MAGNETIC FRONTIERS
MAGNETIC MATERIALS AND MOTORS FOR GREEN ENERGY APPLICATIONS
15 - 19 September 2024 - Darmstadt, Germany

Frontiers in Magnetism: Magnetic Materials and Motors for Green Energy Applications

Darmstadt, Germany
15-19 September 2024

Conference Chairs:
Prof. Oliver Gutfleisch
Prof. Johan Paulides

TECHNISCHE UNIVERSITÄT DARMSTADT

FUNKTIONALE MATERIALIEN

IEEE MAGNETICS

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Welcome

Welcome message

It is our great pleasure to announce Magnetic Frontiers: Magnetic Materials and Motors for Green Energy Applications, sponsored by the IEEE Magnetics Society. The workshop will be held from September 15th to 19th, 2024, in Darmstadt, Germany, at the Georg-Christoph-Lichtenberg-Haus. This year's Magnetic Frontiers has established itself as the leading event on magnetic materials for green energy applications, attracting top experts and innovators. The workshop will feature plenary and invited talks by key researchers, as well as poster presentations showcasing cutting-edge developments. With a select number of participants (approximately 100), the event provides an intimate setting for in-depth discussions and collaborations on the latest advances in magnetic materials and motors for green energy applications. Whether presenting research or networking with colleagues, we hope you will take advantage of this unique opportunity to engage with leading scientists and experts.

Scope

Magnets are key enablers of the green energy transition, and this workshop will focus on recent advances in high performance magnetic materials for energy applications. Topics include permanent magnets, soft magnets, and magnetocaloric materials, with applications ranging from transformers, motors, and generators to cooling systems.

The workshop will cover both fundamental research in academia and industrial developments, addressing primary rare earth mining, resource efficiency, and magnet recycling, with an emphasize on sustainability and life cycle considerations. It will also cover novel computational methods, such as machine learning and data-driven materials discovery, alloy design, and advanced processing and characterization.

We warmly invite you to attend the workshop, participate in the technical sessions, and enjoy the social events.

Committees

Conference Chairs

Prof. Oliver Gutfleisch (TU Darmstadt/Germany)
Prof. Johan Paulides (Advanced Electromagnetic Group/Netherlands)
Dr. Claire Donnelly (MPI CPFS Dresden/Germany)

Program Committee

Dr. Alex Aubert (TU Darmstadt/Germany)
Dr. Semih Ener (TU Darmstadt/Germany)

Local Committee

Maija Laux (TU Darmstadt/Germany)
Kirit Kaiser (TU Darmstadt/Germany)

Sponsors

About us

Our international team at Functional Materials at TU Darmstadt conducts fundamental and applied materials research for the fields of energy conversion, mobility, cooling, medicine and robotics as well as hydrogen liquefaction and storage. The focus is on advanced nanostructured magnetic materials, which are analyzed and modelled on all length scales, from the atom to the device. This enables our FM team to develop novel multi-functional materials encompassing their synthesis, processing, and property characterization. We explore their multi-responsiveness in engineering components exposed to different stimuli and operating environments. We are especially concerned with the criticality of technology metals and the design of materials and devices for circularity from the very beginning.

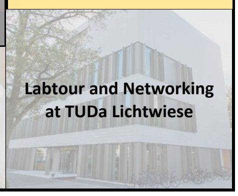
The transformation to renewable energy technologies is first of all a materials´ transition! Sustainable materials are a necessity for a net-zero emission energy scenario.

Visit our website for more!

Venue and Direction

The **welcome reception** will be held at Karo5 in Darmstadt city-center:
Karolinenpl. 5, 64289 Darmstadt, Germany.
The **conference** will be held at Georg-Christoph-Lichtenberg-Haus in Darmstadt:
Dieburger Straße 241, 64287 Darmstadt.
There are direct bus connections between the Darmstadt city center (Luisenplatz) and the Lichtenberg-Haus (approx. 11 min). You can use the bus lines F and FM, which leave from Luisenplatz approximately every 15 minutes. Bus tickets are provided at the welcome reception.
You can get more detailed information about the schedule of the bus lines F and FM, click here.
The bus stop in front of the Lichtenberg-Haus is called Darmstadt Fasanerie (Fasanerie NF in the PDF).

Program

Sunday, 15.09.2024	Time	Monday, 16.09.2024	Tuesday, 17.09.2024	Wednesday, 18.09.2024	Thursday, 19.09.2024
	8:45-9:00	Opening: Oliver Gutfleisch (TU Darmstadt)			
	9:00-9:35	Plenary I: Masato Sagawa (NdFeB)	Plenary II: Franca Albertini (CNR INREM, Parma)	Plenary III: Kiyonori Suzuki (Monash University, Melbourne)	Plenary IV: Alain Rollat (Carester)
	9:35-12:20	Hard magnetic materials and applications (Chair: S. Ener)	Magnetocaloric materials and applications (Chair: K. Skokov)	Soft magnetic materials and applications (Chair: I. Dirba)	From green mining to green motors (Chair: O. Gutfleisch)
	9:35-10:00	Keynote I: Jun Cui (Ames National Lab)	Keynote VIII: Victorino Franco (University of Sevilla)	Keynote XI: Inge Lindemann-Geipel (Fraunhofer IFAM)	Keynote XVIII: Noritsugu Sakuma (Toyota Motor Corporation)
	10:00-10:30	Coffee break	Coffee break	Coffee break	Coffee break
	10:30-10:55	Keynote II: Hossein Sepehri-Amin (NIMS Tsukuba)	Keynote IX: Feng-xia Hu (Chinese Academy of Sciences)	Keynote XII: Silvana Mercone (Université de Tours)	Keynote XIX: Jürgen Gassmann (Fraunhofer IWKS)
	10:55-11:20	Keynote III: Dominik Ohmer (Vacuumschmelze)	Keynote X: Falk Münch (MagnoTherm GmbH)	Keynote XIII: Alberto Bollero (Robert Bosch GmbH)	Keynote XX: Roland Gauss (EIT RawMaterials)
	11:20-11:45	Poster flash talks (60')	Poster flash talks (60')	flash talks (60') Functional Materials (TU Darmstadt)	Keynote XXI: Andreas Jöckel (Flender GmbH)
	11:45-12:10				Closing: Oliver Gutfleisch (TU Darmstadt)
	12:10-12:20				Light snacks and Departure
	12:30-13:30	Lunch break	Photo then Lunch break	Lunch break	
	13:30-15:00	Poster I	Poster II	Poster III	
	15:00-17:00	Accelerated material discovery (Chair: P. Tozman)	 Excursion to Kloster Eberbach	Advanced processing & characterization (Chair: A. Aubert)	
	15:00-15:25	Keynote IV: Nora Dempsey (Institute Néel, CNRS Grenoble)		Keynote XIV: Moataz Attallah (University of Birmingham)	
	15:25-15:50	Keynote V: Heike Herper (University of Uppsala)		Keynote XV: András Kovács (Forschungszentrum Jülich)	
	15:50-16:10	Coffee break		Coffee break	
	16:10-16:35	Keynote VI: Nicola Morley (University of Sheffield)		Keynote XVI: Katharina Ollefs (Universität Duisburg-Essen)	
	16:35-17:00	Keynote VII: Thomas Schrefl (Krems-Danube University)		Keynote XVII: Varun Chaudhary (Chalmers University of Technology)	
 17:00 - 20:00 Welcome Reception in KARO5, TUDa	17:00-18:00	Round Table discussion		 Labtour and Networking at TUDa Lichtwiese	
	18:00-22:00		 Dinner at Orangerie Darmstadt		

Excursion and Dinner

Excursion

Experience the monastery with all of your senses. Learn more about the cistercians and life in the abbey in times gone by and enjoy exquisite wines. Let the almost 900-year-old abbey put you under its spell!
We begin with a walk through the monastery, in which you will gain insights into its colourful history and a first impression of its fascinating atmosphere. You will understand why star director Jean-Jacques Annaud and producer Bernd Eichinger chose Kloster Eberbach in the mid-1980s when looking for a suitable location for their film adaptation of Umberto Eco's classic "The Name of the Rose": The masterful production of this bestseller in the winter of 1985/86 with Sean Connery in the lead role and its film run made Kloster Eberbach at a stroke famous all over the globe.
Our guided tour takes you on a journey through time!

Dinner

The official Conference dinner will take place in Darmstadt right next to the historic orangery building and surrounded by flowers, borders, palms and orange trees, a Mediterranean style of cuisine and perfect hospitality is cultivated with love and dedication.

Plenary talks

Masato Sagawa (NdFeB, Japan)
Nd-Fe-B sintered magnet: Aiming to realize the perfect magnet for green energy applications

Franca Albertini (CNR INREM)
Heusler compounds for magnetocaloric applications

Kiyonori Suzuki (Monash University)
State of the art in soft magnets

Alain Rollat (Carester, France)
The Rare Earths Industry - The radioactivity issue and the separation challenges

Nd-Fe-B sintered magnet: Aiming to realize the perfect magnet for green energy applications

Masato Sagawa*[1]

[1]Daido Steel Co., Ltd. – Japan

Abstract

Nd-Fe-B sintered magnets were created 40 years ago. Due to their large magnetization and strong magneto crystalline anisotropy combined with the phase diagram of the Nd-Fe-B ternary system which is extremely convenient for forming an ideal cellular structure, it is expected that Nd-Fe-B sintered magnets will continue to be the world's strongest magnets for some time. However, there are some unresolved issues regarding these magnets. To address these issues, I have been working on the following three research themes. The purpose and development status of each research theme listed below will be explained in this talk.
(1) Development of a highly heat-resistant Nd-Fe-B sintered magnet that does not use heavy rare earth elements: The most direct way to increase the coercive force and heat resistance of the magnet without heavy rare earth is to reduce the particle size of the starting alloy powder. My research team used a helium gas jet mill to create powder with a particle size of approximately 1 μm, and were able to create a Nd-Fe-B sintered magnet with a coercive force nearly 20 kOe at room temperature.

(2) Development of Near Net Shape Manufacturing Process (NNSMP) for Nd-Fe-B sintered magnets: To produce NNSMP Nd-Fe-B sintered magnets, Nd-Fe-B alloy powder is packed into a mold with cavities of a predetermined shape and size made by assembling metal plates, and then oriented by applying a pulsed magnetic field. We then take out these molded oriented bodies from the mold and sinter them. We found that high-performance sintered magnets can be manufactured using this method, but the dimensional variation of the sintered bodies was as large as $\pm 3\%$ which needs further reduction.
(3) Development of a high-performance laminated magnet for the EV traction motor: Using the NNSMP method, we developed a method to create 2 mm-thick element magnets and stack them to create a laminated magnet. Metal oxide powder is sandwiched between the element magnets, and the entire laminate is hot pressed. Using this method, it is possible to produce a high-performance laminated magnet for the EV traction motors that have high performance and generate almost no eddy current loss during the operation.

Keywords: Nd, Fe, B magnet, Heat resistant magnet, Near Net Shape, Laminated magnet

*Speaker

Heusler compounds for magnetocaloric applications

Franca Albertini*[1]

[1]IMEM-CNR – Italy

Abstract

In the last decades Heusler compounds have constantly shown emerging properties and opened new fields of investigation thanks to their structural and electronic flexibility, arising from a strong coupling between electronic, lattice and magnetic degrees of freedom. Among them, magnetic shape memory Heuslers have been intensively investigated for their multi-functional properties and in particular for their giant magnetocaloric effect. At the basis of their phenomenology there is a martensitic structural transition between a high-temperature cubic phase and a low-temperature phase of lower symmetry. They are rare earth-free, easy to prepare and offer large tailoring possibilities. By exploiting suitable compositional changes, it is possible to control their main physical properties and consequently tune their magnetocaloric performances: e.g. critical temperatures, occurrence of the martensitic transformation, field dependence of the transition temperature, intensity and nature of the magnetocaloric effect (e.g. from direct to inverse). However, to exploit their full potential in magnetic refrigeration, there are still many challenges to be faced.
Some of them are directly related to the hysteretic character of the martensitic transformation, that limits the materials performances in cyclic operations
In my talk I will present some recent results on bulk and micro/nanoscale Heusler compunds obtained by different fabrication methods:, powder metallurgy and arc melted bulk materials, mechanically milled particles, epitaxial thin films. Thin films and micro/nanoparticles are of particular interest not only for the realization of miniaturized devices and suitable composites, but also for providing insights into the magneto-structural coupling at the different length scales, suggesting possible strategies for the optimization of the material performances. The talk will focus on microstructure tuning and microstructure-related effects on the martensitic transformation, in view of the full exploitation of this class of materials in magnetocaloric and thermomagnetic applications.

Keywords: Heusler compounds, magnetocalorics, martensitic microstructure, thin films and nanostructures

*Speaker

State of the art in soft magnets

Kiyonori Suzuki*[1]

[1]Department of Materials Science and Engineering, Monash University, Clayton, VIC 3800, Australia – Australia

Abstract

Small magnetic anisotropy and near-zero magnetostriction are two prerequisites for excellent soft magnetic properties. For conventional Fe-based crystalline materials, these requirements are satisfied by additives. Since this approach usually leads to a considerable reduction of Fe content, the saturation magnetic polarization (Js) is way below the elemental value of Fe. However, the effect of the magnetocrystalline anisotropy ($K1$) is suppressed dramatically by the exchange-softening effect(1) both in amorphous and nanocrystalline alloys, setting the alloy design free from one of the prerequisites. Nevertheless, Fe-based amorphous alloys exhibit large saturation magnetostriction (ls) as their ls is proportional to the square of Js, limiting their soft magnetic properties. Contrarily, near-zero ls is obtainable in Fe-based nanocrystalline alloys, making them one of the most advanced alloy families in soft magnetic materials.

