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Magneto-Hyperdynamic Energetic Liquid Metals

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Abstract

Liquid metals (LMs) are fluidic and conductive, but their high thermal diffusivity and chemical passivity have long excluded them from energetic potentials. Here we report a magneto-hyperdynamic composite (MH-ELM) that breaks this barrier. Fabricated by simple stirring of a Ga-In alloy with in-situ generated Ga_2O_3 , boron and NdFeB particles, the MH-ELM exploits cooperative material system: a percolating oxide network that enables efficient induction heating, a previously unrecognized B- Ga_2O_3 exothermic reaction that serves as an internal chemical amplifier, and the frequency-controlled skin effect that tunes reaction initiation and propagation. Under an alternating magnetic field, the MH-ELM combusts violently and expands to over two times its original volume, reaching 1275 °C within 1 s. This output exceeds the highest recorded temperature for liquid-metal systems by one order of magnitude and accelerates heating rates by five-fold. Our work overturns the dogma that LMs are inherently inert, and establishes a design principle: metastable, soft composites can store chemical energy and release it violently on remote command. This concept may find use in rapid actuation, field repair and deployable systems, and more broadly suggests that deliberate metastability offers a route to extreme performance in otherwise passive materials.

Introduction

Gallium-based liquid metals (LMs), particularly the eutectic Ga-In alloy (75.5 wt% Ga, 24.5 wt% In, melting point 15.7 °C)^{1,2}, have captured intense scientific and industrial interest over the past decades. The unique confluence of metallic bonding and fluidic behavior endows LMs with extraordinary properties: they are nontoxic³⁻⁵, remain in the liquid state at room temperature⁵⁻⁷, and retain high electrical conductivity ($\approx 3.4 \times 10^6 \text{ S m}^{-1}$)⁸⁻¹⁰, high thermal conductivity ($\approx 27 \text{ W m}^{-1} \text{ K}^{-1}$)¹¹⁻¹³, and virtually unlimited deformability¹⁴⁻¹⁶. Therefore, LMs have emerged as versatile platforms across diverse domains, including stretchable electronics^{17,18}, soft robotics¹⁹⁻²², and biomedical devices²³⁻²⁵.

Recent efforts have focused on developing techniques for actively controlling LM responses to external stimuli, enabling on-demand reshaping, movement, or patterning to achieve specific functions. Reversible shape reconfiguration has been achieved by using electric fields to induce electrocapillary motion²⁶, and droplet splitting-to-coalescence becomes possible through electrochemical tuning of surface tension via oxide layer modulation²⁷. In addition, thermal gradients have been applied to drive Marangoni flow, allowing controlled locomotion on surfaces²⁸. Chemical agents, by altering interfacial energy, can also achieve programmable wetting behavior²⁹. Directional transport and mixing, meanwhile, are realized by magnetic fields acting on incorporated ferromagnetic particles³⁰. These strategies have ushered LMs into a new era of programmable functionality, greatly expanding the application landscape.

However, all existing stimuli-induced responses of LMs share three fundamental limitations that severely constrain their practical impact. First, the magnitudes of LM responses are quantitatively limited, and LMs mainly remain chemically inert. For example, the bending- or stretching-induced apparent volume change of the LMs is rarely larger than 5%³¹⁻³³. During heating or other external stimulation, the overall temperature rise does not exceed 314 °C, and no significant exothermic event is observed³⁴⁻³⁷. Second, the response time varies widely depending on the triggering mode. Under conditions that demand instantaneous action, such as ignition systems, fast actuators, or emergency repairs, the response may be insufficient or fail entirely. Third, response controllability in both time and space is poor, lacking precise thresholds or tunable kinetics^{38,39}. These limitations are not accidental, and they reflect a long-standing implicit assumption in the field: LMs are passive, non-energetic materials that can be moved or shaped, but cannot produce rapid, high-temperature exothermic behaviors.

Particularly, previous study has never suggested that LMs could be made to undergo violent combustion or explosive expansion in response to any stimulus. The very idea seems contradictory: LMs are typically used as functional sinks, not fuel. Yet if such behavior could be realized, especially when triggered remotely and wirelessly, it would transform LMs from passive, sluggish media into active, energetic, programmable materials capable of instantaneous volume change and intense heating. Such a capability would open entirely new

application domains: on-demand ignition for micro-thrusters⁴⁰ and self-contained joining for underwater or space welding^{41,42}, deployable structures that expand in milliseconds⁴³, and many others. The key to unlocking this behavior, we reasoned, lies in designing a metastable LM-based composite that stores chemical energy and releases it upon a non-contact magnetic trigger, bypassing the inherent thermal and kinetic barriers of pure LMs.

Here we report a magneto-hyperdynamic energetic liquid metal composite (MH-ELM) that achieves stable, tunable expansion and combustion under an alternating magnetic field (AMF). Prepared by simple ambient stirring of Ga₂O₃ with effective additives, the composite behavior arises from three synergistic effects: a stirring-controlled Ga₂O₃/air susceptor network, a previously unreported boron (B)-Ga₂O₃ exothermic reaction, and the skin effect for spatiotemporal control. Within 1 s, the material expands >200% in volume and reaches 1275 °C. This work overturns the long-standing assumption that LMs cannot be energetic and fast, and establishes a new avenue: soft, safe materials that store energy and release it on command, turning passive putty into a violent power source with a simple external trigger.

Results and discussion

Design and Performance

Figure 1a and **Figure S1** schematically illustrate the fabrication process and microscopic composition of the MH-ELM. The corresponding SEM image reveals that NdFeB, Ga₂O₃ and boron (B) particles are homogeneously distributed within the Ga-In matrix. In the representative demonstration (**Figure 1b**), a 4 g spherical MH-ELM specimen is placed in an alternating magnetic field (AMF) and exhibits the hyperdynamic response shown in **Figure 1c** and **Movie S1**. The response process contains two stages, and the initial heat storage stage is mainly contributed by the combined induction heating and mildly exothermic parasitic reactions between B and ambient oxygen, as well as Ga and oxygen. Under this stage, the composite accumulates thermal energy to approximately 700 °C (**Figure 1d**), which triggers the primary exothermic reaction between B and Ga₂O₃, releasing substantial chemical energy instantaneously (**Figure 1e**). As a result, the MH-ELM undergoes violent combustion, reaching a peak temperature of 1275 °C within 1s (**Figure 1f** and **Figure S2**). **Figure 1g** shows this instantaneous temperature rise of MH-ELM is transformative: it elevates the achievable temperature of liquid metal-based systems from the previously reported maximum of approximately 314 °C by one order of magnitude, and increases the heating rate by five folds relative to conventional LM systems.

Beyond violent combustion, the entire process is accompanied by considerable volumetric expansion. **Figure 2a** and **Figure S1** show that the MH-ELM is prepared by ambient stirring, during which in-situ generated Ga₂O₃ particles entrain ambient air to form a Ga₂O₃/air susceptor

network distributed throughout the LM matrix. The porosity of this network, as shown in the 3D-pore-distribution analysis of **Figure 2b** and **Figure S3**, can be precisely controlled by the stirring duration at a fixed stirring rate. A comparison between samples stirred for 1 hour (**Figure 2c**) and 6 hours (**Figure 2d**) demonstrates that prolonged stirring increases both the volume fraction and density of the entrapped air pockets. The pores are continuously fragmented and reconfigured, leading to progressive homogenization of the network architecture. To establish quantitative control over expansion, we prepared pure Ga-In alloy samples stirred for 10, 15, 20, 25, 30, 60, 120 and 180 minutes. Each 4 g sample was then exposed to the AMF, and the resulting expansion volumes are plotted in **Figure 2e** and **Figure S4**, demonstrating that the expansion magnitude can be finely tuned by the stirring time. Concurrently, the continuous generation of oxide during prolonged stirring substantially reinforces the mechanical integrity of the $\text{Ga}_2\text{O}_3/\text{air}$ network, as reflected in the complex viscosity evolution shown in **Figures 2f** and **2g**, and the viscosity increases with stirring time. Importantly, in the absence of external driving forces, the air trapped within the network remains securely confined even under vacuum, as illustrated in **Figure 2h**, ensuring the composite remains functional in vacuum environments. More surprisingly, the $\text{Ga}_2\text{O}_3/\text{air}$ network also causes a rapid increase in electrical resistivity of the Ga-In with stirring time (**Figure 2i**). This resistivity enhancement substantially amplifies the induction heating effect under AMF, elevating the temperature rise from approximately 20 °C in the unstirred Ga-In to more than 500 °C in the stirred samples. A comparison between **Figures 2j**, **2k** and **Movie S2** further reveals that samples stirred for less than 30 minutes consistently exhibit lower peak temperatures than those stirred for 1 to 3 hours, with a difference of approximately 90 °C. However, beyond 3 hours of stirring at 810 r.p.m., further increases in stirring time produce negligible changes in all the above metrics, and the induction heating effect plateaus, with average temperatures saturating at approximately 600 °C. This saturation prompted us to adopt a rational design strategy: we use controlled stirring to establish a moderate $\text{Ga}_2\text{O}_3/\text{air}$ network as the base susceptor, and then introduce functional particles to further boost induction heating, thereby triggering the highly exothermic chemical reactions that define the MH-ELM. In the following sections, we systematically present the material system, the response mechanism and the tuning strategies that underpin this hyperdynamic energy release.

