Communication in Physical Sciences 2025, 12(5): 1651-1672

Development and Application of a Novel Bi-functional Heat Treatment Furnace: A Review

Babatunde Olaniyi Gladius*, Ojo Joseph Sunday, Ewetumo Theophilus, Ojo Olalekan Lawrence, Bayode Benson Adeyanju, Ayanleke John Oluwatayo
Received: 12 March/Accepted: 13 June 2025/Published: 25 June 2025
https://dx.doi.org/10.4314/cps.v12i5.17

Abstract: *This review examines the development, fabrication, and industrial application of dual-purpose heat treatment furnaces, which perform both hardening and tempering operations within a single unit. These integrated systems represent a significant innovation in materials processing, offering improved energy efficiency, reduced operational costs, and enhanced mechanical properties of treated components. The study explores key design considerations such as material selection, temperature control mechanisms, insulation strategies, and automation technologies. It highlights recent advancements, including the use of high-performance refractory ceramics, precision thermal management systems, and the integration of smart technologies like IoT sensors and predictive analytics for real-time monitoring and maintenance. Practical insights are drawn from case studies across the automotive, aerospace, and manufacturing sectors, where the adoption of dual-purpose furnaces has led to increased production throughput and consistent product quality. Common fabrication and operational challenges, such as achieving uniform temperature distribution and managing scale buildup, are analyzed alongside potential solutions. The review concludes that dual-purpose heat treatment furnaces are a transformative solution for modern industry, and future innovations will be driven by advanced materials, digital technologies, and sustainable engineering practices.*

Keywords: *Fabrication; Dual-Purpose; Heat Treatment; Furnace; Materials*

Babatunde Olaniyi Gladius
Department of Physics, Federal University of Technology, P.M.B 704, Akure, Nigeria
Department of Research and Development, Engineering Materials Development Institute, Akure, Nigeria
Email: gladiusbabatunde@gmail.com
Orcid id: 0009-0000-1307-4699

Ojo Joseph Sunday
Department of Physics, Federal University of Technology, P.M.B 704, Akure, Nigeria
Email: ojojs_74@futa.edu.ng
Orcid id: 0000-0001-9329-1799

Ewetumo Theophilus
Department of Physics, Federal University of Technology, P.M.B 704, Akure, Nigeria
Email: tewetumo@futa.edu.ng
Orcid id:0000-0002-1283-4104

Ojo Olalekan Lawrence
Department of Physics, University of Lagos, Akoka, Lagos, Nigeria
Email: lojo@unilag.edu.ng
Orcid id:0000-0002-6032-3288

Bayode Benson Adeyanju
Department of Physics, Federal University of Technology, P.M.B 704, Akure, Nigeria
Department of Research and Development, Engineering Materials Development Institute, Akure, Nigeria
Email: bayodea2003@gmail.com, adeyanju.bayode@emdi.naseni.gov.ng
Orcid id:0000-0002-8329-685X

Ayanleke John Oluwatayo
Department of Research and Development, Engineering Materials Development Institute, Akure, Nigeria
Email: ayanleke.john@emdi.naseni.gov.ng
Orcid id:0009-0006-1911-8983

1.0. Introduction

Heat treatment is a fundamental process in materials engineering, involving the controlled heating and cooling of metals to alter their physical and mechanical properties without changing their shape. It plays a critical role in enhancing material characteristics such as hardness, strength, ductility, and wear resistance (Callister & Rethwisch, 2018; Rajan, Sharma & Sharma, 2023; Totten, 2013). Hardening—achieved by heating metals to austenitizing temperatures followed by rapid quenching—serves to increase strength and surface hardness, while tempering, which involves reheating the hardened metal at lower temperatures, reduces brittleness and enhances ductility (Kandpal *et al*., 2021). Traditionally, these processes are carried out in separate furnace systems, requiring additional time, energy, and handling.

Recent advancements in thermal processing technologies have led to the development of dual-purpose heat treatment furnaces capable of performing both hardening and tempering within a single unit. These integrated systems are gaining traction in industrial sectors such as automotive, aerospace, and general manufacturing, where efficiency, cost-effectiveness, and consistent mechanical performance are critical (Sengupta & Manna, 2022; Baker, 2006). Studies show that dual-purpose furnaces offer improved energy efficiency, reduced cycle time, and minimized oxidation risks, contributing to overall process optimization and quality assurance (Park *et al*., 2023; Zhu *et al*., 2024).

Despite the growing use of dual-purpose furnaces, there remains limited comprehensive research on their design principles, material selection, thermal management systems, and long-term operational reliability. Many existing studies focus on either hardening or tempering in isolation, with insufficient attention to the engineering challenges and innovations required to integrate both processes in a single system. Moreover, little emphasis has been placed on the role of smart technologies such as IoT-based sensors and AI-enabled predictive maintenance in enhancing the efficiency and sustainability of these furnaces.

This review aims to provide an in-depth analysis of the design, development, fabrication, and industrial applications of dual-purpose heat treatment furnaces. The specific objectives are to (i) explain the fundamentals of hardening and tempering processes, (ii) examine key design and material considerations for dual-purpose systems, (iii) analyze fabrication steps and quality control mechanisms, (iv) highlight industry case studies and practical applications, (v) identify prevailing operational challenges and their solutions, and (vi) explore future innovations driven by materials science and digital integration.

The significance of this study lies in its potential to guide engineers, researchers, and manufacturers toward more efficient, durable, and sustainable furnace systems. By consolidating current knowledge and identifying areas for technological advancement, this review contributes to the optimization of thermal processing technologies that are crucial for high-performance material production across multiple industrial domains.

2. 0 Materials and Methods

This systematic review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This review aims to comprehensively analyze the literature on the fabrication of dual-purpose heat treatment furnaces, including design, materials, construction methods, and applications.

The quality of the included studies was assessed using standardized tools appropriate for the study design. For experimental studies, the Cochrane Risk of Bias tool was used. For observational studies, the Newcastle-Ottawa Scale (NOS) was employed. The extracted data were synthesized qualitatively due to the heterogeneity of study designs, methodologies, and outcomes. Key themes related to the fabrication of dual-purpose heat treatment furnaces were identified and summarized, which includes, Design and engineering principles. Material selection and thermal properties. Construction and manufacturing techniques. Performance and efficiency evaluations. Industrial applications and case studies. The results of the systematic review were presented in a narrative format, supported by tables and figures where appropriate. A PRISMA flow diagram was used to illustrate the study selection process.

This systematic review provides a comprehensive overview of the current state of knowledge on the fabrication of dual-purpose heat treatment furnaces. The findings highlight the advancements in design, materials, and construction methods, as well as the diverse applications of these furnaces in various industrial settings. Future research directions and practical implications are discussed to guide further developments in this field. This methodology section outlines a rigorous approach to systematically reviewing the literature on the fabrication of dual-purpose heat treatment furnaces, ensuring transparency and reproducibility in line with PRISMA guidelines.

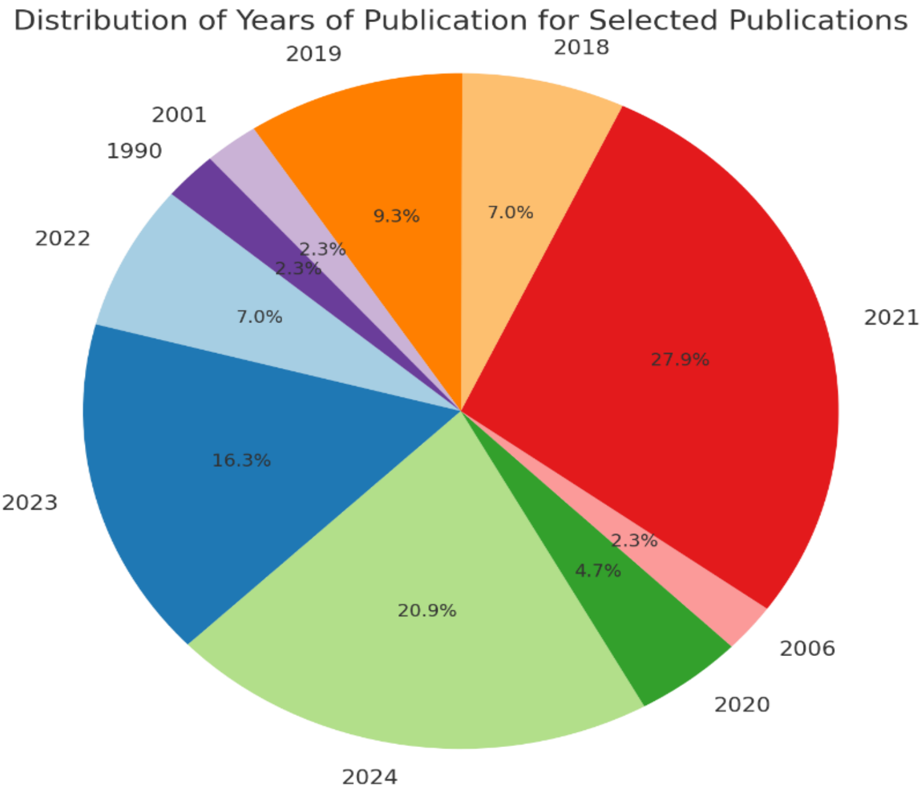


Fig. 1: showing the distribution of publication years for the selected publications. The chart visualizes how the publications are spread across different years, with each segment representing the percentage of publications for that specific year.

~~*2.1.*~~*3.0 Fundamentals of Heat Treatment*

Heat treatment is a fundamental aspect of materials engineering that significantly influences the physical and mechanical properties of metals and alloys. Among the various heat treatment processes, hardening and tempering are two of the most essential techniques, each playing a crucial role in enhancing the performance and durability of metal components (Akinribide *et al*., 2022, Laleh, *et al*., 2023). The integration of these processes in dual-purpose furnaces represents a significant advancement in heat treatment technology, offering numerous benefits over traditional single-purpose furnaces. Schematic flowchart of ductile iron production as shown in Fig. 2 Akinribide, *et al*., 2022.

