Based on practical experience and analysis of information from the sources listed in Table 1, the methods for monitoring the state of induction melting furnace linings have been systematised. The results of the systematisation are shown in Table 3.

It should be noted that the success of wear control depends on systematic, accurate and timely measurements and inspections.

Conclusions

The paper shows the advantages of induction steel melting furnaces, i.e., better mixing of liquid metal layers during the melting process, which allows the production of a more homogeneous metal in terms of chemical composition. It demonstrates the prospects of using induction furnaces for smelting high-quality steels and non-ferrous metals and their alloys. The authors

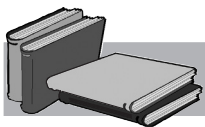
conducted a detailed review and systematisation of methods for increasing the lining life of an induction furnace crucible, and based on this, they formed a classification of methods for controlling the lining wear, including technical, organisational and monitoring methods. The findings can be used in practice to determine the overhaul intervals and the amount of the consumables for repairing induction furnace linings.

Systematisation of methods for increasing the life of induction melting furnace linings

No.	Method for increasing life	Core of the method
1	Appropriate crucible material	Use of high-quality materials that have high heat resistance and strength and meet the requirements of the specific process. Use of special materials, such as silicon carbide or zirconium oxide, which may have improved thermal and chemical resistance [16; 26–29]
2	Thermal insulation	Ensuring effective thermal insulation of the lining to avoid heat loss, overheating and wear under high temperatures. It is used to concentrate heat in the required areas. Thermal insulation coatings are used to reduce heat loss and retain heat in the interior of the crucible. These materials can help maintain constant temperatures and reduce energy consumption [19; 28; 30; 31]
3	Cooling systems	Use of cooling systems to control the lining temperature and prevent overheating [16; 19; 30; 32]. The use of lining with laid ducts for water cooling, pumping and circulation of coolant (water). Injection of a coolant (cold gas) into the crucible itself; use of additional active cooling (e.g., Peltier elements [33; 34])
4	Temperature monitoring and automated control	Installation of temperature monitoring systems for continuous monitoring of operating parameters and timely detection of anomalies in order to avoid drastic temperature changes that can lead to thermal shock of the crucible. Maintaining a constant temperature regime and ensuring smooth heating and cooling. Installation of thermocouples and sensors to continuously monitor the temperature of the crucible and respond to any changes promptly. Use of automatic temperature control systems that can regulate the supply of coolant or gas depending on the need [24; 25; 35]
5	Optimisation of melting processes and crucible design	Analysis and optimisation of processes to reduce excessive hydrodynamic friction and thermal impact on the lining. Study of melting hydrodynamics to identify areas where excessive friction occurs. Use of computer simulations to analyse and improve hydrodynamic processes and thermal models to determine heat distribution and identify areas of excessive thermal stress. Changes to the shape and configuration of the lining to reduce friction resistance. Ensuring the proper design of the crucible taking into account parameters such as wall thickness, shape and dimensions. Mitigating the risk of thermal shock by selecting optimal design parameters [26; 36; 37]
6	Expert assessment, wear and deformation monitoring	Involvement of specialised experts to assess the state of the lining systematically and identify any signs or risks of wear and tear. Visual inspections to identify any signs of wear or deformation. Use of non-destructive testing methods (e.g., ultrasonic inspection) to detect internal defects [13; 15; 16; 20–22; 25]
7	Routine maintenance and repair	Perform routine maintenance of the lining to detect wear and tear and any defects promptly and to ensure its durability. Scheduled repairs, refurbishment or replacement of the crucible [25; 38; 39]
8	Use of protective coatings	Use of protective coatings that can reduce the impact of chemical reactions and wear on the surface of the crucible [26; 27; 40; 41]. Graphite coatings protect the crucible from erosion and oxidation at high temperatures (graphite is chemically resistant and can withstand high temperatures, making it an effective material for crucible shielding). Ceramic coatings are used to create a thermally and chemically resistant layer that protects the crucible from aggressive environments (some types of ceramic coatings have high thermal shock resistance). Oxide ceramic materials such as aluminium oxide or zirconium oxide serve to protect the crucible from oxidation and aggressive reactions at high temperatures. Some manufacturers offer special coatings designed to meet the specific requirements of metallurgical and induction melting processes; these coatings can be optimised for specific operating conditions. Enamels and ceramic coatings that have a low coefficient of friction can be used to reduce frictional resistance and improve crucible performance
9	Electromagnetic field control	Optimising the design and location of the crucible to reduce the impact of the electromagnetic field on its life [42–46]. Transition to innovative solutions of electromagnetic cold crucible (EMCC) [42–45], 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. EMCCs have started to be used in two types of industrial applications: (a) as batch crucibles for melt preparation, and (b) as bottomless cylindrical moulds for continuous casting. The advantages of EMCCs are: reduction of friction in the moulding system (minimisation of melt contact with the crucible), i.e., a significant increase in crucible life, absence of contaminants and impurities in the melt, creation of fluid flow conditions that can control grain structure and accelerate online chemical treatment (high-quality castings), cycle time reduction [46]

