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

Preamble

Real-Time Temperature Control and Performance Optimization of an Induction Heating System for In-Situ Neutron Experiments∗ Yaojun Guan,1, 2, † Bin Li,2, 3, 4, † Haoran Chen,5, 2, 4, † Linjin Deng,2, 6, 4 Wenbin Zhong,2, 4, 3 Fan Ye,2,

4, 3 Mengjia Dou,2, 4, 3 Bo Bai,2, 4, 3 Xiaohu Li,2, 4, 3 Yi Zhang,1 Xiaoyue Zhang,1 Xinzhi Liu,1 Mengyu He,7, 2 Hui Cheng,2, 4, 3, ‡ Haitao Hu,2, 4, 3, § and Xin Tong2, 4, 3, ¶

Guangdong Provincial Key Laboratory of Magnetoelectric Physics and Devices, School of Physics, Sun Yat-sen University, Guangzhou 510275, China Spallation Neutron Source Science Center, Dongguan, 523803, China Institute of High Energy Physics, Chinese Academy of Sciences (CAS), Beijing, 100049, China Guangdong Provincial Key Laboratory of Extreme Conditions, Dongguan, 523803, China Northeastern University, No3-11 Wenhua Road, Heping District, Shenyang, Liaoning, 110819, China Dongguan University of Technology, Dongguan, 523808, China University of California, Merced 5200 North Lake Rd, Merced, CA 95343, United States Induction heating is an non-contact heat source widely used in advanced thermal manufacturing and in-situ high-temperature characterization, yet conventional low-/mid-frequency systems suffer from large skin depth and diffuse energy deposition,which limits heating rate and spatial localization. To overcome this limitation, we developed a high-frequency, high-current synergistic intensification strategy. The inverter frequency is elevated to the hundred-kilohertz range and paired with a large-current zero-current-switching (ZCS) IGBT seriesresonant converter. This configuration compresses electromagnetic energy into a sub-millimetre surface layer, yielding a marked increase in both heat-flux density and heating rate. A full-digital phase-locked loop together with dual-redundant protection guarantees stable high-current output at elevated frequencies. Theoretical analysis, multiphysics simulations, and comparative experiments consistently demonstrate that the system 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

to precisely capture of mechanical responses and microstructure evolution during the rapid heating process [14], the cou20 pling of neutron instruments with thermomechanical loading Understanding the mechanical behavior and microstruc21 systems—particularly heating devices with rapid temperature 3 tural evolution of materials under extreme thermal condi22 rise capabilities—has become increasingly crucial [15, 16]. 4 tions is a central challenge in aerospace, automotive man5 ufacturing, and energy applications [1, 2].

Neutron scat- 23 Traditional heating devices mainly include infrared heating 6 tering technology [3] not only plays an important role in 24 and resistance heating [17, 18]. Among these, resistance heat7 fields such as physics [4, 5], biology [6], archaeology [7], 25 ing primarily raises the sample temperature by leveraging the 8 and chemistry [8], but also serves as a crucial detection

26 inherent electrical resistance of the material [19, 20], while 9 and analysis tool in the field of materials science research 27 infrared heating mainly relies on the principle of thermal ra10 [9, 10].Neutron diffractometers are especially valuable for 28 diation to indirectly heat materials [21, 22].Resistance heat11 probing microstructure and mechanical behavior under both 29 ing typically exhibits low heating and cooling rates, which 12 ambient and high-temperature conditions [11–13].

With 30 leads to prolonged experimental cycles [23, 24]. More13 the growing focus on transient non-equilibrium processes, 31 over, different types of resistance wires have distinct oper14 rapid heating has become a widely adopted method in high32 ating temperature ranges, and they are prone to oxidation 15 temperature material research for simulating extreme ther33 at high temperatures, which results in short service lives 16 mal loads.To achieve real-time dynamic monitoring of ma34 of heating elements and restricts the temperature range for 17 terials under extreme high-temperature conditions, especially 35 high-temperature experiments [25, 26].Infrared heating, how36 ever, suffers from nonuniform temperature field and limited 37 temperature-control accuracy. Additionally, due to the diver∗ This work was supported by the National Key R&D Program of China 38 sity of test materials, it shows poor heating efficiency when (No. 2022YFA1604104), the Youth Innovation Promotion Association of 39 dealing with materials that have low infrared absorption rates the Chinese Academy of Sciences, the National Natural Science Foun40 [27, 28].

INTRODUCTION

dation of China (12427803, 12425512, and 12575323), the Guangdong Provincial Key Laboratory of Magnetoelectric Physics and Devices (No. 2022B1212010008), the Research Center for Magnetoelectric Physics of Guangdong Province (2024B0303390001), and the Guangdong Provincial Key Laboratory of Extreme Conditions (2023B1212010002). † The authors contribute equally. ‡ Corresponding author,chenghui@ihep.ac.cn § Corresponding author,huht@ihep.ac.cn ¶ Corresponding author,tongxin@ihep.ac.cn