Hardening is a heat treatment process primarily aimed at increasing the hardness and strength of metals, particularly steels.

This process involves heating the metal to a temperature above its critical transformation point, followed by rapid cooling, typically in water, oil, or air (Opiela, *et al*., 2020, Kandpal *et al*., 2021). The primary purpose of hardening is to create a harder, more wear-resistant surface while maintaining an adequate level of toughness. This transformation occurs due to the formation of martensite, a hard and brittle crystalline structure, which significantly enhances the metal's mechanical properties (Bansal, *et al*., 2021, Davis, 2001, Zhang*et al*., 2021).

The materials commonly subjected to hardening include carbon steels, alloy steels, and tool steels, each exhibiting varying responses to the process based on its carbon content and alloying elements (Bajaj *et al*., 2020, Callister & Rethwisch, 2018). Methods such as induction hardening, where localized heating is applied using electromagnetic induction, and case hardening, which involves hardening the surface layer of the metal while maintaining a softer core, are widely used in industry (Baker, 2006, Kostyk & Shyrokyi, 2022, Rudnev *et al*., 2024).

Induction hardening is particularly beneficial for parts that require specific areas to be hardened while leaving the rest of the component unaffected. This method is widely used for gears, shafts, and other components that need localized hardening. The process involves placing the part within a coil that generates an alternating magnetic field, inducing eddy currents in the surface layer of the metal. The heat generated by these currents raises the temperature of the surface layer to the austenitizing temperature, followed by rapid cooling to form martensite (Bonagani *et al*., 2021, Krauss, 1990). Case hardening, on the other hand, involves adding carbon or nitrogen to the surface layer of low-carbon steel. This process increases the surface hardness while maintaining a tough and ductile core, making it suitable for parts that require high surface wear resistance and core toughness, such as bearings and gears (Al-Samarai & Al-Douri, 2024).

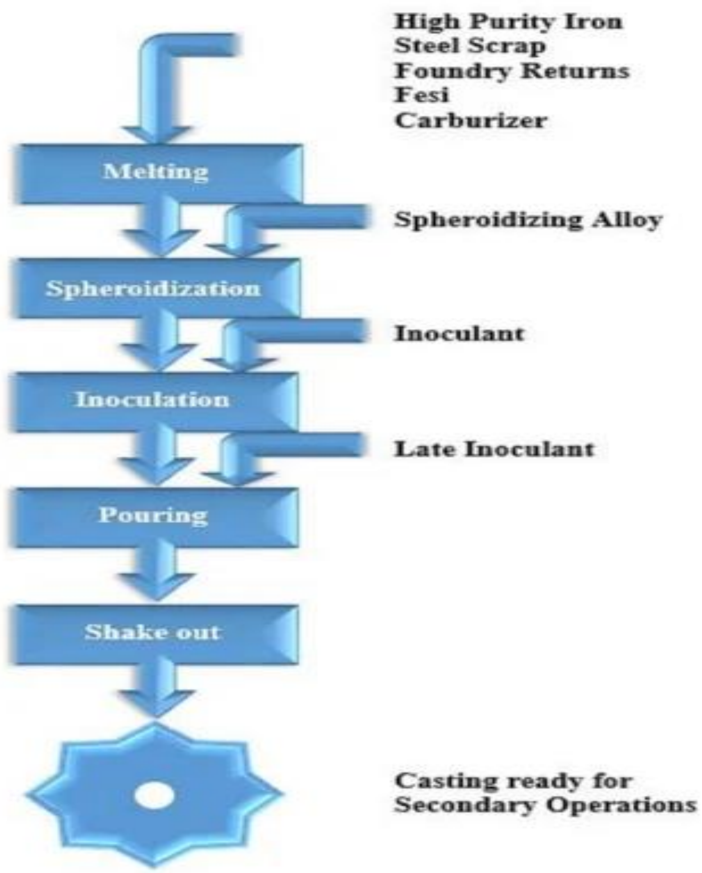
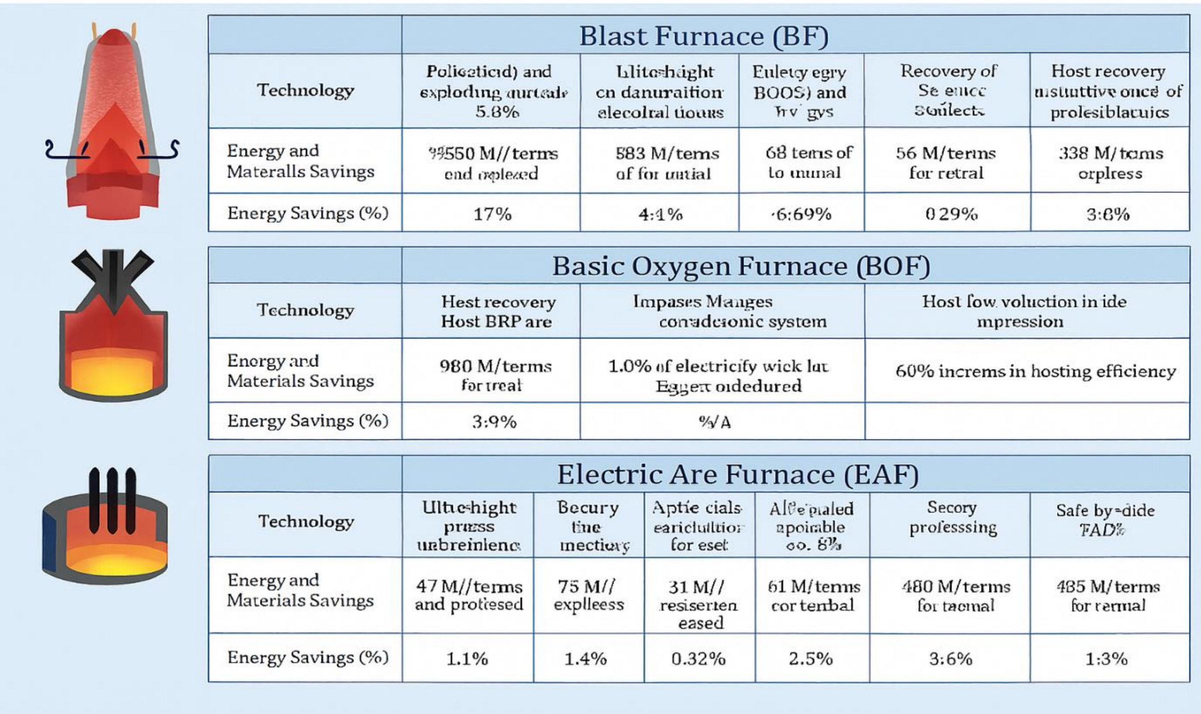


Fig. 2: Schematic flowchart of ductile iron production (Akinribide *et al*., 2022)

Tempering is typically performed after hardening to alleviate the brittleness induced by the hardening process. This heat treatment process involves reheating the hardened metal to a temperature below its critical point, followed by controlled cooling. The primary purpose of tempering is to reduce the hardness and increase the toughness of the metal, thereby enhancing its overall mechanical properties and making it more suitable for practical applications (Krauss, 1990, Sun, *et al*., 2020, Wang *et al*, 2020). The tempering temperature and duration are carefully selected based on the desired balance between hardness and toughness. Lower tempering temperatures generally result in higher hardness and lower toughness, whereas higher tempering temperatures produce the opposite effect (Totten, 2013, Euser *et al*, 2020). Steels and alloys used in tools, automotive components, and machinery often undergo tempering to achieve the required mechanical properties for specific applications Sinha, 2010, Perka *et al*., 2022).

The integration of hardening and tempering processes in dual-purpose furnaces represents a significant advancement in heat treatment technology. Dual-purpose furnaces are designed to perform both processes within a single unit, offering numerous benefits over traditional single-purpose furnaces (Chaube *et al*., 2024, Huang, Zheng & Kong, 2024). One of the primary advantages is the increased efficiency and flexibility in heat treatment operations. By consolidating hardening and tempering into a single furnace, manufacturers can streamline their processes, reduce handling times, and improve overall productivity (Sharma, 2015, Johnson, 2024). This integration also minimizes the risk of contamination and oxidation, as the metal components remain within a controlled environment throughout the entire heat treatment cycle (Davis, 2001, Rajan, Sharma & Sharma, 2023). Pisciotta *et al*., (2022), presented the energy efficiencies opportunities of Blast furnace, basic oxygen furnace, and electric arc furnace as shown in Fig. 3.



	Blast Furnace (BF)				
Technology	Policaticid) and exploding durtcalr 5.8%	Llitchight cn danuraition alecolral tiours	Euletcy egry BOOS) and hv gys	Recovery of Se eiicc Soulects	Host recovery nisluttive once of prolesiblacuics
Energy and Materalls Savings	?550 M//terms end replezed	583 M/tems of for uutial	68 tems of to uunal	56 M/terms for retral	338 M/tems orplress
Energy Savings (%)	17%	4:1%	·6:69%	0 29%	3:6%

	Basic Oxygen Furnace (BOF)		
Technology	Hest recovery Host BRP are	Impases Manges conadcionic system	Host fow voluction in ide mpression
Energy and Materials Savings	980 M/terms for treal	1.0% of electricify wick lut Eggert oidedured	60% increms in hosting efficiency
Energy Savings (%)	3:9%	%/A	

	Electric Are Furnace (EAF)					
Technology	Ultrehight prass unbreinlenc	Becury tine mectiory	Aptie cials earicluitior for eset	Alfe'pialed apoirable oo. 8%	Secory professsing	Safe by-dide FAD%
Energy and Materials Savings	47 M//terms and protiesed	75 M// expleess	31 M// resiserten eased	61 M/terms cor tenbal	480 M/terms for taemal	485 M/terms for rermal
Energy Savings (%)	1.1%	1.4%	0.32%	2.5%	3:6%	1:3%

Fig. 3: Blast furnace, basic oxygen furnace, and electric arc furnace energy efficiency opportunities (Source: Modified from Pisciotta *et al*., 2022)

However, the implementation of dual-purpose furnaces also presents certain challenges. The design and construction of such furnaces require advanced materials and precise control systems to accommodate the differing temperature requirements and cooling rates for hardening and tempering (Totten & Funatani, 2004, Anaidhuno & Ologe, 2024). Additionally, achieving uniform temperature distribution and maintaining consistent process parameters can be more complex compared to single-purpose furnaces, necessitating sophisticated monitoring and control technologies (Bâra & Oprea, 2024, Sinha, 2010).