Material System

Figure 3a illustrates our selection of two representative functional particles, the soft magnetic Fe and the hard magnetic NdFeB, to construct the MH-ELM. After 30 minutes of stirring in air, the Ga-In matrix already contains a stable $\text{Ga}_2\text{O}_3/\text{air}$ network, whose porosity is sufficient to rapidly incorporate functional particles while leaving adequate space for their dispersion. Under these conditions, the Ga-In matrix can accommodate up to 50 wt% of either Fe or NdFeB particles. **Figures 3b** and **3c** show that increasing the mass fraction of Fe particles progressively

enhances the induction heating response (**Figure S5** and **Figure S6**). At a driving power of 1100 W and a frequency of 55 kHz, a 4 g sample of the Fe-containing composite reaches 714 °C within 45 s (**Movie S3**). A similar trend is observed for the NdFeB-containing system (**Figure 3d**), where both the heating rate and the maximum temperature increase with particle loading (**Figure S7** and **Figure S8**). Under identical AMF conditions, the NdFeB-based composite reaches 901 °C within 33 s (**Figure 3e**) and exhibits visible combustion (**Movie S4**). The substantial differences in both heating rate and peak temperature between the two systems (light green marked), quantified in **Figure 3f**, suggest that induction heating alone cannot account for the enhanced performance of the NdFeB system. Energy-dispersive X-ray spectroscopy (EDS) analysis in **Figure 3g** reveals that NdFeB is no longer stable within the Ga-In matrix. In particular, B has migrated into the matrix. This observation led us to hypothesize that the liberated B participates in a chemical reaction that releases additional heat, thereby boosting the overall temperature rise.

To valid this hypothesis, we replaced the functional particles with B powder directly. Owing to the low density of B, the matrix can accommodate only 2 wt% B (**Figure S9**). Under this system, no rapid heating or combustion was observed (**Figure S10**), and the heating rate and maximum temperature were comparable to those of the stirred Ga-In alloy alone, plateauing at approximately 600 °C and failing to trigger any B-related exothermic reaction. Consistent with this finding, composites containing 2 wt% B with variable Fe mass fractions (**Figure 3h**) confirm that at low Fe loadings (8 wt%), the induction heating is insufficient to activate the B-based reaction. However, as the Fe fraction increases, the intensified induction heating does trigger the B-related chemistry, and at 48 wt% Fe, the composite reaches 992 °C within 51 s (**Movie S5** and **Figure S11**), closely matching the performance of the NdFeB system. This correlation unambiguously validates our hypothesis that the exothermic reaction involving B is the key chemical contributor to the hyperdynamic energy release in our material system.

Response Mechanism

As introduced in Figure 1, the response of the MH-ELM comprises two consecutive stages: a physical heating storage stage and a chemical exothermic stage. In the first stage, heat is accumulated primarily through induction heating, supplemented by two auxiliary reactions: the oxidation of B and the oxidation of Ga by ambient oxygen. Once the stored thermal energy reaches a critical threshold, the primary reaction initiates and rapidly enters the second stage, where chemical energy release dominates and provides the major heat source for the violent combustion. Drawing inspiration from the well-established thermite reactions of carbon (C) with Ga₂O₃ and aluminium (Al) thermite systems, we reasoned that B, being adjacent to C in the periodic table and belonging to the same group as Al, should possess analogous thermite-type reactivity toward Ga₂O₃. We therefore constructed a comprehensive reaction network involving B, Ga, O₂ and Ga₂O₃, as illustrated in **Figure 4a**. **Figure 4b** reveals that the two

auxiliary reactions proceed slowly and precede the primary event. Once the onset temperature is reached, **Figures 4c** and **4d** demonstrate that the B-Ga₂O₃ reaction occurs instantaneously, with both reactants being rapidly consumed and generating metallic Ga as the product while releasing a large amount of heat (Figure 1e). Therefore, to maximize the chemical heat release, we finally selected the B+NdFeB co-doping system as the final MH-ELM composition (**Figure 4e**). For a fixed B loading of 2 wt% and NdFeB fractions ranging from 8 wt% to 48 wt%, **Figures 4f-j**, **Figure S12** and **Movie S6** present the corresponding response process and temperature evolution curves. Quantitative analysis shows that increasing the NdFeB content raises the maximum attainable temperature monotonically: the composite with 2 wt% B + 8 wt% NdFeB reaches 1030 °C, and the 2 wt% B + 48 wt% NdFeB formulation attains 1159 °C.

Tuning Strategies

To render the hyperdynamic response controllable, we exploit the skin effect as the primary handle for tuning both the heating rate and the peak temperature of the MH-ELM. As shown in **Figure 5a**, an alternating current preferentially flows near the surface of a conductor, with the current density decaying exponentially with penetration depth. High-speed recording (**Movie S7**) of the MH-ELM response under a 55 kHz AMF reveals that the induced currents are indeed concentrated near the surface, so that induction heating is localized at the periphery. This surface-localized heating (**Figure 5b**) triggers the primary chemical reaction preferentially along the equatorial edge, initiating combustion that subsequently propagates throughout the entire sphere. **Figure 5c** illustrates our FEA simulation of the frequency-dependent skin effect: as the AMF frequency is increased from 1 kHz to 100 kHz, the normalized current density along the radial direction decays more steeply from the edge toward the center (**Figures 5d** and **5e**). Higher frequencies accentuate the disparity between the edge and the interior. This non-uniform current distribution gives rise to two consequences: (i) a pronounced temperature gradient between the edge and the center, and (ii) an overall reduction in bulk heating efficiency. **Figure 5f** quantifies the edge-to-centre temperature difference, which increases with frequency, and this gradient is correspondingly presented in the distinct heating curves recorded at the surface and the interior for all material systems (**Figures 5h-j**). More importantly, at constant power, increasing the frequency substantially improves the induction heating efficacy, and the temperature rise at 55 kHz is approximately 500 °C higher than that at 10 kHz (**Figure 5g**). Thus, by varying the frequency from 48.2 to 68.12 kHz at a fixed power of 9260 W, we achieve tunable response times for the 4 g MH-ELM specimens ranging from 8 s to 1 s, corresponding to peak temperatures between 890 °C and 1068 °C (**Figure 5j**). In addition to frequency modulation, we employ two auxiliary tuning parameters: the applied power and the sample mass. By adjusting the driving power from 5260 to 16400 W, **Figure 5k** demonstrates that the response time of the 4 g MH-ELM can be varied from 155 to 10 s, with corresponding peak temperatures spanning 915 to 1121 °C. Similarly, by varying the sample mass from 4 to 16 g

while maintaining constant frequency and power, **Figure 5i** shows that the response time becomes adjustable from 10 to 1 s, covering a temperature range of 1120 to 1064 °C. The combination or hierarchical integration of these three strategies, whether used separately or in concert, provides broad and flexible control over both the temporal response and the thermal output of the MH-ELM, enabling customization for diverse application scenarios.

Conclusion

We have demonstrated that a rationally designed liquid metal composite, the MH-ELM, can transcend the intrinsic thermal and kinetic barriers that have historically relegated gallium-based alloys to passive heat-spreading roles. The core advance lies in the sequential yet synergistic interplay between thermal and chemical effects: the stirring-controlled Ga₂O₃/air network that electromagnetically harvests external field energy, the B-Ga₂O₃ exothermic couple that supplies autonomous chemical heat, and the skin effect that provides a physically intuitive yet powerful handle for spatiotemporal regulation. The interplay of these effects allows the MH-ELM to store energy in a metastable state and release it within a sub-second timeframe, producing both a high-temperature thermal surge and a volumetric expansion that are unattainable in any previously reported liquid metal system.

This work decisively refutes the implicit assumption that high thermal conductivity and fluidity preclude energetic functionality. Instead, it reveals that the very same oxide layer traditionally viewed as a passivation nuisance can be engineered into a functional network that couples electromagnetic energy into chemical potential. The remote, wireless triggering modality, combined with the tunability afforded by frequency, power and mass, positions the MH-ELM as a versatile platform for applications that demand instantaneous, high-intensity heat sources in inaccessible or hazardous environments. More fundamentally, our results point toward a broader design philosophy for soft matter: by deliberately introducing well-controlled metastable interfaces and reactive couples, one can convert inherently benign, shapable materials into programmable power sources that activate only upon a specific external cue. We anticipate that this strategy may be generalized to other liquid metal systems and oxide-based redox pairs, potentially opening a new frontier in field-controlled energetic, soft materials where safety, programmability and extreme performance are no longer mutually exclusive.

Methods

Fabrication of MH-ELM: Firstly, gallium and indium were weighed separately at a mass ratio of Ga:In = 3:1. Solid gallium at room temperature was placed in a sealed vial, immersed in hot water at 100 °C, and the vial was shaken appropriately to melt gallium into liquid form. The

weighed indium ingots were added into the liquid gallium, and the vial was kept immersed in hot water with gentle shaking until the indium ingots fully melted and mixed uniformly with liquid gallium. The homogenized Ga-In alloy was flowable at room temperature with a viscosity of approximately 900 Pa·s. A dropper was used to transfer 20 g of the Ga-In alloy into a test tube, which was then sealed. An electric stirrer was employed to agitate the alloy at a rotational speed of 800 r/min for 25-30 min. After stirring, the fluidity of the Ga-In alloy inside the tube decreased significantly, with its viscosity ranging from 1000 to 2000 Pa·s. Taking the composite doped with 2 wt% B and 48 wt% NdFeB as an example, NdFeB magnetic powder was weighed to account for 48% of the mass of the Ga-In alloy, and boron powder was weighed to make up 2% of the alloy mass. The two powders were poured into the test tube containing the Ga-In alloy, as illustrated in Figure 2. The mixture was continuously stirred at 800 r/min via the electric stirrer until the magnetic particles were fully dispersed within the Ga-In alloy matrix with no magnetic particles remaining exposed on the surface, yielding the target composite material.