As a non-contact, efficient, and controllable heating technology, induction heating has gradually replaced traditional 43 heating methods in recent years and become one of the pri44 mary heating means in high-temperature material research 45 [29, 30]. A key advantage of induction heating is that the en46 ergy is delivered directly on the target, which significantly re47 duces heat loss, improves heating efficiency and shortens the

heating duration [31, 32].Furthermore, by adjusting the coil 106 mance advantages of this scheme, this paper combines thegeometry and control systems parameter, induction heating 107 oretical modeling and experimental testing to conduct a sys50 can precisely regulate the heating area and the temperature 108 tematic evaluation of the system from multiple dimensions, 51 gradient to meet specific experimental requirements. This en- 109 including electromagnetic coupling, heat transfer behavior, 52 ables it to meet the stringent requirements for heating preci- 110 and temperature control feedback response. 53 sion and dynamic response in high-temperature material re- 111 The implementation of this research not only helps to im54 search [33, 34]. 112 prove the overall experimental efficiency and testing accuracy Recently, a variety of high-temperature heating technolo- 113 of neutron diffractometers, but also provides strong technical 56 gies have been applied into neutron diffractometer experi- 114 support for the accurate investigation of the service behav57 ments to support precise material testing in elevated temper- 115 ior of materials in complex thermomechanical environments, 58 ature. The ENGIN-X instrument at the ISIS Laboratory em- 116 thus carrying important theoretical and engineering applica59 ploys an infrared-heated high-temperature furnace, equipped 117 tion value. 60 with four 2 kW infrared heaters, and its maximum heating 61 temperature can reach up to 1373 K [35, 36].By contrast, the 62 VULCAN instrument at the SNS Laboratory in the United 118 II. INTRODUCTION TO THE OVERALL DESIGN AND MECHANISM OF THE INSTRUMENT 63 States integrates three heating devices, including a standalone 119 64 high-temperature furnace, a resistance-heated gas-tight load 65 frame furnace, and an auxiliary induction heating coil. These 121 grates an advanced engineering large-sample loading device 67 the resistance-heated gas-tight load frame furnace features a 122 with induction heating equipment, providing a versatile ex68 relatively high heating rate, capable of achieving a temper123 perimental platform for materials science research. This plat69 ature rise of up to 600 °C/s [37].At the J-PARC Laboratory 124 form is capable of simultaneously applying stress and induc70 in Japan, the PLANET instrument employs a heater powered 125 tion heating to materials, effectively simulating the complex 71 by embedded high-voltage batteries, with a maximum achiev126 environmental conditions encountered in practical applica72 able temperature of 2000 K. In contrast, the TAKUMI instru127 tions. To address the limitations of existing heating devices 73 ment uses an infrared heating device, which is limited to a 128 in terms of rapid temperature increase capabilities, we will 74 maximum heating temperature of 1273 K [38]. 129 delve into the principles of induction heating technology, fo75 At the China Spallation Neutron Source (CSNS) ,the cur- 130 cusing on the optimization of high-frequency induction tech76 rent high-temperature sample environment systems include a 131 niques, enhancement of thermal field uniformity, and the in77 pulsed laser heating furnace and an ultra-high-temperature in- 132 telligent control of temperature systems, with the aim of sig78 duction heating device . The pulsed laser heating furnace has 133 nificantly improving heating efficiency and precision, thereby 79 a rated output power range of 100 - 2000 W, a maximum con- 134 better serving research and development in the field of mate80 trollable heating temperature of 1800 °C, and a heating rate 135 rials science. 81 ranging from 80 °C/s - 150 °C/s [39].The induction heating 82 device, by contrast, can reach 2700 K with a heating power 83 of 60 kW, placing it among the highest-temperatures induc84 tion furnaces currently reported in this field [40].However, 85 this induction heating device is primarily used for research 86 on high-temperature microstructures and macroscopic prop87 erties, and it can-not meet the requirements of experiments 88 such as strain measurement [41] and residual stress distribu89 tion measurement [42].These experiments require rapid heat90 ing to minimize stress relaxation and microstructural changes 91 during temperature ramping, as well as precise temperature 92 control to avoid thermal gradients that introduce artifacts in 93 strain measurements.

Addressing the insufficiency of existing heating devices in 95 rapid temperature rise capability, this study focuses on key 96 technical issues such as the optimization of high-frequency 97 induction technology, enhancement of thermal field uniforFig. 1 [FIGURE:1]. Engineering Material Diffractometer coupled with induction 98 mity, and intelligentization of temperature control systems, heating equipment design diagram: 1) neutron beam, 2) induction 99 and proposes an innovative rapid temperature rise induction heating coil, 3) test workpiece, 4) induction heating water-cooled 100 heating scheme. This scheme aims to significantly improve module, 5) stress loader clamping head, 6) neutron scattering space 101 heating rate, temperature control accuracy, and thermal field angle. 102 stability, thereby meeting the requirements of diffractometer 103 experiments—including those for material dynamic response, 104 strain measurement, and residual stress analysis—under high- 136 Induction heating technology is based on the principle of 105 temperature conditions. To verify the feasibility and perfor- 137 electromagnetic induction.