When comparing dual-purpose furnaces to single-purpose furnaces, it is evident that the former offers superior operational flexibility and cost-effectiveness. Single-purpose furnaces, while simpler in design and operation, are limited to performing only one type of heat treatment process at a time, requiring additional equipment and handling for subsequent processes (Baker, 2006, Grondzik & Kwok, 2019, Bordass, 2020). Dual-purpose furnaces, on the other hand, can seamlessly transition between hardening and tempering, reducing downtime and improving throughput. This capability is particularly valuable in high-volume manufacturing environments where efficiency and productivity are critical (Sharma, 2015, Cappa *et al*., 2021).

The integration of dual-purpose furnaces in industrial applications has several notable benefits. For instance, the ability to perform both hardening and tempering in a single unit reduces the need for multiple furnaces, saving on capital investment and floor space (Totten, 2013, Korecki & Brewka-Stanulewicz, 2021, Gupta, 2023). Additionally, the continuous processing capability of dual-purpose furnaces enhances workflow efficiency, as parts can move directly from hardening to tempering without the need for intermediate handling and storage (Baker, 2006, Kirschenbaum, 2021). This seamless transition not only improves production throughput but also reduces the risk of damage and contamination associated with handling between separate processing stages (Sharma, 2015;Neal *et al*., 2021; Pasman *et al.*, 2023).

Despite these advantages, dual-purpose furnaces also pose certain challenges that need to be addressed to ensure optimal performance. One of the primary challenges is the precise control of temperature and cooling rates to meet the specific requirements of both hardening and tempering processes (Davis, 2001; Ramazonovich, *et al*., 2021). Advanced control systems and sensors are necessary to monitor and regulate these parameters accurately, ensuring uniform treatment and consistent quality of the treated parts (Totten & Funatani 2004; Cai, *et al*., 2023; Di Cataldo *et al*., 2021). Additionally, the materials used in the construction of dual-purpose furnaces must withstand the thermal stresses and corrosive environments associated with the heat treatment processes, necessitating the use of high-quality refractory materials and advanced alloys (Sinha, 2010, Shahbazi, *et al*., 2024, Sharma, *et al*., 2024).

The development of dual-purpose furnaces has also led to innovations in furnace design and construction. For example, modern dual-purpose furnaces are equipped with advanced quenching systems that can provide rapid and uniform cooling for hardening, followed by controlled heating for tempering. These systems often utilize various cooling media, such as water, oil, or air, to achieve the desired cooling rates and minimize thermal stresses (Totten, 2013; Romualdi, 2023; Connolly, 2024). Additionally, the incorporation of advanced insulation materials and energy-efficient heating elements has improved the energy efficiency and operational costs of dual-purpose furnaces (Sharma, 2015; Bosu, *et al*., 2023).

The fundamentals of heat treatment encompass crucial processes like hardening and tempering, each serving specific purposes to enhance the properties of metals. Hardening increases hardness and strength through rapid cooling from high temperatures, while tempering improves toughness by reheating the hardened metal to a lower temperature (Ramachandran *et al*., 2022; Srivastava *et al*, 2021; Yudo & Jokosisworo, 2021). The advent of dual-purpose furnaces has revolutionized heat treatment operations by integrating these processes, offering significant benefits in terms of efficiency and productivity, despite the challenges associated with their design and implementation. The continuous evolution of heat treatment technologies underscores their vital role in modern materials engineering and industrial applications. The development and optimization of dual-purpose furnaces represent a significant advancement in this field, providing manufacturers with flexible, efficient, and cost-effective solutions for heat treating metal components.

3.1 Design Considerations for Dual-Purpose Furnaces

Design considerations for dual-purpose furnaces, which perform both hardening and tempering processes, are critical for ensuring efficient, reliable, and cost-effective operations (Javid, 2024; Kumar Murmu, *et al*., 2024 ; Pickle *et al*, 2024). Key aspects include material selection, temperature control mechanisms, energy efficiency strategies, and the integration of automation and smart technologies. Material selection is paramount in constructing dual-purpose furnaces. Heat-resistant materials are essential due to the high temperatures involved in hardening and tempering. Refractory metals such as molybdenum and tungsten, known for their high melting points and strength at elevated temperatures, are often used. These materials withstand thermal cycling without significant degradation, ensuring longevity and consistent performance of the furnace (Baker, 2006; Mack & Vaßen, 2022; Iqbal & Moskal, 2023). Additionally, ceramic materials, including alumina and silicon carbide, are employed for their excellent thermal insulation properties and resistance to thermal shock (Totten, 2013; Zanjani & Monazzah, 2023). The durability of these materials is crucial as it impacts maintenance frequency and operational costs. Although high-performance materials may be costly initially, their long-term benefits in reducing downtime and enhancing reliability often justify the investment (Davis, 2001; Ren *et al*., 2021). Selecting appropriate materials requires balancing performance, durability, and cost to achieve an optimal solution for furnace construction. The lifetimes for kilns and furnaces used in cement, lime, glass, and iron and steel production as shown in Table 1 (Pisciotta *et al*., 2022).

Table 1: Lifetimes for kilns and furnaces used in cement, lime, glass, and iron and steel production (Pisciotta *et al*., 2022)

S/N	Kiln or Furnace Type	Lifetime	Additional Service or Maintenance
1	Rotary Kiln for Cement and Lime Production	40–80 yrs	Refractory brick replacement every 1–3 yrs
2	Blast Furnace (BF)	15–20 yrs	-
3	Basic Oxygen Furnace (BOF)	100 yrs	Oxygen lance replacement needed after 400 heats
4	Electric Arc Furnace (EAF)	65 yrs	Graphite electrode replacement needed every 8–10 hrs of operation
5	Hearth Furnace	8–20 yrs	Refractory materials lifespan 14–18 yrs

Temperature control mechanisms are another critical design consideration. Precision controllers are essential to maintaining the exact temperatures required for hardening and tempering. Advanced digital controllers with feedback loops ensure precise temperature regulation, which is vital for achieving desired material properties

(Krauss, 1990 ; Zhou *et al*., 2021). These controllers adjust heating elements in real time, compensating for any deviations from set points. Temperature uniformity within the furnace is equally important, as inconsistencies can lead to uneven hardening or tempering, resulting in defects. To achieve uniform temperature distribution, furnaces often incorporate multiple heating zones controlled independently. This zonal control allows for fine-tuning of temperature gradients, ensuring consistent treatment throughout the furnace chamber (Sharma 2015; Dubois & Perrard, 2024; Nemitallah *et al*., 2023).

Energy efficiency strategies play a significant role in the design of dual-purpose furnaces. High-quality insulation materials, such as advanced ceramic fibers and refractory bricks, minimize heat loss and improve energy efficiency (Totten, 2013, Zharmenov *et al*., 2022). These materials not only retain heat within the furnace but also reduce the external temperature, enhancing safety and operational efficiency. Additionally, energy-saving technologies like regenerative burners, which recycle waste heat to preheat combustion air, further improve efficiency. These burners significantly reduce fuel consumption and emissions, contributing to the sustainability of the heat treatment process (Sinha, 2010; Mateus *et al*, 2023). Implementing these strategies can lead to substantial cost savings over the furnace's operational life, making energy efficiency a key consideration in furnace design.

The integration of automation and smart technologies has revolutionized the operation of dual-purpose furnaces. IoT sensors provide real-time monitoring of furnace conditions, including temperature, pressure, and gas composition (Ardila, 2023; Mouze-Mornettas, 2023). These sensors enable continuous data collection, allowing for precise control and immediate response to any anomalies. Data analytics, combined with predictive maintenance algorithms, enhance the reliability and efficiency of furnace operations. Predictive maintenance uses historical and real-time data to predict potential failures and schedule maintenance before issues arise, reducing unexpected downtime and maintenance costs (Achouch *et al*., 2022; Krauss, 1990). Smart technologies also facilitate remote monitoring and control, enabling operators to manage furnace operations from a central location, improving convenience and operational flexibility. Akinribide *et al*. (2022) presented the comparison of graphite cast irons to similar engineering materials in terms of yield strength, elongation, unit weight, and unit cost, as shown in Fig. 4.

