

Real-Time Temperature Control and Performance Optimization of an Induction Heating System for In-Situ Neutron Experiments

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Abstract

Induction heating is an indispensable non-contact heat source for advanced thermal manufacturing and in-situ high-temperature characterization, yet conventional low-/mid-frequency systems suffer from large skin depth and diffuse energy deposition, resulting in sluggish heating that fails to meet the demands of rapid and highly localized thermal processing. To overcome this limitation, we propose a “high-frequency-high-current” synergistic intensification strategy: the inverter frequency is elevated to the hundred-kHz range and paired with a large-current ZCS-IGBT series-resonant converter, compressing electromagnetic energy into a sub-millimetre surface layer and enabling a quadratic escalation of heat-flux density and an extreme heating rate. A full-digital phase-locked loop together with dual-redundant protection guarantees stable high-current output at elevated frequencies. Theoretical analysis, multi-physics simulations and comparative experiments consistently demonstrate that the strategy can rapidly and uniformly heat the work-piece surface to the target temperature, offering an efficient, controllable and mobile heat source for low-carbon and precision thermal treatments.

Full Text

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Abstract: Induction heating is an indispensable non-contact heat source for advanced thermal manufacturing and in-situ high-temperature characterization, yet conventional low-/mid-frequency systems suffer from large skin depth and diffuse energy deposition, resulting in sluggish heating that fails to meet the demands of rapid and highly localized thermal processing. To overcome this limitation, we propose a “high-frequency-high-current” synergistic intensification strategy: the inverter frequency is elevated to the hundred-kHz range and paired with a large-current ZCS-IGBT series-resonant converter, compressing electromagnetic energy into a sub-millimetre surface layer and enabling a quadratic escalation of heat-flux density and an extreme heating rate. A full-digital phase-locked loop together with dual-redundant protection guarantees stable high-current output at elevated frequencies. Theoretical analysis, multi-physics simulations and comparative experiments consistently demonstrate that the strategy can rapidly and uniformly heat the work-piece surface to the target temperature, offering an efficient, controllable and mobile heat source for low-carbon and precision thermal treatments.

Keywords: High frequency induction heating; Rapid heating; Precision temperature control; Force thermal in-situ loading

Introduction

In key engineering fields such as aerospace, automotive manufacturing, and oil drilling, the in-depth integration of materials science and mechanical engineering has made research on the mechanical behavior and microstructure evolution of materials under extreme high-temperature conditions a core scientific challenge for improving the performance of engineering equipment [?, ?]. Neutron scattering technology [?] not only plays an important role in fields such as physics [?, ?],

biology [?], archaeology [?], and chemistry [?], but also serves as a crucial detection and analysis tool in materials science research [?, ?]. As a key instrument based on this technology, neutron diffractometer is not only suitable for studying the microstructure and mechanical behavior of materials under conventional conditions [?, ?], but also exhibits unique advantages in characterizing the microstructure evolution of materials in high-temperature environments [?]. With the increasing focus on transient non-equilibrium processes, rapid heating, as a crucial method for simulating extreme thermal loads, has been widely applied in research on high-temperature material behavior. To achieve real-time dynamic monitoring of materials under extreme high-temperature conditions, especially the accurate capture of mechanical responses and microstructure evolution during the rapid heating process [?], the coupling of neutron spectrometers with thermomechanical loading systems—particularly heating devices with rapid temperature rise capabilities—has become a key supporting means [?, ?].

Traditional heating devices mainly include infrared heating and resistance heating [?, ?]. Resistance heating primarily raises the sample temperature by leveraging the inherent electrical resistance of the material [?, ?], while infrared heating relies on the principle of thermal radiation to indirectly heat materials [?, ?]. The former exhibits low heating and cooling rates, which leads to prolonged experimental cycles [?, ?]. Moreover, different types of resistance wires have distinct operating temperature ranges, and they are prone to oxidation at high temperatures—this results in short service lives of heating elements and restricts the temperature range for high-temperature experiments [?, ?]. The latter, however, suffers from issues such as uneven temperature field distribution and poor temperature control accuracy. Additionally, due to the diversity of test materials, it shows poor heating efficiency when dealing with materials that have low infrared absorption rates [?, ?].