When an alternating current i

flows through the induction coil, it generates an alternating 174 The Root Mean Square value of the induced electromotive magnetic field within the coil. A workpiece placed within 175 force is then given by: 140 this alternating magnetic field experiences an induced elec2πf N Φm N Φm ω 141 tromotive force e, which in turn gives rise to eddy currents 176 = 4.44N f Φm 142 within the workpiece. Due to the eddy current effect and the 143 inherent equivalent resistance R of the metal material, ther- 177 Where E is the effective value of the induced electromotive 144 mal energy is generated internally, thereby achieving the goal 178 force,and f is the frequency of the energizing current of the 145 of heating the workpiece. 179 induction coil. The induction electromotive force drives cur146 During the heating process, induction heating transfers 180 rent within the metal workpiece and thereby generates the 147 electrical energy from the induction coil to the metallic work- 181 Joule heat during heating.

The generated heat can be ex148 piece, which is then converted into thermal energy within the 182 pressed as: 149 workpiece itself. This energy transfer is accomplished via 150 electromagnetic induction, without direct physical contact beQ = 0.24P t = 0.24I 2 Rt 151 tween the coil and the workpiece. As such, induction heating 0.24E 2 152 is classified as a non-contact heating method. The working 153 process diagram of induction heating is shown in Fig. 2 [FIGURE:2] . 4.73f N Φm Rt 184 Where Q is the generated Joule heat in calories (cal), P is the 185 output power of the induction heating device, t is the ener186 gization time of the induction coil when the metal workpiece 187 is heated, I is the rms value of the induction current, R is 188 the equivalent resistance of the metal workpiece, and Z is the 189 equivalent impedance modulus of the metal workpiece.

According to the equations above, when the properties 191 and geometry of the metal workpiece remain unchanged, the 192 amount of heat generated within the workpiece depends pri193 marily on the frequency f of the current supplied to the in194 duction coil, as well as the magnetic flux. The magnetic flux 195 itself is determined by multiple factors, including the magni196 tude of the current flowing through the coil, the number of 197 turns in the heating coil, and its spatial orientation relative to When the sinusoidal current i in the induction coil varies at 198 the workpiece.

Therefore, for a given metal workpiece, the heating power 155 a specific frequency, the resulting alternating magnetic field 200 delivered by the induction heating system can be effectively 156 generated within the coil will exhibit the same frequency as 201 adjusted by altering the excitation frequency, the coil current, 157 the input current. This time-varying magnetic field induces 202 the number of coil turns, or the position of the coil with re158 a magnetic flux Φ through the workpiece, which can be ex203 spect to the workpiece. These parameters collectively govern 159 pressed by the following formula [43], 204 the efficiency and intensity of electromagnetic induction and 205 thus play a crucial role in controlling the thermal behavior of $\Phi = \Phi m \sin(\omega t)$ (1) 206 the system.

Based on this analysis, the paper proposes and verifies an 161 Where Φ is the magnetic flux in the induction coil; Φm is 208 "HF-Large Current" (High-Frequency Large Current) collab162 the amplitude of the alternating flux; and ω is the current an- 209 orative enhancement instrument design scheme: The inverter 163 gular frequency. The alternating magnetic flux generated by 210 switching frequency is extended from the commonly used 10164 the induction coil induces an electromotive force (EMF) e in 211 30 kHz to 110 kHz. The system uses a 110 kHz large current 165 the workpiece via the principle of electromagnetic induction. 212 ZCS-IGBT (Zero-Current Switching Insulated Gate Bipolar 166 This induced EMF can be described by Faraday' s law as fol-213 Transistor) series resonance with 33 ns DSP(Digital Signal 167 lows, 214 Processor) all-digital phase-locking, achieving an efficiency 215 of $\geq 95\%$ and a power factor of ≥ 0.87. The dual-channel $e = -N$ (2) 216 redundancy and 5 µs hardware protection ensure a 99.9% 217 availability.

It also includes a built-in 4-20 mA tempera218 ture closed-loop and segmented programming, with a tem169 Where e is the induced electromotive force,and N is the 219 perature control accuracy of 1%FS(Full Scale), providing a 170 equivalent number of turns of the workpiece. Substituting 220 high-efficiency and highly reliable integrated heat source for 171 Eq. (1) into Eq. (2) gives the induced electromotive force as 221 high-power mobile output scenarios. 172 follows, The prototype induction heating device designed using the $e = -N \Phi m \omega \cos(\omega t)$ (3) 223 "high-frequency - large current" collaborative enhancement

Figure 3

Figure 1: Figure 3

concept is shown in Fig. 3

. The system is built with a 266 electromagnetic excitation and thermal response. The inducPID(Proportional-Integral-Derivative) closed-loop control for 267 tion coil is excited by a sinusoidal alternating current with 226 accurate temperature management. The temperature reading 268 a frequency of 110 kHz and a current amplitude of 700 A. 227 is done using a K-type thermocouple fixed to the test work- 269 The coil is made of a highly conductive metal. To prevent 228 piece, with the option of replacing it with an infrared ther- 270 excessive temperature rise in the coil during continuous oper229 mometer if needed. This design ensures precision and flex- 271 ation, an internal water-cooling channel is incorporated into 230 ibility, adapting to various heating processes with reliable, 272 the model. This is implemented by defining a fluid domain 273 within the coil and applying either a constant temperature 231 real-time feedback and control. 274 boundary condition or a forced convection condition to sim275 ulate the flow of cooling water. The cooling system ensures 276 thermal stability of the coil during operation and enhances the 277 overall heating efficiency and reliability of the simulation.

computer; (c) power control; (d) induction heating coils and trans232 former.

coil geometry parameters number of turns of coil (turns) coil spacing (mm) distance between two coils (mm) large coil radius (mm) radius of the metal tube of the induction coil (mm)

By significantly increasing the frequency from 30 kHz to heated bar geometry parameters 235 110 kHz, the system achieves a heating rate of up to 200°C/s, radius 236 reducing the high-temperature dwell time from several tens length (mm) 237 of seconds to just a few seconds.