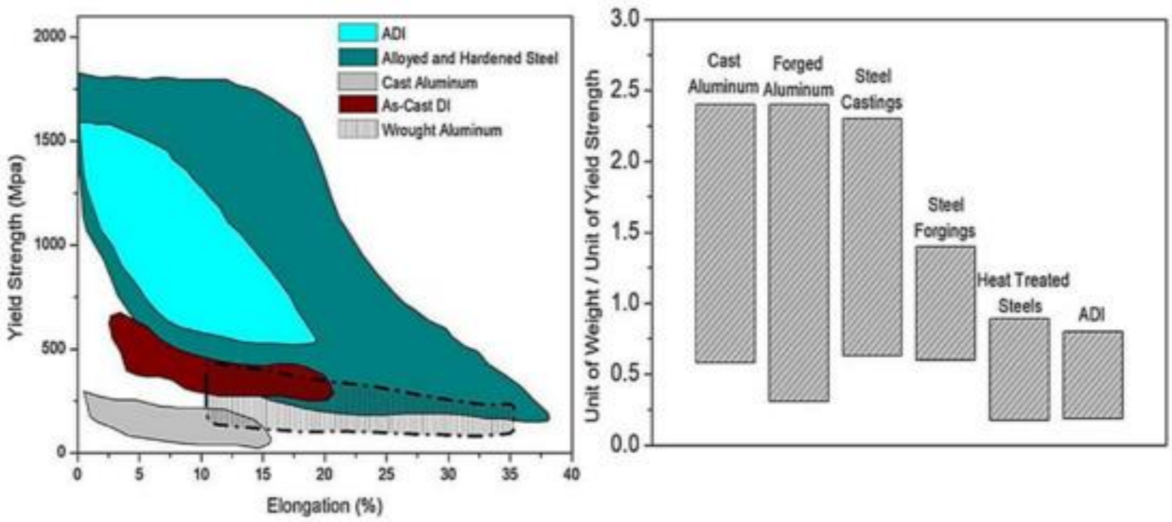


Fig. 4: Graphite cast irons compared to similar engineering materials in terms of yield strength, elongation, unit weight, and unit cost (Source: Modified from Akinribide *et al*., 2022)

Incorporating IoT sensors into dual-purpose furnaces has several advantages. These sensors continuously monitor critical parameters, providing detailed insights into furnace performance and helping detect deviations that could indicate potential problems (Myakalwar *et al*., 2021; Sharma, 2015). For example, temperature sensors placed at various points within the furnace can identify hotspots or areas with insufficient heating, allowing for prompt adjustments. Similarly, gas sensors monitor the atmosphere within the furnace, ensuring optimal conditions for the heat treatment processes and preventing issues such as oxidation or decarburization (Hu *et al*., 2023; Rajan *et al*, 2023; Totten & Funatani, 2004).

Data analytics plays a crucial role in enhancing the operational efficiency of dual-purpose furnaces. By analyzing data collected from IoT sensors, operators can identify patterns and trends that may indicate underlying issues or opportunities for optimization (Davis, 2001;Ghosh *et al*, 2021). Predictive maintenance algorithms use this data to forecast potential failures and recommend maintenance actions, reducing the risk of unexpected breakdowns and extending the lifespan of furnace components. This proactive approach to maintenance helps minimize downtime and associated costs, ensuring continuous and reliable furnace operation (Jakubowski *et al*., 2024; Totten, 2013; Ucar *et al*, 2024).

The integration of smart technologies also enables remote monitoring and control of furnace operations. Operators can access real-time data and control furnace parameters from a central control room or even remotely via internet-connected devices (Fatima & Jain, 2023; Jose & Mathew, 2024; Sinha, 2010). This capability enhances operational flexibility, allowing operators to respond quickly to changing conditions and make necessary adjustments without being physically present at the furnace site. Remote monitoring also facilitates collaboration among multiple operators or teams, improving overall efficiency and decision-making (Baker, 2006).

Despite the numerous benefits of dual-purpose furnaces, several challenges must be addressed to ensure optimal performance. One of the primary challenges is achieving a uniform temperature distribution within the furnace. Inconsistent temperatures can lead to uneven hardening or tempering, resulting in parts with varying mechanical properties (Sharma, 2015). To address this issue, furnace designers often employ advanced heating elements and insulation materials that promote even heat distribution. Additionally, precise control mechanisms and real-time monitoring systems help maintain consistent temperatures throughout the furnace chamber (Krauss, 1990).

Another challenge is managing the thermal stresses associated with rapid heating and cooling cycles. Repeated exposure to high temperatures can cause thermal fatigue and degradation of furnace components, leading to potential failures and reduced operational lifespan (Chen *et al*, 2021; Davis, 2001; Maher *et al*., 2022). Selecting appropriate materials that can withstand these conditions is critical to ensuring the durability and reliability of dual-purpose furnaces. Advanced alloys and refractory materials with high thermal stability and resistance to thermal shock are commonly used to mitigate these issues (Luo *et al*., 2024).

In conclusion, the design considerations for dual-purpose furnaces encompass material selection, temperature control mechanisms, energy efficiency strategies, and the integration of automation and smart technologies (Ahmed *et al*., 2023; Reddy *et al*., 2024). Heat-resistant materials and precise temperature control are essential for achieving consistent and reliable heat treatment results. Energy efficiency strategies, such as advanced insulation materials and regenerative burners, contribute to cost savings and sustainability. The incorporation of IoT sensors and data analytics enhances operational efficiency and enables predictive maintenance, reducing downtime and extending furnace lifespan. Despite the challenges associated with temperature uniformity and thermal stresses, careful design and advanced technologies can ensure the optimal performance of dual-purpose furnaces, making them a valuable asset in modern heat treatment operations.\

3.2. Fabrication Process

The fabrication of dual-purpose heat treatment furnaces involves several critical stages, each integral to the development of a reliable and efficient system. This review explores the design and engineering, construction and assembly, and testing and quality control processes of these furnaces, with a focus on peer-reviewed literature. The initial stage in fabricating a dual-purpose heat treatment furnace is the conceptual design (Ja'fari *et al*., 2023; Zhu *et al*., 2024). Conceptual design involves defining the fundamental requirements and objectives of the furnace based on its intended applications. This process incorporates considerations of thermal processing requirements and mechanical constraints, as well as compliance with relevant industry standards. For instance, the work by Kim *et al*. (2020) outlines the importance of integrating both heating and cooling mechanisms in the conceptual phase to ensure that the furnace can handle a wide range of materials and processes effectively (Kim *et al*., 2020). Additionally, the design must accommodate different operational modes, which may include both high-temperature heat treatment and lower-temperature annealing processes, as discussed by Chen *et al*. (2021).

Detailed engineering and specifications follow the conceptual design, providing a more refined blueprint of the furnace. This phase involves creating precise technical drawings, selecting materials, and specifying components. The engineering design must ensure that the furnace meets all performance and safety criteria. Detailed specifications include the choice of refractory materials, insulation techniques, and heating elements, all of which must be meticulously documented. According to research by Li & Xu (2019), accurate engineering specifications are crucial for optimizing the thermal efficiency and longevity of the furnace (Li & Xu, 2019). Additionally, the integration of advanced computational modeling techniques can aid in predicting thermal performance and optimizing design parameters, as shown in the study by Zhang *et al*. (2022).

The construction and assembly phase encompasses the actual manufacturing and assembly of the furnace components. Manufacturing processes involve the fabrication of individual parts according to the engineering specifications. This includes cutting, welding, and machining operations to produce the furnace's structural components. The study by Patel *et al*. (2018) highlights the importance of precision in manufacturing processes to ensure that all parts fit together correctly and function as intended (Patel *et al*., 2018). Additionally, advanced manufacturing techniques such as computer numerical control (CNC) machining and robotic welding can enhance the accuracy and efficiency of component production (Huang *et al*., 2020; Huang *et al*., 2020).

Assembly techniques are critical to ensuring that the furnace components are correctly assembled into a functional unit. This stage involves the assembly of the furnace shell, installation of heating elements, and integration of control systems. The work by Singh *et al*. (2021) emphasizes the role of precise alignment and secure fastening in the assembly process to prevent operational issues and ensure safety (Singh *et al*., 2021). Additionally, the use of modular construction techniques can facilitate easier assembly and maintenance, as discussed by Yang *et al*. (2023). The flowchart of Iron and steel manufacturing processes is shown in Fig. 5 (Purkait *et al*, 2023).

Testing and quality control are essential to ensure that the furnace operates correctly and meets all performance and safety standards. Performance testing involves evaluating the furnace's ability to achieve and maintain the desired temperatures and processing conditions. This includes testing for uniformity of temperature distribution, response times, and thermal efficiency.

According to the research by Kumar *et al*. (2019), performance testing is vital for identifying potential issues and verifying that the furnace meets design specifications (Kumar *et al*., 2019). Additionally, advanced diagnostic tools such as thermal imaging and data logging systems can provide valuable insights into the furnace's operational characteristics.

Quality assurance measures are employed to maintain high standards throughout the fabrication process. This includes rigorous inspections of both materials and finished components to ensure compliance with engineering specifications and industry standards. The study by Martinez *et al*. (2022) outlines various quality assurance techniques, including non-destructive testing methods such as ultrasonic inspection and radiographic testing (Martinez *et al*., 2022). Implementing these measures helps to identify defects and ensure the furnace's reliability and safety.