Methods for monitoring the state of induction melting furnace linings

No.	Monitoring method	Type of work by monitoring method
1	Visual inspection	Routine inspection of the lining for cracks, loose parts or any signs of mechanical damage. Check for uniformity of lining wear and identification of possible unevenness that could lead to loss of resistance
2	Measuring the thickness and geometrical parameters of the crucibles	Regular measurements of lining thicknesses to detect wear (a decrease in crucible wall thickness may indicate a need for replacement). Monitoring other geometric parameters of the crucible (height, diameter) to detect deviations from standard values. The need to use appropriate equipment for accurate measurements
3	Thermal (thermal and visual) control	Use of thermal imagers to detect possible areas of overheating or uneven heat generation, which may indicate problems in the lining. Measuring the temperature on the lining surface and in the area of contact with the molten metal during thermal parameters control
4	Tracking of furnace performance parameters	Monitor performance parameters such as operating time, capacity and temperature to detect anomalies that may indicate problems with the lining. Sudden temperature changes or overheating can lead to faster lining wear
5	Non-destructive testing	Use of non-destructive testing methods, such as ultrasonography or radiography, to detect internal defects in the lining. Magnetic inspection methods can also be effective in detecting cracks and defects in the lining structure
6	Petrographic analysis of the lining material composition	Sampling of the lining material for further petrographic analysis, which will allow detection of the structural changes in the material, determining the degree of ageing which affects the strength and heat resistance
7	Testing of lining material properties	Measurement of the lining material elasticity properties to assess the degree of its ageing and resistance. Strength testing of the lining to determine its mechanical properties and fatigue life
8	Vibration monitoring	Installation of a vibration monitoring system to detect possible vibrations, shocks or other anomalies that may affect the lining state
9	Scheduled maintenance	Setting up a regular routine maintenance schedule that includes inspection and monitoring of the lining



REFERENCES

- Smirnov, O. M., Timoshenko, S. M., & Narivskiy, A. V. (2023). Vidnovlennia ta innovatsiyni rozvytok vyrobnytstva stali v Ukraini v konteksti enerhoefektyvnosti ta yevropeiskoho zelenoho kursu [Renovation and innovative development of steel production in Ukraine in the context of energy efficiency and Green Deal]. *Visnyk of the National Academy of Sciences of Ukraine*, (4), 21–38. <https://doi.org/10.15407/visn2023.04.021> [in Ukrainian].
- Rissman, J. et al (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, 266, 114848. <https://doi.org/10.1016/j.apenergy.2020.114848>
- Ren, W., & Wang, L. (2022). Precipitation behavior of $M_{23}C_6$ in high nitrogen austenitic heat-resistant steel. *Journal of Alloys and Compounds*, 905, 164013. <https://doi.org/10.1016/j.jallcom.2022.164013>
- Garin, J. L., & Mannheim, R. L. (2009). Sigma-phase precipitation upon industrial-like heating of cast heat-resistant steels. *Journal of Materials Processing Technology*, 209(7), 3143–3148. <https://doi.org/10.1016/j.jmatprotec.2008.07.026>
- Bubis, A. O., & Fedorov, H. Ye. (2016). Pidvyshchennia vlastyvoستي zharostiikykh stalei dlia roboty v ekstremalnykh umovakh mikrolehuvanniam i modyfikuvanniam [Improving the properties of heat-resistant steels for operation in extreme conditions by microalloying and modification]. *Pratsi VII Mizhnarodnoi naukovo-tekhnichnoi konferentsii "Novi materialy i tekhnologii v mashynobuduvanni – 2015"* [Proceedings of the VII International Scientific and Technical Conference "New Materials and Technologies in Mechanical Engineering – 2015"], 21...22 travnia 2015 r., Kyiv, Ukraina [21...22 May 2015, Kyiv, Ukraine], pp. 158–159. <https://metalcasting-proc.kpi.ua/article/view/63405> [in Ukrainian].
- Veretilnik, O. V., Biktagirov, F. K., Shapovalov, V. O., Gnatushenko, O. V., & Ignatov, A. P. (2020). Tekhnologii pererobky metalevoi struzhky (Ohliad) [Technology of processing metal chips (Review)]. *Electrometallurgy Today*, 2, 31–38. <https://doi.org/10.37434/sem2020.02.06> [in Ukrainian].
- Bedarkar, S. S., & Singh, R. (2013). Removal of phosphorous from steel produced by melting sponge iron in induction furnace. *Transactions of the Indian Institute of Metals*, 6, 207–211. <https://doi.org/10.1007/s12666-013-0244-z>
- Wang, B., Zhang, Y., Qiu, F., Cai, G., Cui, W., Hu, Z., Zhang, H., Tyrer, N., & Barber, G. C. (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>