Since the exchange-softening effect in nanocrystalline alloys is manifested in the dramatic reduction of the coercivity (Hc) by grain refinement, disproportionate emphasis has often been laid on grain refinement. Indeed, small Hc in the order of a few A/m is obtained for nanostructures with a grain size of 10 to 20 nm even with a large ls in the order of 10ˆ-5 and thus, the significance of magnetostriction is often underestimated. However, one must realize that Hc reflects the static pinning effect of the domain wall displacement determined by $< K >$ while the core loss is governed also by the wall damping effect. Most recently, we have confirmed(2) that the excess core loss of amorphous and nanocrystalline ribbons depends highly on ls. Moreover, high initial permeability above _˜ 10,000 at 1 kHz is limited to materials with ls in the order of a few ppm(3), suggesting that further alloy development may be possible by focusing on reducing the saturation magnetostriction of current nanocrystalline alloys. In this talk, the recent progress of our attempt in reducing the core loss of Fe-based nanocrystalline alloys by suppressing ls is presented along with an example of electric motor prototypes containing a nanocrystalline stator core(4).

1. G. Herzer, Acta Mater. **61** (2013) 718.

2. H. Huang, H. Tsukahara, A. Kato, K. Ono and K. Suzuki, Phys. Rev. B **109** (2024) 104408.

3. H. Huang, H. Tsukahara, A. Kato, K. Ono and K. Suzuki, J. Magn. Magn. Mater. **592** (2024) 171810.

4. R. Parsons and K. Suzuki, AIP Advances **12** (2022) 035316.

Keywords: Coercivity, permeability, core losses, crystallization, magnetostriction

*Speaker

The Rare Earths Industry - The radioactivity issue and the separation challenges

Alain Rollat*†[1]

[1]CARESTER – CARESTER – France

Abstract

The magnet industry is a large consumer of some specific rare earths (Pr, Nd, Tb and Dy), but what are the specific problems related to the mining and separation of RE ?
All the rare earths (RE) deposits contain radioactive elements, uranium and thorium, even if the absolute level in the ore can be low. In order to really assess this issue we must consider not only this absolute number, but the radioactivity level related to the RE content and the behaviour of the various radioelements all along the mining and separation processes.

The RE formulated in the magnets are always high purity RE, although RE minerals contain all lanthanides and yttrium. The separation process is a key step of the RE industry. Nowdays solvent extraction (SX) is the only process used at industrial level. The assessment of this process is essential for two reasons: Can western rare earths industry be competitive with China and can we developp in Europe a sustainable value chain compliant with the ESG standards?

Keywords: rare earths, radioactivity, solvent extraction, competitiveness

*Speaker
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Keynotes talks

Hard magnetic materials and applications

Jun Cui (Ames National Lab and Iowa State University)
Near net shape fabrication of anisotropic magnest using hot roll method

Hossein Sepehri-Amin (NIMS Tsukuba)
High Performance Permanent Magnets; How to solve element criticality while considering new demands?

Dominik Ohmer (Vacuumschmelze)
NdFeB and SmCo magnets made in Europe

Near net shape fabrication of anisotropic magnets using hot roll method

Jun Cui*[1]

[1]Ames Laboratory [Ames, USA] – United States

Abstract

Nd-Fe-B (Neo) based magnet plays a dominant role in the energy efficiency and renewable energy applications. However, Neo magnets need heavy rare earth elements (HREE) to function at higher temperatures. Nanocrystalline anisotropic Neo magnets may attain high coercivity due to their nano scale grains comparable to the magnetic domain size, thereby become a viable approach to address concerns on HREE criticality. However, making nanograin magnet requires a two-steps process: hot-press for densification followed by hot-deformation for texture. It is an inherently expensive process with limited productivity. Here, we report a novel nanograin Neo magnet fabrication method that is semi-continuous and near-net-shape. We showed that cold rolling of hot tubes at 780◦C with 75% thickness reduction can result in nearly full density anisotropic magnet with good BHmax 40 MGOe. We will also discuss how processing conditions may affect microstructures and magnetic properties.

Keywords: nanograin, Neo magnet, hot roll

*Speaker

High Performance Permanent Magnets; How to solve element criticality while considering new demands?

H. Sepehri-Amin*†[1]

[1]NIMS – Japan

Abstract

Permanent magnets are widely used in green energy conversion and play an important role in achieving net-zero CO2 emissions. In order to maintain sustainable production of permanent magnets in the long term, it is necessary to eliminate the dependence of permanent magnets on critical elements such as Dy and to diversify the use of rare earths while maintaining their performance close to their theoretical limits. In this talk, we will first present our fundamental research on why the coercivity of permanent magnets with different microstructural features are far below their theoretical limits (magnetic anisotropy field) (1,2). We will present several examples in different permanent magnet systems of how defect engineering can lead to an enhancement of the extrinsic magnetic properties, in particular the coercivity. This will be demonstrated for Dy-free Nd-Fe-B based permanent magnets and Nd-lean (Nd,Ce)-Fe-B magnets. Furthermore, we will discuss the potential of SmFe12 based compounds and the current challenges to realize these materials as new permanent magnets. We will show our recent successes in microstructure engineering of these materials, both in magnetic thin films and in bulk magnetic materials, to realize sufficiently large coercivities above 1.4 T supported by machine learning (3,4). Based on detailed microstructural characterizations, magnetic thin films and micromagnetic simulations, the optimal microstructure that can lead to higher coercivity and remanent magnetization in the SmFe12-based magnets will be discussed. Finally, we will discuss future strategies in the development of permanent magnets that need to be considered in view of the emergence of new applications (5).

(1) J. Li, H. Sepehri-Amin, T. Ohkubo, K. Hono, Phys. Rev. B 105 (2022) 174432.
(2) X. Tang, J. Li, H. Sepehr-Amin et al. NPG Asia Mater. 15 (2023) 50.
(3) H. Sepehri-Amin et al. Scripta Mater. 242 (2024) 119869.
(4) A. K. Srinithi, X. Tang, H. Sepehri-Amin, J. Zhang, T. Ohkubo, K. Hono, Acta Mater. 256 (2023) 119111.
(5) K. Uchida, T. Hirai, F. Ando, H. Sepehri-Amin, Adv. Energy Mater. 14 (2024) 247011.

Keywords: Permanent magnets, microstructure, coercivity, element criticality

*Speaker
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NdFeB and SmCo magnets made in Europe

Dominik Ohmer*[1]

[1]Vacuumschmelze GmbH Co. KG – Germany

Abstract

The increased demand of NdFeB magnets comes along with an increased desire to reduce the HRE content, while maintaining high-end magnetic properties. Technological progress and continued research allows for the reduction of HRE in NdFeB to some degree, but especially for high-end permanent magnets, there are theoretical and practical limitations. Latest developments in HRE reduction of NdFeB magnets are presented together with a brief comparison with low HRE containing and HRE-free magnet systems.
At the same time, SmCo-based magnets are gaining interest due to their high thermal stability compared to NdFeB magnets. However, SmCo magnets suffer from lower remanence. Latest developments in the increase of remanence in SmCo-based magnets is presented together with a comparison of magnetic properties between NdFeB and SmCo permanent magnets.

Keywords: NdFeB, SmCo, Permanent magnet, Production

*Speaker

Keynotes talks

Accelerated material discovery

Nora Dempsey (Institute Neel, CNRS Grenoble)
Thin film combinatorial studies of hard magnetic materials

Heike Herper (University of Uppsala)
Rare-earth-free permanent magnets from crystal structure databases

Nicola Morley (University of Sheffield)
Digital Magnetic Materials Discovery

Thomas Schrefl (Krems University Danube)
Materials informatics for the discovery of magnetic materials

Thin film combinatorial studies of hard magnetic materials

N. M. Dempsey*[1], Yuan Hong[1], William Rigaut[1], Stéphane Grenier[1], and Thibaut Devillers[1]

[1]Institut NEEL CNRS – CNRS – France

Abstract

Combinatorial studies based on the preparation and characterisation of compositionally graded thin films are being used for the screening and optimization of a range of functional materials (1). When combined with Machine Learning (ML), such high-throughput film-based studies hold much potential to guide data driven design of new materials (2,3). In this talk I will present combinatorial studies of hard magnetic materials. By way of introduction to the high throughput fabrication and characterisation techniques we use, I will begin by presenting a study of compositionally graded Fe-Pt films (4). I will then present on-going studies of the effect of element substitution and annealing conditions on both structural and magnetic properties of compositionally graded RE-TM films based on the 2-14-1 and 1-5 high anisotropy phases. I will finish up by briefly outlining the potential of combining high throughput experimentation and ML-driven data analysis for the accelerated development of functional magnetic materials with reduced dependence on critical elements (5).

(1) ML Green et al., J. Appl. Phys. 113 (2013) 231101

(2) A.G. Kusne et al. Sci. Rep. 4 (2014) 6367

(3) A. Ludwig, npj Comput. Mater. 5 (2019) 70

(4) Y. Hong et al., J. Mater. Res. Technol. 18 (2022) 1245

(5) Kovacs et al., Front. Mater. 9 (2023) 1094055

Keywords: Hard magnetic materials, Combinatorial studies, High throughput analysis

*Speaker

Rare-earth-free permanent magnets from crystal structure databases

Heike Herper*†[1], Madhura Marathe[2,3], and Alena Vishina[2]

[1]Department of Physics and Astronomy [Uppsala] – 751 05 Uppsala, Sweden
[2]Department of Physics and Astronomy [Uppsala] – Sweden
[3]Applied Physics, KTH Royal Institute of Technology – Sweden

Abstract

Striving to reduce CO2 emissions the use of green technologies for power generation and transportation is steadily increasing. However, the reliance on magnetic materials, which contain rare earths, cobalt, and other critical elements in these applications, presents a problem. The goal is to find new magnetic materials with the efficiency of the current ones while surpassing them ecologically as well as economically. In the last decades, the main research focus was on a small number of systems known to have some potential for permanent magnets aiming to optimize the performance or reduce the rare earth concentration. Though improvements could be achieved this way (1) different strategies are needed to find new materials that have not yet been explored regarding their potential for magnetic applications.
With today's computing power, high-throughput studies are feasible and we can scan a large body of data and bring to light new so far not considered systems for permanent magnetic applications. Knowing that materials modelling is a multiscale problem which ranges from intrinsic materials properties over magnetic grains to the actual device level our computational approach focuses on the intrinsic magnetic properties. These are of fundamental importance and can be used as input for simulations on larger length scales.

Materials design grounded in first principles methods has proven to be a powerful tool for this purpose. To identify new magnetic materials with promising intrinsic properties we perform big data searches using structural databases in combination with high-throughput ab initio calculations. First, pre-screening (no hazardous, expensive elements, cubic phases) is made to extract suitable structures for new permanent magnets (2-4). In some cases, more restrictive screening is used to extract a specific class of materials (5). Structures that pass our filter criteria are studied in detail using a combination of first-principles electronic structure methods and thermodynamic modelling. The first provides the ground state properties and phase stability while the latter caters to finite temperature properties and is also important to rule out the occurrence of complex magnetic structures that can reduce magnetic performance.

Several promising phases have been found in our high-throughput searches and one system has been successfully synthesized, showing the characteristics of a good permanent magnet (4).

(1) JALCOM **786**, 969 (2019), (2) Phys. Rev. B **101**, 094407 (2020), (3) Acta Materialia **212**, 116913 (2021), (4) Materials Research Letters **11**, 76-83 (2023), (5) Phys. Rev. B **107**, 174402 (2023)

Keywords: density functional theory, high throughput methods, Monte Carlo simulation, magneto crystalline anisotropy, rare earth free magnets

*Speaker
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Digital Magnetic Materials Discovery

Nicola Morley*[1], Richard Rowan-Robinson[1], Zhaoyuan Leong[1], Xianyuan Liu[1], Alan Thomas[1], Tom Wilkinson[1], Emily Read[1], Coyun Oh[1], and Sophia Carpio[1]

[1]University of Sheffield – United Kingdom

Abstract

The climate emergency has established the need for sustainability within existing and new technologies, which is driving a demand for material innovation. New materials need to be economically sourced from abundant elements, whilst still obtaining the functional characteristics of the existing leading materials. Functional Magnetic Materials (FMMs) are central to new green technologies and an excellent example of a sector with great industrial demand for innovation. At the present, existing hard magnets: NdFeB and SmCo, consist of elements on the critical list, while soft magnets are limited due to processing costs and eddy losses.

The need for innovation is clear: by improving the material properties of FMMs, industries can fully capitalise on the aforementioned engineering advances in green technologies, thus saving money and benefiting the environment. Traditional material discovery methods, where existing material compositions are tweaked and optimised, are too slow and costly, and not practical or sufficient to address the current material challenges. Material informatics will overcome these existing problems, by using data-driven solutions to reduce the use of natural resources and expensive experiments.

Our research has focused on using Natural Language Processing (NPL), including large language models to data mine open access papers to create a FMM database. This has been achieved by combining the linear approach NPL, which searches for defined compositions and parameters within papers, with semantic networks, to allow the compositions related parameters to be correctly linked together. In doing this we are able to data mine papers, which contain more than one composition and magnetic parameter for the database. Having created this database, machine learning (ML) algorithms are trained on it, which are then used to observe trends within the data, along with predicting compositions with specific magnetic parameters. A range of different ML algorithms have been investigated, to determine the "best" for the magnetic databases available. These compositions are then fabricated and characterised using high throughput techniques, including combinatorial sputtering (over 50 compositions on one wafer), XRD, FMR and MOKE magnetometry. This allows us to verify the results from the ML, quickly and cheaply, along with discovering new FMMs, plus the results are then feedback into the database, allowing for a full circle discovery methodology.