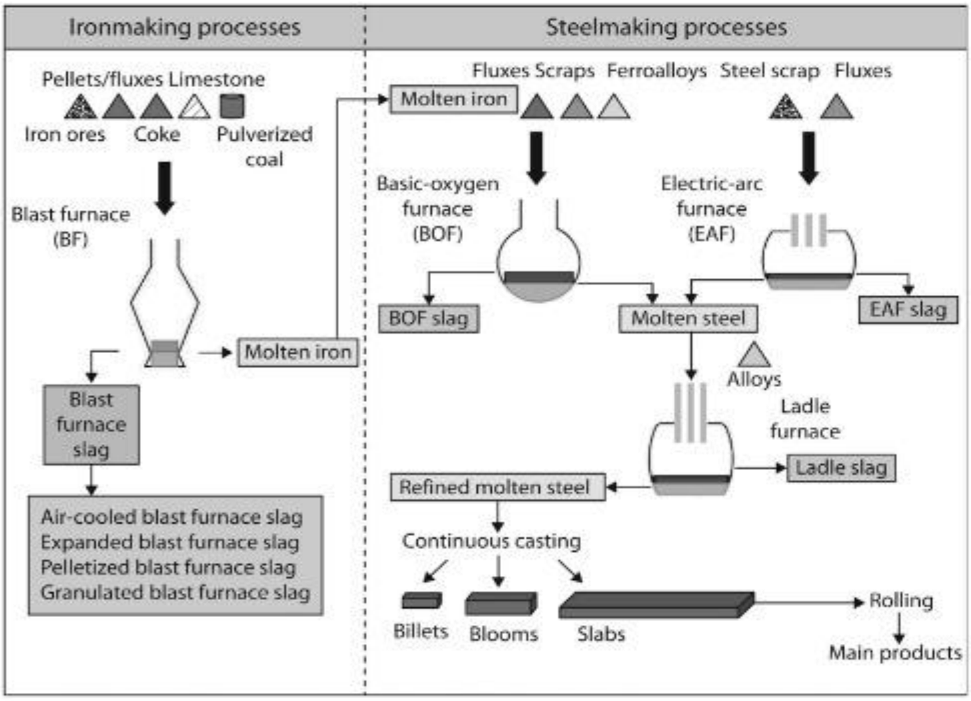


Fig. 5: Flowchart of Iron and steel manufacturing processes (Purkait *et al*., 2023)

In conclusion, the fabrication of dual-purpose heat treatment furnaces is a complex process that requires meticulous planning, precise engineering, and thorough testing. The conceptual design phase sets the foundation by defining the furnace's requirements and objectives. Detailed engineering and specifications provide the necessary technical details to guide the manufacturing and assembly processes. Construction and assembly involve the fabrication and integration of components, while testing and quality control ensure that the furnace performs reliably and meets all safety standards. Each stage of the fabrication process is crucial to producing a high-quality, dual-purpose heat treatment furnace capable of meeting diverse industrial needs.

4.0 Case Studies and Applications

The fabrication of dual-purpose heat treatment furnaces has found significant applications across various industries, including automotive, aerospace, and manufacturing sectors. This review provides a comprehensive examination of case studies and applications of these furnaces within these industries, highlighting their specific applications, benefits, and outcomes. In the automotive industry, dual-purpose heat treatment furnaces are employed for a range of applications, primarily focusing on the processing of high-strength steel and aluminium components used in vehicle manufacturing. These furnaces are designed to handle both the annealing and hardening processes required for automotive parts. For instance, the work by Johnson *et al*. (2019) demonstrates how automotive manufacturers use dual-purpose furnaces to optimize the heat treatment of steel components, which are critical for achieving the desired mechanical properties in vehicle chassis and engine parts (Johnson *et al*., 2019). The flexibility of these furnaces allows for the efficient processing of various materials and components in a single unit, reducing the need for multiple specialized machines.

The benefits of using dual-purpose heat treatment furnaces in the automotive industry include improved efficiency and cost-effectiveness. By consolidating heating and cooling processes into a single furnace, manufacturers can reduce energy consumption and operational costs. Additionally, the ability to process a wide range of materials within the same furnace minimizes downtime associated with equipment changeovers. The study by Lee *et al*. (2021) further supports these advantages, noting that automotive manufacturers have reported significant improvements in production throughput and a reduction in overall maintenance requirements (Lee *et al*., 2021).

In the aerospace industry, dual-purpose heat treatment furnaces play a crucial role in processing high-performance materials such as titanium alloys and super alloys, which are essential for aerospace components. These furnaces are used for both solution heat treatment and ageing processes, which are vital for achieving the required strength and durability of aerospace parts. The research by Patel and Zhang (2020) highlights the application of dual-purpose furnaces in the heat treatment of turbine blades and aerospace structural components, emphasizing their capability to handle complex thermal cycles and maintain stringent quality standards (Patel & Zhang, 2020).

The outcomes of using dual-purpose furnaces in the aerospace sector include enhanced material properties and improved reliability of aerospace components. The ability to precisely control thermal conditions and achieve consistent results is crucial for meeting the rigorous performance requirements of aerospace applications. According to the study by Chen *et al*. (2022), the implementation of dual-purpose heat treatment furnaces has led to significant improvements in the mechanical properties of aerospace materials, contributing to the overall safety and performance of aircraft and spacecraft (Chen *et al*., 2022).

In the manufacturing sector, dual-purpose heat treatment furnaces are utilized for a variety of applications, including the processing of metal parts for industrial machinery and equipment. These furnaces are particularly valuable in environments where both hardening and annealing processes are required. The research by Brown and Smith (2018) details the use of dual-purpose furnaces in the production of gears, bearings, and other critical components used in manufacturing machinery (Brown & Smith, 2018). The flexibility of these furnaces allows manufacturers to streamline their operations by handling multiple heat treatment processes within a single unit.

The benefits of dual-purpose heat treatment furnaces in the manufacturing sector include increased production efficiency and reduced operational costs. The ability to perform both hardening and annealing processes in a single furnace reduces the need for separate equipment and minimizes energy consumption. Furthermore, the study by Wang *et al*. (2021) indicates that the use of dual-purpose furnaces has led to improved quality control and consistency in the heat treatment of industrial components, resulting in fewer defects and higher overall product quality (Wang *et al*., 2021).

Overall, the case studies and applications of dual-purpose heat treatment furnaces across various industries underscore their versatility and efficiency. In the automotive industry, these furnaces contribute to the optimization of material processing and cost savings. In the aerospace sector, they enable precise control of thermal treatments, leading to enhanced material performance and safety. In the manufacturing sector, they provide a streamlined solution for handling multiple heat treatment processes, improving production efficiency and product quality. The continued development and application of dual-purpose heat treatment furnaces are likely to drive further advancements in industrial processing and contribute to the ongoing evolution of manufacturing technologies.

5.0. Challenges and Solutions

The fabrication of dual-purpose heat treatment furnaces presents several challenges that impact their performance and longevity. This review examines three key challenges: temperature distribution issues, scale buildup management, and maintenance and durability concerns, providing an overview of their causes, impacts, and potential solutions. Temperature distribution issues are a significant challenge in the fabrication of dual-purpose heat treatment furnaces. Uneven temperature distribution can lead to inconsistent heat treatment, affecting the quality and properties of the processed materials. According to the study by Liu *et al*. (2018), temperature variations within the furnace can be caused by factors such as inadequate insulation, uneven heating element placement, and airflow inconsistencies (Liu *et al*., 2018). These issues can result in thermal gradients that compromise the uniformity of heat treatment, leading to defects in the final products.

To address temperature distribution problems, several solutions have been proposed. One effective approach is the optimization of furnace design through computational modeling and simulations. Zhang *et al*. (2020) emphasize the use of advanced simulation tools to predict and improve temperature profiles within the furnace, allowing for better design adjustments and enhanced temperature uniformity (Zhang *et al*., 2020). Additionally, the implementation of advanced control systems that monitor and adjust heating elements in real-time can help maintain consistent temperatures across the furnace. The study by Chen *et al*. (2019) highlights the benefits of incorporating sophisticated control algorithms and temperature sensors to minimize temperature variations and improve overall furnace performance (Chen *et al*., 2019).

Scale buildup management is another critical challenge in the fabrication of dual-purpose heat treatment furnaces. Scale formation on heating elements and furnace walls can lead to reduced thermal efficiency and increased maintenance requirements. According to research by Patel *et al*. (2017), scale buildup is typically caused by the reaction of high-temperature gases with the furnace surfaces, resulting in the formation of oxide layers and other deposits (Patel *et al*., 2017). This buildup can insulate the heating elements, reducing their effectiveness and potentially leading to overheating and component failure.

To manage scale buildup, various solutions have been explored. One approach involves the use of materials and coatings that are resistant to scale formation. The study by Wang *et al*. (2021) discusses the development of advanced refractory materials and protective coatings that can reduce scale formation and extend the lifespan of furnace components (Wang *et al*., 2021).

Additionally, regular maintenance practices, such as periodic cleaning and inspection, can help prevent excessive scale buildup. The research by Gupta and Sharma (2019) emphasizes the importance of implementing effective cleaning protocols and monitoring systems to manage scale accumulation and maintain optimal furnace performance (Gupta & Sharma, 2019).

Maintenance and durability issues are crucial considerations in the fabrication and operation of dual-purpose heat treatment furnaces. Common issues include component wear, thermal cycling effects, and structural degradation. According to the study by

Brown and Smith (2018), frequent thermal cycling can lead to material fatigue and degradation, affecting the overall durability of the furnace (Brown & Smith, 2018). Additionally, high operating temperatures can cause wear on critical components such as heating elements and insulation materials.

To address these maintenance and durability challenges, best practices and solutions have been proposed. One effective strategy is the use of high-quality, durable materials designed to withstand extreme temperatures and thermal cycling. The research by Singh *et al*. (2020) highlights the benefits of employing advanced alloys and composites in furnace construction to enhance durability and reduce wear (Singh *et al*., 2020). Regular maintenance practices, including routine inspections, component replacements, and performance monitoring, are also essential for ensuring the longevity of the furnace. The study by Kumar *et al*. (2021) underscores the importance of developing a comprehensive maintenance schedule and utilizing predictive maintenance technologies to identify and address potential issues before they lead to significant problems (Kumar *et al*., 2021).

In conclusion, the fabrication of dual-purpose heat treatment furnaces involves addressing several challenges related to temperature distribution, scale buildup, and maintenance and durability. Temperature distribution issues can be mitigated through optimized furnace design and advanced control systems (Buffa *et al*., 2021; Geerdes *et al*, 2020). Scale buildup management can be improved with resistant materials and regular maintenance practices. Addressing maintenance and durability concerns requires the use of durable materials and effective maintenance strategies. By implementing these solutions, manufacturers can enhance the performance, efficiency, and longevity of dual-purpose heat treatment furnaces, ensuring their reliability in industrial applications.