Actuation of MH-ELM: The as-prepared composite was actuated under alternating magnetic fields with frequencies ranging from 40 kHz to 70 kHz. A 4 g composite sample was scooped with a medicine spoon, simply shaped into a small sphere, and placed at the center of the coil generating the alternating magnetic field. Upon equipment activation, the composite sphere underwent rapid expansion and combustion within 2 s. The oxidation and displacement reactions occurring inside the sphere continuously raised its temperature, which reached 900-1300 °C.

Temperature recording: It was carried out using a Raytek 3i Smart LT handheld industrial infrared thermometer. The infrared laser of the thermometer was turned on and vertically aimed at the target point on the MH-ELM for temperature acquisition. The thermometer was fixed by a clamping bracket with the temperature measurement button kept pressed continuously. A USB cable was used to connect the thermometer to a computer for recording temperature curves. The measurement button was pressed at the start of magnetic actuation and released after the magnetic driving coil was removed and the temperature had declined for a period of time.

3D-pore-distribution analysis: To investigate the variation in volume and quantity of bubbles encapsulated by the oxide film inside Ga-In alloys with prolonged stirring time, micro-CT tests were conducted on pure Ga-In alloy samples stirred for 1 h and 6 h respectively. The stirred samples were loaded into hollow plastic cylinders with an inner diameter of approximately 3 mm and a height of 1 cm, and X-rays were applied to image their internal structures. The test results are presented in Figure S3. It can be seen from the figure that the Ga-In alloy stirred for 6 h exhibits more uniform and compact internal pores with obviously smaller pore diameters compared with the sample stirred for 1 h.

X-ray Photoelectron Spectroscopy Test: To verify whether Ga₂O₃ thin films formed during

stirring, the sample stirred for 30 minutes was coated thinly onto a glass slide. The test data were plotted using Avantage software. After spectrum fitting, the contaminated carbon peak was calibrated at 284.8 eV, and distinct characteristic peaks of Ga_2O_3 were clearly observed.

Vacuum test: Vacuum tests were performed using the AVB-series vacuum chamber manufactured by Tongrun Company. The vacuum chamber was opened under atmospheric pressure, and a 4 g prepared liquid metal was placed at the chamber center. The chamber door and air vent valve were closed, and the valve connected to the vacuum pump was opened. The pump evacuated air inside the chamber down to -0.1 MPa. During this process, air trapped inside the Ga-In alloy escaped outward due to pressure variation, expanding the sample into a porous spherical shape. The volume remained constant once the maximum expansion limit was reached. After the valve was opened to restore atmospheric pressure, the sphere collapsed into a flat porous disk.

Scanning Electron Microscope and Energy Dispersive Spectroscopy: The surface morphologies of the as-prepared and magnetically actuated samples were observed using a SU3900 scanning electron microscope (SEM). SEM characterization was adopted to investigate the surface features of pure Ga-In alloy after stirring, as well as the distribution and agglomeration of doped particles within the Ga-In alloy matrix. Scanning EDS mapping was utilized to analyze the elemental distribution and overlapping relationships of elements before and after magnetic actuation. The samples before actuation possessed fluidity, which were spread into thin layers on glass slides. The glass slides coated with different samples were fixed on stainless steel substrates with conductive tape, followed by platinum sputtering with a thickness of 3 nm via a coating machine. After sputtering, the stainless steel substrates were taken out and adhered to the SEM sample stage with conductive tape. Additional conductive tape was attached between the glass slide surface and the stage to enhance sample conductivity prior to SEM and EDS characterization.

Resistance test: Resistance tests were carried out using a precision LCR digital bridge. The primary display was set to R_s (series equivalent resistance) to eliminate errors from the parallel mode. The measurement frequency was set to 1 kHz, the AC level to 100 mV, and the measurement speed to slow mode with 10-point averaging enabled, while the measuring range was set to auto-range. For Ga-In alloy samples with different stirring durations, 1 g of each sample was weighed, shaped into small spheres and placed in a plastic container. The test fixture held 20 mm-long copper probes coated with tin. The distance between the two probes was fixed at 10 mm, and the immersion depth of the probes beneath the liquid surface remained constant at 6 mm throughout all tests. The electrodes were symmetrically positioned and fixed inside the container. Before each sample loading, the electrode positions were calibrated to be identical to the previous test. The instrument readings were monitored until stable, then the steady R_s values in ohms (Ω) were recorded.

Viscosity test: The viscosity of pure Ga-In alloys stirred for different durations was measured using a DHR-2 rheometer. Approximately 1 mL of sample was placed at the center of the upper and lower rotary plates at room temperature. Parameters were adjusted to clamp the sample tightly between the plates, and the viscosity curve of the sample was obtained.

High-speed camera recording: A high-speed camera (model MER2-240-159U3M) was used to capture the 4 g Ga-In alloy substrate doped with 2 wt% B and 48 wt% NdFeB under magnetic actuation. The frame rate was adjusted to 700 FPS. At this frame rate, the images maintain high definition, and the flame generated during subsequent complete combustion will not cause overexposure of the entire field of view.

Modeling:

Simulation of chemical reactions in the material system: To reveal the kinetic characteristics of borothermal reduction composite combustion mediated by liquid metal, a zero-dimensional reaction kinetic model containing three core paths: main borothermal reduction reaction, solid boron oxidation and liquid gallium oxidation was established. The model takes the molar amount of 5 components and system temperature as state variables, and the reaction rate is described by Arrhenius law. An ignition penalty function in Fermi-Dirac form is introduced for the borothermal reduction reaction to characterize the inhibition of the reaction by interfacial barrier at low temperature. Combined with stoichiometric relationship, a system of ordinary differential equations coupled with mass conservation and energy conservation is constructed, and the total exothermic power of chemical reaction is included. Aiming at the multi-scale stiffness problem of millisecond-scale reaction and second-scale heat transfer in the system, the simulation is calculated by ode15s stiff solver in MATLAB, and zero-value truncation of materials and 3500 K temperature upper limit are set to ensure numerical stability.

Skin effect simulation: To reveal the physical mechanism behind the observed thermal lag in experiments, a two-dimensional axisymmetric magneto-thermal coupled model was established using COMSOL Multiphysics. The excitation source consisted of a three-turn induction coil carrying a current of 240 A, accurately replicating the magnetic field environment in the experiment. Based on effective medium theory, the composite material was assigned the following intrinsic parameters: effective electrical conductivity (σ_{eff}) of 5×10^6 S/m, effective thermal conductivity (κ_{eff}) of 26.6 W/(m·K), and effective relative permeability (μ_r) of 2.0. The thermal boundary conditions included natural air convection ($h = 5$ W/(m²·K)), surface emissivity for thermal radiation to the environment $\varepsilon = 0.8$, and reference temperature $T = 293.15$ K. Boundary layer grids were deployed at the edge of the sphere, and the thickness of the first layer of grids was much smaller than the theoretical skin depth, in order to capture the exponential decay of the induced current within the microscopic skin depth.

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Author contributions

Yifei Li, Yi Li, Yongyu Lu and Yinxiang Meng conceived the study and designed the experiments. Yifei Li, Yinxiang Meng performed the experimental work and data collection. Naiyu Guan and Jingran Wang carried out the numerical simulations. Jixin Chu and Zhongzheng Pei prepared the visualizations and methods. The manuscript was drafted by Yifei Li, Yi Li, Yongyu Lu and Yinxiang Meng, and revised by all authors. Supervision and were provided by Chi Zhang, Ying Chang, Mengxi Wu, Junshan Liu and Yi Li.

Competing interests

Authors declare that they have no competing interests.

Data and materials availability

All data are available in the main text or the supplementary materials.

Reference

- 1 Zhao, Z., Soni, S., Lee, T., Nijhuis, C. & Xiang, D. Smart Eutectic Gallium-Indium: From Properties to Applications. *Advanced Materials* **35** (2023). <https://doi.org/10.1002/adma.202203391>
- 2 Lin, Y., Genzer, J. & Dickey, M. Attributes, Fabrication, and Applications of Gallium-Based Liquid Metal Particles. *Advanced Science* **7** (2020). <https://doi.org/10.1002/advs.202000192>
- 3 Babatain, W., Kim, M. & Hussain, M. From Droplets to Devices: Recent Advances in Liquid Metal Droplet Enabled Electronics. *Advanced Functional Materials* **34** (2024). <https://doi.org/10.1002/adfm.202308116>
- 4 Wang, J. *et al.* Preparation of eGaIn NDs/TPU Composites for X-ray Radiation Shielding Based on Electrostatic Spinning Technology. *Materials* **17** (2024). <https://doi.org/10.3390/ma17020272>
- 5 Zhang, X. *et al.* Liquid metal derived MOF functionalized nanoarrays with ultra-wideband electromagnetic absorption. *Journal of Colloid and Interface Science* **606**, 1852–1865 (2022). <https://doi.org/10.1016/j.jcis.2021.08.143>
- 6 Dickey, M. *et al.* Eutectic gallium-indium (EGaIn): A liquid metal alloy for the formation of stable structures in microchannels at room temperature. *Advanced Functional Materials* **18**, 1097–1104 (2008). <https://doi.org/10.1002/adfm.200701216>
- 7 Park, Y. *et al.* Liquid Metal-Based Soft Electronics for Wearable Healthcare. *Advanced Healthcare Materials* **10** (2021). <https://doi.org/10.1002/adhm.202002280>
- 8 Yan, J. *et al.* Solution processable liquid metal nanodroplets by surface-initiated atom transfer radical polymerization. *Nature Nanotechnology* **14**, 684+ (2019). <https://doi.org/10.1038/s41565-019-0454-6>
- 9 Dai, Y. *et al.* Liquid metal droplets bouncing higher on thicker water layer (vol 14, 3532, 2023). *Nature Communications* **15** (2024). <https://doi.org/10.1038/s41467-024-46487-2>
- 10 Jabbar, F. *et al.* Controlled generation of high-frequency liquid metal microdroplets. *Chemical Engineering Journal* **479** (2024). <https://doi.org/10.1016/j.cej.2023.147626>
- 11 Bark, H., Tan, M., Thangavel, G. & Lee, P. Deformable High Loading Liquid Metal Nanoparticles Composites for Thermal Energy Management. *Advanced Energy Materials* **11** (2021). <https://doi.org/10.1002/aenm.202101387>
- 12 Zhang, C. *et al.* Liquid metal compartmented by polyphenol-mediated nanointerfaces enables high-performance thermal management on electronic devices. *Infomat* **6** (2024). <https://doi.org/10.1002/inf2.12466>
- 13 Jeong, G., Moon, J., Kim, D. & Kang, J. Electric field-driven oscillatory liquid metal for highly efficient thermal management. *Nano Energy* **149** (2026). <https://doi.org/10.1016/j.nanoen.2026.111706>
- 14 Kim, M., Alrowais, H., Pavlidis, S. & Brand, O. Size-Scalable and High-Density Liquid-Metal-Based Soft Electronic Passive Components and Circuits Using Soft Lithography. *Advanced Functional Materials* **27** (2017). <https://doi.org/10.1002/adfm.201604466>
- 15 Kazem, N., Bartlett, M. & Majidi, C. Extreme Toughening of Soft Materials with Liquid Metal. *Advanced Materials* **30** (2018). <https://doi.org/10.1002/adma.201706594>

