



Magnetocaloric refrigeration is a promising alternative to the conventional gas-based refrigeration systems. It is based on the reversible temperature variation produced in certain materials by exposing them to an alternating external magnetic field. This technique offers low environmental impact, higher efficiency and compact, solid state-based refrigeration capacity. To facilitate the integration of magnetocaloric refrigeration in miniaturized devices, the generation of magnetocaloric structures with custom geometries at micrometric resolution is required.

Printing cool magnets

How laser-assisted generation and direct writing of magnetocaloric nanomagnets can influence the advancement of miniaturized technologies

By Shabbir Tahir, Carlos Doñate-Buendía, Bilal Gökce

Advancements in technology miniaturization have transformed our everyday life, from the development of baby monitors to complicated sensors for space exploration; information can be easily stored and retrieved. Although the devices are getting more and more compact and faster, efficient heat extraction without increasing the devices' dimensions still represents a challenge. The most common approach nowadays is to use cooling systems based on conventional CFC/FC gas-based refrigeration, which are not very efficient, not environmentally friendly and difficult to design

for complex geometries. Magnetocaloric refrigeration is a promising alternative to the conventional gas-based refrigeration systems. It is based on the reversible temperature variation produced in certain materials by exposing them to an alternating external magnetic field. This technique offers low environmental impact, higher efficiency and compact, solid state-based refrigeration capacity. To facilitate the integration of magnetocaloric refrigeration in miniaturized devices, the generation of magnetocaloric structures with custom geometries at micrometric resolution is required.

We propose a laser-based way to generate and sinter iron-rhodium nanoparticles to form custom 2D magnetocaloric structures. FeRh nanoparticles were generated by laser ablation in ethanol, formulated into an ink and sintered onto glass substrate. The laser irradiation does not only facilitate the custom nanoparticle ink sintering but also triggers the phase transition from initially laser synthesized paramagnetic (PM) FeRh nanoparticles to the desired antiferromagnetic and ferromagnetic phase (AFM + FM).

Magnetocaloric refrigeration

Magnetocaloric refrigeration is based on the magnetocaloric effect (MCE). MCE is an adiabatic temperature variation response observed in specific materials when an external magnetic field is applied or removed.¹ The temperature difference of these materials after applying and removing the external magnetic field make magnetocaloric materials ideal for use as core elements for a refrigeration cycle.

The first observation of the magnetocaloric effect was reported by Warburg in 1881 with regard to iron, where he showed that the total change in temperature during the magnetization and demagnetization process is zero.² In 1918, the first notable temperature change was observed in nickel by Weiss and Picard, when they observed a change of 0.7 K at 1.5 T.³ They were the first to discover that the phase transition process is reversible, which means that the material can be heated and cooled again by the application and removal of the magnetic field when the material is close to the

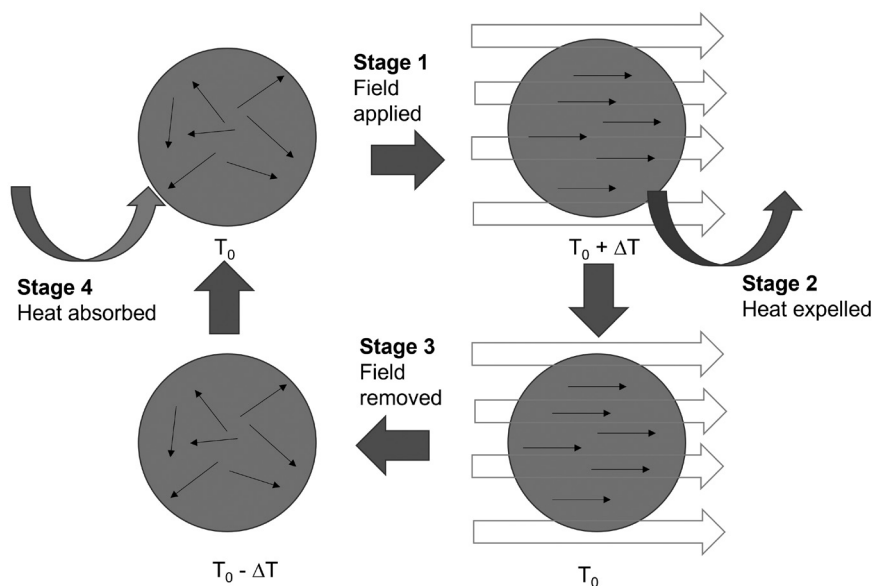
phase transition temperature. They showed that this effect is stronger at the Curie temperature. In 2001, the first room-temperature magnetocaloric refrigerator was built using $Gd_5(Si_2Ge_2)$ by the Astronautics Corporation of America with later, improved designs following.⁴ Among the magnetocaloric materials, near-equiatomic FeRh composition alloys have been widely investigated due to their antiferromagnetic-ferromagnetic phase transition at room temperature upon the application of a magnetic field.⁵ At room temperature, the alloy is in the B2 phase with an antiferromagnetic order (AFM). At approximately 350 K (depending on the composition), the first order transition takes place from AFM to the ferromagnetic (FM) phase with a lattice expansion of 1%. FeRh is known to exhibit the largest magnetocaloric effect with an adiabatic temperature change.