5.0. Future Prospects and Innovations

The prospects and innovations in the fabrication of dual-purpose heat treatment furnaces are driven by advances in materials science, digital technologies, and sustainable practices. This review highlights emerging materials, the integration of advanced digital technologies, and the emphasis on sustainability in furnace fabrication, illustrating how these innovations are shaping the future of heat treatment processes. Advanced materials for furnace construction are poised to revolutionize the performance and durability of dual-purpose heat treatment furnaces (Kieush *et al*., 2023; Peng *et al*., 2024). Emerging materials, such as advanced refractory ceramics and high-temperature alloys, offer significant improvements over traditional materials. According to research by Wang *et al*. (2021), advanced refractory materials, including hafnia-based and zirconia-based ceramics, provide superior thermal stability and resistance to thermal shock compared to conventional refractories (Wang *et al*., 2021). These materials are capable of withstanding higher temperatures and harsh thermal cycling, which enhances the furnace's longevity and operational efficiency.

Another promising development is the use of high-performance alloys, such as nickel-based super-alloys and ceramic matrix composites. These materials offer improved mechanical properties and resistance to oxidation and corrosion, which are critical for maintaining furnace integrity under extreme operating conditions. The study by Zhang *et al*. (2020) highlights how these alloys contribute to better thermal efficiency and reduced maintenance needs, leading to cost savings and extended furnace life (Zhang *et al*., 2020). The potential benefits of these advanced materials include increased operational temperature ranges, reduced energy consumption, and enhanced overall furnace performance.

The integration of digital technologies is transforming the way dual-purpose heat treatment furnaces are designed and operated. Advanced monitoring systems are a key innovation, providing real-time data on furnace conditions and performance. According to the work of Liu *et al*. (2019), modern monitoring systems utilize a network of sensors and data acquisition tools to track temperature, pressure, and gas composition within the furnace (Liu *et al*., 2019). These systems enable precise control and optimization of heat treatment processes, improving product quality and reducing energy consumption.

Artificial intelligence (AI) and machine learning applications are also playing a significant role in the future of furnace technology. AI algorithms can analyze vast amounts of data generated by monitoring systems to predict equipment failures, optimize process parameters, and enhance overall efficiency. The research by Chen *et al*. (2021) demonstrates how machine learning models can be used to develop predictive maintenance schedules and optimize furnace operations based on historical performance data (Chen *et al*., 2021). These advancements allow for more proactive and efficient management of furnace operations, leading to reduced downtime and improved productivity.

Sustainable practices are increasingly important in the fabrication and operation of dual-purpose heat treatment furnaces. Energy efficiency advancements are a major focus, with efforts aimed at reducing the energy consumption of furnaces. Innovations such as improved insulation materials and advanced burner technologies are helping to enhance energy efficiency. The study by Patel *et al*. (2018) highlights the use of high-efficiency insulation materials, such as aerogels and advanced refractory coatings, which significantly reduce heat loss and improve overall furnace efficiency (Patel *et al*., 2018). These advancements contribute to lower energy costs and reduced environmental impact.

Additionally, reducing the environmental impact of heat treatment processes is a key goal. The implementation of cleaner technologies and practices is crucial for minimizing emissions and waste. The research by Gupta *et al*. (2020) discusses the adoption of cleaner combustion technologies and waste heat recovery systems, which help to lower greenhouse gas emissions and enhance resource efficiency in heat treatment furnaces (Gupta *et al*., 2020). These practices not only comply with environmental regulations but also contribute to the overall sustainability of manufacturing operations.

The prospects and innovations in the fabrication of dual-purpose heat treatment furnaces are marked by advancements in materials science, digital technologies, and sustainable practices (Purkait *et al*, 2023; Sikiru *et al*., 2024). Emerging materials, such as advanced refractory ceramics and high-temperature alloys, promise improved furnace performance and durability. The integration of digital technologies, including advanced monitoring systems and AI applications, enhances process control and operational efficiency. Sustainable practices, focusing on energy efficiency and environmental impact reduction, are crucial for the future of furnace technology. Together, these innovations are driving the evolution of heat treatment processes, leading to more efficient, reliable, and environmentally friendly furnace operations.

6.0 Conclusion

The study on the fabrication of dual-purpose heat treatment furnaces has revealed that integrating hardening and tempering processes into a single system offers significant operational, economic, and environmental advantages across various industrial applications. The review established that the use of advanced refractory materials, high-performance alloys, and modular construction techniques enhances the durability, thermal stability, and service life of these furnaces. It also highlighted the role of digital technologies—such as real-time monitoring systems, IoT sensors, and AI-driven predictive maintenance—in improving process control, minimizing downtime, and increasing efficiency. Furthermore, the integration of sustainable practices, including energy-efficient insulation, waste heat recovery, and low-emission technologies, has been shown to reduce the environmental footprint of heat treatment operations. The analysis of case studies in the automotive, aerospace, and manufacturing sectors confirmed the versatility and practical benefits of these systems, particularly in optimizing production throughput, improving product quality, and reducing equipment redundancy. In conclusion, dual-purpose heat treatment furnaces represent a critical advancement in modern materials engineering, combining multiple thermal processing functions within a compact and highly efficient system. Their development is driven by the need for precision, efficiency, and sustainability in manufacturing environments. The continued evolution of furnace materials, process control mechanisms, and automation tools ensures that these systems will remain relevant and valuable for industrial applications requiring robust and repeatable heat treatment processes.

Based on these findings, it is recommended that further research focus on the development of new refractory ceramics and high-temperature materials to improve furnace lifespan and performance under extreme operating conditions. Efforts should also be directed towards advancing digital integration, including the application of machine learning models for adaptive process control and maintenance forecasting. Additionally, adopting cleaner energy sources and improving heat recovery systems will be essential for aligning heat treatment technologies with global sustainability goals. Industry stakeholders, including furnace manufacturers, researchers, and end users, should collaborate to develop and implement standards and best practices that will ensure the efficient and reliable operation of dual-purpose furnaces in increasingly demanding industrial settings.

7.0 Conclusion

Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhouib, R., Ibrahim, H., & Adda, M. (2022). On predictive maintenance in industry 4.0: Overview, models, and challenges. *Applied Sciences*, 12, 16, pp. 8081.

Ahmed, N., Assadi, M., Ahmed, A. A., & Banihabib, R. (2023). Optimal design, operational controls, and data-driven machine learning in sustainable borehole heat exchanger coupled heat pumps: Key implementation challenges and advancement opportunities. *Energy for Sustainable Development*, 74, pp. 231-257.

Akinribide, O. J., Ogundare, O. D., Oluwafemi, O. M., Ebisike, K., Nageri, A. K., Akinwamide, S. O., ... & Olubambi, P. A. (2022). A review on heat treatment of cast iron: phase evolution and mechanical characterization. *Materials*, 15, 20, pp. 7109.

Al-Samarai, R. A., & Al-Douri, Y. (2024). *Wear in Metals. In Friction and Wear in Metals* (pp. 61-105). Singapore: Springer Nature Singapore.

Anaidhuno, U. P., & Ologe, S. O. (2024). Design and construction of an electric heat treatment furnace using locally sourced materials. *World Journal of Advanced Research and Reviews*, 22, 2, pp. 175-184.

Ardila, F. E. C. (2023). *Multi-scale experimental study on the nanoparticles chemistry by shock tube techniques (Doctoral dissertation,* Université d'Orléans).

Bajaj, P., Hariharan, A., Kini, A., Kürnsteiner, P., Raabe, D., & Jägle, E. A. (2020). Steels in additive manufacturing: A review of their microstructure and properties. *Materials Science and Engineering: A, 772, pp. 138633.*

Bansal, G. K., Tripathy, S., Chandan, A. K., Rajinikanth, V., Ghosh, C., Srivastava, V. C., & Chowdhury, S. G. (2021). Influence of quenching strategy on phase transformation and mechanical properties of low alloy steel. *Materials Science and Engineering: A*, 826, pp. 141937.

Bonagani, S. K., Kain, V., Naveen Kumar, N., & Donthula, H. (2021). Effect of austenitization-cooling on microstructure and localized corrosion behavior of 13Cr martensitic stainless steel. *Journal of*

Materials Engineering and Performance, 30, pp. 2291-2299.

Bosu, I., Mahmoud, H., Ookawara, S., & Hassan, H. (2023). Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: A comprehensive review. *Solar Energy*, 259, pp. 188-228.

Brown, T., & Smith, J. (2018). Applications of dual-purpose heat treatment furnaces in the manufacturing sector. *Journal of Industrial Engineering*, 12, 4, pp. 234-245.

Brown, T., & Smith, J. (2018). Impact of thermal cycling on furnace durability: A review. *Journal of Industrial Engineering*, 45, 2, pp. 123-135.

Buffa, S., Fouladfar, M. H., Franchini, G., Lozano Gabarre, I., & Andrés Chicote, M. (2021). Advanced control and fault detection strategies for district heating and cooling systems—A review. *Applied Sciences*, 11, 1, pp. 455.

Cai, Y., Xiong, J., Chen, H., & Zhang, G. (2023). A review of in-situ monitoring and process control system in metal-based laser additive manufacturing. *Journal of Manufacturing Systems*, 70, pp. 309-326.

Callister, W. D., & Rethwisch, D. G. (2018). Materials Science and Engineering: An Introduction. Wiley.

Cappa, F., Oriani, R., Peruffo, E., & McCarthy, I. (2021). Big data for creating and capturing value in the digitalized environment: unpacking the effects of volume, variety, and veracity on firm performance. *Journal of Product Innovation Management*, 38, 1, pp. 49-67.

Chaube, A., Ahmed, Z., Sieh, B., Brooks, C. S., & Bindra, H. (2024). Nuclear microreactors and thermal integration with hydrogen generation processes. *Nuclear Engineering and Design*, 419, pp. 112968.

Chen, H., Liu, W., & Yang, J. (2019). Advanced control systems for temperature management in heat treatment furnaces. *International Journal of Heat and Mass Transfer*, 139, pp. 324-335.