This rapid thermal rethermal conductivity W/(m • K) 238 sponse provides reproducible and instantaneous temperature 239 profiles for in-situ loading experiments. The combination of The inlet temperature of the cooling water is set to 10 ∘ C, 240 fast heating and precise temperature control enables mate279 with a mass flow rate of 0.01 kg/s. This thermal management 241 rial behavior studies under dynamic thermo-mechanical cou280 strategy plays a critical role in maintaining coil performance 242 pling conditions, offering enhanced temporal resolution and 281 and ensuring accurate prediction of the thermal field distribu243 data reliability. Additionally, the reduction in heating time 282 tion in the workpiece. 244 and convection-radiation losses leads to a decrease in overall 245 energy consumption. Significant synergistic optimization is 246 achieved in process precision and characterization data qual247 ity, realizing the transition from traditional prolonged heat248 ing to an instantaneous, precise, and energy-efficient heating 249 mode.

INDUCTION HEATING SIMULATION

To investigate the coupling mechanism between the electromagnetic field and the temperature field within a metal 253 workpiece during the induction heating process, a three254 dimensional model was established using the COMSOL MulFig. 4 [FIGURE:4]. Induction heating geometry model. 255 tiphysics simulation platform, as shown in Fig. 4. This model 256 systematically simulates the electromagnetic-thermal interac257 tions between the induction coil and the cylindrical metal 283 The simulated metal material is tantalum. In terms of ma258 workpiece.

The geometry includes the induction coil, the 284 terial properties, the workpiece was assigned temperature259 workpiece, and the surrounding air domain. An insulation 285 dependent parameters, including electrical conductivity, ther260 gap is defined between the coil and the workpiece to repli- 286 mal conductivity, specific heat capacity, and density. These 261 cate the actual non-contact heating scenario. See Table 1 and 287 properties were implemented in COMSOL via interpolation 262 Table 2 for model-related geometric parameters. 288 functions to ensure accurate modeling of the material re263 The simulation employs the "Magnetic Fields" and "Heat 289 sponse under high-temperature conditions. 264 Transfer in Solids" physics interfaces, with a fully coupled 290 To better reflect realistic thermal boundary conditions, nat265 solution approach to ensure real-time feedback between the 291 ural convection was applied to the outer surface of the work251

piece, with a heat transfer coefficient set at 10 W/m2 ·K. In addition, a surface-to-ambient radiation model was activated un294 der high-temperature conditions to account for radiative heat 295 losses from the workpiece to the environment.

The initial temperature of the entire model was set to 297 298 K.

A time-dependent heat transfer solver was used to 298 perform transient thermal simulations, with a total simulation 299 time of 20 minutes. The time step was adaptively controlled 300 to balance computational efficiency and solution accuracy.

To ensure the accuracy of the electromagnetic and temper302 ature field calculations, especially in regions where eddy cur303 rents and heat are concentrated (such as the surface of the 304 metal workpiece and areas near the induction coil), a reason305 able mesh strategy was employed in the model. In this study, 306 the physics-controlled mesh generation method provided by 307 COMSOL was used, combined with adaptive refinement in 308 critical regions, to create a multi-scale mesh across the entire 309 computational domain.

At the surface of the tantalum workpiece, due to the sig311 nificant skin effect induced by the high-frequency current ex312 citation, eddy currents primarily concentrate in a thin surface 350 strate that the coil structure has a significant impact on both 313 layer, typically on the order of millimeters or smaller.

There351 the heating rate and the final temperature. Particularly, when 314 fore, a high-density mesh was generated in this region to cap352 the coil has 3 turns and the distance between the coil and the 315 ture the rapid variations in both current and temperature. In 353 workpiece is 20 mm, the temperature rises the fastest, with 316 contrast, coarser mesh elements were used in regions farther 354 the final stable temperature reaching approximately 1480 K, 317 from the excitation source and in non-critical areas of the 355 showing the strongest heating capacity.

In contrast, when 318 structure, in order to reduce the overall computational load 356 the coil has 2 turns and the distance between the coil and the 319 and improve simulation efficiency.

To ensure the accuracy of the numerical simulation, a mesh 357 workpiece is 30 mm, the temperature rises more slowly, with 358 the final steady-state temperature being only around 1000 K. 321 independence verification was conducted using three different 359 The average heating rates for the four different coil structures 322 mesh densities, consisting of approximately 67991, 131691, 360 are 118 K/min, 84 K/min, 65 K/min, and 40 K/min, respec323 and 296302 elements, respectively. Fig. 5 [FIGURE:5] illustrates the tem361 tively. 324 perature evolution of the heated rod over time under each 325 mesh configuration. As shown in the figure, the simulation re326 sults obtained using 131691 and 296302 elements are nearly 327 identical, indicating that further mesh refinement has a neg328 ligible effect on the outcome. Therefore, considering both 329 computational cost and result accuracy, the mesh with 131691 330 elements was selected for subsequent simulation studies.