The working principle of a magnetocaloric refrigeration cycle can be defined with four different stages as a first approach (Fig. 1). Initially, the material presents disoriented magnetic domains when no

magnetic field is present. When the external field is applied, the magnetic moments of the material orient themselves in the magnetic field direction, increasing the material's temperature. This heat is released to the surroundings (refrigerant media), finding an equilibrium temperature where the magnetic domains are still aligned with the magnetic field. When the external field is removed, the magnetic moments again disorient themselves, reducing the temperature. The material can then collect the excess heat from the desired device/element and cool it down, returning to the initial situation. This cycle is repeated to initially reduce the device temperature and later keep it constant.⁶

The magnetocaloric material selection has a crucial effect on the performance of the refrigeration cycle and the operation temperature range. To select the ideal materials, there are some factors that should be considered. For instance, the magnetocaloric effect occurs due to the magnetic field coupling with the magnetic sublattice. In principle, all magnetic materials exhibit a magnetocaloric effect.⁷ However, the temperature change is larger near magnetic phase transitions where even a small external field can change the spin state significantly. Generally, the effect is larger near the Curie temperature (T_c), where magnetic spin experiences an order-disorder phase transition.⁷ Consequently, based on the targeted cooling temperature range, a material with a magnetic phase transition in that range should be selected.

In a more detailed description of the process, the temperature variations occurring in magnetocaloric materials can be explained in terms of material entropy changes. Entropy is defined as the degree of disorder or randomness of a system. For example, a solved Rubik's Cube can be seen as a system with low entropy, since all of the coloured panels of the cube are located on their respective face. However, when



(1) Magnetocaloric refrigeration cycle showing heating and cooling after the magnetization and demagnetization processes.

Source: own illustration

shuffled, the entropy of the system increases because all the colours are oriented randomly. In accordance with Clausius' definition, entropy refers to the amount of thermal energy per kelvin that is not available to be converted into mechanical work:

$$\partial S = \frac{\partial Q}{T} \quad (\text{Eq. 1})$$

In a material system, the general entropy term can be described by the addition of different contributions, see Eq. 2.⁸ Configuration entropy, S_C , refers to the way atoms are arranged in the lattice. Similarly, thermal entropy or lattice entropy, S_L , describes how the material lattice vibrates around the equilibrium position of its lattice site at any finite temperature. Magnetic entropy, S_M , refers to the orientation of magnetic moments within a material. Electronic entropy, S_{EP} , is related to the sum of probabilities of electron occupation states.

For a perfect metal (no defects) or alloy system (homogeneous elemental distribution), the configuration entropy is zero and the total entropy $S(T, H)$ is the sum of the lattice entropy S_L , electronic entropy S_{EL} and magnetic entropy S_M .⁹

$$S(T, H) = S_M(T, H) + S_L(T) + S_{EL}(T) \quad (\text{Eq. 2})$$

The overall entropy depends on temperature (T) (Eq. 1), but only magnetic entropy varies with the magnetic field strength (H) (Eq. 2). Hence, when the magnetic field is applied, magnetic entropy decreases due to the magnetic moment alignment (Fig. 1, Stage 1). The magnetic entropy reduction is compensated by the increase in lattice entropy; thereby, the entropy change is 0 as expected in an adiabatic process. The higher lattice entropy state increases lattice vibrations, promoting the material's temperature increase. Under the isothermal condition, the heat is then released to the surround-

ings, resulting in a lattice entropy increase that relaxes lattice vibrations and reduces the material's temperature (Fig. 1, Stage 2).