Keywords: Natural Language Processing, Machine Learning, High, Throughput experiments

*Speaker

Materials informatics for permanent magnet optimization

Thomas Schrefl*†[1,2], Alexander Kovacs[2], Clemens Wager[1,2], Qais Ali[1,2], Johann Fischbacher[2], David Boehm[1,2], Leoni Breth[1,2], Masao Yano[3], Noritsugu Sakuma[3], Akihito Kinoshita[3], Tetsuya Shoji[3], and Akira Kato[3]

[1]Christian Doppler laboratory for magnet design through physics informed machine learning – Austria

[2]Danube University Krems – Austria

[3]Toyota Motor Corporation (JAPAN) – Japan

Abstract

The transition to a carbon-free society relies heavily on high-performance magnets for green technologies. However, these magnets contain a high fraction of critical elements, such as light and heavy rare-earth elements, which may lead to a shortage in the future. In Europe, the demand for rare earth metals is set to rise six to seven times by 2050, primarily for use in wind turbines and electric vehicles. To mitigate supply risks, researchers are developing heavy-rare-earth-free and Nd-substituted magnets.
Artificial intelligence methods, such as genetic optimization, can be used for the inverse design of permanent magnets. These methods require rapid evaluation of the objective function, often achieved by substituting experimental measurements and physics simulations with surrogate models. Partial least square regression can be used to map chemical composition to intrinsic magnetic properties, while neural networks can predict the coercive field from the granular microstructure of the magnet. By linking these models, it is possible to identify potential chemical compositions for a given granular microstructure that will minimize costs and produce a magnet with the desired properties at its operating temperature.

In contrast to other fields of artificial intelligence, there is no big data in materials science. Like principal component analysis, the partial least square regression reduces the dimensionality. Therefore, partial least square regression is well suited for problems in which the number of features is large as compared to the number of samples.

X-ray diffraction (XRD) patterns and power spectra obtained from scanning electron microscopy (SEM) images of the microstructure can also be used to predict the coercive field. Again, dimensionality is essential for reliable coercivity prediction. Using a genetic algorithm for feature selection, regions the spectra associated phases or structural features that have a strong impact on the coercive field of permanent magnets can be identified.

In summary, artificial intelligence and materials informatics assist the design of permanent magnets for a sustainable, carbon-free future. Data from diverse sources, such as computer simulations and experiments, are integrated. Dimensionality reduction addresses the issue of limited data sets. Genetic optimization identifies potential chemical compositions and microstructures, leading to improved magnet performance.
The financial support by the Austrian Federal Ministry of Labor and Economy, the National Foundation for Research, Technology and Development, Austria and the Christian Doppler Research Association is gratefully acknowledged.

Keywords: permanent magnets, micromagnetics, machine learning

*Speaker

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Keynotes talks

Magnetocaloric materials and applications

Victorino Franco (University of Sevilla)
Decoding Magnetostructural Transitions: A Combined Analysis Using TFORC and Thermography

Fengxia Hu (Chinese Academy of Sciences)
Magnetocaloric/barocaloric effect and device

Falk Münch (MAGNOTHERM Solutions GmbH)
Efficient protection of La(FeMnSi)$_{13}$H$_y$-based magnetocaloric regenerators during operation in a cooling engine

Decoding Magnetostructural Transitions: A Combined Analysis Using TFORC and Thermography

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Abstract

The eventual implementation of magnetocaloric temperature control systems as a replacement of less environmentally friendly devices in sectors ranging from home appliances to gas liquefaction requires a detailed knowledge of the thermomagnetic response of the phase transformations that take place during device operation, with a significant focus on hysteresis and reversibility. Despite this requirement, materials are usually characterised under experimental conditions that do not resemble those of the device for which they are supposedly designed: quasistatic instead of dynamic; complete transformations instead of partial transformations; single-shot operation instead of cyclic. These approximations simplify the way in which materials are characterised but complicate the predictability of the actual performance of the material in real devices.

In this talk, we present the physics behind the recently proposed Temperature-First-Order-Reversal-Curves (TFORC) technique for magnetocaloric materials, its use to identify detailed information of phase transitions, and for predicting the thermomagnetic response of a material in arbitrary conditions. The reversible response under cyclic excitations will also be independently determined by thermography, showing that some of the simple approximations present in the literature should be used with caution. Examples are presented for Heusler, MM'X and high-entropy alloys.

The methodology presented here will be instrumental in the implementation of more efficient magnetocaloric refrigeration devices.

Keywords: Phase transitions, TFORC, Reversibility, Thermography

*Speaker

Magnetocaloric/barocaloric effect and device

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Abstract

Solid state refrigeration based on calorics has important application and is one of the research hotspots of material science, condensed matter physics and engineering thermophysics (1,2). Recently, we carried out a series of studies on magnetocaloric, barocaloric and coupled-caloric effect, as well as devices (3-8). We reported the first experimental study on the modulation of barocaloric effect (BCE) by magnetic field in Ni50Mn35In15 with strong magnetostructural coupling (5). The results demonstrated that the modulating behavior of BCE by magnetic field, which is dominated by cross-response, depends crucially on the magnitude of pressure. The enhanced ratio of barocaloric entropy change —ΔSBCE— can be as much as ˜ 40 % when a magnetic field of 5 T is applied. *Ab initio* calculations provide a theoretical explanation about the driving effect by single pressure, single magnetic field, and dual-fields on the magnetostructural transition. We reported low pressure reversibly driving colossal barocaloric effect in two-dimensional van-der-Waals alkylammonium halides (4). Via introducing long carbon chains in ammonium halide plastic crystals, two-dimensional structure forms in (CH3–(CH2)n-1)2NH2X (X: halogen element) with weak interlayer van-der-Waals force, which dictates interlayer expansion as large as 13% and consequently volume change as much as 12% during phase transition. Such anisotropic expansion provides sufficient space for carbon chains to undergo dramatic conformation disordering, which induces colossal entropy change with large pressure-sensitivity and small hysteresis. The record reversible colossal BCE with entropy change DSr ˜400 Jkg-1K-1 at 0.08GPa and adiabatic temperature change DTr ˜11 K at 0.1GPa highlights the design of novel barocaloric materials by engineering the dimensionality of plastic crystals. We proposed a full solid-state conceptual magnetocaloric refrigerator based on hybrid regeneration (3). This novel working mode could significantly improve the regeneration efficiency at high working frequencies.

References:

(1) Gottschall, T.*; Gutfleisch, O.* et al, *Nature Mater.* 2018, 17: 929.

(2) Li, B.* et al. *Nature* 2019, 567: 506.

(3) Lin Y.; Hu, FX*; Shen, BG*, et al, *Innovation.* Accepted.

(4) Gao, YH; Hu, FX*; Shen, BG*, et al, Nature Commun. 2024, 15: 1838.

(5) Hao, JZ; Hu, FX*; Shen, BG*, et al, Acta Mater. 2024, 265: 119596.

(6) Zhou, HB; Hu, FX*; Shen, BG*, et al, Acta Mater. 2023, 260: 119312.

(7) Gao YH; Hu, FX*; Shen, BG*, et al, NPG Asia Mater. 2022, 14: 34.

(8) Yu ZB; Hu, FX*; Shen, BG*, et al, NPG Asia Mater. 2022, 14: 96.

*Speaker

Efficient protection of La(FeMnSi)13Hy-based magnetocaloric regenerators during operation in a cooling engine

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Abstract

Magnetic cooling represents the currently most developed caloric cooling technology, is considered amongst its peers most promising in terms of anticipated energy efficiency gain, and allows for a complete elimination of harmful coolants, running particularly well on water instead. The advent of performant and cost-efficient magnetocaloric materials systems which can be employed at ambient temperatures has brought the technology to the brink of market entry. By now, functional magnetocaloric elements (so-called regenerators) based on Mn-substituted and hydrogenated La-Fe-Si alloys are commercially available. While tunable, effective, and composed of sufficiently abundant elements, this alloy system is susceptible to mechanical fracture and oxidation and does not passivate well, rendering it prone to corrosion when operated with water as favorable heat exchange medium. Accordingly, successfully ensuring the long-term stability of La-Fe-Si-based regenerators in device constitutes a prerequisite for their use in reliable and maintenance-friendly magnetic cooling engines and thus represents a key milestone in de-risking the materials system. In this presentation, we will upon our fundamental corrosion analysis by showcasing Magnotherm Solutions' latest achievements in protecting La-Fe-Si under operating conditions, combining a protective coating with a tailored inhibitor strategy.

Keywords: LaFeSi, MCE, cooling

*Speaker

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Keynotes talks

Soft magnetic materials and applications

Inge Lindemann-Geipel (Fraunhofer IFAM)
Innovative powder metallurgical manufacturing technologies for soft magnetic materials

Silvana Mercone (Université de Tours)
Co(x)Cu(1-x) bimetallic nanoparticles: a magnetic properties overview vs cobalt content

Alberto Bollero (Robert Bosch GmbH)
Soft magnetic materials for e-drives

Innovative powder metallurgical manufacturing technologies for soft magnetic materials

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[2]TUD Dresden University of Technology, Faculty Mechanical Engineering, Institute of Materials Science, Chair Powder Metallurgy – Germany

Abstract

In the context of electrification, soft magnetic cores are becoming increasingly important in terms of efficiency and power density. Loss reduction at higher frequencies for miniaturization of these components requires development especially in their manufacturing technologies. Exploitation of the applicational needs is possible by materials design which is strongly connected to the manufacturing strategies. Current constraints are mainly due to limitations in conventional fabrication techniques. Powder metallurgical approaches offer excellent options for processing of high-performance soft magnetic materials in alternative geometries and materials combinations. Therefore, resource-saving production of soft magnetic components with a broad portfolio of properties is possible using both conventional powder pressing and additive manufacturing methods.

Keywords: soft magnets, manufacturing, loss reduction, powder metallurgy, microstructure, anisotropy

*Speaker

Co(x)Cu(1-x) bimetallic nanoparticles: a magnetic properties overview vs cobalt content

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Abstract

Nanostructured CoCu bimetallic particles have been previously investigated as a model of granular system to study the spin-dependent transport processes in metallic alloys containing a fine dispersion of nano-magnetic p articles. Those studies have focused on synthesis and characterization of very small Co particles embedded in a Cu-matrix (1-2) as well as on core@shell nanomaterials. A recent work from S. Dhara et al. (3) reports the magnetic behavior of CoxCu1-x(x $\leq$ 0.3) nano-alloys for catalytic and nano-magnet applications. Although no segregation of copper and cobalt was observed, they conclude on a core@shell type structure with the Co-rich part at the core after the magnetic properties analysis. In the frame of future application in nanotechnologies, low concentration of cobalt is obviously mandatory for sustainable devices based on these compounds but as reported before (3) better magnetic performances are expected and observed for higher concentration. We thus focus here, on the characterization and modeling of the magnetic behavior in CoxCu1-x(0 $\leq$ x $\leq$ 1) nanoparticles, from pure cupper to pure cobalt nanomaterials synthesized via the polyol process. To the best of our knowledge, this process has only been used for the preparation of FeAu NPs (4). Our studies of zero-field c ooled/field-cooled (ZFC/FC) magnetization have been performed in the temperature range from 4K to 350K and showed no blocking of magnetization down to 4K for all our samples. We analyzed the magnetization by the study of hysteresis loops showing that at any temperature between 4–350K the magnetization is a sum of ferromagnetic (FM), superparamagnetic (SPM) and paramagnetic (PM) contributions. This multi-phase model allowed us to demonstrate that, contrary to the core@shell observations, in the nano-alloys case the FM part does not increase at the expense of the SPM behavior as Co content increases. This latter lays dominant regardless of the dipolar and exchange interactions between agglomerates (powders). The nano-shape effect at all concentration is dominant when the nano-alloys is synthesized. Exchange-bias and ferromagnetic behavior have been also analyzed and they are far from being intuitive and strongly correlated to the alloy structure behavior. All these properties will be discussed during the presentation in view of future magneto-optical applications..

(1) B.J. Hickey et al., JMMM 147 (1995) 253.
(2) B.J. Hickey et al., Phys.Rev.B 51 (1995) 667.
(3) S. Dhara et al., JMMM 374 (2015) 647–654
(4) H. Liu et al., J. Mater. Res. 26 (2011) 2040–2049.

Keywords: nano, alloys, ferromagnetism, superparamagnetism, magnetic transition

*Speaker

Soft magnetic materials for e-drives

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Abstract

Realization of electrical machines dates back to the 19th century, but the fast development in the field of traction drives throughout the last years requires further research across different domains on the topic. Moreover, the new EU regulation stating that all new cars registered in the EU must set to be zero emission from 2035 is setting a clear timeline, as part of an international commitment towards achievement of net-zero emissions by no later than 2050. Performance, procurement of a sustainable supply of raw materials, low carbon emissions, circular economy, and affordable cost of the technology for the citizens are key drivers that will dictate success or failure towards a timely achievement of such a major goal. Magnetic materials are at the core of materials and technology development. Power density and machine efficiency in e-cars are determined by magnetic saturation and magnetic losses of e-steels under variable operation conditions. Mechanical properties need to be also considered to guarantee workability. Composition, thickness, grain size, morphology and texture of the e-steels, together with an understanding on the impact of manufacturing (e.g. stamping and stacking) on magnetic losses, are levers that must be taken simultaneously into consideration towards successful optimization of the machine performance. On top of that, magnetic losses are strongly dependent on the operation frequency, which means that there is no ideal material in terms of providing the same optimum performance at all frequencies, but a compromise must be met based on a wise definition of requirements towards achievement of a clear definition of objectives.