As a non-contact, efficient, and controllable heating technology, induction heating has gradually replaced traditional heating methods in recent years and become one of the primary heating means in high-temperature material research [?, ?]. Its notable advantages lie in its ability to act directly on the heating target, which significantly minimizes heat loss—thus ensuring efficient heating while drastically shortening the heating duration [?, ?]. Furthermore, through the precise adjustment of the induction coil and associated control systems, induction heating can accurately regulate the heating area and temperature gradient according to experimental requirements. This enables it to meet the stringent requirements for heating precision and dynamic response in high-temperature material research [?, ?].

Recently, a variety of high-temperature heating technologies have been applied in neutron diffractometer experiments to achieve high-precision high-temperature material testing. The ENGIN-X instrument at the ISIS Laboratory employs an infrared-heated high-temperature furnace, equipped with four 2 kW infrared heaters, and its maximum heating temperature can reach up to 1373 K [?, ?]. By contrast, the VULCAN instrument at the SNS

Laboratory in the United States integrates three heating devices, including a standalone high-temperature furnace, a resistance-heated gas-tight load frame furnace, and an auxiliary induction heating coil. Their maximum temperature can reach 1600 °C; among these devices, the resistance-heated gas-tight load frame furnace features a relatively high heating rate, capable of achieving a temperature rise of 600 °C/s [?]. At the J-PARC Laboratory in Japan, the PLANET instrument employs a heater powered by embedded high-voltage batteries, with a maximum achievable temperature of 2000 K; in contrast, the TAKUMI instrument uses an infrared heating device, which can only reach a maximum heating temperature of 1273 K [?].

The China Spallation Neutron Source (CSNS) currently has high-temperature sample environment devices including one pulsed laser heating furnace and one ultra-high-temperature induction heating device. The pulsed laser heating furnace has a rated output power range of 100 W to 2000 W, a maximum controllable heating temperature of 1800 °C, and a heating rate ranging from 80 °C/s to 150 °C/s [?]. The induction heating device, on the other hand, has a maximum heating temperature of 2700 K and a heating power of 60 kW, ranking among the induction heating furnaces with the highest temperatures in the field currently [?]. However, this induction heating device is mainly used for research on high-temperature microstructures and macroscopic properties, and cannot meet the requirements of experiments such as strain measurement [?] and residual stress distribution measurement [?].

Addressing the insufficiency of existing heating devices in rapid temperature rise capability, this study focuses on key technical issues such as the optimization of high-frequency induction technology, enhancement of thermal field uniformity, and intelligentization of temperature control systems, and proposes an innovative rapid temperature rise induction heating scheme. This scheme aims to significantly improve heating rate, temperature control accuracy, and thermal field stability, thereby meeting the requirements of diffractometer experiments—including those for material dynamic response, strain measurement, and residual stress analysis—under high-temperature conditions. To verify the feasibility and performance advantages of this scheme, this paper combines theoretical modeling and experimental testing to conduct a systematic evaluation of the system from multiple dimensions, including electromagnetic coupling, heat transfer behavior, and temperature control feedback response.

The implementation of this research not only helps to improve the overall experimental efficiency and testing accuracy of neutron diffractometers, but also provides strong technical support for the accurate investigation of the service behavior of materials in complex thermo-mechanical environments, thus holding significant theoretical significance and engineering application value.

Overall Design and Mechanism of the Instrument

[Figure 1: see original paper] illustrates an innovative coupling design that integrates an advanced engineering large-sample loading device with induction heating equipment, providing a versatile experimental platform for materials science research. This platform is capable of simultaneously applying stress and induction heating to materials, effectively simulating the complex environmental conditions encountered in practical applications. To address the limitations of existing heating devices in terms of rapid temperature increase capabilities, we will delve into the principles of induction heating technology, focusing on the optimization of high-frequency induction techniques, enhancement of thermal field uniformity, and the intelligent control of temperature systems, with the aim of significantly improving heating efficiency and precision, thereby better serving research and development in the field of materials science.

Induction heating technology is based on the principle of electromagnetic induction. When an alternating current i flows through the induction coil, it generates an alternating magnetic field within the coil. A workpiece placed within this alternating magnetic field experiences an induced electromotive force e , which in turn gives rise to eddy currents within the workpiece. Due to the eddy current effect and the inherent equivalent resistance R of the metal material, thermal energy is generated internally, thereby achieving the goal of heating the workpiece.