Finally, the process is reversed when the magnetic field is removed, and the magnetic moments orient randomly, increasing the material's magnetic entropy (Fig. 1, Stage 3). To keep the overall entropy constant, this results in the decrease of lattice entropy and the material's temperature decreases (Fig. 1, Stage 4). At this point, the magnetocaloric material absorbs heat from the source/device to be cooled down to return to the initial equilibrium state, while reducing the temperature of the desired target system. It should be pointed out that the cycle steps explained can vary for specific materials. In material systems such as Heusler alloys and anisotropic materials, the application of the external magnetic field leads to a reduction of the magnetization. In such cases, an inverse magnetocaloric effect is observed.

The decrease in entropy in Stage 1 (Fig. 1) after the application of the magnetic field leads to an increase in the temperature of the material in Stage 2 (Fig. 1). Similarly, when the magnetic field is removed, the increase in entropy in Stage 3 (Fig. 1) leads to a decrease in temperature of the material. To analytically describe the process in terms of entropy and the temperature changes of the magnetocaloric material, the variation dependence relationship between entropy ΔS_M and temperature ΔT_{ad} as a function of the external magnetic field can be derived from Maxwell's equations:¹⁰

$$\left(\frac{\partial(T, H)}{\partial H}\right)_T = \left(\frac{\partial S(T, H)}{\partial T}\right)_H \quad (\text{Eq. 3})$$

Here, S is the entropy, H is the magnetic field and M the magnetization. The relationship between the temperature change and entropy is given by:

$$\Delta T_{ad}(T, \Delta H) = -\Delta S_M(T, \Delta H) \int_{H1}^{H2} \left(\frac{T}{C(T, H)}\right)_M \quad (\text{Eq. 4})$$

This equation shows that the adiabatic temperature rise is inversely proportional to the heat capacity and is directly proportional to the absolute temperature, magnetic field and derivative of magnetization with temperature at constant field. When the magnetic field is applied, the entropy change ($\Delta S_M(T, \Delta H)$) is negative due to the alignment of magnetic moment and, according to Equation 4, the change in temperature is positive (leading to the heating of the material). When the magnetic field is removed, ($\Delta S_M(T, \Delta H)$) is positive and $\Delta T_{ad}(T, \Delta H)$ is negative (leading to the cooling of material).

Nanoscale magnetocaloric materials

Magnetocaloric refrigeration has the potential to replace conventional gas-based refrigeration systems due to the higher thermodynamic efficiency and the fact that no ozone-depleting gases are employed.¹¹ However, even though commercial products exist on the market, there are some issues that limit the large-scale implementation of this technology for room temperature cooling systems. Firstly, there are very few materials that exhibit a magnetocaloric effect at room temperature.¹² Secondly, most of the materials consist of rare elements, increasing the costs of the final product, which is noticeable when used in substantial amounts.¹³ However, reducing the amount of material required by extending the application of magnetocaloric structures to cooling in miniaturized applications such as heat sensors, microelectromechanical devices and thermal diodes, as well as in cooling compact electronics, represents a trade-off between reaching high cooling potential at room temperature, as required for the efficient operation of such devices, while minimizing the amount of material needed. To fabricate these

devices, we propose generating magnetocaloric nanoparticles using the method of laser ablation in liquids that can be used as the initial building blocks of custom magnetocaloric nano/microstructures created by laser sintering.¹⁴

Laser-generated Fe₅₀Rh₅₀ room temperature nanocoolers

At the nanoscale, as the particle size is reduced, the physical, chemical and magnetic properties of the particle also change due to the increase in surface-to-volume ratio and quantum confinement effects. When the size is reduced below 20 nm, it was found that FeRh particles possess a magnetic moment of less than half of the bulk alloy.¹⁵ This fact can be related to size effects, but the synthesis method also highly influences nanoparticle size and composition, affecting their properties. Additionally, the smaller nanoparticles are more prone to oxidation due to the large surface-to-volume ratio.