Keywords: electrical steel, edrives, magnetic induction, magnetic losses

*Speaker

Keynotes talks

Advanced processing and characterization

Moataz Attallah (University of Birmingham)
Additive Manufacturing of Magnetic Materials: Metallurgical and Processing Challenges

Andras Kovacs (Forschungszentrum Jülich)
Resolving magnetism and structure down to the atom

Katharina Ollefs (Universität Duisburg-Essen)
Synchrotron based insights into functional magnetic materials

Varun Chaudhary (Chalmers University of Technology)
Accelerated materials discovery through high-throughput experiments, thermodynamic modeling and machine learning

Additive Manufacturing of Magnetic Materials: Metallurgical and Processing Challenges

Moataz Attallah*[1], Abdelmoez Mohamed[1], Kun Sun[2], and Anastassia Milleret[3]

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[2]City University of Hong Kong [Hong Kong] – Hong Kong SAR China
[3]Department of Mechanical Engineering [University College of London] – United Kingdom

Abstract

The present gives an overview of the work performed at the University of Birmingham on the additive manufacturing (AM) of several magnetic materials using laser powder bed fusion (LPBF), focusing on high permeability soft magnets for magnetic shielding, magnetocaloric materials for magnetic refrigeration, and magnetic shape memory alloys (MSMAs). The processability of these materials varies significantly. Soft magnets demonstrate high processability; however, optimising process parameters and conducting post-processing heat treatments are crucial to enhance magnetic anisotropy and achieve the desired performance. In contrast, magnetocaloric materials present processing challenges due to their tendency to crack. Despite this, with careful processing optimisation and post-processing, high-performance outcomes were attained. The use of AM is particularly advantageous for magnetocaloric materials, such as NiMnSn and LaFeSi-based alloys, as it maximises the surface area to volume ratio of structures, thereby enhancing their thermal efficiency. MSMAs, specifically NiMnGa, are also prone to cracking and suffer from potential Mn evaporation, which can affect their performance. Process optimisation improved the performance of these materials, though the polycrystalline nature of the builds resulted in performance that does not match that of single crystal MSMAs. This research underscores the critical importance of tailored process optimszation and post-processing to overcome metallurgical and processing challenges in the AM of magnetic materials.

Keywords: Soft magnets, Heusler alloys, Magnetocaloric materials, Additive Manufacturing

*Speaker

Resolving magnetism and structure down to the atom

Andras Kovacs*[1]

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Abstract

Transmission electron microscopy (TEM) offers several different methods to visualise and measure the magnetic properties of materials with nanometer resolution, which can be combined with atomic resolution structural and spectroscopic measurements. By exploiting the interaction between electron beam and in-plane magnetic field within materials, TEM enables direct visualization and manipulation of magnetic domains allowing to probe phenomena such as domain walls, magnetic vortices, and spin textures quantitatively with high resolution. In this presentation, the correlation between the structure and magnetic states in AlCo(Cr)FeNi high entropy alloys and the domain wall pinning in cellular Sm2Co17-type permanent magnets will be presented. The structure and chemical composition were measured using aberration-corrected scanning TEM images combined with energy-dispersive X-ray and electron energy-loss spectroscopies. We use aberration corrected Lorentz TEM and off-axis electron holography to image and measure magnetic domain walls and the distribution of the in-plane magnetic induction. The experimental measurements were combined with model-based reconstruction of the projected magnetization and micromagnetic simulations.

Keywords: TEM, domain wall, electron holography

*Speaker

Synchrotron based insights into functional magnetic materials

Katharina Ollefs*[1]

[1]Universität Duisburg-Essen – Germany

Abstract

Polarization-dependent x-ray absorption spectroscopy (XAS) is a well-established and powerful tool to study the electronic and magnetic properties of matter in an element- and orbital-selective manner. These properties can be significantly altered by external stimuli to achieve a specific functionality of the material e.g. a tailoring of magnetic properties. Various stimuli can be used to achieve this goal: temperature, pressure or electromagnetic fields like visible light or microwaves but also static electric or magnetic fields for example. External stimuli affect the crystallographic atomic structure, the magnetic interactions and the electronic configuration of atoms in the materials andhence these stimuli can drive and modify various phase transitions, which are at the heart e.g. of magneto-caloric materials (1,2). A thorough understanding of the mechanisms involved in these processes on atomic length scales are important both from a fundamental point of view, but also for design of new multifunctional materials for advanced applications (1). To fully characterize a material, it is crucial to disentangle the intrinsic and extrinsic properties in an element selective manner. A combination of X-ray absoprtion spectroscopy and X-ray microscopy exploitig the x-ray magnetic circular dichroism effect allows us to analyse the magnetic structure in two and three dimensions.
In this talk, I will introduce the concept of polarization-dependent XAS for (magnetic) materials and present several examples of external stimuli applied to identify and tailor individual material properties, for example the change in temperature and external magnetic field drive the phase transition in magneto-caloric FeRh (2) and La(Fe,Si)13(1). Furthermore I will show how ptychographic X-ray holography allows us to derive the magnetic domains structure inside nanocrystalline Nd2Fe14B8 in three dimensions.

References:

(1) K.P. Skokov et al., *A multi-stage, first-order phase transition in LaFe11.8Si1.2: Interplay between the structural, magnetic, and electronic degrees of freedom*, Appl. Phys. Rev. 10, 031408 (2023), DOI: 10.1063/5.0133411

(2) A. Aubert et al., *Simultaneous Multi-Property Probing During Magneto-Structural Phase Transitions: An Element-Specific and Macroscopic Hysteresis Characterization at ID12 of the ESR*F, IEEE Trans. Instrum. Meas. 71, 1-9 (2022). DOI: 10.1109/TIM.2022.3157001.

Keywords: magneto, caloric materials, permanent magnets, xray spectroscopy, microscopy

*Speaker

Accelerated materials discovery through high-throughput experiments, thermodynamic modeling and machine learning

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Abstract

The next generation of materials for electrical machines must possess an attractive combination of multiple properties. However, developing such materials using conventional approaches is expensive and time-consuming. In contrast, the accelerated discovery approach relies on high-throughput synthesis, characterization, property evaluation, and predictive AI/ML modelling to rapidly screen many compositions. We deployed several advanced high-throughput techniques, such as additive manufacturing, spark plasma sintering, chemical flow synthesis, magnetron co-sputtering, thermodynamic modelling, and machine learning to quickly discover new high-performance materials. As an example, we compiled a detailed heterogeneous database of the magnetic, electrical, and mechanical properties of Fe-Co-Ni alloys, employing a novel ML-based imputation strategy to address gaps in property data. Leveraging this comprehensive database, we developed predictive ML models using tree-based and neural network approaches to optimize multiple properties simultaneously. An inverse design strategy utilizing multi-objective Bayesian optimization enabled the identification of promising alloy compositions. The results demonstrate the attractiveness of high-throughput techniques for the rapid development of novel materials exhibiting optimum set of properties.

Keywords: highthroughput experiments, machine learning

*Speaker

Keynotes talks

From green mining to green motors

Noritsugu Sakuma (Toyota Motor Corporation)
Towards sustainable magnets and motors

Jürgen Gassmann (Fraunhofer IWKS)
Short loop versus long loop recycling of Nd-Fe-B magnets

Roland Gauss (EIT RawMaterials)
European efforts to build a sustainable rare earths value chain. Lessons learnt

Andreas Jöckel (Flender GmbH)
Direct Drive and Midspeed Generator Concepts for Large Offshore Wind Turbines – with special Focus on Permanent Magnet Requirements

Towards sustainable magnets and motors

Noritsugu Sakuma*[1], Akihito Kinoshita[1], Akira Kato[1], and Tetsuya Shoji[1]

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Abstract

Achieving carbon neutrality requires accelerating vehicle electrification through multi-pathway(1), which are BEV, PHEV, HEV, and FCEV. Increasing in electrified vehicle units means increasing in demand for electric motors. The rapid increase in demand for electric motors may result in a shortage of materials such as NdFeB magnets and electromagnetic steel in the future. In NdFeB magnets, not only heavy rare earth elements but also rare earths such as Nd and Pr are exposed to supply risks. In order to achieve stable procurement in the future, it is necessary to eliminate or reduce the use of these rare earth elements. And we must also consider recycling and reuse of magnets.
Toyota has developed Nd-reduced magnet that has made it possible to significantly reduce the amount of Nd used. Nd-reduced magnet made by hot-deformation can also reduce CO2 during manufacturing compared to conventional sintered magnet. Therefore, Nd-reduced magnet contribute to carbon neutrality in the manufacturing process.

We will also work on multi-pathway items for magnet development. In addition to Nd-reduced magnet, we also develop Nd-free magnets and beyond NdFeB magnet that can achieve high magnetization at high temperatures. In order to develop these multiple items at the same time, material informatics is key technology. Artificial intelligence methods lead to high speed exploration of magnetic materials. We will also introduce development of Nd-reduced magnet using the WAVEBASE system(2)-(4), which is a tool developed by Toyota that can reduce the dimensions of XRD and SEM images, extract features, and visualize the latent space.

Reference

(1) https://toyotatimes.jp/en/toyota_news/new_management_policy/001.html

(2) https://www.toyota.co.jp/wavebase/

(3)M.Yano *et.al.*, *TOYOTA Technical Review*, **69**, 47(2024)
(4)A. Kovacs *et.al.*, *Front. Mater.*, **9**, 1094055 (2023)

Keywords: Nd, reduced magnet, hot, deformation, WAVEBASE, material informatics, multi, pathway

*Speaker

Short loop versus long loop recycling of Nd-Fe-B magnets

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Abstract

Magnetic materials are key components in future mobility, energy technology, robotics, sensors, and information technology. Hence, permanent magnets are inseparable from our everyday life. Green technologies such as electro-mobility and wind powder, rely on high performance magnetic materials which have to be available in bulk quantities, at low-cost and with tailored magnetic properties. The realisation of future technologies is generally linked to the sustainable availability of strategic metals such as the group of rare earth elements (REE) namely Nd, Pr, Dy, and Tb. Consequently, there is an ever-growing demand for the benchmark high performance Nd-Fe-B magnets. The increase in e-mobility and wind energy and other smart magnet usages in the future has yet to have its impact on the rare earth market. No substitute is at hand for the massive amounts of high-energy density magnets needed, placing the demand of rare earth elements and the sustainability during mining and production in the area of focus from industry. One option to partially reduce the European dependency on the Chinese supply monopoly for rare earth is establishing a circular economy for Nd-Fe-B permanent magnets. In this contribution, we will highlight short and long loop recycling methods of magnets, especially for end-of-life products from electro-mobility. Nowadays, these thin magnets are usually processed by grain boundary diffusion to decrease the heavy RE content and by segmentation to reduce eddy current losses during operation, making recycling challenging. Nevertheless, the recycled magnets from short and long loop recycling processes compete well with those made from primary materials, that is, in terms of magnetic properties as well as in terms of production costs. They excel by far rare earth permanent magnets made from primary materials regarding the environmental footprint.

Keywords: rare earth, NdFeB, recycling, sustainability

*Speaker
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European efforts to build a sustainable rare earths value chain. Lessons learnt

Roland Gauss*[1]

[1]EIT RawMaterials – Germany

Abstract

Since the Rare Earth crisis in 2010/11, Europe has invested hundreds of millions of Euros into rare earths related research and innovation projects, to advance science and revive its industry. The technical feasibility of a complete European value chain from mine to magnet has been demonstrated. Several national and European Think Tanks, strategic advisory groups, and industry stakeholder clusters have filed recommendations. Rare earths have become the role model of Critical Raw Materials as recurringly defined by the European Commission every two to three years since 2010. Fourteen years later, the European industry is still fully dependent on low-cost Chinese imports from all along the value chain – diversification efforts have failed, and no suitable substitute material or technology solution has been identified. Now, the early 2020s mark a historical crossroad for Europe: for the first time, a non-diversified rare earths supply chain substantially impacts key emerging industrial and energy-related sectors, particularly electric mobility and wind energy – sectors that Europe wants to gain global leadership. Only via an effective Industrial Policy, Europe can trigger a disruptive change; four key efforts that have been repeatedly put forward include: i) create a level playing field; ii) drive a commitment by EU OEMs to source from EU rare earths industry; iii) make End-of-life products containing rare earths stay in Europe to promote a Circular Economy; iv) provide CAPEX support initiating investments. The European Critical Raw Materials Act published in 2024 reflects some of these recommendations and is a first step in the right direction.

Keywords: rare earth magnets and motors, value chain, policy

*Speaker

Direct Drive and Midspeed Generator Concepts for Large Offshore Wind Turbines – with special Focus on Permanent Magnet Requirements

Andreas JÖckel*[1]

[1]Flender GmbH – Germany

Abstract

Offshore Wind has become one of the fastest growing renewable energy sources. Power ratings of wind farms keep growing while costs of the produced energy keep falling. One of the most important factors for this is the steady increase of power rating for a single wind turbine having reached 15MW for commercially available turbines and surpassing 20MW for prototypes. The lecture addresses the consequences of this steady grow in power rating for the type and design of wind generators for offshore. In combination with the need for reliable power trains it shows why only very reliable generator types based on permanent magnets have made their way in offshore wind. PM generators with a planetary gear unit are competing with direct drives, and the race is still open. Finally, scaling rules are explained showing how to minimize the amount and the grade of the applied permanent magnets.

Keywords: Offshore Wind, Wind Turbine, Wind Generator, Permanent Magnet Synchronous Generator, Electromagnetic Design

*Speaker

Poster Session I

Monday 16th September

Welcome to the Poster Session I!