- 16 Zhang, H. *et al.* An integrated self-healing anode assembled via dynamic encapsulation of liquid metal with a 3D Ti₃C₂Tx network for enhanced lithium storage. *Energy & Environmental Science* **15**, 5240–5250 (2022). <https://doi.org/10.1039/d2ee02147a>
- 17 Park, J., Kang, H., Koo, M. & Park, C. Autonomous Surface Reconciliation of a Liquid-Metal Conductor Micropatterned on a Deformable Hydrogel. *Advanced Materials* **32** (2020). <https://doi.org/10.1002/adma.202002178>
- 18 Sanati, A. *et al.* Recyclable liquid metal - Graphene supercapacitor. *Chemical Engineering Journal* **479** (2024). <https://doi.org/10.1016/j.cej.2023.147894>
- 19 Ma, J. *et al.* Shaping a Soft Future: Patterning Liquid Metals. *Advanced Materials* **35** (2023). <https://doi.org/10.1002/adma.202205196>
- 20 Do, T., Phan, H., Nguyen, T. & Visell, Y. Miniature Soft Electromagnetic Actuators for Robotic Applications. *Advanced Functional Materials* **28** (2018). <https://doi.org/10.1002/adfm.201800244>
- 21 Lee, G. *et al.* Large-area photo-patterning of initially conductive EGaIn particle-assembled film for soft electronics. *Materials Today* **67**, 84–94 (2023). <https://doi.org/10.1016/j.mattod.2023.05.025>
- 22 Guan, Y. *et al.* Inchworm-Inspired soft robot with magnetic driving based on PDMS, EGaIn and NdFeB (PEN) combination. *Chemical Engineering Journal* **466** (2023). <https://doi.org/10.1016/j.cej.2023.142994>
- 23 Feig, V. *et al.* Actively Triggerable Metals via Liquid Metal Embrittlement for Biomedical Applications. *Advanced Materials* **35** (2023). <https://doi.org/10.1002/adma.202208227>
- 24 Zhang, Y. *et al.* Strain-Adaptive Liquid Metal Interfaces Overcome Poisson's Ratio Constraints in Piezoresistive Sensors for Infant Sleep Monitoring. *Advanced Science* **12** (2025). <https://doi.org/10.1002/advs.202515117>
- 25 Yan, J., Lu, Y., Chen, G., Yang, M. & Gu, Z. Advances in liquid metals for biomedical applications. *Chemical Society Reviews* **47**, 2518–2533 (2018). <https://doi.org/10.1039/c7cs00309a>
- 26 Eaker, C. & Dickey, M. Liquid metal actuation by electrical control of interfacial tension. *Applied Physics Reviews* **3** (2016). <https://doi.org/10.1063/1.4959898>
- 27 Khan, M., Eaker, C., Bowden, E. & Dickey, M. Giant and switchable surface activity of liquid metal via surface oxidation. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 14047–14051 (2014). <https://doi.org/10.1073/pnas.1412227111>
- 28 Hwang, H. *et al.* A Universal Way to Manipulate Droplet via Light-Fueled Thermocapillary Convection. *Advanced Functional Materials* **36** (2026). <https://doi.org/10.1002/adfm.202507795>
- 29 Kim, D. *et al.* Recovery of Nonwetting Characteristics by Surface Modification of Gallium-Based Liquid Metal Droplets Using Hydrochloric Acid Vapor. *Acs Applied Materials & Interfaces* **5**, 179–185 (2013). <https://doi.org/10.1021/am302357t>
- 30 Li, X. *et al.* Programmable Digital Liquid Metal Droplets in Reconfigurable Magnetic Fields. *Acs Applied Materials & Interfaces* **12**, 37670–37679 (2020). <https://doi.org/10.1021/acsami.0c08179>
- 31 Wang, H. *et al.* Multi-stimulus perception and visualization by an intelligent liquid

- metal-elastomer architecture. *Science Advances* **10** (2024). <https://doi.org/10.1126/sciadv.adp5215>
- 32 Liao, J. & Majidi, C. Muscle-Inspired Linear Actuators by Electrochemical Oxidation of Liquid Metal Bridges. *Advanced Science* **9** (2022). <https://doi.org/10.1002/advs.202201963>
- 33 Wang, H. *et al.* Large-Magnitude Transformable Liquid-Metal Composites. *Acs Omega* **4**, 2311–2319 (2019). <https://doi.org/10.1021/acsomega.8b03466>
- 34 Jo, H. *et al.* Liquid metal eutectic gallium-indium (EGaIn) blended with paraffinic wax for enhanced solar-to-heat conversion. *Journal of Materials Chemistry A* **14**, 637–650 (2026). <https://doi.org/10.1039/d5ta07484c>
- 35 Qi, Y., Miyahara, M., Iwata, S. & Miyako, E. Light-Activatable Liquid Metal Immunostimulants for Cancer Nanotheranostics. *Advanced Functional Materials* **34** (2024). <https://doi.org/10.1002/adfm.202305886>
- 36 Maurin, V. *et al.* Liquid Crystal Elastomer-Liquid Metal Composite: Ultrafast, Untethered, and Programmable Actuation by Induction Heating. *Advanced Materials* **36** (2024). <https://doi.org/10.1002/adma.202302765>
- 37 Li, Y. *et al.* A Novel Flexible Liquid Metal Microheater with a Textured Structure. *Micromachines* **15** (2024). <https://doi.org/10.3390/mi15010075>
- 38 Kim, D., Jeong, J., Chung, S. & Lee, J. Magnetic Liquid Metals: A Review. *Advanced Functional Materials* **34** (2024). <https://doi.org/10.1002/adfm.202311153>
- 39 He, Y., You, J., Dickey, M. & Wang, X. Controllable Flow and Manipulation of Liquid Metals. *Advanced Functional Materials* **34** (2024). <https://doi.org/10.1002/adfm.202309614>
- 40 Paperny, V., Gorbunov, S. & Pukhilas, K. Plasma microthruster based on spark discharge with a liquid metal cathode. *Technical Physics Letters* **39**, 236–239 (2013). <https://doi.org/10.1134/s1063785013030127>
- 41 Guo, R., Sun, X., Yuan, B., Wang, H. & Liu, J. Magnetic Liquid Metal (Fe-EGaIn) Based Multifunctional Electronics for Remote Self-Healing Materials, Degradable Electronics, and Thermal Transfer Printing. *Advanced Science* **6** (2019). <https://doi.org/10.1002/advs.201901478>
- 42 Zhang, H. *et al.* Mussel-Inspired Polymer-Based Composites for Efficient Thermal Management in Dry and Underwater Environments. *Acs Nano* **18**, 21399–21410 (2024). <https://doi.org/10.1021/acsnano.4c05894>
- 43 Wang, H. *et al.* PLUS-M: a Porous Liquid-metal enabled Ubiquitous Soft Material. *Materials Horizons* **5**, 222–229 (2018). <https://doi.org/10.1039/c7mh00989e>

Figure legends

Figure 1 Performance characterization of magneto-hyperdynamic composite (MH-ELM).

(a) Schematic composition of the MH-ELM shows B, NdFeB and Ga₂O₃ particles dispersed in the Ga-In matrix, and the upper-right inset presents the corresponding SEM image. (b) Schematic magnetic field line distribution of the MH-ELM under alternating magnetic field (AMF). (c) Illustration of the two-stage response of the MH-ELM; the first two panels correspond to the volume expansion, and the latter two panels represent that combustion initiates at the edge and spreads across the entire MH-ELM. (d) Temperature rise curve of the MH-ELM under AMF actuation. (e) B-Ga₂O₃ reaction occurs when the temperature reaches approximately 700 °C. (f) B-Ga₂O₃ reaction triggers heat release profile. (g) Comparison of peak temperature and temperature rise rate with other reported works. The similar results are repeated in three independent experiments (a).

Figure 2 Ga₂O₃/air susceptor network induced expansion and enhanced induction heating.