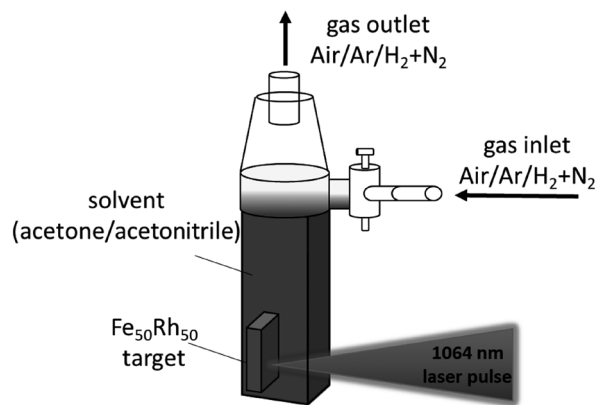
Laser ablation in liquid is a method to produce nanoparticles based on the interaction of laser radiation with the target material immersed in a liquid medium. The laser beam is focused onto the target surface by an f-theta lens, generating ablation of the target and collecting the expelled material in the surrounding liquid, forming the nanoparticle colloid. The synthesis mechanism can be summarized in the following stages:¹⁶

1) The focused laser beam interacts with the material and energy is absorbed creating a plasma plume.

2) The plasma is cooled by the surrounding liquid, leading to the formation of a cavitation bubble. This bubble acts as a reactor for the formation of the nanoparticles.

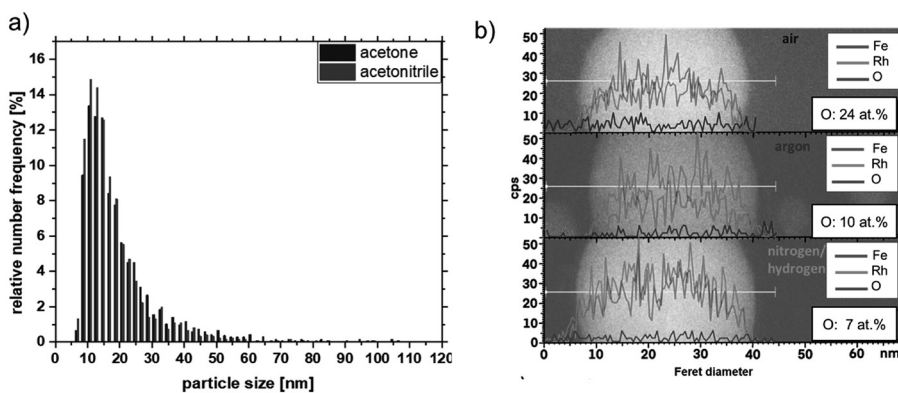
3) The cavitation bubble collapses resulting in the release of particles into the solvent.

Compared to the majority of wet chemical processes, laser ablation in liquid removes the requirement of reactants that can lead



(2) Illustration of laser ablation in liquid in a Schlenk chamber.

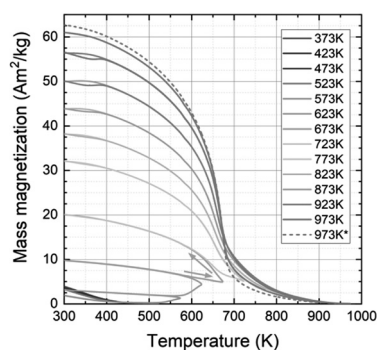
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(3a) Particle size distribution of FeRh nanoparticles produced by laser ablation in acetone.

(3b) EDX line scans of the FeRh nanoparticles produced in air, Ar, and N atmospheres.

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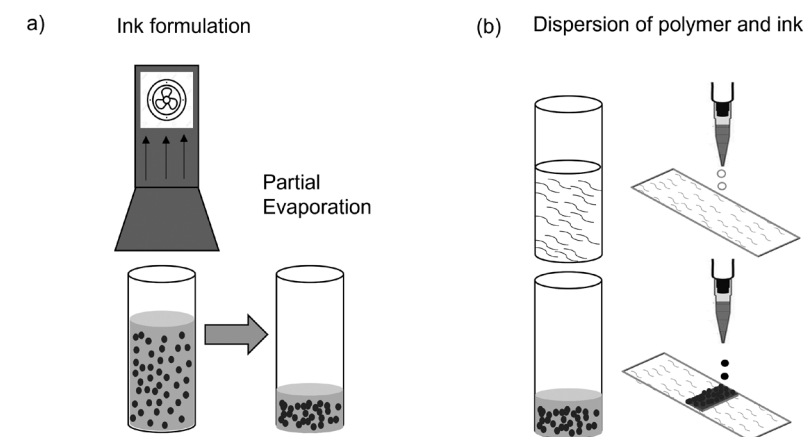
(4) Magnetization as a function of the temperature curves of the FeRh nanopowder after annealing.