9. Skachok, O. E., Prylutskiy, M. I., & Shapovalov, V. O. (2011). Plavka midnykh vidkhodiv [Smelting of copper waste]. *Materialy IX Mizhnarodnoi naukovo-praktychnoi konferentsii: "Spetsialna metalurhiia: vchora, sohodni, zavtra" [Proceedings of the IX International Scientific and Practical Conference: "Special metallurgy: yesterday, today, tomorrow"]*, 24 travnia 2011 r., m. Kyiv [24 May 2011, Kyiv]. Kyiv, NTUU "KPI", pp. 209–215. <http://www.fhotm.kpi.ua/labours/labours-2011.pdf> [in Ukrainian].
10. Verkhovliuk, A. M., Rusakov, P. V., Lakhnenko, V. L., Petrovskiy, R. V., & Chervonyi, I F. (2019). Protses oderzhannia vtorynykh kolorovykh splaviv z vykorystanniam induktsiinoi plavky [The process of obtaining secondary non-ferrous alloys using induction melting]. *Casting processes*, 134(2), 40–48. <https://plit-periodical.org.ua/index.php/plit/article/view/141> [in Ukrainian].
11. Li, H., Wang, A., Liu, T., Chen, P., He, A., Li, Q., Luan, J., & Liu, C.-T. (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>
12. Hryhoriev, S. M., Kyrychenko, O. H., Voliar, R. M., & Zinchenko, O. Ya. (2019). Vykorystannia bryketiv, shcho vmishchiut khrom, u vyrobnytstvi poroshkovykh spetsialnykh stalei [Use of chromium-containing briquettes in the production of special powder steels]. *Metalurhiia [Metallurgy]*, 1, 38–41. http://nbuv.gov.ua/UJRN/Metalurg_2019_1_9 [in Ukrainian].
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 (Special Issue 1), 159–163. <https://doi.org/10.17148/IARJSET/NCDMETE.2017.36>
14. Chaabet, M., & Dötsch, E. (2012). Steelmaking based on inductive melting. *Induction Technology: Reports*, 1, 49–58. https://abpinduction.com/wp-content/uploads/2020/02/ABP-Steelmaking_based_on_inductive_melting_M._Chaabet_E._Doetsch.pdf
15. *Znakomstvo s systemoi kontrolia tolshchyny futerovky SAVEWAY [Familiarisation with the SAVEWAY lining thickness monitoring system]*. Agenstvo Lite++. <https://on-v.com.ua/novosti/tehnologii-i-nauka/znakomstvo-s-sistemoj-kontrolya-tolshhiny-futerovki-saveway> [in Russian].
16. Kozlov, H. O., & Topolov, V. L. (2008). *Induktsiini pechi: Navchalnyi posibnyk dlia studentiv VNZ [Induction ovens: A study guide for university students]*, Nikopol: NT NMetAU, 32 p. <https://kema.at.ua/docs/met8.pdf> [in Ukrainian].
17. Naumyk, V. V. (2021). Provedennia doslidnykh plavok z vyrobnytstva iz svizhykh komponentiv suchasnoho lyvarnoho zharomitsnoho nikelovoho splava [Research melting on production from fresh components of modern foundry heat-resistant nickel alloy]. *Casting processes*, 146(4), 3–13. <https://doi.org/10.15407/plit2021.04.003> [in Ukrainian].