During the heating process, induction heating transfers electrical energy from the induction coil to the metallic workpiece, which is then converted into thermal energy within the workpiece itself. This energy transfer is accomplished via electromagnetic induction, without direct physical contact between the coil and the workpiece. As such, induction heating is classified as a non-contact heating method. [Figure 2: see original paper] shows the working process diagram of induction heating.

When the sinusoidal current i in the induction coil varies at a specific frequency, the resulting alternating magnetic field generated within the coil will exhibit the same frequency as the input current. This time-varying magnetic field induces a magnetic flux Φ through the workpiece, which can be expressed by the following formula [?]:

$$\Phi = \Phi_m \sin(\omega t)$$

where Φ is the magnetic flux in the induction coil; Φ_m is the amplitude of the alternating flux; and ω is the current angular frequency. The alternating magnetic flux generated by the induction coil induces an electromotive force (EMF) e in the workpiece via the principle of electromagnetic induction. This induced EMF can be described by Faraday's law as follows:

$$e = -N \frac{d\Phi}{dt}$$

where e is the induced electromotive force; N is the equivalent number of turns of the workpiece. Substituting Eq. (1) into Eq. (2) gives the induced electromotive force as follows:

$$e = -N\Phi_m \omega \cos(\omega t)$$

The Root Mean Square value of the induced electromotive force is:

$$E = \frac{N\Phi_m \omega}{\sqrt{2}} = \frac{2\pi f N\Phi_m}{\sqrt{2}} = 4.44 N f \Phi_m$$

where E is the effective value of the induced electromotive force; f is the frequency of the energizing current of the induction coil. The induction electromotive force in the metal workpiece produced by the induction current enables the workpiece to achieve heating. The Joule heat generated during the heating process is given by:

$$Q = 0.24Pt = 0.24I^2 Rt = 0.24 \frac{E^2}{Z^2} Rt = 4.73 f^2 N^2 \Phi_m^2 Rt$$

where Q is the generated Joule heat, P is the output power of the induction heating device, t is the energization time of the induction coil when the metal workpiece is heated, I is the rms value of the induction current, R is the equivalent resistance of the metal workpiece, and Z is the equivalent impedance modulus of the metal workpiece.

According to the above equations, when the properties and geometry of the metal workpiece remain unchanged, the amount of heat generated within the workpiece depends primarily on the frequency f of the current supplied to the induction coil, as well as the magnetic flux. The magnetic flux itself is determined by multiple factors, including the magnitude of the current flowing through the coil, the number of turns in the heating coil, and its spatial orientation relative to the workpiece.

Therefore, for a given metal workpiece, the heating power delivered by the induction heating system can be effectively adjusted by altering the excitation frequency, the coil current, the number of coil turns, or the position of the coil with respect to the workpiece. These parameters collectively govern the efficiency and intensity of electromagnetic induction and thus play a crucial role in controlling the thermal behavior of the system.

Based on this, the paper proposes and verifies an “HF-Large Current” collaborative enhancement instrument design scheme: The inverter switching frequency

is extended from the commonly used 10-30 kHz to 110 kHz. This uses a 110 kHz large current ZCS-IGBT series resonance with 33 ns DSP all-digital phase-locking, achieving an efficiency of $\geq 95\%$ and a power factor of ≥ 0.87 . The dual-channel redundancy and 5 μs hardware protection ensure a 99.9% availability. It also includes a built-in 4–20 mA temperature closed-loop and segmented programming, with a temperature control accuracy of 1%FS, providing a high-efficiency and highly reliable integrated heat source for high-power mobile output scenarios.

The prototype induction heating device designed using the “high-frequency - large current” collaborative enhancement concept is shown in [Figure 3: see original paper]. The induction coil is excited by a sinusoidal alternating current with a frequency of 110 kHz and a current amplitude of 700 A. The coil is made of a highly conductive metal. To prevent excessive temperature rise in the coil during continuous operation, an internal water-cooling channel is incorporated into the model. This is implemented by defining a fluid domain within the coil and applying either a constant temperature boundary condition or a forced convection condition to simulate the flow of cooling water. The cooling system ensures thermal stability of the coil during operation and enhances the overall heating efficiency and reliability of the simulation.

and list the parameters for the induction coil and heated samples, respectively. The inlet temperature of the cooling water is set to 10°C, with a mass flow rate of 0.01 kg/s. This thermal management strategy plays a critical role in maintaining coil performance and ensuring accurate prediction of the thermal field distribution in the workpiece. The system is built with a PID closed-loop control for accurate temperature management. The temperature reading is done using a platinum-rhodium thermocouple fixed to the test workpiece, with the option of replacing it with an infrared thermometer if needed. This design ensures precision and flexibility, adapting to various heating processes with reliable, real-time feedback and control.