Source: image reproduced from: Nadarajah, R.; Landers, J.; Salamon, S.; Koch, D.; Tahir, S.; Doñate-Buendía, C.; Zingsem, B.; Dunin-Borkowski, R. E.; Donner, W.; Farle, M.; Wende, H.; Gökce, B., Towards laser printing of magnetocaloric structures by inducing a magnetic phase transition in iron-rhodium nanoparticles. *Scientific Reports* 2021, 11 (1), 13719.

to by-products in the final colloid, modifying the material composition and requiring extra purification steps. In addition, the technique is environmentally friendly since it only requires the solvent and base material. It reduces the waste material generated and ensures safe handling without expensive security measures such as a vacuum atmosphere since no harmful substances or material dust are released into the air, as they are being collected in the liquid. The laser ablation in liquid process does not require any ligand or precursors, providing ligand-free nanoparticles. However, since this process involves very high temperatures and pressure, the particles can be prone to oxidation. The oxidation does not only disrupt the magnetic properties of FeRh but also affects the composition of the alloy, thereby indirectly affecting the phase transition and magnetocaloric properties of the material. To reduce this problematic effect, our group¹⁴ has synthesized FeRh (with near-equimolar composition) nanoparticles by picosecond laser ablation in organic solvents. The organic solvents were treated with molecular sieves to remove water and were bubbled using argon flow or nitrogen flow to remove dissolved oxygen (Fig. 2).

Using the proposed experimental system – and unlike other synthesis approaches – with this method we were able to produce nanoparticles consisting of a wide size range with particle diameters ranging from 5 to 110 nm (Fig. 3a) with a mean particle size of 16 ± 7 nm. For our application (as discussed later), the broad size range facilitates the pore-free sintering of nanoparticles, thereby increasing the packing density during sintering and reducing the isolated pores. The oxidation content was reduced using inert atmosphere from 24at% in air to 7at% in nitrogen, leading to a reduction in the oxygen content to about 7at% as shown by the EDX result (Fig. 3b).¹⁴

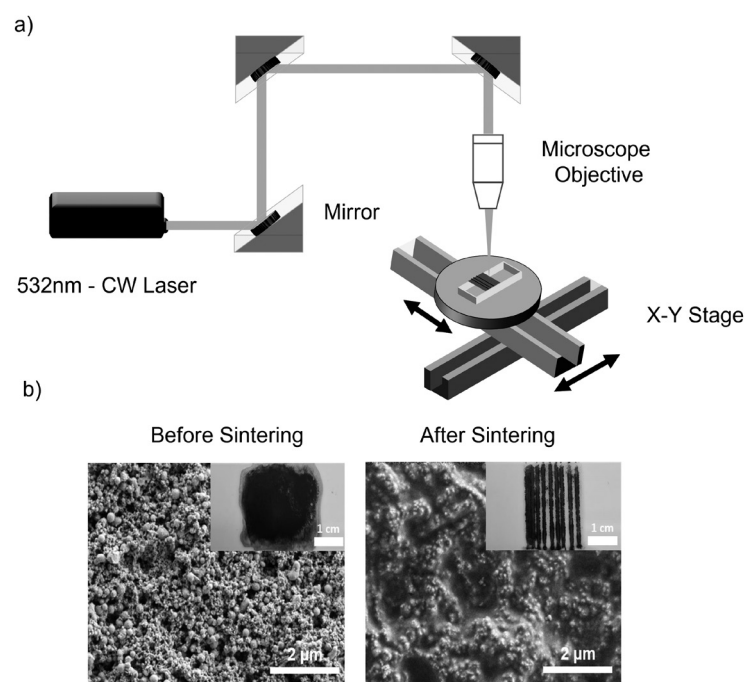
The magnetic characterization was performed using magnetometry



(5a) Illustration displaying the procedure of ink preparation by solvent evaporation.

(5b) Illustration of the procedure of deposition of the polymer coating and FeRh ink on the glass substrate.

Source: Tahir, S., Landers, J., Salamon, S., Koch, D., Doñate-Buendía, C., Ziefuß, A.R., Wende, H. and Gökce, B. (2023), Development of Magnetocaloric Microstructures from Equiatomic Iron–Rhodium Nanoparticles through Laser Sintering. *Adv. Eng. Mater.*, 25: 2300245.



(6a) Illustration of the laser sintering process on a glass substrate, controlled by an X-Y linear stage.

(6b) SEM images of the samples before and after the sintering process.