18. Seredenko, V. O., Seredenko, O. V., & Pareniuk, O. A. (2019). Vyplavka metaliv ta splaviv z vysokoiu elektroprovodnistiu v induktsiinykh tyhelnnykh pechakh [Smelting of metals and alloys with high electrical conductivity in induction crucible furnaces]. *Lytvo. Metalurhiia. 2019 : materialy 15-yi, 8-yi mizhnar. nauk.-prakt. konf. [Casting. Metallurgy. 2019 : materials of the 15th, 8th International scientific and practical conf.]*, 21–23 travnia 2019 r. [21-23 May 2019], Zaporizhzhia : AA Tandem, pp. 180–182. <https://repository.kpi.kharkov.ua/handle/KhPI-Press/66399> [in Ukrainian].
19. Taiwo, O., Adediran, A., Akinwande, A., & Okoyeh, F. (2023). A review on design and fabrication of fuel fired crucible furnace. *International Journal of Materials and Metallurgical Engineering*, 17(3), 48–58. <https://publications.waset.org/10013016/a-review-on-design-and-fabrication-of-fuel-fired-crucible-furnace>
20. Khaydarov, A. K., & Karimov, B. Y. (2022). Features of the use of induction crucible furnaces for melting metals. *International Journal of Social Science & Interdisciplinary Research*, 11(03), 33–39. <https://www.gejournal.net/index.php/IJSSIR/article/view/312>
21. Patel, K. M. (2019). An overview of applications of induction heating. *International Journal of Electrical Engineering and Technology*, 10(2), 81–85. <https://ssrn.com/abstract=3536945>
22. Rudnev, V., Fett, G. A., Griebel, A., & Tartaglia, J. (2014). Principles of induction hardening and inspection. In: Rudnev V., Totten G. E. (eds.). *Induction heating and heat treatment, ASM handbook*. ASM International, Vol. 4C. <https://doi.org/10.31399/asm.hb.v04c.a0005863>
23. 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>
24. Razzhivin, O., Markov, O., & Subotin, O. (2022). Automated melt temperature control system in induction furnace. In *2022 IEEE 4th International Conference on Modern Electrical and Energy System (MEES)*, Kremenchuk, Ukraine, pp. 01–04. <https://doi.org/10.1109/MEES58014.2022.10005650>
25. Dötsch, E. (2014). Operation of induction furnaces in iron foundries. In: Rudnev V., Totten G. E. (eds.). *Induction heating and heat treatment, ASM handbook*. ASM International, Vol. 4C. <https://doi.org/10.31399/asm.hb.v04c.a0005904>
26. Grishenkov, Ye. E. (2007). *Ogneupornie materialy i tekhnologiya futerovki induktsionnykh tigelnnykh pechei [Refractory materials and lining technology for induction crucible furnaces]*. Moscow: Metallurg, 30 p. [in Russian].
27. Sassa, V. S. (1989). *Futerovka induktsionnykh elektropechei [Lining of induction electric furnaces]*. Moscow: Metallurgiya, 232 p. [in Russian].
28. Panov, Ye. M., Bozhenko, M. F., & Korzhyk, M. V. (2022). Avtomatyzovani rozrakhunky pry rozrobtsi enerhoefektyvnykh konstruktsii pechei dlia pereplavlennia aliuminiivoho brukhtu [Automated calculations in the development of energy-efficient designs of furnaces for aluminum scrap remelting]. *Energy Technologies & Resource Saving*, (3), 95–104. <https://doi.org/10.33070/etars.3.2022.07> [in Ukrainian].