By significantly increasing the frequency from 30 kHz to 110 kHz, the system achieves a heating rate of up to 200°C/s, reducing the high-temperature dwell time from several tens of seconds to just a few seconds. This rapid thermal response provides reproducible and instantaneous temperature profiles for in-situ loading experiments. The combination of fast heating and precise temperature control enables material behavior studies under dynamic thermo-mechanical coupling conditions, offering enhanced temporal resolution and data reliability. Additionally, the reduction in heating time and convection-radiation losses leads to a decrease in overall energy consumption. Significant synergistic optimization is achieved in process precision and characterization data quality, realizing the transition from traditional prolonged heating to an instantaneous, precise, and energy-efficient heating mode.

Induction Heating Simulation

To investigate the coupling mechanism between the electromagnetic field and the temperature field within a metal workpiece during the induction heating process, a three-dimensional model was established using the COMSOL Multiphysics simulation platform, as shown in [Figure 4: see original paper]. This model systematically simulates the electromagnetic-thermal interactions between the induction coil and the cylindrical metal workpiece. The geometry includes the induction coil, the workpiece, and the surrounding air domain. An insulation gap is defined between the coil and the workpiece to replicate the actual non-contact heating scenario. See and for model-related geometric parameters.

The simulation employs the “Magnetic Fields” and “Heat Transfer in Solids” physics interfaces, with a fully coupled solution approach to ensure real-time feedback between the electromagnetic and thermal phenomena. The simulated metal material is tantalum. In terms of material properties, the workpiece was assigned temperature-dependent parameters, including electrical conductivity, thermal conductivity, specific heat capacity, and density. These properties were implemented in COMSOL via interpolation functions to ensure accurate modeling of the material response under high-temperature conditions.

To better reflect realistic thermal boundary conditions, natural convection was applied to the outer surface of the workpiece, with a heat transfer coefficient set at $10 \text{ W/m}^2 \cdot \text{K}$. In addition, a surface-to-ambient radiation model was activated under high-temperature conditions to account for radiative heat losses from the workpiece to the environment. The initial temperature of the entire model was set to 298 K. A time-dependent heat transfer solver was used to perform transient thermal simulations, with a total simulation time of 20 minutes. The time step was adaptively controlled to balance computational efficiency and solution accuracy.

To ensure the accuracy of the electromagnetic and temperature field calculations, especially in regions where eddy currents and heat are concentrated (such as the surface of the metal workpiece and areas near the induction coil), a reasonable mesh strategy was employed in the model. In this study, the physics-controlled mesh generation method provided by COMSOL was used, combined with adaptive refinement in critical regions, to create a multi-scale mesh across the entire computational domain.

At the surface of the tantalum workpiece, due to the significant skin effect induced by the high-frequency current excitation, eddy currents primarily concentrate in a thin surface layer, typically on the order of millimeters or smaller. Therefore, a high-density mesh was generated in this region to capture the rapid variations in both current and temperature. In contrast, coarser mesh elements were used in regions farther from the excitation source and in non-critical areas of the structure, in order to reduce the overall computational load and improve simulation efficiency.

To ensure the accuracy of the numerical simulation, a mesh independence verification was conducted using three different mesh densities, consisting of approximately 67,991, 131,691, and 296,302 elements, respectively. [Figure 5: see original paper] illustrates the temperature evolution of the heated rod over time under each mesh configuration. As shown in the figure, the simulation results obtained using 131,691 and 296,302 elements are nearly identical, indicating that further mesh refinement has a negligible effect on the outcome. Therefore, considering both computational cost and result accuracy, the mesh with 131,691 elements was selected for subsequent simulation studies.

In practical applications, heating efficiency and temperature control precision directly affect the stability of the process and the final performance. As a core energy coupling component in the induction heating system, the structural parameters of the coil have a significant impact on the distribution of the electromagnetic field and the path of eddy currents, which in turn significantly affect the generation of Joule heating and the distribution of the temperature field. Therefore, systematically studying the impact of structural factors, such as the number of coil turns and the distance between the coil and the workpiece, on heating capacity is essential for optimizing the design of induction heating systems and improving heating efficiency and temperature uniformity. This is of great engineering application value and theoretical significance.