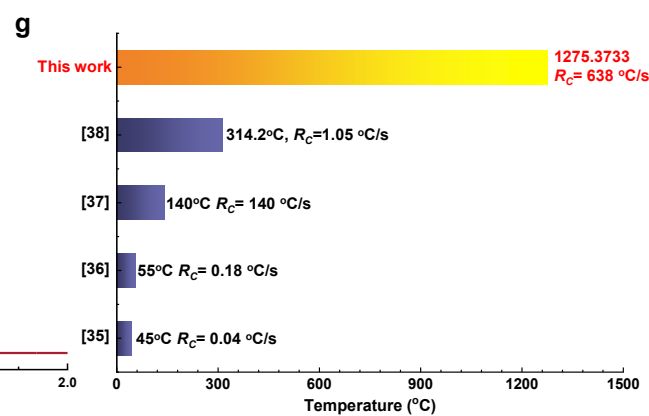
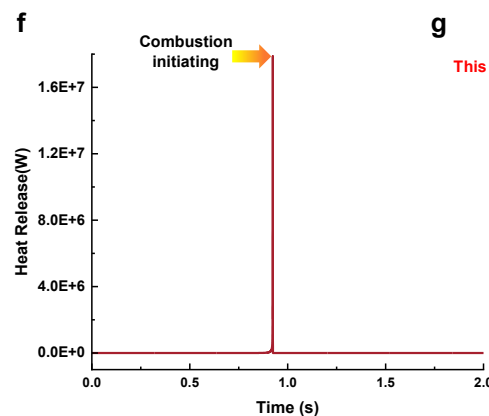
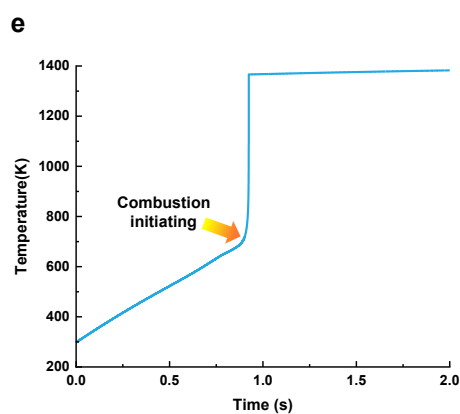
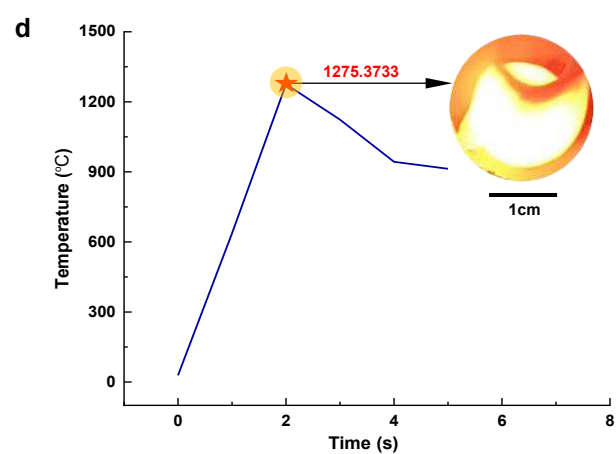
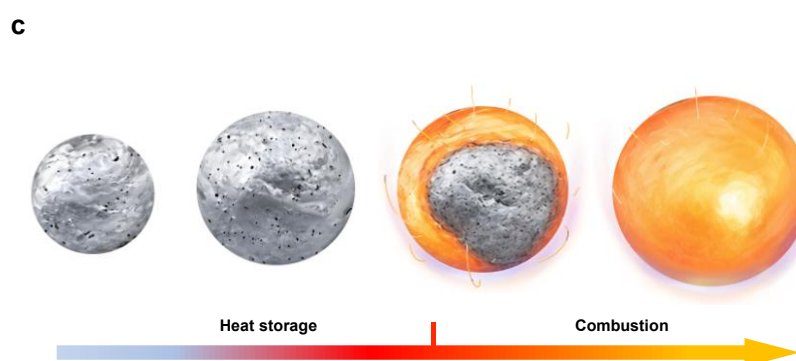
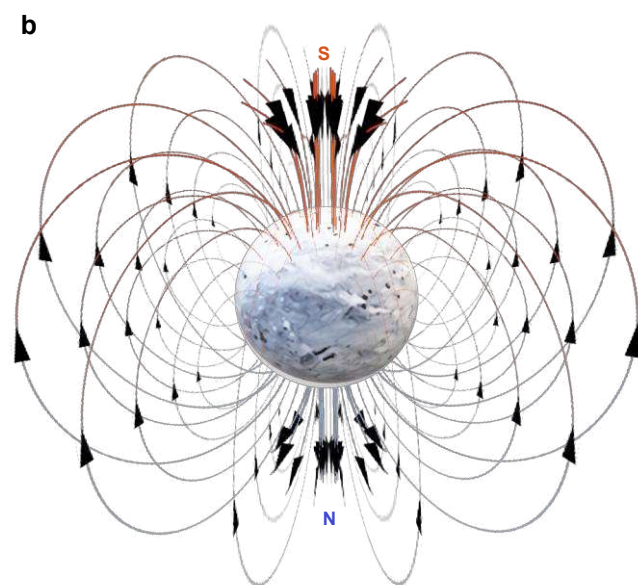
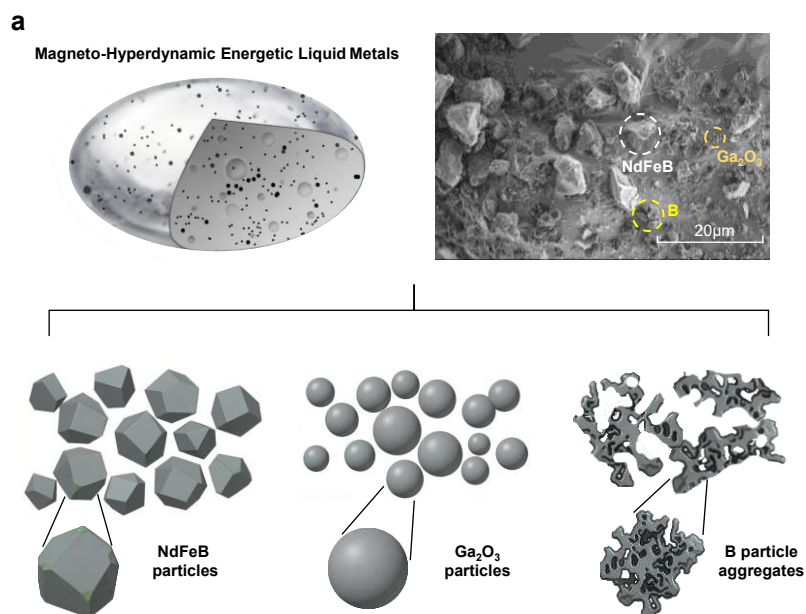
(a) Schematic diagram of pore generation inside Ga-In alloy, and a thin oxide film covers the surface of Ga-In alloy. (b) X-ray micrographs of the samples stirred for 1 h and 6 h respectively. The sample stirred for 1 h contains large, unevenly sized internal pores, as shown in the left panel; the sample stirred for 6 h features finer internal pores with smaller dimensional differences, as shown in the right panel. (c) Statistical distribution diagram of internal pores in Ga-In alloy stirred for 1 h. Excluding a small number of oversized pores, the volumes of most residual pores range from 10⁶ to 10⁸ μm³. (d) Statistical distribution diagram of internal pores in Ga-In alloy stirred for 6 h. Excluding a small number of oversized pores, the volumes of most residual pores range from 10⁴ to 10⁶ μm³. (e) Volume expansion curves of pure Ga-In alloy samples with different stirring durations. The maximum expandable volume of samples actuated under a 55 kHz alternating magnetic field rises significantly with prolonged stirring time. (f) XPS spectrum of pure Ga-In alloy after 1 h of stirring. The blue peaks correspond to Ga₂O₃. (g) Viscosity variation curve of pure Ga-In alloy samples with different stirring durations. Viscosity increases with extended stirring time, and a sharp viscosity surge occurs for samples stirred longer than 1 h. (h) Volume expansion images of pure Ga-In alloys stirred for 25 min, 1 h and 3 h under -0.1 MPa. Longer stirring time increases alloy viscosity and enhances the constraining force on bubbles encapsulated by internal oxide films. (i) Resistance variation plot of 1 g pure Ga-In alloy samples with different stirring durations, and the resistance rises as stirring time increases. (j) Average temperature and fluctuation range plot of pure Ga-In alloys stirred for 3-30 min under actuation by a 55 kHz alternating magnetic field. The average peak temperature reaches 558 °C, with a heating duration of 170 s to hit this temperature. (k) Average temperature and fluctuation range plot of pure Ga-In alloys stirred for 1-3 h under actuation by a 55 kHz alternating magnetic field. The average peak temperature reaches 647 °C, with a heating duration of 144 s to hit this temperature. Data were presented as