29. Kushchenko, P. O., Shulyk, I. H., Kushchenko, K. I., Krakhmal, Yu. O., Tkachenko, L. P., & Mishnova Yu. Ye. (2021). Zalezhnist vlastyvostei vysokohlynozemoi zernystoi masy ta zrazkiv z nei vid vydu dobavky ZrO_2 [Dependence of properties of high alumina granular mass and samples from it on the type of ZrO_2 additive]. *Tez. dop. Kh Mizhnarodnoi naukovo-tekhnichnoi konferentsii «Tekhnolohiia ta zastosuvannia vohnetryviv i tekhnichnoi keramiky u promyslovosti» [Proceedings of the X International Scientific and Technical Conference "Technology and Application of Refractories and Technical Ceramics in Industry"]*: DISA PLIUS, pp. 11–12. https://refractories-journal-ua.com/downloads/tezisy_2021.pdf [in Ukrainian].
30. Dötsch, E., & Nacke, B. (2014). Components and design of induction crucible furnaces. In: Rudnev V., Totten G. E. (eds.). *Induction heating and heat treatment, ASM handbook*. ASM International, Vol. 4C. <https://doi.org/10.31399/asm.hb.v04c.a0005899>
31. Pitak, Ya. M. (2005). *Vohnetryvki ta zharostiiki neformovani materialy na osnovi kompozytsii systemy $RO-R_2O_3-RO_2-P_2O_5$* [Refractory and heat-resistant unmoulded materials based on $RO-R_2O_3-RO_2-P_2O_5$ system compositions] : avtoref. dys. ... d-ra tekhn. nauk : 05.17.11 [PhD thesis abstract ... Doc. of Tech. Sci.: 05.17.11], National Technical University "Kharkiv Polytechnic Institute", Kharkiv, 38 p. <https://repository.kpi.kharkov.ua/handle/KhPI-Press/40380> [in Ukrainian].
32. 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>
33. Freer, R., & Powell, A. V. (2020). Realising the potential of thermoelectric technology: a Roadmap. *Journal of Materials Chemistry C*, 8, 441–463. <https://doi.org/10.1039/c9tc05710b>
34. Nesarajah, M., & Frey, G. (2016). Thermoelectric power generation: Peltier element versus thermoelectric generator, *IECON 2016 – 42nd Annual Conference of the IEEE Industrial Electronics Society*, Florence, Italy, (23–26 October 2016), 4252–4257. <https://doi.org/10.1109/IECON.2016.7793029>
35. 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>
36. Blozhko, N. K., & Gorshenkov, A. N. (1971). Instrument for measuring the speed at which fused metals move in induction furnaces. *Measurement Techniques*, 14, 571–573. <https://doi.org/10.1007/BF00980162>
37. Przyłucki, R., Gola, 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](https://doi.org/10.1016/S1644-9665(12)60181-2)
38. Kita, T., Hashimoto, K., Ishida, A., Yoneda, T., & Osho, Y. (1993). Decrease in number of repair mandays and refractory material cost for the high frequency induction furnace [Koshuha yudoro no roshukosu to taika zairyohi no teigen]. *Journal of the Japan Foundrymen's Society (Imono), Japan: N. p.*, 65(6), 517–519. <https://www.osti.gov/etdweb/biblio/5996358>
39. Ung, D. (2023). Enhancing crucible performance in non-ferrous applications. *Foundry Practice*, (272), 13–17. <https://27097971.fs1.hubspotusercontent-eu1.net/hubfs/27097971/FP%20272%20en.pdf>
40. Prokhorova, I. Ya., Novikova, O. V., Lazarev, V. V., & Sergeev, B. I. (1981). A protective coating for the tamped lining of induction furnaces. *Refractories*, 22, 522–525. <https://doi.org/10.1007/BF01406895>
41. Cherepova, T. S., Tisov, O. V., Kindrachuk, M. V., Yurchuk, A. O., & Radionenko, O. V. (2020). Trybotekhnichni vlastyvosti poroshkovoho splavu systemy Co-TiC v umovakh vysokotemperaturnoho fretynhu [Tribotechnical properties of sintered co-tic alloy in conditions of high temperature fretting wear]. *Problems of Friction and Wear*, 3(88), 99–108. [https://doi.org/10.18372/0370-2197.3\(88\).14923](https://doi.org/10.18372/0370-2197.3(88).14923) [in Ukrainian].
42. Buliński, P., Smolka, J., Gola, S., Przyłucki, R., Palacz, M., Siwiec, G., Lipart, J., Białecki, R., & Blacha, L. (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>
43. Yang, Y., Chen, R., Guo, J., Ding, H., & Su, Y. (2018). Numerical analysis for electromagnetic field influence on heat transfer behaviors in cold crucible used for directional solidification. *International Journal of Heat and Mass Transfer*, 122, 1128–1137. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.067>
44. Smirnov, O. M., Osypenko, V. V., Semiryagin, S. V., Goryuk, M. S., Semenko, A. Yu., & Skorobagatko, Yu. P. (2023). Peremishuvannia metalevykh rozplaviv yak zasib pidvyshchennia efektyvnosti funktsionuvannia ahrehatu «kivsh-pich». Povidomlennia 2. Novyi metod elektromahnitnoho peremishuvannia metalevoho rozplavu v ahrehati «kivsh-pich» [Stirring of metal melts for improving the efficiency of the "ladle-furnace" units. Message 2. New method for electromagnetic stirring of metallic melt in "ladle-furnace" unit]. *Casting processes*, 2(152), 3–15. <https://doi.org/10.15407/plit2023.02.003> [in Ukrainian].
45. Nesterenko, T. (2022). *Suchasnyi stan i tekhnolohii vyrobnytstva tytanovykh splaviv (rozdil 1)* [Modern state and technologies of titanium alloys production (chapter 1)]. *Innovatsii u suchasni nautsi : kolektyvna monohrafiia* [Innovations in modern science : a collective monograph], Part 1, no. sge 12-01, 8–34. <https://doi.org/10.30890/2709-2313.2022-12-01-020> [in Ukrainian].
46. 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>