To this end, in this study, four different coil structure parameters were simulated and compared under the same excitation current (700 A) and frequency (30 kHz) conditions, with the results shown in [Figure 6: see original paper]. The results clearly demonstrate that the coil structure has a significant impact on both the heating rate and the final temperature. Particularly, when the coil has 3 turns and the distance between the coil and the workpiece is 20 mm, the temperature rises the fastest, with the final stable temperature reaching approximately 1480 K, showing the strongest heating capacity. In contrast, when the coil has 2 turns and the distance between the coil and the workpiece is 30 mm, the temperature rises more slowly, with the final steady-state temperature being only around 1000 K. The heating rates for the four different coil structures are 118 K/min, 84 K/min, 65 K/min, and 40 K/min, respectively.

The analysis indicates that, under the same conditions, increasing the number of coil turns effectively enhances the intensity of the alternating magnetic field, thereby increasing the induced electromotive force within a unit volume, which further intensifies the generation of eddy currents and releases more Joule heat. At the same time, reducing the distance between the coil and the workpiece helps improve the coupling efficiency of the magnetic field with the workpiece, allowing the electromagnetic energy to be more efficiently transferred to the metal. Increasing the number of turns or decreasing the distance between the coil and the workpiece not only accelerates the temperature rise rate but also significantly shortens the time required to reach steady-state temperature, indicating a high sensitivity of the induction heating system to structural design optimization.

Therefore, in practical engineering design, the coil configuration with more turns and a smaller distance between the coil and the workpiece should be prioritized, based on specific requirements, to achieve higher heating efficiency and shorter heating times. The results of this study provide strong theoretical support for the structural optimization of induction heating systems and serve as an important reference for achieving precise target temperature control, localized heating, and multi-stage power adjustment.

In the experiment investigating the influence of heating frequency on the performance of an induction heating system, we have selected a coil structure with 2 turns and a 20-millimeter gap between the coil and the workpiece. This selection is based on a comprehensive consideration of multiple factors. From the perspective of coil turns, a 2-turn coil can generate a moderate magnetic field strength while meeting the basic requirements for induction heating. This not only ensures that sufficient eddy currents are induced in the workpiece to achieve heating but also avoids the issues of increased system inductance and reduced power factor that may arise from an excessive number of turns. Moreover, the simplicity of this coil structure facilitates experimental operation and control, reduces experimental costs, and makes heat dissipation easier, thereby contributing to the stable operation of the experimental system. Regarding the gap, the 20-millimeter spacing is carefully designed. This spacing ensures effective magnetic field coupling to the workpiece, preventing local overheating of the workpiece surface due to excessively small gaps and magnetic field energy loss due to excessively large gaps. Additionally, the 20-millimeter spacing accommodates workpieces of various sizes and shapes, enhancing the universality of the experimental results. It also prevents collisions between the workpiece and the coil during the heating process due to thermal expansion, ensuring the safety of the experiment and the stability of the system.

Considering the above factors, we have chosen a coil structure with 2 turns and a 20-millimeter gap between the coil and the workpiece to further investigate the impact of heating frequency on the performance of the induction heating system. To validate the advantages of the 110 kHz high-frequency induction heating device we designed in terms of rapid heating, a comparative analysis was conducted between it and a conventional 30 kHz heating system under the same operating conditions. The study primarily focused on examining the effects of frequency variation on energy coupling efficiency, the distribution of eddy currents within the workpiece, and the rate of temperature rise, in order to reveal the potential benefits of high-frequency induction heating in improving heating response time and thermal efficiency.

As depicted in [Figure 7: see original paper], the 110 kHz induction heating achieves a temperature rise of 200 K every 5 min, doubling the 100 K/5 min rate observed at 30 kHz. [Figure 8: see original paper] further reveals that the current density peaks at 6×10^6 A/m² and is confined to the surface layer at 110 kHz, whereas the 30 kHz profile exhibits a lower, more gradual radial decay. Therefore, increasing the frequency can not only effectively accelerate

the heating process but also significantly enhance the skin effect. Under the configuration of 110 kHz, the induction heating efficiency is greatly improved, providing a more efficient and energy-saving solution for relevant applications.