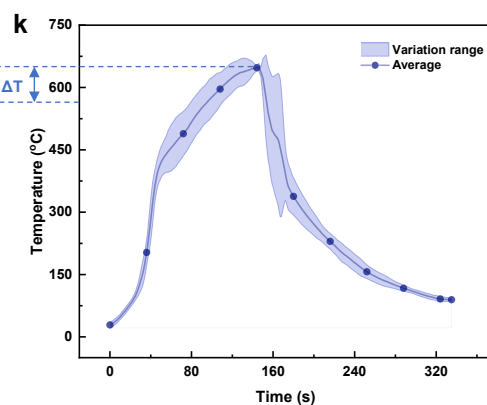
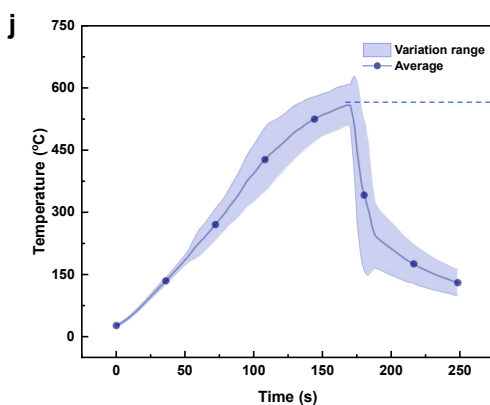
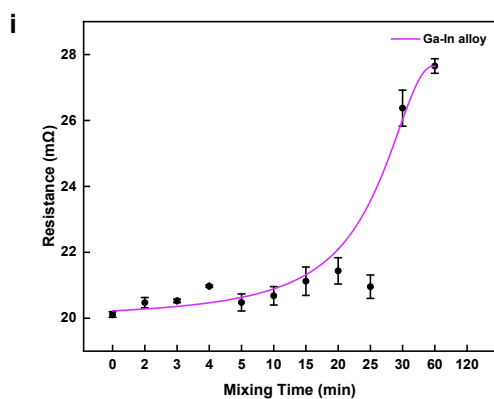
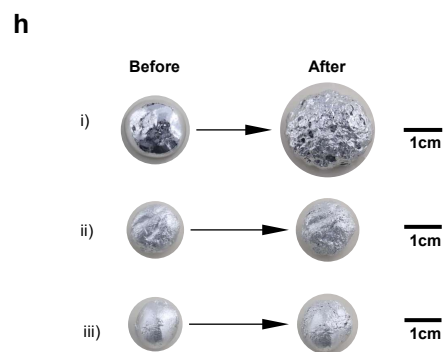
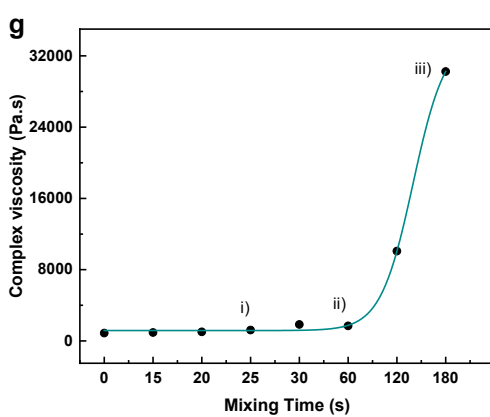
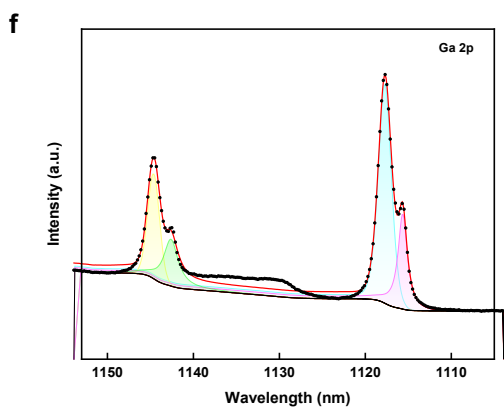
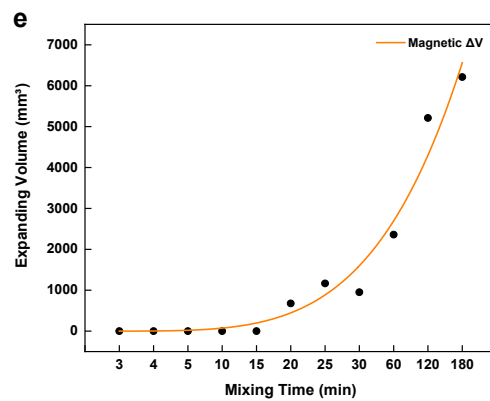
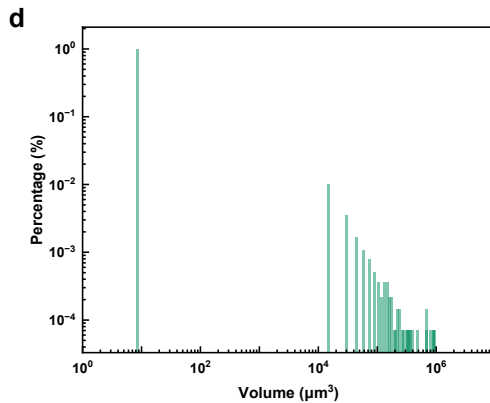
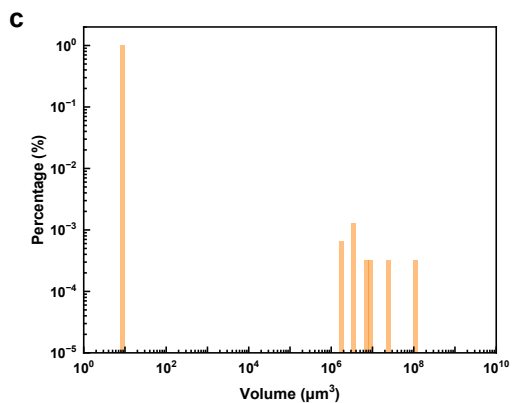
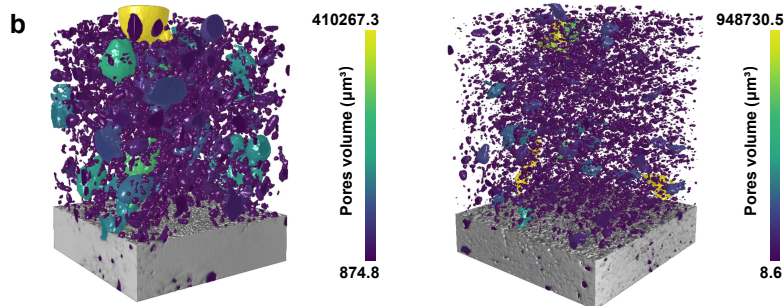
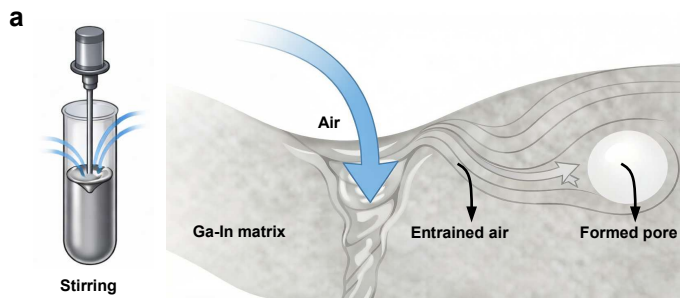
mean $\pm$ SD, with plot representing the mean and shaded area denoting the SD of three independent samples (j, k).

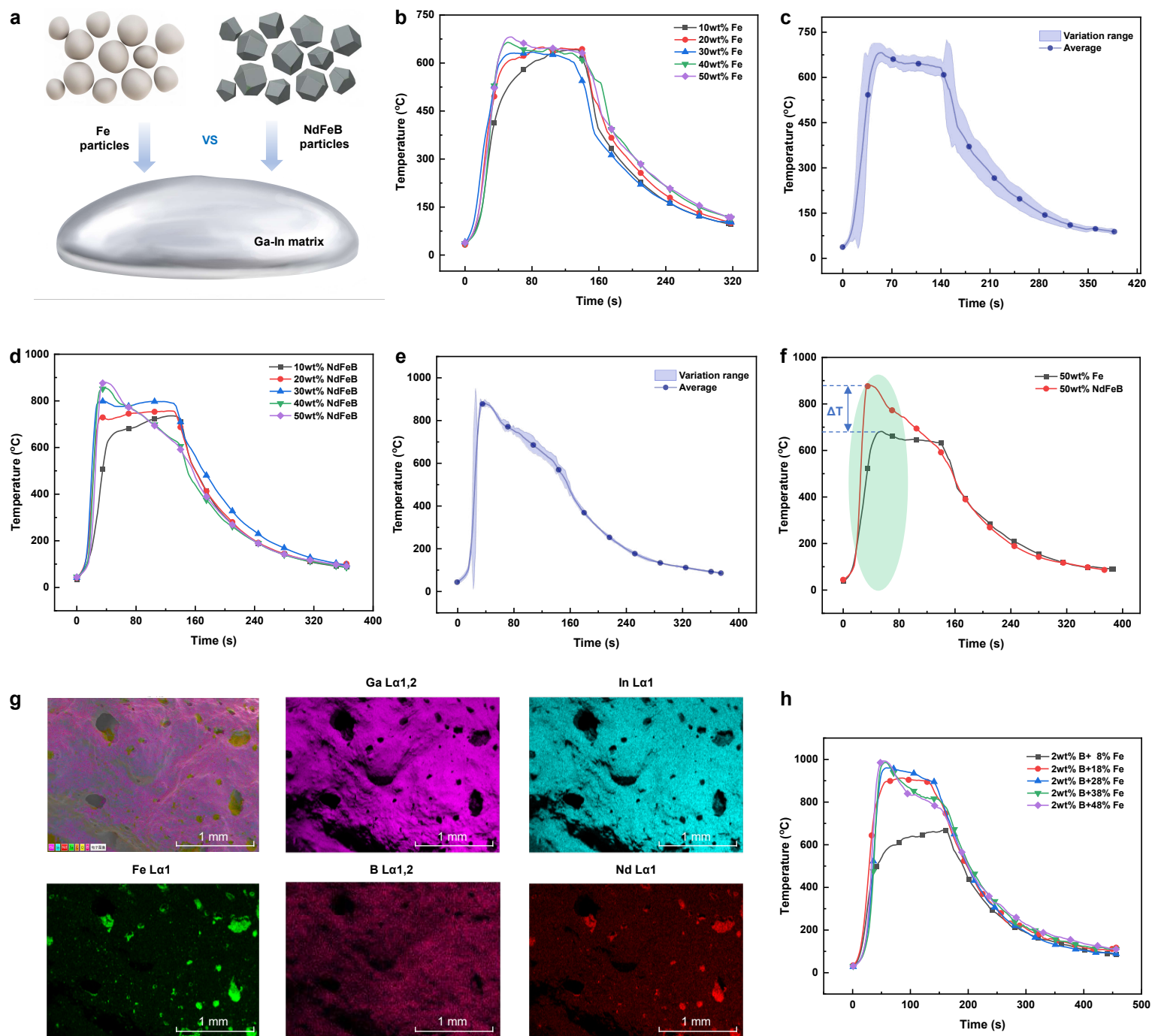
Figure 3 Two material systems and corresponding performance comparison. (a) Comparative schematic of Ga-In matrix doped with Fe and NdFeB particles. (b) Temperature rise curves of Ga-In alloy doped with 10-50 wt% Fe particles under AMF. The peak temperature achievable by the system increases with the rise of doping mass fraction. (c) Temperature rise curve of Ga-In matrix doped with 50 wt% Fe particles under AMF. (d) Temperature rise curves of Ga-In matrix doped with 10-50 wt% NdFeB particles under AMF. The peak temperature achievable by the system increases with the rise of doping mass fraction. (e) Temperature rise curve of Ga-In matrix doped with 50 wt% NdFeB particles under alternating magnetic field. (f) Comparison of temperature rise curves between Ga-In matrices doped with 50 wt% Fe and 50 wt% NdFeB particles. The heat generation capacity of the NdFeB-doped composite system is remarkably superior to that of the Fe-doped system, with a temperature difference of nearly 200 °C. (g) EDS mapping of Ga-In matrix doped with NdFeB particles. B originally contained in NdFeB dissociates and distributes within the Ga-In matrix to participate in chemical reactions. (h) Temperature rise curves of Ga-In alloy matrix doped with 2 wt% B and 8-48 wt% Fe particles under AMF. Data were presented as mean $\pm$ SD, with plot representing the mean and shaded area denoting the SD of three independent samples (b-e). The similar results are repeated in three independent experiments (g).