Source: image reproduced from: Nadarajah, R.; Landers, J.; Salamon, S.; Koch, D.; Tahir, S.; Doñate-Buendía, C.; Zingsem, B.; Dunin-Borkowski, R. E.; Donner, W.; Farle, M.; Wende, H.; Gökce, B., Towards laser printing of magnetocaloric structures by inducing a magnetic phase transition in iron-rhodium nanoparticles. *Scientific Reports* 2021, 11 (1), 13719.

measurements.¹⁷ The samples were heated in steps of 50 K up to 973 K and magnetization was recorded against the temperature. The nanoparticles were initially paramagnetic due to the ultrafast heating and

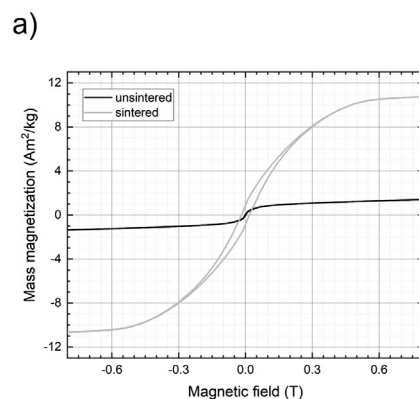
cooling process and were converted to the B2 phase (ferromagnetic and antiferromagnetic) after annealing, as shown by the magnetization as a function of the temperature curve (Fig. 4). The first irreversible increase

in $M(T)$ was witnessed at 550 K and the maximum magnetization of 62 A/m^2 was achieved at around 973 K. The reversible thermal hysteresis is shown between 300 and 550 K, which was assigned to phase transition from the AFM to the FM phase of the B2 phase when annealed above 773 K.

FeRh magnetocaloric nanoparticle ink formulation

In order to employ the produced FeRh nanoparticles as building blocks for nano-/microscale magnetocaloric structures, the synthesized colloids need to exhibit long-term stability for concentrations above 1wt%. Furthermore, a suitable viscosity is also required to allow their dispersion in the substrate to be cooled. To achieve this, it is necessary to formulate a nanoparticle ink from the initially produced colloids. Ink formulation of different nanomaterials still represents a demanding trend, with high technological interest for the printing of flexible electronics and sensors¹⁸.

In our case, the synthesized FeRh nanomagnets do not contain any surfactants during the synthesis process. Therefore, to increase stability at high nanoparticle concentrations and modify the ink viscosity, stabilizers are later added for the ink formulation. The formulation process is performed starting with the nanoparticles synthesized in ethanol. To achieve a higher concentration, the solvent was removed by evaporating it in a fume hood (Fig. 5a). Heating was avoided to reduce the oxidation of the particles. The solvent was evaporated to achieve 1wt% ink. Before nanoparticle laser sintering, a 10wt% PVP polymer solution was added on the glass used as substrate to create the magnetocaloric microstructures. Later, the FeRh ink was ultrasonicated to remove agglomeration and improve the ink's homogeneity, before being dispersed onto the glass surface (Fig. 5b).



(7a) Magnetization against the magnetic field curves of the FeRh nanoparticles before and after sintering.

(7b) Images before and after removing the non-irradiated ink after laser sintering, showing the formation of custom magnetocaloric geometries.

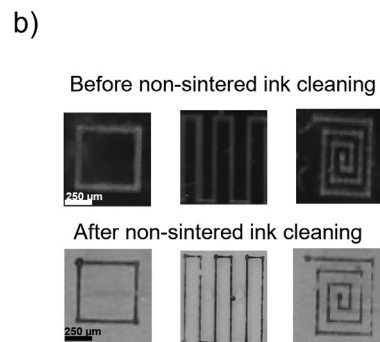
Source: 7a) Tahir, S., Landers, J., Salamon, S., Koch, D., Doñate-Buendía, C., Ziefuß, A.R., Wende, H. and Gökce, B. (2023), Development of Magnetocaloric Microstructures from Equiatomic Iron–Rhodium Nanoparticles through Laser Sintering. *Adv. Eng. Mater.*, 25: 2300245.

7b) Nadarajah, R.; Landers, J.; Salamon, S.; Koch, D.; Tahir, S.; Donate-Buendia, C.; Zingsem, B.; Dunin-Borkowski, R. E.; Donner, W.; Farle, M.; Wende, H.; Gokce, B., Towards laser printing of magnetocaloric structures by inducing a magnetic phase transition in iron-rhodium nanoparticles. *Scientific Reports* 2021, 11 (1), 13719.