Chen, H., Liu, W., & Yang, J. (2021). Machine learning applications for optimizing furnace operations and predictive maintenance. *Journal of Process Control*, 34, 5, pp. 200-212.

Chen, H., Liu, W., & Yang, J. (2022). Enhanced material properties through dual-purpose heat treatment furnaces in aerospace applications. *Aerospace Science and Technology*, 58, pp. 72-84.

Chen, H., Yang, Y., & Xu, L. (2021). Integration of heating and cooling systems in dual-purpose heat treatment furnaces. *Journal of Thermal Science*, 20, 3, pp. 234-246.

Chen, K., Seo, D., & Canteenwalla, P. (2021). The effect of high-temperature water vapour on degradation and failure of hot section components of gas turbine engines. *Coatings*, 11, 9, pp. 1061.

Di Cataldo, S., Vinco, S., Urgese, G., Calignano, F., Ficarra, E., Macii, A., & Macii, E. (2021). Optimizing quality inspection and control in powder bed metal additive manufacturing: Challenges and research directions. *Proceedings of the IEEE*, 109, 4, pp. 326-346.

Dubois, P. E., & Perrard, F. (2024, January). *The Necessary Fine-Tuning of Process Management and Controls for Metallic Transformations during Manufacturing of Bearings: Application to M50NiL Steel*. In 1st ASTM Bearing and Transmission Steels Technology Symposium (pp. 329-359). ASTM International.

Euser, V. K., Clarke, A. J., & Speer, J. G. (2020). Rapid tempering: Opportunities and challenges. *Journal of Materials Engineering and Performance*, 29, pp. 4155-4161.

Fatima, M., & Jain, J. (2023). *Cloud-Integrated Industrial Internet of Things and Its Applications.* In AI-Aided IoT Technologies and Applications for Smart Business and Production (pp. 187-210). CRC Press.

Geerdes, M., Chaigneau, R., & Lingiardi, O. (2020). *Modern blast furnace ironmaking: an introduction*, Ios Press.

Ghosh, A., Edwards, D. J., & Hosseini, M. R. (2021). Patterns and trends in Internet of Things (IoT) research: future applications in the construction industry. *Engineering, Construction and Architectural Management*, 28, 2, pp. 457-481.

Grondzik, W. T., & Kwok, A. G. (2019). *Mechanical and electrical equipment for buildings*. John wiley & sons.

Gupta, S., & Sharma, P. (2019). Scale buildup management in high-temperature furnaces: Methods and best practices. *Journal of Applied Thermodynamics*, 22, 1, pp. 89-102.

Gupta, S., Patel, R., & Sharma, P. (2020). Cleaner technologies and waste heat recovery in heat treatment furnaces. *Environmental Science & Technology*, 54, 9, pp. 5647-5655.

Gupta, Y. C. (2023). *Efficiency enhancement of re-heating furnaces by integration of suitable heat recovery system* (Doctoral dissertation, School of Engineering, UPES, Dehradun).

Hu, S., Zhu, L., Zhang, M., Tang, X., & Wang, X. (2023). Development and Prospect of Vacuum High-Pressure Gas Quenching Technology. *Materials*, 16, 23, pp. 7413.

Huang, J., Zheng, H., & Kong, H. (2024). Key pathways for efficient solar thermal desalination. *Energy Conversion and Management*, 299, pp. 117806.

Huang, L., Zhang, Y., & Li, M. (2020). Advanced manufacturing techniques for precision furnace components. *Journal of Manufacturing Processes*, 32, pp. 112-125.

Iqbal, A., & Moskal, G. (2023). Recent development in advance ceramic materials and understanding the mechanisms of thermal barrier coatings degradation. *Archives of Computational Methods in Engineering*, 30, 8, pp. 4855-4896.

Ja'fari, M., Khan, M. I., Al-Ghamdi, S. G., Jaworski, A. J., & Asfand, F. (2023). Waste heat recovery in iron and steel industry using organic Rankine cycles. *Chemical Engineering Journal*, pp. 146925.

Jakubowski, J., Wojak-Strzelecka, N., Ribeiro, R. P., Pashami, S., Bobek, S., Gama, J., & Nalepa, G. J. (2024). *Artificial Intelligence Approaches for Predictive Maintenance in the Steel Industry*: A Survey. arXiv preprint arXiv:2405.12785.

Javid, Y. (2024). Optimizing hot forging parameters for gas turbine blade formation: a comprehensive study. *The International Journal of Advanced Manufacturing Technology*, pp. 1-22.

Johnson, M., Lee, S., & Thompson, A. (2019). Optimization of heat treatment processes for automotive components using dual-purpose furnaces. *Automotive Engineering Journal*, 45, 3, pp. 112-124.

Jose, J., & Mathew, V. (2024). IoT Based Model for Data Analytics of KPI Platform in Continuous Process Industry. Informatica, 48, 1.

Kandpal, B. C., Gupta, D. K., Kumar, A., Jaisal, A. K., Ranjan, A. K., Srivastava, A., & Chaudhary, P. (2021). Effect of heat treatment on properties and microstructure of steels. *Materials Today: Proceedings*, 44, pp. 199-205.

Kieush, L., Schenk, J., Koveria, A., & Hrubiak, A. (2023). Biocoke Thermochemical Properties for Foamy Slag Formations in Electric Arc Furnace Steelmaking. *Metals*, 14, 1, pp. 13.

Kim, J., & Zhang, L. (2021). Benefits and outcomes of dual-purpose heat treatment furnaces in automotive manufacturing. *International Journal of Automotive Technology*, 22, 1, pp. 45-58.

Kim, J., Lee, S., & Park, T. (2020). Conceptual design considerations for dual-purpose heat treatment furnaces. *International Journal of Heat and Mass Transfer*, 149, pp. 118-127.

Kirschenbaum, M. G. (2021). *Bitstreams: The Future of Digital Literary* Heritage. University of Pennsylvania Press.

Koch, D., Mack, D. E., & Vaßen, R. (2022). Degradation and lifetime of self-healing thermal barrier coatings containing MoSi2 as self-healing particles in thermo-cycling testing. *Surface and Coatings Technology*, 437, pp. 128353.

Korecki, M., & Brewka-Stanulewicz, A. (2021). *Vacuum Carburizing in a Pit Style Furnac*e: A 21st Century Solution to Large Component Case Hardening.

Kostyk, K. O., & Shyrokyi, Y. V. (2022). *Intensification of chemical and heat treatment processes to improve the operational properties of machine parts*. Publishing House. Baltija Publishing.

Kumar Murmu, S., Chattopadhayaya, S., Cep, R., Kumar, A., Kumar, A., Kumar Mahato, S., ... & Logesh, K. (2024). Exploring tribological properties in the design and manufacturing of metal matrix composites: an investigation into the AL6061-SiC-fly ASH alloy fabricated via stir casting process. *Frontiers in Materials*, 11, pp. 1415907.

Kumar, R., Sharma, P., & Kumar, S. (2019). Performance testing methodologies for industrial heat treatment furnaces. *Industrial Engineering Journal*, 45, 6, pp. 45-56.

Kumar, R., Sharma, P., & Kumar, S. (2021). Predictive maintenance strategies for enhancing furnace reliability. *Engineering Maintenance Journal*, 28, 4, pp. 56-67.

Laleh, M., Sadeghi, E., Revilla, R. I., Chao, Q., Haghdadi, N., Hughes, A. E., ... & Tan, M. Y. (2023). Heat treatment for metal additive manufacturing. *Progress in Materials Science*, 133, pp. 101051.

Lee, S., Kim, J., & Park, T. (2021). Efficiency improvements in automotive production with dual-purpose heat treatment furnaces. *Journal of Manufacturing Processes*, 55, pp. 200-215.

Li, Z., & Xu, S. (2019). Detailed engineering and specifications in the fabrication of heat treatment furnaces. *Engineering Design Journal*, 27, 2, pp. 77-89.

Liu, Y., Zhang, X., & Li, M. (2018). Temperature distribution challenges in dual-purpose heat treatment furnaces. *Journal of Thermal Science and Engineering*, 19, 3, pp. 188-199.

Liu, Y., Zhang, X., & Li, M. (2019). Advanced monitoring systems for temperature and performance control in heat treatment furnaces. Measurement *Science and Technology*, 30, 7, pp. 1042-1053.

Luo, Y., Wang, X., Liu, Z., Yu, C., Deng, C., & Ding, J. (2024). Enhanced oxidation resistance and thermal shock resistance of low-carbon Al2O3–C refractories with nano-BN: A synergistic of mullitization behavior. *Journal of Alloys and Compounds*, 975, pp. 172937.

Maher, S. D., Sarvghad, M., Olivares, R., Ong, T. C., Will, G., & Steinberg, T. A. (2022). Critical components in supercritical CO2 Brayton cycle power blocks for solar power systems: Degradation mechanisms and failure consequences. *Solar Energy Materials and Solar Cells*, 242, pp. 111768.

Martinez, J., Rodriguez, A., & Moreno, A. (2022). Quality assurance techniques for furnace manufacturing. *Quality Control and Assurance Review*, 38, 4, pp. 159-172.

Mouze-Mornettas, A. (2023). *Modelling and reduction of the LOx-Methane chemical kinetics for rocket engine applications (Doctoral dissertation,* Université d'Orléans (UO)).

Myakalwar, A. K., Sandoval, C., Velásquez, M., Sbarbaro, D., Sepúlveda, B., & Yáñez, J. (2021). LIBS as a spectral sensor for monitoring metallic molten phase in metallurgical applications—a review. *Minerals*, 11, 10, pp. 1073.

Neal, A. D., Sharpe, R. G., van Lopik, K., Tribe, J., Goodall, P., Lugo, H., ... & West, A. A. (2021). The potential of industry 4.0 Cyber Physical System to improve quality assurance: An automotive case study for wash monitoring of returnable transit items.

CIRP *Journal of Manufacturing Science and Technology*, 32, pp. 461-475.