Hard magnetic material modelling using a measured main hysteresis loop and first order reversal curves

Marko Jesenik*†[1] and Mislav Trbušić[1]

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Abstract

Accurate models of the materials' characteristics are crucial when applied to the mathematical modelling of efficient electromagnetic devices. The Finite Element Method is often used for dimensioning of electromagnetic devices. The description of the magnetic materials should be as good as possible, so it is important that the hard magnetic material is described with hysteresis. Different hysteresis models have been developed in the past. The presented model is based on the measurement of the main hysteresis loop and first order reversal curves for increasing and decreasing magnetisation. Each of them is presented with an extended Elliot expression. Based on our experience in working with magnetic materials, we added some parts to the original Elliot mathematical expression. It is important to determine the appropriate parameters of the Elliots expression based on the measured curve, so that the calculated curve is as similar as possible to the measured one. Differential Evolution is chosen for parameters' determination. It has a remarkable ability to balance exploration and exploitation, and, as such, avoid local optima. It is often used for technical problems, and also to determine the parameters of different models describing real material properties. A good feature of the presented model is the easy calculation of magnetisation in the area where no measured curves are available. The curve between measures can be determined based on only two points, (for example, a point at the end of the hysteresis loop and a point where the excitation is changed from increasing to decreasing, or from decreasing to increasing), and on the bases of the nearest calculated curve, which is described mathematically using a modified Elliot's expression with six parameters (P1, P2, P3, P4, P5 and P6), obtained from the measured curve using Differential Evolution for the parameter's determination. Only parameters P1 and P6 need to be corrected appropriately, as parameters P2, P3, P4 and P5 remain unchanged. Based on two known points, a system of two equations with two unknown parameters is obtained, which is the basis for the modification of the parameters P1 and P6. The measured curves of the hard magnetic material AlNiCo (the main hysteresis loop and first-order reversal curves for increasing and decreasing magnetisation) are applied to the hysteresis model. The measurements were made in our laboratory (the Laboratory of Applied Electromagnetics at the University of Maribor). A detailed description of the procedure will be presented in the final paper.

Keywords: hysteresis, finite element method, evolutionary optimization methods

*Speaker

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Improvement of coercivity for Sm(Fe-Co)12-B thin film by grain boundary diffusion and Sm seed layer insertion

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Abstract

RFe12 compounds with a tetragonal ThMn12-type crystal structure are expected to surpass the magnetic properties of Nd-Fe-B magnets due to excellent magnetic properties of Sm(Fe0.8Co0.2)12 thin films(1). Recently, we have reported that a large coercivity of 1.2 T can be obtained in a B-doped Sm(Fe-Co)-B thin film due to the formation of a columnar structure in which SmFe12 grains are enveloped with B-rich amorphous grain boundary phase(2). Furthermore, it is predicted that if the α-(Fe, Co) phase existing near the initial interface between the V under layer and the Sm(Fe-Co)-B main layer is suppressed, a huge coercivity of 6 T can be obtained(3). In this study, in order to suppress the formation of the soft magnetic phase, Sm was selected as a seed layer and inserted under the Sm(Fe-Co)-B layer, and the structure and magnetic properties were investigated in detail.
The samples were prepared by an ultra-high vacuum magnetron sputtering system. A V buffer layer and a Sm seed layer were deposited onto MgO (100) single crystal substrate at 400 ºC. Then, the Sm(Fe-Co)-B layer was deposited. The composition of B and thickness of the main layer were changed. Finally, a V cover layer of 10 nm was deposited.
From the XRD patterns of Sm-(Fe,Co)12 thin film and Sm/Sm-(Fe,Co)12 thin film, the intensity of the peak from α-(Fe,Co) phase decreased, but that from (002) and (004) of ThMn12-type structure increased by the introduction of Sm seed layer to the Sm(Fe,Co)12 thin films. It was confirmed that from the magnetization curve measured in the in-plane direction, a rapid increase at the low applied magnetic field contributing to the generation of the soft magnetic phase was suppressed by introducing Sm seed layer between V buffer layer and Sm(Fe-Co)-B layer. In addition, improvement of remanent magnetization ratio while maintaining coercivity above 1.0 T was confirmed for the Sm/ Sm(Fe,Co)12-B thin films. Then, it was concluded that the Sm seed layer plays an important role to suppress the formation of α-(Fe,Co) phase and to improve the orientation of the 1:12 phase.

Keywords: permanent magnet, ThMn12, type structure, thin film, coercivity, grain boundary diffusion

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A new eco-friendly method that allows manufacturing various self-biased rare earth free hexaferrites, covering a large range of magnetocrystalline anisotropies and applications.

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Abstract

We developed a method for manufacturing multiple self-polarized hexaferrite magnets such as M, W, X types of hexaferrites or Cu-18H - all of which can be subjected to various element substitutions, without rare earth and very few critical elements. The fabrication process meets other requirements of environmentally friendly technologies: frugality in water and energy consumption. As all rare earth free oxides are, they are easily recyclable. This method, based on (1), was first presented in (2), then in (3), (4). Compared to classical techniques, the process is greatly simplified. The precursors being non-ferromagnetic, thus not interacting, no lubricant is needed and no magnetic field is applied. The required equipments are only standard uniaxial press and furnace.
We present new results for self-biased MnTi-substituted BaM, on one hand, and for the exotic uniaxial hexaferrite Cu-18H, on the other. To the wide range of these self-biased magnets (remanent magnetization MR/MS ranging from 97% to 63%) corresponds a wide range of magnetocrystalline anisotropy fields (HK), making it possible to address applications in the quasi-static as well as in the telecom ranges, up to 77GHz. Regarding Cu-18H, magnetic measurements performed on cylinder-shaped samples show that the value of HK measured along the direction of easy magnetization (ie: the axial direction of the cylinder) is 750 kA/m , according to (5), but that it is equal to 320 kA/m in a perpendicular direction. This repeatable result was not reported until today. Its interpretation could suggest a structural anisotropy resulting from a Jahn-Teller effect, induced by Cu substitution. Although these results are still not fully interpreted, we believe that they are likely to open up new technological perspectives for these materials. A telecom device (circulator), using Cu-18H and operating at 2 GHz, is under development.

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(1) F. K. Lotgering, ”Topotactical reactions with ferrimagnetic oxides” J. Inorg. Nucl. Chem., vol. 9, no. 2, pp. 113–123, 1959

(2) J. L. Mattei et al., ”A simple process to obtain anisotropic self-biased magnets ” J.*Magn. Magn. Mater.*, vol. 451, pp. 208–213, 2018

(3) A. Hoëz et al, ”New Manufacturing Process for Granular Texture Management in Polycrystalline BaM Hexaferrites” *Magnetochemistry*, vol. 9, no. 1, p. 30, 2023.

(4) A. Hoez et al, ”Zn − Ti and Co − Ti Equally Co-Substituted BaM Ferrites,” *IEEE Trans. Magn.*, vol. 59, no. 1, p. 5, 2023

(5) Q. Li, ” Cu 18H hexaferrite,” *J. Eur. Ceram. Soc.*, vol. 44, pp. 936–943, 2024.

Keywords: rare earth free hexaferrites, friendly technologies, Cu18H, magnetocrystalline anisotropy

Eutectoid Ordering Morphologies in Fe-Pd and Shockley's (Controversial?) L1' Phase

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Abstract

In Fe-Pd alloys, the microstructure resulting from eutectoid decomposition, A1 -> L10 + L12, has never been explored, despite the potential for exchange-coupled ferromagnetism. We show that thermal aging of Fe–61.8 at% Pd bulk alloys at 650 produces well-known L10 polytwin microstructure, where L12 now coexists as nm-scale lamellae by wetting both the {110} twin boundaries and similarly faceted L10 anti-phase boundaries. Coexistence of these phases is nominally consistent with prior predictions from phase field modeling, however the microstructural *evolution* is non-trivial. In particular, the L12 phase forms first upon continuous cooling through the eutectoid isotherm. Nucleation of L10 occurs in localized fashion then proceeds by extended, anisotropic growth. For samples processed at lower temperatures (i.e. 525 C), further chemical ordering along (110) yields the tetragonal Shockley L1' phase in lieu of L10. Single-phase L1' samples present with atypical polytwin morphology. However, L1' + L12 coexistence presents as a mixed microstructure, where L12 not only wets L1' polytwin {110} orientation boundaries but also exists as single-phase blocks bounded by twinned regions. Predictions regarding L1' have been debated over decades, and direct experimental evidence has been quite limited. Our investigations have aimed to understand the stability, microstructure, and the nature of the phase transformation (first- vs. higher-order, and the role of magnetic energy) of L1'. National Science Foundation support through grant DMR-1709914 is gratefully acknowledged.

Keywords: Magnetic Fe, Pd alloy, Polytwin structure, Orientation domain boundary, Antiphase boundary, Nanometer, scale interface, L10

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Bonded Magnets based on melt-spun High-Entropy-Alloy (La-Ce-Nd-Pr-Zr)2Fe14B

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Abstract

Bonded magnets represent a pioneering class of composite materials, melding magnetic powders-typically ferrite or rare earth materials-with a resilient polymer matrix (1). This union allows for the creation of intricate shapes and sizes beyond the scope of traditional magnetic materials. Boasting corrosion resistance, isotropic magnetic properties, and the capacity for precise molding, these magnets serve diverse industries like automotive, electronics, medical devices, and consumer goods. Where conventional magnets falter due to constraints in shape, size, or cost, bonded magnets emerge as the versatile solution.
The energy product of NdFeB bonded magnets typically spans from 40 kJ m-3 (5MGOe) to 120 kJ m-3 (15 MGOe), contingent on the specific formulation and manufacturing process. They encompass a range overlapping with Gap magnets (40-200 kJm-3) albeit at a slightly higher cost than sintered magnets, attributable to additional processing steps. Gap Magnets, through the adept utilization of less critical materials and innovative sintering techniques, not only excel in performance but also epitomize sustainability.

In a bid to mitigate costs and cater to the surging demand for rare-earths in high-performance sintered magnets, we introduce the concept of High-Entropy-Alloy-based magnetic alloys for permanent magnets (2). Presenting novel data, we unveil bonded magnets derived from melt-spun high-entropy alloys (HEAs), exemplified by (La-Ce-Nd-Pr-Zr)2Fe14B, harboring potential across myriad applications. A spectrum of alloys, varying in the ratio of (La,Ce) to (Nd,Pr)-Zr, was cast and amalgamated with Fe and B to yield rare-earth rich alloys akin to NdFeB, subsequently subjected to melt spinning for isotropic magnetic powder production. Injection molding then fashioned a series of bonded magnets.

Our report delineates structural and magnetization data for the melt-spun and bonded magnets across diverse stoichiometries. Structural insights, derived from Rietveld analysis at all stages, affirm the formation of the Nd2Fe14B phase. Magnetization measurements span from cast alloys to melt-spun powders and bonded magnets, culminating in a comprehensive understanding. The anisotropy field of bonded magnets was gauged via singular point detection (SPD). Future prospects will be presented to achieve higher energy products employing compression molding and sintering.

References

1.Takashi Horikawa, et al. Sci Technol Adv Mater. 2021; 22(1): 729–747, doi: 10.1080/14686996.2021.1944780
2. D. Niarchos, PCT/EP2019/076449: WO2021/063479 A1

Keywords: Bonded Magnets, High ENtropy Alloys, SPD

*Speaker

Additive Manufacturing of AlNiCo Magnets: Process Development and Magnetic Property Investigation

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Abstract

Additive Manufacturing (AM) presents a novel approach to fabricate AlNiCo magnets, traditionally manufactured using conventional methods. Our study focuses on utilizing the Laser Powder Bed Fusion (LPBF) process, a relatively new technique in this domain, to explore the feasibility of AM for AlNiCo magnet production.
Our research hereby primarily aims to establish a stable LPBF printing process for AlNiCo magnets and subsequently investigate the influence of process conditions on the magnetic properties.

A detailed printing process development study has been done on an AlNiCo 9 alloy using a technique called in- situ alloying where a blend of elemental powder is used instead of a pre- alloyed powder. After establishing a stable printing process, the influence of the process on the chemical homogeneity, the microstructure and the crystallographic texture has been investigated using EDS and EBSD analysis. Magnetic properties of each sample have been measured in the as- printed and in the homogenised state to evaluate the necessity of post-processing.
Our findings contribute to a better understanding of the feasibility of using AM for AlNiCo magnet production and offer insights into optimizing printing parameters for desired magnetic properties. In summary, this study presents initial steps towards leveraging AM for AlNiCo magnet manufacturing, highlighting opportunities and challenges in this emerging field.

Keywords: AlNiCo, LPBF, additive manufacturing, insitu alloying, rare earth free permanent magnets

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An Approach for Sustainable Manufacturing of Nd-Fe-B Permanent Magnets: The 2-Powder Method

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Abstract

In the context of green energy transition technologies, Nd-Fe-B-based permanent magnets are mostly the material of choice. Because of their outstanding magnet properties, they are needed in climate-friendly magnetic cooling devices or electrical machines like generators of wind turbines or traction motors of electrical vehicles.
The critical heavy rare earth (HREs) elements like Dysprosium or Terbium have to be added to increase the temperature stability of Nd-Fe-B magnets. One way for highly efficient usage of the HREs is the 2-Powder Method (2PM). By using this sustainable manufacturing approach, a coarse heavy rare-earth free main phase powder (approx. 5 μm) and a finer HRE-containing anisotropy powder (approx. 2.5 μm) are blended and sintered to bulk magnets. During the sintering procedure, a core-shell structure develops in the microstructure in that the HREs are located only in the outer regions of the magnetic 2:14:1-grains. Because of the higher magnetocrystalline anisotropy of the HREs compared to the light rare earths (LREs) like Neodymium or Praseodymium, the coercivity of the magnets increases which finally leads to better temperature stability.

The advantage of the 2PM to the industrial-used grain boundary diffusion process (GBDP) is that no additional cost and time-intensive diffusion treatment has to be performed. Further, the 2PM allows the production of magnets independent of their size, since by using the GBDP the magnet thickness is limited to less than 10 mm.
In addition, the 2PM can be further used for the utilization of the rare earth balance. The natural abundance of the LREs Cerium and Lanthanum has the potential to lower marked needs for Nd and Pr by substitution in Nd-Fe-B-based magnets. However, due to the comparable lower magnetic properties of Ce/La substituted magnets, this is quite challenging. Here the 2PM can be used to engineer sintered magnets having a microstructure of Ce or La cores surrounded with Nd/Pr or Dy/Tb containing shells to compensate for the loss of coercivity and temperature stability.