To fully and deeply analyze the heating behavior under the 110 kHz configuration, we have conducted multidimensional investigation work. We have not only monitored the dynamic variation trend of the heating power but also measured the steady-state radial temperature distribution along the central diameter direction. In addition, we have carried out a detailed analysis of the corresponding distribution between the overall temperature and the magnetic flux density.

[Figure 9: see original paper] summarizes the induction-heating behavior at 110 kHz. The panel sequence provides the three-dimensional temperature field, three-dimensional magnetic-flux-density field, two-dimensional temperature contour, two-dimensional magnetic-flux-density contour, instantaneous heating-power curve, and the steady-state temperature distribution along the diameter at the geometric centre. In electromagnetic induction heating systems, numerical simulation techniques enable us to analyze the distribution of magnetic flux density and temperature. The transient response of the heating power curve at system startup, although initially exhibiting an overshoot phenomenon, rapidly decays within a certain timeframe, demonstrating the system's ability to quickly achieve electromagnetic-thermal equilibrium. The radial temperature distribution features a typical saddle shape, which is the result of the combined effects of surface convection cooling and axial heat conduction, with the surface forming a shallow temperature minimum due to convective heat dissipation. This temperature distribution characteristic is crucial for understanding and predicting the thermodynamic behavior during the heating process and also confirms the rapid establishment of electromagnetic-thermal equilibrium, which is of significant importance for improving heating efficiency and ensuring heating quality.

Induction Heating Experimental Test

To evaluate the rapid heating performance of the designed induction heating system, an experimental platform was established in this study, as illustrated in [Figure 10: see original paper]. This platform was specifically developed to systematically verify the heating efficiency of the high-frequency induction system and to enable the synchronized control of heating and mechanical loading processes. The platform integrates the high-frequency induction heating module, mechanical loading unit, precision temperature monitoring system, closed-loop water cooling system, and a supervisory control platform, providing a stable and high-responsive testing environment for high-temperature thermomechanical coupling experiments.

Before the experiment begins, a comprehensive inspection and preheating of the equipment are conducted to ensure the proper operation of all modules. Special

attention is given to the induction heating system's power supply, coil, water cooling system pipes, and temperature control system, all of which undergo rigorous checks to prevent issues such as overheating or energy overload during the experiment. Simultaneously, the mechanical loading system is calibrated to confirm that its loading accuracy and range meet the experimental requirements. During this process, the surface of the specimen is cleaned and polished to remove oxides and oil, ensuring the accuracy and consistency of both temperature measurement and mechanical loading.

Once the experiment begins, the induction heating system is activated, and the output frequency and power of the power supply are set. The specimen is then subjected to induction heating via a dual-turn copper coil. At a frequency of 110 kHz, the system rapidly heats the specimen surface to the desired temperature (typically between 1000 K and 1400 K), with temperature accuracy monitored in real time. To avoid interference during temperature measurement, the system is equipped with an infrared non-contact temperature sensor and a K-type thermocouple, and the real-time data is fed back to the control platform for calibration and validation. Temperature data is recorded every second to ensure continuous monitoring of dynamic temperature changes, with the system capable of automatically adjusting the heating parameters as required. Additionally, power, frequency, and other electrical parameters of the induction heating process are recorded synchronously for subsequent data analysis and verification.

While the induction heating system operates stably, the mechanical loading system is activated. The loading force starts from 0 N and gradually increases. The loading process is precisely controlled by an electronic servo universal testing machine, which applies axial tension or compression at a set rate, with different loading modes switched according to the experimental design. All force and displacement data during the loading process are continuously collected by sensors, ensuring the accuracy and consistency of the parameters throughout the loading phase.

The core of the experiment is the thermomechanical coupling process, during which the high temperature induced by the heating and the mechanical loading simultaneously act on the specimen, simulating real-world working conditions. The high-frequency current generates a strong skin effect, causing the specimen's surface temperature to rise rapidly. Concurrently, due to the applied mechanical loading, the specimen undergoes deformation, and the material's microstructure, strength, and deformation behavior change significantly with varying temperature and stress. Once the experiment reaches the predetermined duration, the loading process ends, and the induction heating system is turned off, completing the thermomechanical coupling experiment.