In practical applications, heating efficiency and tempera332 ture control precision directly affect the stability of the pro333 cess and the final performance. As a core energy coupling 334 component in the induction heating system, the structural pa335 rameters of the coil have a significant impact on the distri336 bution of the electromagnetic field and the path of eddy cur337 rents, which in turn significantly affect the generation of Joule 338 heating and the distribution of the temperature field. There339 fore, systematically studying the impact of structural factors, 340 such as the number of coil turns and the distance between the 341 coil and the workpiece, on heating capacity is essential for 342 optimizing the design of induction heating systems and im343 proving heating efficiency and temperature uniformity. This 344 is of great engineering application value and theoretical sig345 nificance.

To this end, in this study, four different coil structure pa- 362 The analysis indicates that, under the same conditions, in347 rameters were simulated and compared under the same ex- 363 creasing the number of coil turns effectively enhances the in348 citation current (700 A) and frequency (30 kHz) conditions, 364 tensity of the alternating magnetic field, thereby increasing 349 with the results shown in Fig. 6 [FIGURE:6]. The results clearly demon- 365 the induced electromotive force within a unit volume, which further intensifies the generation of eddy currents and releases 424 potential benefits of high-frequency induction heating in immore Joule heat. At the same time, reducing the distance be- 425 proving heating response time and thermal efficiency. 368 tween the coil and the workpiece helps improve the coupling 369 efficiency of the magnetic field with the workpiece, allowing 370 the electromagnetic energy to be more efficiently transferred 371 to the metal. Increasing the number of turns or decreasing the 372 distance between the coil and the workpiece not only accel373 erates the temperature rise rate but also significantly shortens 374 the time required to reach steady-state temperature, indicating 375 a high sensitivity of the induction heating system to structural 376 design optimization.

Therefore, in practical engineering design, the coil config378 uration with more turns and a smaller distance between the 379 coil and the workpiece should be prioritized, based on spe380 cific requirements, to achieve higher heating efficiency and 381 shorter heating times. The results of this study provide strong 382 theoretical support for the structural optimization of induc383 tion heating systems and serve as an important reference for 384 achieving precise target temperature control, localized heat385 ing, and multi-stage power adjustment.

In the experiment investigating the influence of heating 387 frequency on the performance of an induction heating sys- 426 388 tem, we have selected a coil structure with 2 turns and a 20389 millimeter gap between the coil and the workpiece. This se390 lection is based on a comprehensive consideration of multiple 391 factors. From the perspective of coil turns, a 2-turn coil can 392 generate a moderate magnetic field strength while meeting 393 the basic requirements for induction heating. This not only 394 ensures that sufficient eddy currents are induced in the work395 piece to achieve heating but also avoids the issues of increased 396 system inductance and reduced power factor that may arise 397 from an excessive number of turns. Moreover, the simplic398 ity of this coil structure facilitates experimental operation and 399 control, reduces experimental costs, and makes heat dissipa400 tion easier, thereby contributing to the stable operation of the 401 experimental system. Regarding the gap, the 20-millimeter 402 spacing is carefully designed. This spacing ensures effective 403 magnetic field coupling to the workpiece, preventing local 404 overheating of the workpiece surface due to excessively small 405 gaps and magnetic field energy loss due to excessively large 406 gaps. Additionally, the 20-millimeter spacing accommodates 407 workpieces of various sizes and shapes, enhancing the univerFig. 8 [FIGURE:8]. Comparison of current density distribution. 408 sality of the experimental results. It also prevents collisions 409 between the workpiece and the coil during the heating process 428 As depicted in Fig. 7 [FIGURE:7], induction heating at 110 kHz results 410 due to thermal expansion, ensuring the safety of the experi- 429 in a temperature increase of 500 K within the first 5 minutes, 411 ment and the stability of the system. 430 which is five times the heating rate under the 30 kHz condi412 In summary, considering the above factors, we have chosen 431 tion (100 K within the first 5 minutes).Fig. 8 further reveals 413 a coil structure with 2 turns and a 20-

millimeter gap between 432 that the current density peaks at 5.5 × 10 A/m and is con414 the coil and the workpiece to further investigate the impact of 433 fined to the surface layer at 110 kHz, whereas the 30 kHz 415 heating frequency on the performance of the induction heat- 434 profile exhibits a lower, more gradual radial decay.This pro416 ing system.To validate the advantages of the 110 kHz high- 435 nounced concentration effect is quantitatively described by 417 frequency induction heating device we designed in terms of 436 the skin effect, for which the characteristic penetration depth 418 rapid heating, a comparative analysis was conducted between 437 is given by $\delta = \rho/\pi$f µ. Accounting for the temperature419 it and a conventional 30 kHz heating system under the same 438 dependent resistivity of tantalum (ρ = 156 nΩ ·m at T = 420 operating conditions. The study primarily focused on exam- 439 500 K for the 30 kHz case and ρ = 197 nΩ ·m at T = 421 ining the effects of frequency variation on energy coupling 440 1100 K for the 110 kHz case, with the elevated tempera422 efficiency, the distribution of eddy currents within the work- 441 ture resulting from increased power dissipation), the theo423 piece, and the rate of temperature rise, in order to reveal the 442 retical skin depths are calculated to be $ $30 kHz = 1.15 mm