Keywords: Nd, Fe, B, criticality, rare earth balance, sintered magnets

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Resolving magnetic contribution in Mn-Al-Cu alloys using First Order Reversal Curves Analysis

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Abstract

Mn-Al-Cu alloys have been investigated by hysteresis loop, Thamm-Hesse plots and first order reversal curves (FORC) analysis. The effect of adding different Cu content (0, 0.5, 1.0, 1.5, 2.0, and 2.5 wt. %) on the magnetic properties and behavior of Mn-Al-Cu nanostructured magnets were investigated. The Mn-Al-Cu samples were produced by melt spinning and annealing, aiming to maximize the ferromagnetic
tau-phase fraction. XRD analysis revealed that the metastable
tau-phase partially decomposed into gamma ($\gamma 2$) and beta (β) phases, resulting in a reduction of the magnetic properties. Hysteresis loop shows a hard magnetic behavior. The sample with a 1.5% Cu content shows the best magnetic properties with a coercive field (Hc) values of 1327 Oe and a remanent magnetization (Mr) of 46.3 Am2kg-1, respectively and Thamm-Hesse and FORC analyses disclose an increase in the competition between the magnetic dipolar interaction and exchange interaction with increasing Cu concentration in the alloy.

Keywords: First order reversal curves (FORC) analysis, Thamm, Hesse Plots, exchange interaction, Mn, Al, Cu alloys

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Unlocking the Potential of FeCoNi-Based Medium Entropy Alloys Across Diverse Applications

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Abstract

Medium entropy alloys (MEAs) derived from the FeCoNi system have garnered considerable interest owing to their remarkable physical properties (magnetic, electrical, and mechanical) due to the presence of Fe, Co, and Ni. In the present study, the structural and physical properties of equiatomic FeCoNi and FeCoNiAl arc melted have been explored. The samples were annealed at 900 0C for 48 hrs in vacuum-sealed quartz tube, followed by water quenching. The XRD study has confirmed the presence of FCC and FCC+BCC phase in FeCoNi and FeCoNiAl alloys, respectively. The addition of Al in FeCoNi alloys increased the BCC phase along with the FCC phase. The lattice parameters of FeCoNiAl alloys are less than FeCoNi alloy for both cases (as casted and annealed) due to the inclusion of Al in FeCoNi creating strain in the system. The EDS suggests that all the expected elements with At% have been observed. The observed At% of elements for FeCoNi and FeCoNiAl alloys are Fe (33.36%), Co (33.28%), Ni (33.36%), and Fe (25.59%), Co (23.93%), Ni (25.52%), Al (24.96%). It shows that there is no major loss of elements during preparation and annealing time. The grain size of annealed sample is larger than as cast due to high annealing temperatures producing a more homogenous grain size distribution; as increased mobility of atoms allows for more uniform grain growth. The magnetic hysteresis loop of both samples shows soft magnetic nature at 2K and 300K due to low coercivity. The saturation magnetization of annealed FeCoNi alloys at 2K and 300K are 158 emu/g and 162 emu/g, respectively, whereas for annealed FeCoNiAl alloys show 121 emu/g and 108 emu/g, respectively. As we know, saturation magnetization increases with a decrease the temperature due frozen spin in the field direction. The addition of Al in FeCoNi alloy decreases the saturation magnetization due to disturbance of the strong exchange interaction between ferromagnetic elements Fe, Co, Ni. The Law of Approach to saturation methods has been explored to determine the saturation magnetization. The hardness of materials has been examined by the Vickers hardness test. The observed hardness is 564 Hv and 498 Hv for FeCoNi and FeCoNiAl alloys, respectively. The good hardness value suggests improved mechanically stablility, long durablility, and enhanced strength.

Keywords: Soft Magnetic Materials, Medium Entropy Alloys

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Tailoring the Morphology of Strontium Hexaferrite (SFO) Nanofibers for Rare Earth Free Permanent Magnet Applications

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Abstract

Permanent magnets (PMs) are a key component to accelerate the transition into green technology. Primarily PMs are based on rare earth elements (high energy product), whose raw materials are critical and vulnerable resources. Therefore, a collective effort is still being pursued to substitute them in some of the applications, where weight and high energy products are not essential. Particularly, strontium hexaferrite (SFO) offers a potential alternative due to their chemical stability, high resistivity and low cost. However, it is challenging to enhance their coercivity and saturation magnetization and hence the energy product as desired. Therefore, recent research has focused on development of novel nanostructures and nanoparticles to overcome these challenges.

Here, we present a novel synthesis of 1D anisotropic SFO nanostructures in the form of interconnected chain of nanoparticles using low cost polymer sol-assisted electrospinning technique followed by a systematic calcination by varying the temperature (600 ◦C, 800 ◦Cand 950 ◦C) and heating rate (2 ◦C/ min, 6 ◦C/ min and 10◦C/ min). Controlled calcination procedures lead to modification of the width and morphology of the as synthesized nanofibers and strongly affect the magnetic properties. A complete phase formation is observed at 800 ◦C and 950 ◦C as seen from XRD with small amount of hematite as impurity phase. The morphological characterization shows the conversion of the as synthesized nanofibers into 1D chain of interconnected SFO nanoparticles/nanoplatelets due to the evaporation of the polymer (PVP) during calcination process. They have porosity, which decreases with increasing calcination temperature and heating rate due to particle growth. It also resulted in increase of the width of the nanofibers from 140 nm to 250 nm. Moreover, these nanofibers have distinct morphology within the fiber structure, which varies from regular shape particles (avg. size 90 nm) at 2 ◦C / min heating rate into platelet like shape (avg. particle size 240 nm) at 10◦C/ min. The hysteresis measurements indicate a complex reversal process correlated to this unique morphology. At 800 ◦C the coericivity increases moderately from 4.8 kOe to 5.8 kOe with increasing heating rate whereas the saturation magnetization gets enhanced from 65 to 76 emu / g, which could be attributed to the platelet morphology.

We demonstrate a facile route to obtain 1D SFO nanofibers with unique particle morphologies and a strong correlation between the morphology and magnetic properties for potential application for green technology.

Keywords: Hexaferrite, rare earth free magnets, nanofibers, hexagonal platelets, 1D nanostructures

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Combined ab initio and Experimental Design of Low-Cost NiFe L10 Permanent Magnets

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Abstract

High-performance permanent magnet demand is skyrocketing for use in electric vehicles and wind turbines and this warrants designing alternatives that don't rely on rare earth elements with their associated price volatility and environmental impact. A promising candidate is the L10 ordered phase of NiFe, however, it is not yet commercially viable to produce due to the low transition temperature and the resulting sluggish ordering kinetics. First principles DFT computations allow for a high-throughput search of potential dopants to stabilize L10 NiFe relative to the disordered phase. This search focussed on the effect of _˜1% concentrations of interstitial and substitutional alloying elements to produce a list of candidate systems. Experimental synthesis and characterization are performed to confirm stability and test commercial feasibility with the goal of identifying competitive alternative magnets.

Keywords: Rare Earth, Free, DFT, Permanent Magnets, Computational Materials, Materials Design

*Speaker

Production of NdFeB magnets by Metal Injection Molding (MIM) – New possibilities in magnet design

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Abstract

MIMPLUS is specialized in manufacturing metal components and assemblies by means of Metal Injection molding (MIM). In the recent years, its R&D department has developed a process route to manufacture NdFeB magnets via MIM.
NdFeB magnets show the highest energy products of all known magnetic materials. These outstanding magnetic properties are responsible for making them state-of-the-art products in many application fields (e.g. E-mobility, renewable energy and electronics). Leading magnet applications require increasingly complex, smaller and more powerful magnets. However, with conventional production technologies it is often not possible to meet these requirements.

With the newly developed MIM magnets it is possible to combine the advantages of the two main conventional manufacturing methods (press and sintering and polymer-bonding) in one process. Sintering leads to very high magnetic performances. Depending on the magnet grade maximum values for remanence of about 1.4 T and coercivity of about 2900 kA/m are possible. However, in this process only simple geometries like cylinders or cuboids can be produced. If complex shapes are required it is necessary to perform time- and cost-intensive post-sintering treatments, like EDM or grinding. In contrast polymer-bonded magnets enable a high level of design freedom. However, the magnetic properties are considerably lower compared to a press and sintered magnet. With MIM it is possible to achieve both at a reasonable price: Complex shapes and excellent magnetic properties. This offers a unique opportunity for a wide range of industrial sectors to combine high magnetic performances with a high level of design freedom.

The necessary steps to produce MIM magnets from either virgin material or from end-of-life (EOL) magnets consist of (i) Hydrogen decrepitation and milling of the raw material, (ii) feedstock production, (iii) injection molding, (iv) debinding and (v) sintering.
As the final magnetic properties of a MIM magnet are significantly influenced by numerous factors along the process route a high amount of engineering and effort is necessary. Therefore, the focus in this work is a review of the different challenges that exist for this new production method to achieve state of the art magnetic properties that are known from press and sintered magnets.

Keywords: NdFeB, Hard magnetic materials, Metal Injection Molding, MIM, Complex shapes

*Speaker

Strontium Hexaferrite Synthesis from Industrial Waste: Recycling Mill Scale for Sustainable Permanent Magnet Production

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Abstract

Among other ferrites, strontium hexaferrites (SrFe12O19) are a fundamental material widely used in industrial sectors such as automotive and household appliances. Due to their high Curie temperature, large magnetocrystalline anisotropy, cost-effectiveness, and chemical stability, SrFe12O19 magnets have become an ideal option for energy conversion, magnetic separation, magnetic resonance imaging, and many other applications. These properties are essential for enhancing the performance of magnets in industrial applications while reducing production costs.
The current research highlights the importance of recycling and reusing Strontium metal, a significant material for the industry, given that around 80% of the magnetic industry relies on ferrite-based materials. The European Union's listing of Strontium metal as a "critical raw material" highlights its strategic significance and the necessity for its sustainable management. In this study, we aim to transform Mill Scale, a by-product of steel production accounting for approximately 4% of steel production, into an economically feasible end product.

The experimental methodology involved the process of ball milling the Mill Scale for 12-hour to reduce the size below 10 microns. Then, the Mill Scale was blended with strontionate, SrCo3, and followed by a wet Ball Milling process of 64 hours, The annealing above 1200 C yielded SrFe12O19.
The results from the current research emphasize the importance of strontium hexaferrites in industrial domains and demonstrate the potential of repurposing recyclable materials, such as Mill Scale, as a sustainable material source. Further studies indicate that as recycling techniques advance, the manufacturing of Strontium ferrite will also progress.

Keywords: Critical raw materials, Green Energy Technology, Magnet to magnet recycling, Rare earths, Recycling, Sustainable development goals

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Hard magnetic SmCo5-Sn nanocomposites produced by high-pressure torsion – microstructural evolution and magnetic properties

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Abstract

In recent years a lot of research and development has been done to overcome the discrepancies between intrinsic and extrinsic magnetic properties. Beside the search on novel materials and optimizing already existing ones, there is the challenge to develop new unconventional processing techniques, that allows the adjustment of a specific micro- or nanostructure. Severe plastic deformation (SPD) processes like high-pressure torsion (HPT) are well known for its potential to refine microstructures of a variety of metals and alloys. Yet, the method is not limited to the processing of monolithic samples but also capable of consolidating powders and powder blends, thus, paving the way towards nanocomposite materials and microstructures that are inaccessible via conventional melting-based routes (1,2). In this work, HPT is applied to powder blends consisting of hard magnetic SmCo5 and diamagnetic Sn. The ductile binder phase Sn enables the plastic deformation of the composite and furthermore it decouples the hard magnetic SmCo5 particles due to its nonmagnetic behavior. Microstructural analyses show a refinement of the brittle SmCo5 phase with increasing applied strain up to the single domain region. At the same time the individual particles are well surround by Sn leading to magnetic decoupling of the SmCo5 grains. The structural refinement of the SmCo5 while simultaneously encircling by Sn, correlates with an increase in coercivity up to more than 1.6 T. Furthermore, a crystallographic texture with the c-axis being preferably aligned parallel to the rotation axis of the HPT disc evolves, thus, leading to anisotropic magnetic properties. The results emphasize the wide freedom of microstructural design for magnetic materials using HPT of powder blends, which enables the generation of textured nanocomposites with excellent magnetic properties.

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References

(1) L. Weissitsch, F. Staab, K. Durst, A. Bachmaier, Magnetic Materials via High-Pressure Torsion Deformation of Powders, Mater. Trans. (2023).
(2) F. Staab, E. Bruder, L. Schäfer, K. Skokov, D. Koch, B. Zingsem, E. Adabifiroozjaei et al., Hard magnetic SmCo5-Cu nanocomposites produced by severe plastic deformation, Acta Materialia 246 (2023) 118709.

Keywords: Nanocomposite, High, pressure torsion, Severe plastic deformation, Magnetic hardening, Deformation induced texture

Tuning Strontium M-type Hexaferrite Nanopowders Coercive Field Through pH Control

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Abstract

Nanopowders of Sr M-type hexagonal ferrites have been successfully synthesized using the citrate precursor sol-gel method. The pH of the solution at the stage of precursor precipitation was controlled in order to study its effect on the magnetic properties of the powders. For each pH value, from 1 to 10, the powders were calcined at 600◦C, 800◦C, 900◦C and 1000◦C to track the intermediate phases during the formation of the Sr M-type hexagonal hard magnetic phase. XRD, SEM microscopy and magnetometry measurements were performed.