Received 26.07.2024

Анотація

В.В. Кухар, доктор технічних наук, професор, проректор з науково-дослідної роботи, професор кафедри металургії, матеріалознавства та організації виробництва, e-mail: volodymyr.kukhar@mipolytech.education, <https://orcid.org/0000-0002-4863-7233>

Х.В. Малій, кандидат технічних наук, керівник науково-дослідного департаменту, доцент кафедри металургії, матеріалознавства та організації виробництва, e-mail: kristina.maliy@mipolytech.education, <https://orcid.org/0000-0002-9046-4268>

В.В. Кустіков, студент магістратури,
e-mail: vladyslav.kustikov@mipolytech.education

ТОВ «ТЕХНІЧНИЙ УНІВЕРСИТЕТ «МЕТІНВЕСТ ПОЛІТЕХНІКА»
(Запоріжжя, Україна)

Методи підвищення стійкості футерівки індукційних тигельних плавильних печей та контролю її стану

Вступ. Одним із способів зменшення викидів парникових газів для боротьби зі зміною клімату є впровадження електрометалургійних процесів виробництва сталі, включаючи плавку в індукційних печах. Однак, короткий термін служби футерування є значним обмеженням цього методу. Індукційні сталеплавильні установки ефективні для плавлення невеликих об'ємів високоякісних сталей, однак їх футерування піддається значному зносу через термічні, механічні та корозійні впливи.

Методи. Дослідження охоплює аналіз наукової та технічної літератури з теми футерування індукційних печей, а також практичний досвід металургійних підприємств, таких як ТОВ «Запорізький ливарно-механічний завод». Методологія включає систематизацію способів збільшення терміну служби футерування та методів моніторингу його стану, включаючи використання високоякісних матеріалів, систем охолодження, автоматизованих систем контролю температури та регулярного обслуговування.

Результати. Дослідження виявило, що термін служби футерування може бути збільшено шляхом оптимізації матеріалів футерування, застосування систем охолодження та автоматизованих систем контролю. Практичні приклади використання індукційних печей на металургійних підприємствах показують ефективність запропонованих методів. Зокрема, застосування графітових покриттів та оксидних керамічних матеріалів значно покращує стійкість футерування до високих температур та хімічного зносу.

Обговорення. Наукова новизна роботи полягає в систематизації та класифікації методів збільшення терміну служби футерування індукційних печей. Практична значущість дослідження полягає в можливості застосування отриманих результатів для прогнозування зносу футерування та планування ремонтних робіт. Запропоновані методи можуть бути використані для покращення надійності та ефективності індукційних печей при виробництві високоякісної сталі.

Ключові слова

виплавка сталі; електрометалургія; зношування футерівки; індукційна піч; методи контролю стану футерівки; руйнування тигля; термін служби.