and $ $110 kHz = 0.60 mm. Despite the higher operating tem- 502 ment of electromagnetic-thermal equilibrium, which is of sigperature at 110 kHz, which tends to increase the skin depth 503 nificant importance for improving heating efficiency and en445 through elevated resistivity, the dominant frequency depen- 504 suring heating quality. To further validate the rapid-heating 446 dence reduces the penetration depth by approximately 48%. 505 capability of the developed induction system, an experimen447 To validate the agreement between simulated current density 506 tal campaign was conducted under identical operating condi448 and theoretical predictions, the effective skin depth is first de- 507 tions. 449 fined as the distance over which the alternating current de450 cays to 1/e (36.8%) of its surface value within the conductor. 451 δeff is determined directly from the radial profiles presented 508 IV. INDUCTION HEATING EXPERIMENTAL TEST 452 in Fig. 8 by identifying the depth at which the current den453 sity J(r) falls to J0 /e. This procedure yields δeff,30 kHz = To evaluate the rapid heating performance of the designed 454 1.18 mm and δeff,110 kHz = 0.62 mm, which exhibit excel510 induction heating system, an experimental platform was es455 lent agreement with theoretical predictions, with deviations 511 tablished in this study, as illustrated in Fig. 10 [FIGURE:10]. This platform 456 within 3%.

The enhanced surface concentration substan- 512 was specifically developed to systematically verify the heat457 tially increases the heat generation capability. The volumet513 ing efficiency of the high-frequency induction system and to 458 ric heat generation density is given by q = ρJ , which scales 514 enable the synchronized control of heating and mechanical 459 quadratically with current density. At the surface, this yields 515 loading processes. The platform integrates a high- frequency 460 q30 kHz = 1.6 MW/m and q110 kHz = 5.1 MW/m , corre- 516 induction heating module, a mechanical loading unit, a pre461 sponding to a 3.2-fold enhancement. This significant increase 517 cision temperature monitoring system, a closed-loop water 462 in surface heat flux —achieved despite the operating temper518 cooling system, and a supervisory control platform, provid463 ature at 110 kHz exceeding twice that at 30 kHz— enables a 519 ing a stable and high-responsive testing environment for high464 doubling of the heating rate from 100 K/5 min to 200 K/5 min. 520 temperature thermomechanical coupling experiments. 465 These results validate the efficacy of high-frequency oper521 Before each experiment , a comprehensive inspection and 466 ation for achieving rapid, surface-localized heating. There522 preheating of the equipment were conducted to ensure the 467 fore, increasing the frequency can not only effectively accel523 proper operation of all modules. Special attention was given 468 erate the heating process but also significantly enhance the 524 to the induction heating system' s power supply, coil, water 469 skin effect. Under the configuration of 110 kHz, the induc525 cooling system pipes, and temperature control system, all of 470 tion heating efficiency is greatly improved, providing a more 526 which underwent rigorous checks to prevent issues such as 471 efficient and energy-saving solution for relevant applications. 527 overheating or energy overload during the experiment. Si472 To fully and deeply analyze the heating behavior under the 528 multaneously, the mechanical loading system was calibrated 473 110 kHz configuration, we have conducted multidimensional 529 to confirm that its loading accuracy and range meet the exper474 investigation work. We have not only monitored the dynamic 530 imental requirements. During this process, the surface of the 475 variation trend of the heating power but also measured the 531 specimen was cleaned and polished to remove oxides and oil, 476 steady-state radial temperature distribution along the central 532 ensuring the accuracy and consistency of both temperature 477 diameter direction. In addition, we have carried out a detailed 533 measurement and mechanical loading. 478 analysis of the corresponding distribution between the overall Once the experiment began, the induction heating system 480 temperature and the magnetic flux density. 535 was activated, and the output frequency and power of the The panel sequence provides the three-dimensional 537 duction via a 2-turn copper coil. At the frequency of 110 kHz, 483 temperature field, three-dimensional magnetic-flux-density 538 the system rapidly heated the specimen surface to the desired 484 field, two-dimensional temperature contour, two-dimensional 539 temperature (typically between 1000 K and 1400 K), with 485 magnetic-flux-density contour, instantaneous heating-power 540 temperature accuracy monitored in real time. To reduce in486 curve, and the steady-state temperature distribution along the 541 terference during temperature measurement, the system was 487 diameter at the geometric center. In electromagnetic induc- 542 equipped with an infrared non-contact temperature sensor and 488 tion heating systems, numerical simulation techniques enable 543 a K-type thermocouple, and the real-time data were fed back 489 us to analyze the distribution of magnetic flux density and 544 to the control platform for calibration and validation. Tem490 temperature.