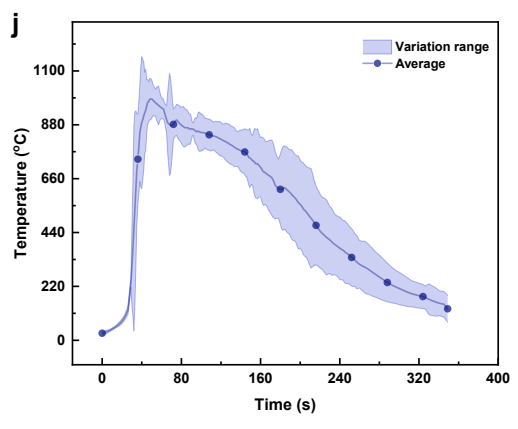
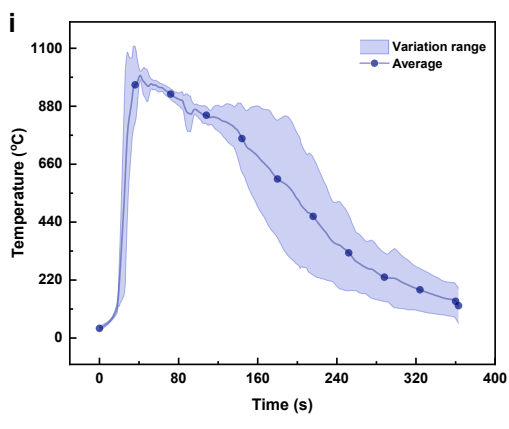
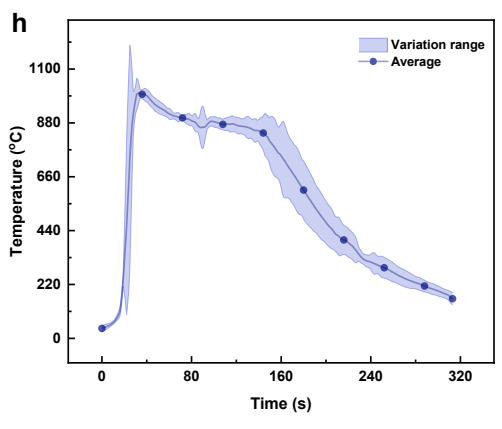
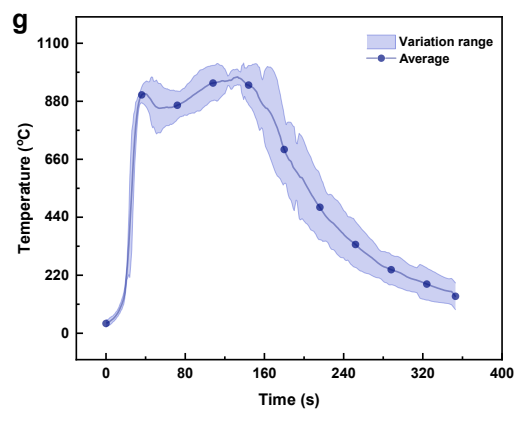
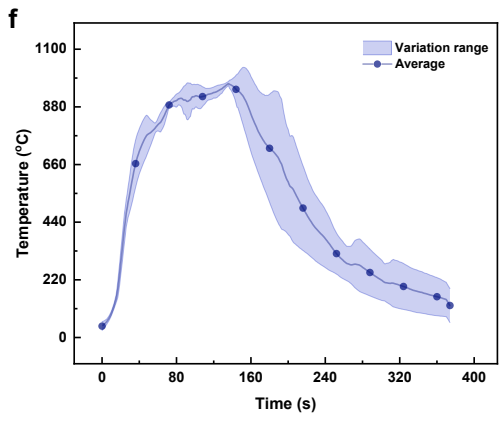
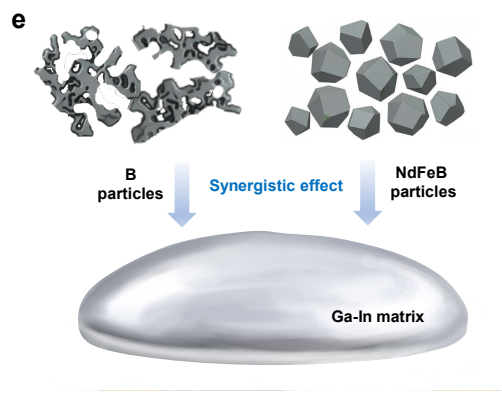
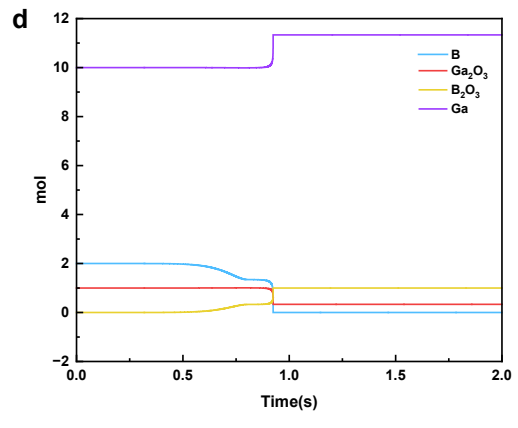
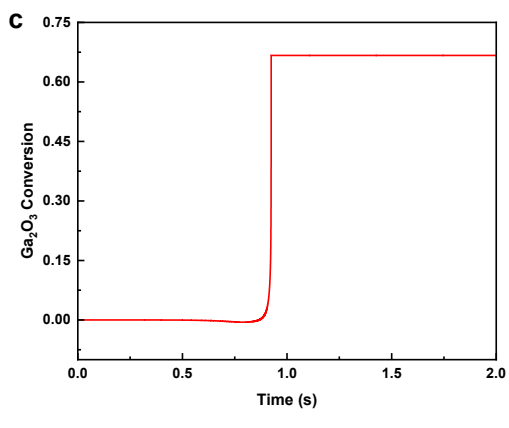
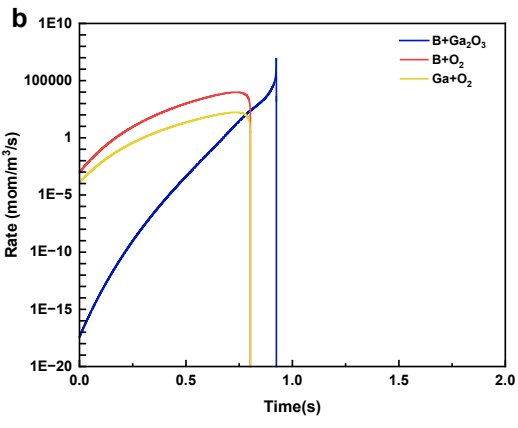
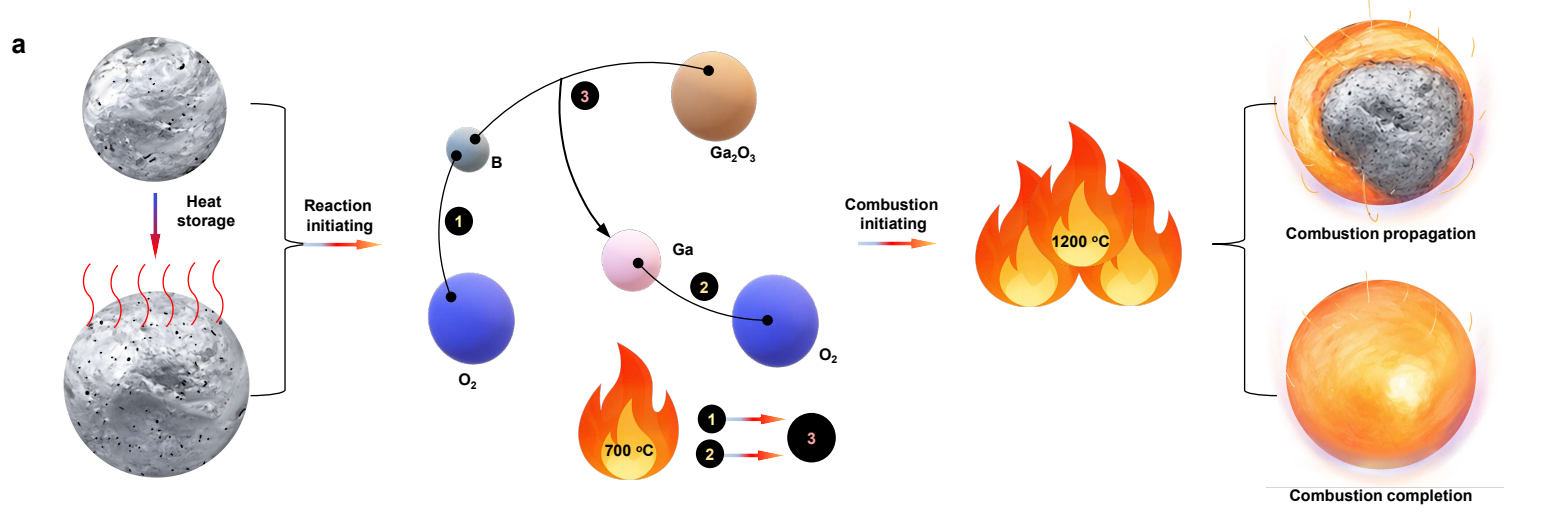
Figure 4 Response mechanism of MH-ELM and the optimal material system selection. (a) Schematic illustration of the response mechanism of MH-ELM. (b) The curves show the variation in reaction rates of different chemical reactions. (c) The transformation curve of Ga_2O_3 . Consistent with Figure (b), the displacement reaction between B and Ga_2O_3 completes at approximately 1 s, accompanied by a sharp surge in the Ga_2O_3 content shown in the curve. (d) The molar variation curves of Ga_2O_3 , B_2O_3 and Ga. At around 1 s, the molar amounts of Ga_2O_3 and B decrease, while the molar amounts of B_2O_3 and Ga increase simultaneously. (e) Schematic illustration of Ga-In matrix co-doped with B and NdFeB particles. (f) Temperature rise curve of Ga-In alloy matrix doped with 2 wt% B + 8 wt% NdFeB particles under alternating magnetic field. (g) Temperature rise curve of Ga-In alloy matrix doped with 2 wt% B + 18 wt% NdFeB particles under alternating magnetic field. (h) Temperature rise curve of Ga-In alloy matrix doped with 2 wt% B + 28 wt% NdFeB particles under alternating magnetic field. (i) Temperature rise curve of Ga-In alloy matrix doped with 2 wt% B + 38 wt% NdFeB particles under alternating magnetic field. (j) Temperature rise curve of Ga-In alloy matrix doped with 2 wt% B + 48 wt% NdFeB particles under alternating magnetic field. Data were presented as mean $\pm$ SD, with plot representing the mean and shaded area denoting the SD of three independent samples (f-j).