To systematically verify the rapid heating performance, a frequency comparison group was established in this experiment, using identical coil structures and loading parameters to conduct comparative tests at frequencies of 110 kHz and 30 kHz. The experimental results, as shown in [Figure 11: see original paper], indicate that at 110 kHz, the induction heating system is able to heat the specimen

to the target temperature in a shorter time, with a higher heating rate. Under high-frequency excitation, the skin effect is enhanced, resulting in a higher density of circulating currents on the specimen's surface. This effect significantly increases the power density of Joule heating, thereby effectively improving the efficiency of heat energy input. This characteristic not only accelerates the heating process of the specimen but also provides a uniform high-temperature environment for the subsequent loading process, ensuring the stability and consistency of the heating procedure.

Subsequently, to ascertain the viability of force-thermal loading, we conducted an experiment on 310S stainless steel under force-thermal conditions, as depicted in [Figure 12: see original paper], which illustrates the stress-strain curve obtained from tensile testing of 310S stainless steel at 800°C. This curve meticulously delineates the entire deformation process of the material, transitioning from the elastic to the plastic phase and culminating in fracture. At the onset, the curve exhibits a steep slope, indicative of the material's elastic behavior. As strain progresses, the slope diminishes gradually, signifying the onset of plastic deformation where the rate of stress increment slows down. The curve reveals a yield strength of 277 MPa for the material, beyond which a decline is observed, signifying the initiation of necking prior to fracture. Additionally, the curve denotes a fracture elongation of 19.6%, reflecting the ductility of the material before rupture. These experimental findings are instrumental in evaluating the mechanical properties of 310S stainless steel under high-temperature conditions, particularly in research scenarios necessitating precise temperature control and rapid thermal response, such as dynamic high-temperature loading, stress measurement, and in-situ monitoring of material behavior.

In neutron scattering experiments, it is crucial to ensure that the induction heating device does not significantly affect the scattering results of the sample. To this end, we designed an experiment to assess whether the introduction of the induction heating device would introduce additional diffraction peaks in the scattering pattern. The experimental setup is shown in [Figure 13: see original paper]. In the experiment, we used vanadium-nickel alloy samples and recorded the neutron scattering data of the vanadium-nickel alloy samples under the combined action of the materials testing system (MTS system) and the induction heating device, as well as under the action of the MTS system alone, as shown in [Figure 14: see original paper]. By subtracting the control group data from the experimental group data, we were able to effectively eliminate the scattering signals from other devices, thereby revealing the scattering contribution of the induction heating device. After performing a difference analysis on the two sets of data and normalizing the differences, we obtained a straight line close to 1 as shown in [Figure 15: see original paper], which clearly indicates that the introduction of the induction heating device did not introduce additional diffraction peaks in the scattering pattern and had no significant impact on the scattering results of the samples. Through experimental verification, the induction heating device we designed had no significant impact on the scattering results of vanadium-nickel alloy samples in neutron scattering experiments, especially

not introducing any extra diffraction peaks. This conclusion not only proves the reliability of the induction heating device but also provides an important reference for future high-temperature mechanical property tests.

Summary

This study presents a high-frequency induction heating scheme. After rigorous validation through theoretical analysis, simulation studies, and experimental verification, the scheme has demonstrated significant improvements in heating rate and temperature control accuracy, effectively overcoming the limitations of conventional heating systems. By increasing the frequency to 110 kHz and employing a high-current zero-voltage switching (ZCS) IGBT series resonant converter, this study has successfully achieved efficient compression of electromagnetic energy into the submillimeter surface layer. This not only significantly enhances the thermal flux density but also greatly increases the heating rate.

Both simulation and experimental results consistently show that, under the same power conditions, the high-frequency heating technology can rapidly heat samples to higher temperatures. When reaching the same target temperature, the technology exhibits a faster heating rate and higher stability. This characteristic is crucial for in situ characterization experiments, as it provides repeatable and precise temperature profiles, significantly improving the temporal resolution and data quality of the experiments. In neutron scattering experiments, the induction heating device designed in this study exhibits low background characteristics, making it suitable for application on neutron diffractometers, thereby ensuring the integrity and accuracy of sample data. Compared with traditional low-frequency heating systems, the high-frequency technology adopted in this study shows clear advantages in energy efficiency and control accuracy. The technology has broad application prospects and significant engineering value in fields such as low-carbon precision heat treatment, high-temperature material testing, and advanced in situ characterization.

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