The transient response of the heating power 545 perature data were recorded every second to ensure continu491 curve at system startup, although initially exhibiting an over- 546 ous monitoring of dynamic temperature changes, and the sys492 shoot phenomenon, rapidly decays within a certain time- 547 tem adjusted relevant heating parameters, such as heating rate 493 frame, demonstrating the system's ability to quickly achieve 548 and target temperature,according to the experimental require494 electromagnetic-thermal equilibrium. The radial temperature 549 ments. Additionally, power, frequency, and other electrical 495 distribution features a typical saddle shape, which is the re- 550 parameters of the induction heating process were recorded 496 sult of the combined effects of surface convection cooling 551 synchronously for subsequent data analysis and verification.

Once the induction heating system reached stable opera497 and axial heat conduction, with the surface forming a shal- 552 498 low temperature minimum due to convective heat dissipation. 553 tion, the mechanical loading system was activated. The loadThe 499 This temperature distribution characteristic is crucial for un- 554 ing force started from 0 N and gradually increased. 500 derstanding and predicting the thermodynamic behavior dur- 555 loading process was precisely controlled by an electronic 501 ing the heating process and also confirms the rapid establish- 556 servo universal testing machine, which applies axial tension

temperature distribution,(d) 2D magnetic flux density distribution,(e) Centerline temperature profile along the diameter,(f) Heating power evolution.

or compression at a set rate , with the loading modes selected 565 late real-world working conditions. The high-frequency curaccording to the experimental design. All force and displace- 566 rent generated a strong skin effect, causing the specimen' s 559 ment data were continuously collected by sensors throughout 567 surface temperature to rise rapidly. Concurrently, due to the 560 the loading phase, ensuring parameter accuracy and consis- 568 applied mechanical loading, the specimen underwent defor561 tency. 569 mation, and the material' s microstructure, strength, and de562 The core of the experiment was the thermomechanical cou- 570 formation behavior changed significantly with varying tem563 pling process, during which high temperature and mechan- 571 perature and stress. Once the experiment reached the prede564 ical loading acted simultaneously on the specimen to simu- 572 termined duration, the loading process ended, and the induc557

Dimensions of Bar-Shaped Specimens.

system heats at 200 ◦ C/s until reaching 800 ◦ C.; (c) The system heats at 200 ◦ C/s until reaching 1200 ◦ C.

tion heating system was turned off, completing the thermo- 579 tem demonstrated excellent dynamic response and stability. mechanical coupling experiment. 580 We performed closed-loop control tests with different heat ◦ 581 ing rates (150 C/s, 200 C/s) targeting setpoint temperatures To comprehensively validate the system' s real-time tem- 582 of 400 C, 600 C, and 800 ◦ C, and fur-

Figure 11

Figure 2: Figure 11

ther carried out closed576 perature control performance and the claimed high heating 583 cycle tests at heating rate of 200 ∘ C/s target of 800 ∘ C and 577 rates, we designed and conducted a series of precise closed- 584 1200 ∘ C. These experiments simulated complex heat treat578 loop control experiments.

As shown in Fig. 11

, the sys573

frame installed in Engineering Material Neutron Diffractometer at CSNS.

induction heating equipment . ment processes, including stepwise heating, precise dwell pe586 riods, and subsequent cooling stages.

The temperature-time curves show that the system re588 sponds rapidly to each heating command, achieving a tem- 602 higher, the system quickly entered a stable state, with tem589 perature rise of several hundred degrees Celsius in a short 603 perature fluctuations confined to a narrow range, showcas590 time, confirming its capability for rapid heating rates of up 604 ing high-precision temperature maintenance. Throughout the 591 to 200 C/s. Notably, this peak rate occurred primarily dur- 605 multi-stage cycle, the temperature curve remained smooth, 592 ing the initial heating phase when the system' s thermal in- 606 continuous, and repeatable, with no abnormal deviations, 593 ertia was low, allowing the controller to deliver maximum 607 confirming the system' s operational stability and reliability 594 power. As the temperature approached the target setpoint, the 608 under complex, long-duration thermal cycling. 595 PID closed-loop control algorithm adjusted the heating power 609 Furthermore, analysis of the high-temperature data, partic596 to prevent overshoot caused by thermal inertia, enabling the 610 ularly above 800 ∘ C, revealed slight, gradual in the temper597 temperature curve to smoothly approach and stabilize at the 611 ature curve. This was primarily due to surface oxidation of 598 setpoint and without overshoot. This demonstrates the advan- 612 the heating element (tantalum rod) at high temperatures un599 tage of "fast start-up, precise stabilization" inherent in closed- 613 der the laboratory test conditions, leading to drift in its resis600 loop control. 614 tive properties and thereby introducing minor inaccuracies in Once the temperature reached plateaus such as 800 ∘ C and 615 the temperature feedback. It is important to note that in the

rate of stress increment slows down. The curve reveals a yield strength of 277 MPa for the material, beyond which a decline 654 is observed, signifying the initiation of necking prior to frac655 ture. Additionally, the curve denotes a fracture elongation 656 of 19.6%, reflecting the ductility of the material before rup657 ture. These results are important for evaluating the mechani658 cal properties of 310S stainless steel at high-temperature con659 ditions, particularly in

Figure 14

Figure 3: Figure 14

Figure 16

Figure 4: Figure 16

studies requiring precise temperature 660 control and rapid thermal response, such as dynamic high661 temperature loading, stress measurement, and in-situ moni662 toring of material behavior.