Custom magnetocaloric microstructure printing by laser sintering

For centuries, we have seen graphics and text printed on paper and textiles. Nowadays, printing is also a valuable technique for electronics, optoelectronics and biomedical applications. For such applications, various printing technologies have emerged that deposit functional materials onto different substrates, such as inkjet printing, roll-to-roll printing, flexographic printing, gravure, screen and microcontact printing. With regard to the choice of printing technology, there are critical issues such as resolution, adhesion to the substrate, process reliability and stability, manufacturing speed, cost and environmental impact.¹⁹ Among the different printing technologies, laser sintering has been widely used because of its high speed, resolution and versatility in printing on different material substrates of glass, ceramics and flexible plastics.²⁰

To process the prepared FeRh magnetocaloric ink dispersed on a glass substrate and generate magnetocaloric custom structures, a continuous-wave 532 nm laser and a



two-axis linear stage were employed (Fig. 6a).¹⁷ The effect of the laser and scanning parameters during sintering was determined, obtaining continuous structures at an intensity of 0.85 W/mm^2 . We were able to sinter a continuous structure with a sheet resistance of $81.3 \text{ k}\Omega/\text{sq.}$, i.e. three orders of magnitude lower than the initial ink. The merging of the nanoparticles into a bulk structure was confirmed by SEM. The images of before and after the sintering process show that the nanoparticles merged to form a continuous structure (Fig. 6b).

The laser irradiation also promoted the magnetic phase transition without further annealing, as shown by the M-H curve (Fig. 7a). Before laser processing, the particles were paramagnetic with no hysteresis loop and almost zero magnetization. The laser sintering resulted in the induction of magnetization with minimum hysteresis, which was required to maximize the magnetocaloric effect of the material.

The micrometric resolution of the printed magnetocaloric structures was achieved by the employment of a microscope objective lens, reaching a resolution of $40 \mu\text{m}$. The shape of the generated microstruc-

ture is controlled by the two-axis stage, resulting in different geometries being printed, as can be observed in Figure (7b).

Summary

We were able to demonstrate for the first time how FeRh magnetocaloric nanomagnets can be generated and printed into custom structures through laser irradiation. The nanomagnets were fabricated by the laser ablation in ethanol of a bulk FeRh target. The solid-solution, near-equiatom FeRh alloy particles produced were synthesized with minimized oxidation in order to avoid any adverse effects on their magnetic and magnetocaloric properties. The FeRh nanoparticles were formulated into an ink with 1wt% nanoparticle content by evaporating the solvent. Ethanol was chosen as the liquid medium for the ink formulation during ablation to facilitate nanoparticle dispersion on a glass substrate. The ink was then dispersed onto the polymer-coated glass substrate and sintered using a CW laser to demonstrate the sintering of custom structures with reduced electrical sheet resistance and a spatial resolution of 40 μm . This procedure can be applied to different materials and prospectively used to print magnetocaloric inks for the cooling of miniature devices, heat pumps, heat sensor and biomedical applications.

Zusammenfassung

Erstmals konnte gezeigt werden, wie magnetokalorische FeRh-Nanomagnete durch Laserbestrahlung erzeugt und in maßgeschneiderten Strukturen gedruckt werden können. Die Nanomagnete wurden mithilfe der Laserablation eines massiven FeRh-Targets in Ethanol hergestellt. Die nahezu äquiatom

FeRh-Legierungspartikel wurden unter Vermeidung von Oxidation synthetisiert, um negative Auswirkungen auf ihre magnetischen und magnetokalorischen Eigenschaften zu verhindern. Die FeRh-Nanopartikel wurden dann durch Verdampfen des Lösungsmittels zu einer Tinte mit einem Anteil von 1 Gew.-% Nanopartikeln formuliert. Ethanol wurde als flüssiges Medium für die Tintenformulierung während der Ablation gewählt, um eine optimale Dispersion der Nanopartikel auf einem Glassubstrat zu ermöglichen. Anschließend wurde die Tinte auf das mit Polymer beschichtete Glassubstrat aufgetragen und mit einem CW-Laser gesintert, um die Herstellung maßgeschneiderter Strukturen mit reduziertem elektrischen Schichtwiderstand und einer räumlichen Auflösung von 40 μm zu demonstrieren. Dieses Verfahren kann auf verschiedene Materialien angewendet werden und voraussichtlich zur Herstellung magnetokalorischer Tinten für die Kühlung von Miniaturgeräten, Wärmepumpen, Wärmesensoren und biomedizinischen Anwendungen verwendet werden.