From the M-H loops of SrM nanopowders prepared at different pH values and calcined at 900◦C, the results show that for low pH values the coercive field is higher and reaching a maximum of 0.68 T for pH=1 which represents 77% of the theoretical value of isotropic SrM (0.88 T (1,2)). This value is the highest value ever reported to our knowledge. This high value maybe attributed to the fine particle size (˜114 nm by SEM analysis and ˜ 128 $\pm$ 17 nm after a Rietveld refinement) and/or to the shape anisotropy of the particles.

SEM images showed that the pH of the starting solution has an effect on the morphology of the particles. At pH $<$ 7 the particles are equiaxial hexagonal prisms,but this morphology changes to a mixture of the same and flat hexagal prisms for pH $>$ 7. This confirms that the pH induces a favorite crystal growth in the a-axis direction.

Contrarily to previous reports (3), the results showed also that the pH has a limited effect of the saturation magnetization (60 to 66 Am^2/kg in a field of 1.9 T) and the remanence (33 to 36 Am/kg). Likewise, the excess of NH4OH did not favour the formation of α-Fe2O3 as confirmed with XRD analyses.

To conclude, this study highlights the the role of pH on the magnetic properties of the hexaferrite particles. It is suggested, that the content of nitrates through amonia addition in the precursor activates the reaction at the stage of calcination, favouring nucleation to grain growth, thus forming smaller particles.

References:

(1) E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London, Ser. A 244, 599 (1948)

(2) J.M.D. Coey, Magnetisme and magnetic materials, Cambridge University Press, 2010.

(3) Mustaffa, M.S., Azis, R.S., Sulaiman, S., Sol-Gel Method - Design and Synthesis of New Materials with Interesting Physical, Chemical and Biological Properties, February 2019, DOI: 10.5772/intechopen.80667

Keywords: Hexaferrite, permanent magnets, nanopowders

*Speaker

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Tuning Spark Plasma Sintered Nanostructured Strontium M-type Hexaferrites Magnetic Properties Through pH Control

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Abstract

M-type Ba/Sr hexagonal ferrites, discovered in the 1930s, have garnered significant research attention due to their numerous benefits, including chemical stability, abundant raw materials, and favorable magnetic properties (1). Their versatility extends to a wide array of applications, particularly within the permanent magnet industry.
Spark plasma sintered pellets of Sr M-type hexagonal ferrites were prepared from nanopowders of Sr M-type hexagonal ferrites synthesized using the citrate precursor sol-gel method. The pH during the preparation of the latter was varried from 1 to 10 in order to study its effect on the final powders magnetic properties. For each pH value, the powders were calcined at 600, 800, 900 and 1000◦C. The powders were then sintered at 800◦C for 5 min. XRD and SEM microscopy as well as magnetometry measurements were performed on each pellet.

The magnetic measurements showed that increasing the pH of the starting nanopowders, calcined at 900◦C, decreases the coercive field of the bulk magnet. The later reaches a maximum of 0.56 T for a very low pH (=1), eventhough it represents ˜82% of that of the starting nanopowder, it is the highest value for an isotropic magnet ever reported to our knowledge. This high value is attributed to the very fine grain size (< 100 nm) which is way less than the theoretical size of a magnetic single-domain (2).

The energy product BHmax and the remanent induction Br on the other hand, seem to be relatively higher for higher pH values reaching a maximum of ˜12 kJ/m3 and ˜0.27 T respectively and this for pH = 9, but nevertheless staying within the range of 8-12 kJ/m3 and 0.21-0.27 T for BHmax and Br respectively.

This study showed the interest of conducting more investigations on the effect the starting powders in Spark Plasma Sintering of Strontium hexaferrite which is widely used in industry for the production permanent magnets but relatively less investigated in the nanostrutured form compared to Barium hexaferrites.

References:

(1) F. Kools, A. Morel, R. Grössinger, J. M. Le Breton, P. Tenaud, J. Magn. Magn. Mat., Vol. 242-245, p. 1270-1276 (2002)

(2) J. Smit, H.P.J. Wijn, Les Ferrites, Dunod, Paris, 1961.

Keywords: SPS, Strontium M, type hexaferrite, permanent magnet, nanostructuring

*Speaker

Fabrication of high-performance HREE-free Nd-Fe-B hot-deformed magnet

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Abstract

(Introduction) Anisotropic Nd-Fe-B hot-deformed magnets have high coercivity without the addition of heavy rare earth elements (HREE) due to their fine crystal grains. Magnetic properties of the hot-deformed magnet depend on the quality of the raw powder which is made by melt spinning. If coarse grains exist in the powder, crystal grains in the magnet become coarse during the hot deformation process, resulting in the coercivity decrease. In this study, we tried to obtain high quality ribbons which have finer and more homogeneous crystal grains than usual by optimizing the melt-spinning process, and to fabricate the high-performance HREE-free Nd-Fe-B hot-deformed magnets.
(Experimental) The melt spun ribbons with a composition of Nd13.7Febal.Co1.5Ga0.5B5.6 (at%) were made by single wheel melt spinner. Here, nozzle diameter, differential pressure and wheel speed were changed. The ribbons were crushed into flake powders with a diameter of 53 _˜ 355 um. The hot-deformed magnets were produced by hot-pressing followed by hot deforming. The microstructure of the melt spun ribbons and the hot-deformed magnets were observed by field emission scanning electron microscopy (FE-SEM). The magnetic properties of melt spun ribbons and hot-deformed magnets were measured by vibrating sample magnetometer (VSM) and DC magnetometer, respectively.
(Results) We confirmed that the melt spun ribbons had nano-crystalline structure by the SEM observation. The median grain size of the ribbon made through the optimized melt-spinning process was around 37 nm, which is finer than conventional ribbon with the grain size of 45 nm. Also, the grain size distribution index of the optimized ribbon was 4% smaller than that of the conventional one, which means the grains in the optimized ribbon were more homogeneous. The hot-deformed magnets using the optimized ribbon showed excellent hard magnetic properties; the remanence Br at room temperature was 1.416 T, the coercivities HcJ at room temperature and 150 ℃ were 1520 kA/m and 580 kA/m, respectively. The Br was 6 % higher and the HcJ at 150℃ was 14 % higher than that of the conventional magnets. The temperature coefficient of the HcJ was -0.487 %/K, which is better value than commercial sintered Nd-Fe-B magnets. These results indicate that the microstructure of the melt spun ribbons is one of the crucial factors to obtain high-performance HREE-free Nd-Fe-B hot-deformed magnets.

Keywords: Permanent magnet, Nd, Fe, B, Hot, deformed magnet, Melt spinning, Heavy rare earth free

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Effect of Hydrogen Decrepitation Temperature and Milling on Crystal Structure and Particle Size in End-of-Life NdFeB Magnets

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Abstract

Recycling NdFeB magnets from secondary sources is a vital strategy for addressing the supply risks associated with critical raw materials such as Neodymium (Nd) and Dysprosium (Dy). Among various recycling methods, Hydrogen Decrepitation (HD) is recognized as an efficient process for recovering the end-of-life (EoL) magnets. This study aims to examine the impact of different HD temperatures on the crystal structure and particle size of milled HD-NdFeB. End-of-Life (EoL) NdFeB magnets were subjected to HD process at ambient pressures and varying temperatures between 30○C to 200○C. It was observed that increasing the HD temperature up to 50○C exhibits a shift to lower 2
theta angles in XRD crystal patterns while further increasing the HD temperature resulted in reversed behavior. The optimum HD process resulted in 92.7% NdFeBH (Neodymium Iron Boride Hydride) along with some oxide phases. It was revealed that following milling of the optimum HD powders, the crystallite size decreased from 12.512 Å to 302 Å and this reduction is accompanied by a dramatic shift to higher angles. Overall, the milling resulted in a particle size distribution of 10μm (Dv50).

Keywords: NdFeB, Recycling, Hydrogen Decrepitation

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On the Preparation of Highly Coercive Nd2Fe14B Powders from Scrap Magnets

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Abstract

Securing a supply chain of rare earths while enabling a sustainable magnet production has been driving efforts worldwide to recycle end-of-life Nd-Fe-B magnets. The most straightforward strategy is the magnet-to-magnet approach, where the sintered magnet is simply reintroduced in the production chain and processed via powder metallurgy techniques to obtain the recycled magnet. However, this approach presents some issues depending on the condition of the scrap, especially when the end-of-life magnet is highly corroded. Oxidation of the magnet during its lifetime means, first and foremost, that there will be a depletion in the Nd-rich phase (as well as the Nd2Fe14B phi phase), hindering the development of an adequate microstructure during sintering and consequently leading to poor magnetic properties.
In this work, the recovery of the phi phase from highly corroded magnet scrap (overall oxygen content around 60000 ppm) was investigated. Initially, the scrap was submitted to a demagnetization heat treatment under vacuum. Afterwards, the demagnetized product was strategically mixed with metallic calcium and a reduction-diffusion (RD) process was conducted. The RD process has been previously reported in the context of recovering the phi phase from machining chips. On the other hand, as far as we know, the same recovery process has not been thoroughly addressed for end-of-life magnets.

X ray diffraction and Mossbauer Spectroscopy analyses showed that after optimal conditions of RD processing the phi phase was successfully recovered, and magnetic measurements showed that the RD product presented values of coercivity larger than 1000 kA/m, representing 86% of the coercivity of the original magnet before its use. Furthermore, the phi phase crystals formed were fine-grained, with average grain size of 1.8 +- 0.3 μm, as observed via scanning electron microscopy.

The reasoning behind this fine-grained microstructure lies in the demagnetization heat treatment. During demagnetization there was still some preserved Nd2Fe14B phase, which reacted with the iron oxides present at the scrap under the conditions imposed by the treatment. The iron oxides were reduced into very fine iron crystals in detriment of the oxidation of the phi phase and the decomposition of the matrix phi phase. The formation of fine Fe-α crystals was confirmed via x-ray diffraction and Mossbauer spectroscopy.
We prospect the use of the recycled RD powder in the obtention of composite magnets. Currently we are exploring the preparation of feedstocks for additive manufacturing using such powder.

Keywords: recycling, Nd, Fe, B magnets, reduction, diffusion, high coercive powders

*Speaker

On the Use of Nanocrystalline Powders Obtained from Scrap Magnets in the Additive Manufacturing of Bonded Nd–Fe–B Magnets

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Abstract

Recycling Nd-Fe-B is gaining prominence due to the increasing availability of end-of-life magnets, and issues related especially with rare earth supply security. Thus far most efforts have aimed to obtain sintered magnets by reintroducing the end-of-life magnet in the traditional powder metallurgy processing route. Nevertheless, reprocessing means unavoidable pickup of oxygen, leading to a depletion of the Nd-rich phase in the recycled magnet, compromising densification and the development of proper magnetic properties.
The recycling strategies can be rethought towards the fabrication of bonded magnets instead of sintered ones, because for bonded magnets the scenario is different: densification is driven by the binder, and high coercivity can be assured by using nanocrystalline powders obtained via grain refinement techniques such as the hydrogenation-disproportionation-desorption-recombination (HDDR) process.

Previous contributions have addressed the use of such nanocrystalline powders in the fabrication of bonded magnets using conventional shaping processes. On the other hand, our contribution aims to explore Additive Manufacturing (AM) as a complementary strategy to process nanocrystalline powders obtained from scrap. For that purpose, Nd-Fe-B scrap magnets were subjected to hydrogen processing to obtain nanocrystalline powders. The nanocrystalline powders were then used to prepare feedstocks with varying volume fractions of ferromagnetic powder (up to 45% vol.), from which 3D print recycled bonded magnets were fabricated via three AM techniques: Laser Powder Bed Fusion (LPBF), Stereolithography (SLA), and Fused Deposition Modelling (FDM). The obtained bonded magnets have shown increasing remanence as the magnetic phase volume fraction increased in feedstock, as well as a slight coercivity loss of around 10% in relation to the recycled powder, which lies around 750 kA/m. Aging experiments showed that such loss may be related to oxidation of the particles during AM processing.

The present work has demonstrated the obtention of ready-to-use AM feedstock i.e. LPBF powders, UV-light-curing resins and FDM filaments, suitable for successfully producing complex-shaped bonded magnets, which opens an enormous variety of new possible applications and, at the same time, eases the burden on rare-earth magnets production chain.

Keywords: recycling, Nd, Fe, B magnets, nanocrystalline powders, additive manufacturing

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Poster Session II

Tuesday 17th September

Welcome to the Poster Session II!

Neodymium Proton Rings Compared to Iron's Rings

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Abstract

A new theory of nuclear structure is shown using geometry instead of algebra. The NdFeB magnets are popular for electric vehicles. The nuclear structure of Nd has 18 protons on one ring and 18 protons in a second coaxial ring. Iron has 12 protons in each of its rings. Two superconducting currents are in the proton rings of magnetized iron atoms. The triangular rings are similar to the iron atomic triangles in photographs from a scanning tunneling microscope (Trishin, PhRevLet 127). The distinction between the ferromagnetic Fe and the nonferrous Nd has two parts. Iron has a single proton at the center of each ring but Nd does not. Nd has several protons in the core of the nucleus. Nd has rings that are not as smooth at some corners, compared to iron. A line of flux travels from a proton to an electron. In a NdFeB magnet, each Nd atom has 36 lines of flux that can be gathered by the 12 lines of flux of one iron atom. The integers 12 and 18 are confirmed by an independent alloy GdFeCo with its picosecond spin-reversal due to a flash of light, (Radu, Nature 472). This detailed understanding of the nucleus of Nd can serve as justification for adjusting compositions of the alloys. Nonferrous neodymium has free lines of magnetic flux that the ferromagnetic iron lines of flux can induce to move. The magnetic vortex of Fe gathers the free lines of Nd flux, each of which originates on a Nd "ring of coordinated proton spins". The electron spins associated with those protons also have coordinated spins. New laws of physics teach that protons make lines of protons. Each element heavier than boron has a cubic lattice of stacked protons and neutrons at the core. All elements have digital sphere-stacking models of nuclei on my website: nuclear-data.com. This theory was revealed at the APS-2022 meeting in New York City. That poster-session paper was "Carbon nuclear structure" at the American Physical Society meeting. The theory is called, *The Static Nucleus Theory of the Face-Armored Cubic Lattice.* The nuclear shapes of Cr, Fe, Nd and Gd are being related to their magnetic phenomena, and to molecular electron positioning. My 535-page reference book gives more theory about 118 chemical elements. The book is, Charge Distributions on the Nuclei.