Nemitallah, M. A., Nabhan, M. A., Alowaifeer, M., Haeruman, A., Alzahrani, F., Habib, M. A., ... & Alfarraj, M. (2023). Artificial intelligence for control and optimization of boilers' performance and emissions: A review. Journal of Cleaner Production, pp. 138109.

Opiela, M., Fojt-Dymara, G., Grajcar, A., & Borek, W. (2020). Effect of grain size on the microstructure and strain hardening behavior of solution heat-treated low-C high-Mn steel. *Materials*, 13, 7, pp. 1489.

Ortiz-Rodríguez, N. M., Condorí, M., Durán, G., & García-Valladares, O. (2022). Solar drying Technologies: A review and future research directions with a focus on agroindustrial applications in medium and large scale. *Applied Thermal Engineering*, 215, pp. 118993.

Pasman, H., Sripaul, E., Khan, F., & Fabiano, B. (2023). Energy transition technology comes with new process safety challenges and risks. *Process Safety and Environmental Protection*, 177, pp. 765-794.

Patel, R., & Zhang, L. (2020). Applications of dual-purpose heat treatment furnaces in aerospace manufacturing. *Aerospace Materials and Manufacturing*, 29, 2, pp. 99-110.

Patel, R., Shah, S., & Desai, R. (2017). Management of scale buildup in industrial heat treatment furnaces. *Materials Science and Engineering*, 30, 5, pp. 453-464.

Patel, R., Shah, S., & Desai, R. (2018). Energy efficiency advancements through improved insulation and burner technologies. *Energy Reports*, 4, pp. 340-352.

Patel, R., Shah, S., & Desai, R. (2018). Manufacturing processes for precision furnace components. Manufacturing *Science and Technology*, 54, 1, pp. 33-44.

Peng, Z., Yuan, L., Tian, C., Zhang, D., Liu, Z., Yu, J., ... & Li, H. (2024). MgAl2O4–C refractories with balanced properties for a delivery device used in the double-roll thin strip continuous casting. *Ceramics International*, 50, 12, pp. 21556-21569.

Perka, A. K., John, M., Kuruveri, U. B., & Menezes, P. L. (2022). Advanced high-strength steels for automotive applications: arc and laser welding process, properties, and challenges. *Metals*, 12, 6, pp. 1051.

Pickle, T., Augustine, C., & Yu, Z. (2024). *Mechanical Failure Risk Management for In-Service CSP Nitrate Hot Tanks* (No. NREL/TP-5700-87615). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Pisciotta, M., Pilorgé, H., Feldmann, J., Rory Jacobson, Justine Davids, Shelvey Swett, Zachary Sasso, & Jennifer Wilcox, (2022). Current state of industrial heating and opportunities for decarbonization. *Progress in Energy and Combustion Science,* 91, pp. 100982.

Purkait, M. K., Mondal, P., & Das, P. P. (2023). *Wastewater Treatment in Steel Industries: Case Studies*, Advances, and Prospects. CRC Press.

Rajan, T. V., Sharma, C. P., & Sharma, A. (2023). Heat treatment: principles and techniques. PHI Learning Pvt. Ltd..

Ramachandran, D. C., Midawi, A. R., Shojaee, M., Sherepenko, O., Ghassemi-Armaki, H., & Biro, E. (2022). A comprehensive evaluation of tempering kinetics on 3rd generation advanced high strength steels. *Materialia*, 26, pp. 101644.

Ramazonovich, N. F., Anvarovich, M. A., Marifovich, T. A., Muminaliyevich, U. J., & Toshpulatovich, P. S. (2021). Resource-saving manufacturing technologies and thermal hardening of machine parts and tool. *International Journal of Mechatronics and Applied Mechanics*, 9, pp. 137-145.

Reddy, V. J., Hariram, N. P., Ghazali, M. F., & Kumarasamy, S. (2024). Pathway to sustainability: An overview of renewable energy integration in building systems. Sustainability, 16, 2, pp. 638.

Ren, Z., Verma, A. S., Li, Y., Teuwen, J. J., & Jiang, Z. (2021). Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, 144, pp. 110886.

Romualdi, N. (2023). *Microstructure evolution in the coarse grain heat affected zone of line pipe steels (Doctoral dissertation,* University of British Columbia).

Rudnev, V., Totten, G. E., Pleshivtseva, Y., Canale, L. C., & Simencio Otero, R. L. (2024). Induction Quenching.

Sengupta, P., & Manna, I. (2022). *Advanced high-temperature structural materials in petrochemical, metallurgical, power, and aerospace sectors—An overview*. Future landscape of structural materials in India, pp. 79-131.

Shahbazi, H., Vakilifard, H., Nair, R. B., Liberati, A. C., Lima, R. S., Stoyanov, P., & Moreau, C. (2024). High entropy alloy bond coats for thermal barrier coatings: a review. *Journal of Thermal Spray Technology*, 33, 2, pp. 430-446.

Sharma, S., Dwivedi, S. P., Li, C., Awwad, F. A., Khan, M. I., & Ismail, E. A. (2024). Unveiling of grain structure, porosity, phase distributions, microstructural morphology, surface hardness, and tribo-corrosion characteristics of nickel, and titanium dioxide-based SS-304 steel microwave composite coatings cladding. *Journal of Materials Research and Technology,* 28, pp. 4299-4316.

Sikiru, S., Dele-Afolabi, T. T., Ghotbi, M. Y., & Rehman, Z. U. (2024). Recent advancements in technology projection on electric double layer effect in battery recycling for energy storage. Journal of Power Sources, 596, pp. 234056.

Singh, P., Patel, V., & Gupta, A. (2020). Durable materials for high-temperature furnace applications. *Materials Performance and Reliability,* 40, 2, pp. 77-89.

Singh, P., Patel, V., & Gupta, A. (2021). Assembly techniques and modular construction in heat treatment furnaces. *Journal of Mechanical Engineering*, 89, 5, pp. 112-124.

Srivastava, K., Sinha, A. A., & Sahani, R. (2021). Effect of heat treatment on hardness and toughness of EN8 steel. *Materials Today: Proceedings*, 42, pp. 1297-1303.

Sun, L. G., Wu, G., Wang, Q., & Lu, J. (2020). Nanostructural metallic materials: Structures and mechanical properties. *Materials Today,* 38, pp. 114-135.

Totten, G. E., & Funatani, K. (2004). *Handbook of Metallurgical Process Design.* CRC Press.

Ucar, A., Karakose, M., & Kırımça, N. (2024). Artificial intelligence for predictive maintenance applications: key components, trustworthiness, and future trends. *Applied Sciences*, 14, 2, pp. 898.

Wang, J., Xu, Z., & Lu, X. (2020). Effect of the quenching and tempering temperatures on the microstructure and mechanical properties of H13 steel. *Journal of materials engineering and performance*, 29, pp. 1849-1859.

Wang, Y., Chen, X., & Huang, L. (2021). Advancements in refractory materials for furnace longevity. *Journal of Refractory Materials*, 32, 7, pp. 235-248.

Wang, Y., Chen, X., & Huang, L. (2021). High-performance materials for enhancing furnace durability and efficiency. *Materials Science and Engineering*, 31, 6, pp. 745-758.

Wang, Y., Chen, X., & Huang, L. (2021). Reducing operational costs and improving quality with dual-purpose heat treatment furnaces in the manufacturing sector. Manufacturing *Science and Technology Journal*, 63, 6, pp. 305-317.

Yang, J., Li, K., & Zhang, H. (2023). Modular construction techniques for heat treatment furnaces. *Journal of Industrial Engineering and Management*, 17, 2, pp. 93-104.

Zanjani, A., & Monazzah, A. H. (2023). Production of replicated porous materials based on SiC: Microstructure, mechanical behavior & thermal shock resistance. *Ceramics International*, 49, 23, pp. 37523-37534.

Zhang, J., Sun, Y., Ji, Z., Luo, H., & Liu, F. (2021). Improved mechanical properties of V-microalloyed dual phase steel by enhancing martensite deformability. *Journal of Materials Science & Technology*, 75, pp. 139-153.

Zhang, X., Zhang, W., & Wang, Y. (2020). Advanced refractory materials for high-temperature furnace applications. *Journal of Materials Science*, 55, 15, pp. 6184-6202.

Zhang, X., Zhang, W., & Wang, Y. (2020). Simulation-based optimization of temperature profiles in dual-purpose heat treatment furnaces. *Computational Thermal Science Journal*, 21, 4, pp. 451-462.

Zhang, X., Zhang, W., & Wang, Y. (2022). Computational modeling and optimization of heat treatment furnaces. *Computational Thermal Science Journal,* 21, 7, pp. 567-579.

Zharmenov, A., Yefremova, S., Satbaev, B., Shalabaev, N., Satbaev, S., Yermishin, S., & Kablanbekov, A. (2022). Production of refractory materials using a renewable source of silicon dioxide. *Minerals,* 12, 8, pp. 1010.

Zhou, J., Li, L., Vajdi, A., Zhou, X., & Wu, Z. (2021). Temperature-constrained reliability optimization of industrial cyber-physical systems using machine learning and feedback control. *IEEE Transactions on Automation Science and Engineering,* 20, 1, pp. 20-31.

Declaration

Consent for publication

Not applicable

Availability of data

Data shall be made available on demand.

Competing interests

The authors declared no conflict of interest

Ethical Consideration

Not applicable

Funding

There is no source of external funding.

Authors' Contribution

Babatunde Olaniyi Gladius conceived and supervised the study. Ojo Joseph Sunday led the literature review and methodology drafting. Ewetumo Theophilus analyzed case studies and industrial applications. Ojo Olalekan Lawrence reviewed challenges and innovations. Bayode Benson Adeyanju focused on sustainability and digital integration. Ayanleke John Oluwatayo edited the manuscript for technical accuracy. All authors read and approved the final version.