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The authors

Shabbir Tahir, M.Sc., started his academic career at the NED University of Engineering and Technology in Pakistan where he completed his bachelor's degree in Material Engineering in 2014. He gained industrial experience at Dawood Engineering Pvt. Ltd. in Pakistan as a quality control officer. To pursue further education, he moved to Germany in 2016, where he acquired his master's degree in Advanced Materials and Processes from Friedrich-Alexander-Universität Erlangen-Nürnberg. During this time, he won second place in the European BEST Engineering Competition. In 2018, he did an internship at Robert Bosch GmbH, where he applied atomic layer deposition coatings on steels for use in PEM fuel cell bipolar plates. In 2019, he was appointed as a research assistant at Forschungszentrum Jülich where he worked on his master's thesis on the synthesis of bimetallic, shaped nanoparticles as model catalysts for electrochemical reactions. He completed his master's thesis and degree in April 2020. Later, he started his Ph.D. in Professor Bilal Gökce's research group at the University of Duisburg-Essen within the CRC/TRR 270 project, where he is working on the synthesis and printing of magnetocaloric nanoparticles using laser processing. In 2021, he moved to the University of Wuppertal together with Professor Gökce. During this time, he has presented his work at many conferences and workshops and recently won the best poster award at the 2022 Joint MMM-Intermag Conference.

Dr. Carlos Doñate-Buendía began his academic career at the University of Valencia in Spain where he received his B.Sc. degree in Physics in 2014 and an M.Sc. degree in Advanced Physics with a specialisation in Material Science and Photonics in 2015. He subsequently obtained an M.Sc. degree in Applied Physics from the Universitat Jaume I (UJI) in Spain and, in parallel, was awarded an FPI-UJI grant to pursue his Ph.D. on the topic of 'Synthesis of nanomaterials by high throughput pulsed-laser based systems: Application in biomedicine and material processing'. He defended his Ph.D. thesis in 2019. His doctorate included an international mention and was awarded the overall result of summa cum laude. During his time as a doctoral researcher, he also contributed to preliminary work for a Marie Skłodowska-Curie fellowship that was awarded to the GROU-UJI research group, as well as helping to obtain a patent in the context of the Marie Skłodowska-Curie project. He continued his career path in academic research and joined Professor Stephan Barcikowski's research group at the University of Duisburg-Essen as a postdoctoral researcher in 2020 and, within

a short period of time, he became a junior research group leader. During this period, he contributed to the SPP 2122 'Materials for Additive Manufacturing' DFG priority programme and CRC/TRR 270 'Hysteresis design of magnetic materials for efficient energy conversion'. In 2021, he joined Professor Bilal Gökce's chair at the University of Wuppertal, where he is currently the leader of the Particles and Additive Manufacturing of Polymers group.

Professor Bilal Gökce started his academic career at and the Fraunhofer Institute for Laser Technology ILT and RWTH Aachen University, where he completed his Diplom degree in Physics in 2008. He pursued his Ph.D. in Solid State Physics at North Carolina State University in the USA where he was granted the Provost's Fellowship in 2009. He received his doctorate in 2012 and continued his career path as a postdoctoral researcher on non-linear optics. After moving back to Germany, he first worked as a researcher on laser applications at T-Systems International before deciding to dedicate his further career to academia and being appointed as a research group leader for Laser Material Processing & Additive Manufacturing at the University of Duisburg-Essen in 2014. In 2015, he was selected for the Global Young Faculty where outstanding and dedicated young academic minds are brought together for the development of innovative projects. In 2017, he received a DAAD scholarship for a research stay at the Massachusetts Institute of Technology's Center for Materials Science and Engineering. In 2018, he received his habilitation and *venia legendi* in Technical Chemistry from the University of Duisburg-Essen. In the same year, he was awarded the Fojtík-Henglein Prize at the ANGEL conference for his pioneering research results that contributed to the laser synthesis of colloids in liquids. In 2020, he was accepted into the German Research Foundation's (DFG) Heisenberg Programme. He is currently a full professor of Materials Science and Additive Manufacturing at the University of Wuppertal, holding one of the few Heisenberg professorships funded by the DFG.



Carlos Doñate Buendía (oben), Bilal Gökce (unten). Foto: Vladimir Unković

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