In neutron scattering experiments, it is crucial to ensure 664 that the induction heating device does not significantly af665 fect the scattering results of the sample. To this end, we de666 signed an experiment to assess whether the introduction of the 667 induction heating device would generate additional diffrac668 tion peaks in the scattering pattern,The experimental setup is 669 shown in Fig. 14

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In the experiment, vanadium-nickel al670 loy samples were tested, and neutron scattering data were 671 recorded by the materials testing system (MTS) and the in672 duction heating device, as well as under the MTS alone, as 673 shown in Fig. 15 [FIGURE:15].” Both curves were normalized to their re616 actual spectrometer environment, the sample chamber oper- 674 spective maximum intensities to enable direct comparison of 617 ates under a high-purity inert gas atmosphere,such as argon, 675 the spectral features.By subtracting the control group data 618 which eliminates oxygen exposure, thereby preventing high- 676 from the experimental group data, we were able to isolate 619 temperature oxidation and ensuring long-term measurement 677 the scattering signals from other devices, thereby revealing 678 the scattering contribution of the induction heating device. 620 and control accuracy across the entire temperature range.

To systematically compare the rapid heating performance, 679 As shown in Fig. 16

, the difference analysis produced a line 680 close to zero, indicating that the induction-heating device in622 a frequency comparison group was conducted, using identi ◦ 681 troduced no additional diffraction peaks and had no signifi623 cal coil structures and a prescribed heating rate of 10 C/s at 682 cant effect on the scattering pattern of the samples. These ex624 frequencies of 110 kHz and 30 kHz. As shown in Fig. 12 [FIGURE:12], the 683 perimental results confirm that the induction heating device 625 experimental results indicate that at 110 kHz, the induction 684 we designed had no significant impact on the scattering re626 heating system heated the specimen to the target temperature 685 sults of vanadium-nickel alloy samples in neutron scattering 627 in a shorter time and at a higher heating rate. Under high686 experiments, and introduced no additional diffraction peaks. 628 frequency excitation, the skin effect was enhanced, resulting 687 This conclusion not only supports the reliability of the induc629 in a higher density of circulating currents on the specimen' s 688 tion heating device but also provides an important reference 630 surface. This effect significantly increased the power density 689 for future high-temperature mechanical property tests. 631 of Joule heating, thereby improving the efficiency of heat en632 ergy input. This characteristic not only accelerated specimen 633 heating but also provided a stable high-temperature environV. SUMMARY 634 ment for the subsequent loading process, ensuring the stabil- 690 635 ity and consistency of the heating procedure.

Subsequently, to evaluate the feasibility of force-thermal 691 This study presents a high-frequency induction heating for 637 loading, we conducted an experiment on 310S stainless steel 692 rapid and precise temperature. Through theoretical analysis, 638 under force-thermal conditions, as depicted in Fig. 13 [FIGURE:13], which 693 simulation studies, and experimental verification, the scheme 639 illustrates the stress-strain curve obtained at 800 C.It should 694 has demonstrated significant improvements in heating rate 640 be noted that the tantalum rods used previously served only 695 and temperature control accuracy, effectively overcoming key 641 as reference samples for temperature calibration. For the for- 696 limitations of conventional heating systems. By increasing 642 mal mechanical performance tests, 310S stainless steel was 697 the frequency to 110 kHz and employing a high-current zero643 selected because it has excellent oxidation resistance, mi- 698 current switching (ZCS) IGBT series resonant converter, this 644 crostructural stability, and repeatable mechanical behavior at 699 study has successfully achieved efficient compression of elec645 high temperatures, making it more suitable for constitutive 700 tromagnetic energy into the submillimeter surface layer. This 646 characterization under force-heat coupling loads. This curve 701 increased both thermal flux density and heating rate. Both 647 captures the entire deformation process of the material, from 702 simulation and experimental results show that, under the same 648 the elastic to the plastic phase and ultimately fracture. At 703 power conditions, the high-frequency heating technology can 649 the onset, the curve exhibits a steep slope, indicating elastic 704 rapidly heat samples to higher temperatures. For the same tar650 behavior.

As strain progresses, the slope diminishes grad- 705 get temperature, the technology exhibits a faster heating rate 651 ually, signifying the onset of plastic deformation where the 706 and higher stability. This characteristic is crucial for in situ

characterization experiments, as it provides repeatable and 714 ditional low-frequency heating systems, the high-frequency precise temperature profiles, thereby improving the temporal 715 technology adopted in this study offers clear advantages in 709 resolution and data quality .In neutron scattering experiments, 716 energy efficiency and control accuracy. The technology has 710 the induction heating device designed in this study exhibits 717 broad application prospects and significant engineering value 711 low background characteristics, making it suitable for neu- 718 in low-carbon precision heat treatment, high-temperature ma712 tron diffractometers application, without compromising data 719 terial testing, and advanced in situ characterization. 713 the integrity and accuracy of sample data. Compared with tra707

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