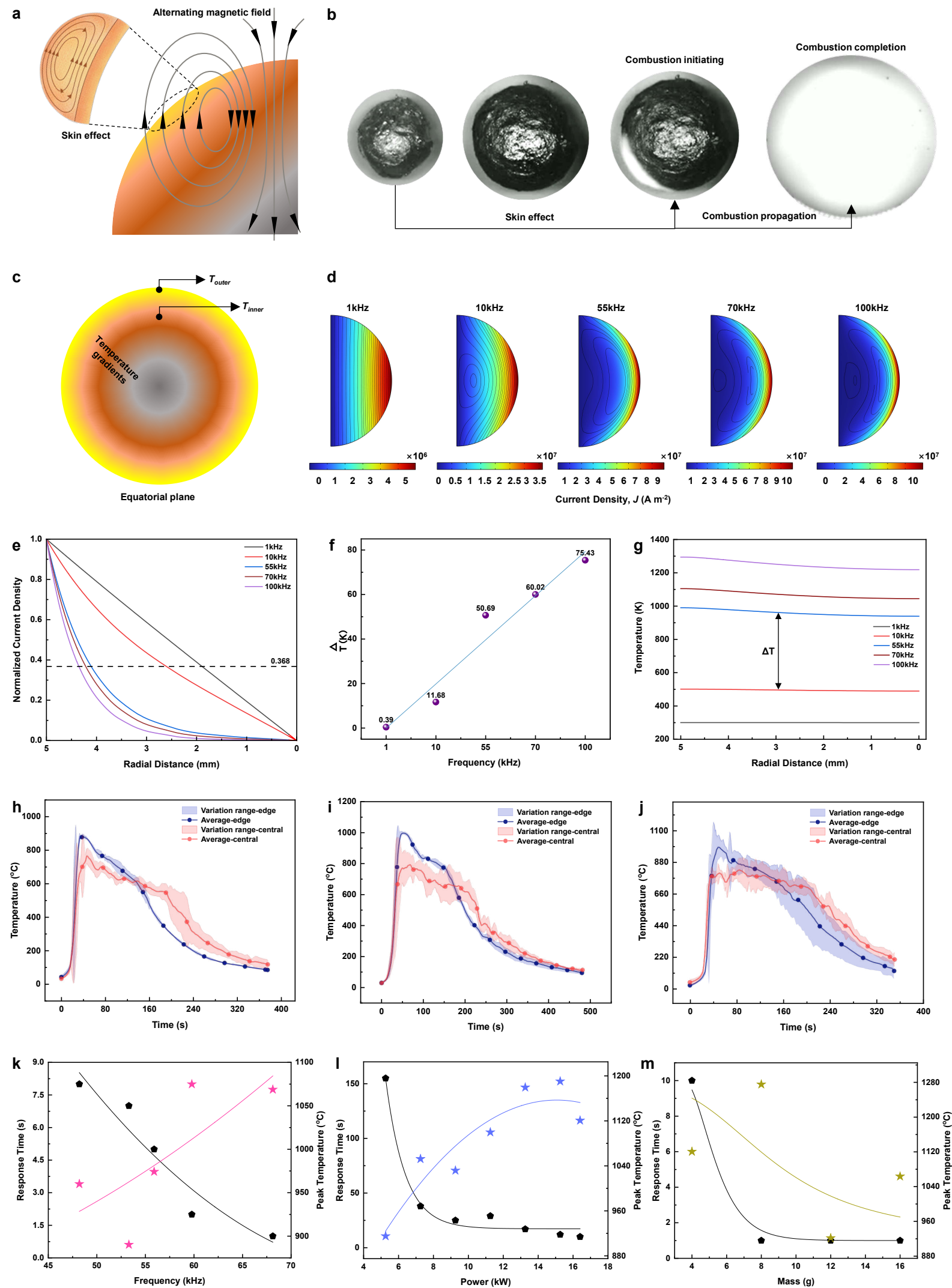
Figure 5. Skin effect on response tuning of MH-ELM. (a) Schematic illustration of skin effect during induction heating. High-frequency alternating magnetic field induces eddy currents inside conductive liquid metal; limited by the skin effect, currents and Joule heat are concentrated on the conductor surface, with markedly higher intensity at edges than the interior. (b) Morphological evolution of MH-ELM (2 wt% B + 48 wt% NdFeB) captured by high-speed camera. (c) Schematic illustration of radial temperature gradient at the equatorial cross-section of MH-ELM; T_{inner} and T_{outer} denote the characteristic temperatures of the inner and outer regions of the sample, respectively. (d) Current density distribution on cross-sections of MH-ELM under different excitation frequencies. (e) Normalized radial distribution of current density on MH-ELM cross-sections under different excitation frequencies. With the increase of alternating magnetic field frequency, the tendency of induced currents gathering at the conductor periphery is greatly strengthened, the internal current density decays rapidly, and the skin effect becomes more prominent; the dashed line at 0.368 serves as the characteristic threshold for judging skin depth (corresponding to $1/e$ of the maximum surface current density). (f) Radial temperature distribution on MH-ELM cross-sections under different alternating magnetic field frequencies. The horizontal axis represents radial distance r ($r = 0$ refers to the cross-section center, $r = 5$ mm refers to the conductor outer edge). (g) Radial temperature differences on MH-ELM cross-sections under different alternating magnetic field excitation frequencies. (h) Comparison of center and edge temperature curves of MH-ELM based on Ga-In doped with 50 wt% NdFeB under AMF actuation. The red curve represents central temperature, and the blue curve represents edge temperature; the average maximum temperature difference between the two positions reaches 100 °C. (i) Comparison of center and edge temperature curves of MH-ELM based on Ga-In doped with 2 wt% B + 48 wt% Fe under AMF actuation; the average maximum temperature difference between the two positions reaches 200 °C. (j) Comparison of center and edge temperature curves of MH-ELM based on Ga-In doped with 2 wt% B + 48 wt% NdFeB under AMF actuation; the average maximum temperature difference between the two positions reaches 160 °C. (k) Effects of different driving frequencies on response time and peak temperature. The blue curve with square markers represents response time, and the red curve with square markers represents peak temperature. (l) Effects of different driving powers on response time and peak temperature. The blue curve with square markers represents response time, and the red curve with square markers represents peak temperature. (m) Effects of different sample masses on response time and peak temperature. The blue curve with square markers represents response time, and the red curve with square markers represents peak temperature. Data were presented as mean $\pm$ SD, with plot representing the mean and shaded area denoting the SD of three independent samples (h-j).











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