Keywords: neodymium, chromium, ferromagnetic, iron, alloy, demagnetize, magnetic lines of flux, flux, theoretical, ring, loop, NdFeB, nuclear

*Speaker

Revealing material inhomogeneities from MOKE data

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Abstract

When it comes to device applications based on magnetic materials, any inhomogeneity of the sample can strongly influence the devices' efficiency (1). The magneto-optical Kerr effect (MOKE) measurement is an experimental tool to probe materials' magnetisation dynamics. The scope of the study is to reveal inhomogeneities hidden in MOKE video data by applying physically-inspired, computationally cost-efficient latent tools: the latent entropy and the latent dimension (2,3).
The analysis of the MOKE video data using latent methods is based on the dynamic variations between the individual video frames and performs the calculation of the latent entities and the denoising of the data in the same step. This makes it possible to visualise inhomogeneities and other potentially hidden features in the material more precisely.

In this regard, we set a Co/Pd multilayer exhibiting strong perpendicular anisotropy as a benchmark system for inhomogeneities' and hidden features' detection (4).

(1) O. Gutfleisch et. al., Adv. Mater., 23, 821-842 (2011).

(2) D. R. Rodriges et. al., iScience, 24, 3 (2021).

(3) I. Horenko et. al., Comm. App. Math. And Comp. Sci., 16, 2 (2021).

(4) W. R. Bennett et. al., J. Appl. Phys. 69, 4384 (1991).

Keywords: magnetic inhomogeneities, latent inference methods, magnetic materials, MOKE

*Speaker

Effect of cycling on the thermomagnetic response of Ni-Mn-(In,Sn)-X Heusler alloys

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Abstract

Magnetic shape memory materials with Heusler structure are characterized by, usually, having both the magnetic transition (from ferro-to paramagnetism) and the structural one (from austenite to martensite). The Ni-Mn-(In,Sn) alloys with the best thermomagnetic response are off-stoichiometric. On the other hand, it has been found that the minor addition of a fourth element (Fe, Co, Ga, Si, B, Al, Pd, Cr, Ti) can lead to a shift in the transformation temperatures of more than 50 K. In consequence is a good system for producing alloys customized to obtain a specific working temperature interval (1). In this work, the alloys have been produced in ribbon form by melt-spinning (from bulk specimens obtained by arc melting). One of the potential applications of these alloys is the magnetic refrigeration due to the magnetocaloric effect. The generation of transformation temperature diagrams allows the desired composition to be fine-tuned. Two of the intervals analyzed are that of close to ambient temperature (for conventional cooling) and that of temperatures slightly higher than ambient (cooling in data centers). Refrigeration processes are cyclic and the stability of the functional response after cycling must be analyzed. The experimental analysis a done with differential scanning calorimetry and vibrating sample magnetometry. In this study, thermal cycles have been carried out, noting that the thermodynamic and thermomagnetic response is reduced by between 5 and 15% after the first 2-3 cycles, but then remains quite stable regardless of the number of cycles. Regarding the transformation temperatures, cycling produces minor changes, of about 2 K at most. In addition, simulations of heat transfer during cyclic cooling have been carried out using experimental data from one of the Ni-Mn-Sn based Heusler alloys.

(1) A. Wederni; M. Ipatov, M. Khitouni, J.J. Suñol,. *J Therm Anal Calorim* (2023). https://doi.org/10.1007/s10973-023-12580-9.

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Keywords: magnetocaloric, Heusler, cycling, simulation, magnetic refrigeration

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The HyLICAL project - Overview and Progress

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Abstract

The HyLICAL project "Development and validation of a new magnetocaloric high performance hydrogen liquefier prototype" is a Research and Innovation (RIA) action funded in the framework of HORIZON Europe (project number 101101461). Within its five years duration, the project will develop new high-performance materials for magnetocaloric hydrogen liquefaction (MCHL) that are either free of heavy rare earth (HRE) elements or have a strongly reduced HRE-content ($< 50\%$). A highlight will be the construction of a magnetocaloric hydrogen liquefier with a production capacity of 100 kg, a first-of-a-kind for Europe.This presentation introduces the project partners, outlines the scope and highlights some of the scientific results obtained within the first 18 months.

Keywords: magnetocaloric, hydrogen liquefaction, materials design, prototype

*Speaker

Magnetocaloric Entropy and Universal Critical Behaviors study in La1-xCsxMnO3 Ceramics

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Abstract

Hole doped lanthanum manganites of La1–xAxMnO3 (A= Ce,Sr,Na....) have been the subject of a large number of recent studies due to their interesting physical properties such as magnetocaloric effect. In this study, our central focus is to investigate the effect of Cs-doping on the magnetocaloric properties, and the temperature range of the magnetic entropy change for La1-XCsXMnO3 ($0 \leq x \leq 0.1$) submicron powders. The magnetocaloric effect has been calculated in terms of isothermal magnetic entropy change. All our compositions present a maximum and large Curie temperature (TC). The maximum magnetic entropy values under a magnetic field change of 5 T, determined from Maxwell relation, are found to be 3.89, 2.32 and 1.56 J/kg K-1 for respectively x= 0: 0.05 and 0.1. The corresponding relative cooling power (RCP) reaches 220 J/Kg for the smallest Cs-doping. The obtained values are very interesting for application in ecologically friendly magnetic refrigerants technology near room temperature. From the Arrott curves, it was observed that all samples exhibited a second-order magnetic phase transition. Critical behavior of the investigated materials is studied around their Curie temperatures (TC) through various techniques such as modified Arrott plot (MAP), Kouvel–Fisher (KF) method and critical isotherm (CI) analysis based on the data of static magnetic measurements recorded around the Curie temperature TC. The estimated critical exponents obtained for x=0 are close to the tri-critical mean-field model at Tc=195K, whereas, for x=0.05 sample, these exponents are close to those expected one for 3D-Heisenberg model. We aim to discuss the different magnetic models and their link to the low Cs-doping in order to apply a universal behavior approach.

Keywords: Manganites, Phase transition, Entropy, Magnetocaloric effect, Critical behavior

*Speaker

Inducing magnetostructural coupling near room temperature in Cu-doped (Fe,Mn)NiSi alloys

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Abstract

Magnetocaloric materials (MCM) are called to play an essential role in the energy transition due to their superior refrigeration performance and environmental safety compared with gas compression-based current technologies. However, high-performance MCM usually contain elements, such as rare-earths (RE), cobalt and germanium, which have been identified with high supply risk. In recent years, the MnNiSi-related system has attracted a lot of attention due to its low material criticality and, simultaneously, the possibility of large magnetocaloric effect. MnNiSi, itself, possesses a martensitic transition (MT) from a high-temperature Ni2In-type hexagonal austenitic phase to a low-temperature TiNiSi-type orthorhombic martensitic phase at 1210 K, while the Curie temperature (Tc) of martensite is located at 622 K. Then, the structural transition occurs in the paramagnetic region. To couple both magnetic and structural transitions together (indispensable to achieve a large dM/dT and therefore, a potentially large magnetocaloric effect), one possible approach is to replace half of the Mn with Fe, which decreases the MT temperature down to 840 K. However, the Tc of the low-temperature phase is also reduced to 455 K and the two transitions remain decoupled. With the aim of reducing the temperature of the structural transition below the Tc of the martensitic phase, we designed the series, based on abundant elements, Fe0.5Mn0.5Ni1-xCuxSi alloys (where x = 0, 0.10, 0.15, 0.20 and 0.23), and studied their structural and magnetic properties using powder X-ray diffraction, scanning electron microscopy, differential scanning calorimetry and vibrating sample magnetometry. Gradually replacing Ni by Cu, we achieve a remarkable decrease in the temperature of the structural transition, while only slight reductions in the Curie temperature of the martensitic phase are noticed. This doping strategy results in a coupling of the magnetic and structural transitions leading to a transformation from ferromagnetic orthorhombic structure to a paramagnetic hexagonal phase for x > 0.15. For the x = 0.2 sample, the martensitic transition decreases from more than 830 K to around 300 K, obtaining a first-order magnetostructural transition near room temperature with a significant improvement of the magnetocaloric response with respect to the Cu-free alloy, correlated to an increase in the total entropy change calculated from differential scanning calorimetry.

Keywords: MM'X alloys, first order phase transitions, magnetostructural coupling, low, criticality materials

*Speaker

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Machine Learning-Guided Discovery of Magnetocaloric Materials for Hydrogen Liquefaction

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Abstract

Because of the climate crisis, it is important to find renewable alternatives, where hydrogen is an important candidate in many sectors. Liquefaction of hydrogen is essential to make it a competitive energy carrier due to easier transportation because of increased energy density. Magnetocaloric Hydrogen Liquefaction (MCHL) has the potential to replace conventional vapor compression-expansion technology, which suffers high cost, high complexity, and energy inefficiency as one approaches the liquefaction point of hydrogen (20 K).
One of the challenges with MCHL is to identify materials with relevant Curie temperature (Tc). Many Cubic (C15) Laves phases (AB2) are possible candidates for this application. Conventionally, heavy rare earths have been explored in the position of the A atoms in the crystal structure due to their large magnetic moments. However, these are categorized as critical raw materials, making light rare earth an attractive alternative as they are of higher abundance and still have quite large magnetic moments. In this work, these heavy rare earths are substituted by light rare earths, namely Nd and Pr. Transition and p-block metals were used in the position of the B atoms.

Machine learning (ML) is an efficient tool to predict material properties given a sufficiently large database. Random forest regression (RFR), gradient boosting regression (GBR), and neural networks (NN) are ML methods explored in this work, developed using a five-fold cross-validation method. Chemical composition was used as features and the Tc as the target for the models. Light rare earth based cubic Laves phase materials were screened using the ML models, and promising candidates for MCHL were synthesized and characterized to verify the models. The structural and magnetic properties of the samples were characterized using SEM, XRD and PPMS, with the purpose of investigating their performance for MCHL applications.
Characterization revealed that the samples in this work exhibit Tc relevant for MCHL applications, showing that ML can be an important tool to predict Tc for cubic Laves phase materials.

Keywords: Magnetocaloric, Machine Learning, Laves phase, Hydrogen Liquefaction

*Speaker

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Anomalous thermal expansion and magnetocaloric effect in transition metal based compounds

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Abstract

Long range magnetic order is well-known for giving rise to a number of effects, from magneto-structural phase transitions and spin reorientation to anomalous thermal expansion, to name a few. Recently the work put into optimizing the overall properties of magnetocaloric materials has been put to use in the field of zero and negative thermal expansion (ZTE and NTE, respectively). Thermal expansion in magnetic materials tends to be highly anomalous and anisotropic due to the magnetic interactions and magnetocrystalline anisotropy which often clamp the lattice when compared to the thermal expansion observed in the paramagnetic state. In this context we took advantage of the extensive previous work done on the structural characterization and phase diagram mapping of two highly anisotropic systems, (Mn,Fe)5Si3 and MMX, to develop NTE materials suitable for applications. This was achieved by creating strong textture in polycrystalline samples using different synthesis and/or processing methods. The result is that we observe a ZTE of 0.22×10–6 K–1 in Mn1Fe4Si3 and a remarkably large NTE coefficient of –328.7×10–6/K between 288.2 and 431.1K in multi-component MnCo(Ge,Si)/epoxy composites.

(1) Gong, Y., Miao, XF., Samanta, T. *et al.* Anomalous thermal expansion and enhanced magnetocaloric effect in< 001> -textured MnxFe5–xSi3 alloys. *Rare Met.* **43**, 2263–2274 (2024)
(2) Guo, W., Miao, X., Yan, Z., Chen, Y., Gong, Y., Qian, F., ... Caron, L. (2024). Colossal negative thermal expansion over a wide temperature span in dynamically self-assembled MnCo(Ge,Si)/epoxy composites. *Materials Research Letters*, *12*(4), 315–323 (2024)

Keywords: thermal expansion, magnetocaloric effect, transition metal, phase transition

*Speaker

Reprogramming Magnetic Anisotropy: Field Annealing of Fe-Based Soft Amorphous Alloys

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Abstract

Magnetic field annealing can be used to create a unified easy magnetization direction in Fe-based amorphous magnetic alloys. However, annealing at a too-high temperature usually comes with the cost of severe embrittlement (1). In this study, a systematic investigation is carried out on the magnetic domain evolution, structural changes, and mechanical responses in Fe80B12P4Si2.7C1.3 soft-magnetic amorphous ribbons to elucidate the effect of different annealing conditions. The ribbons are annealed at different temperature ranges before crystallization under longitudinal and transverse applied magnetic field conditions while varying the incubation times. It is found that optimal annealing conditions lead to relieving internal stress. The effect of the annealing on the magnetic properties is studied using the Kerr microscopy technique. Figure 1 shows the Kerr microscopy images of the same region of the ribbon before and after longitudinal magnetic field annealing, suggesting homogeneous domain formation along the applied field direction, indicating both stress relieving and a reprogrammed and unified anisotropy direction. By identifying optimal annealing conditions, this study offers insights into enhancing the magnetic performance of these alloys without compromising the mechanical properties.

Keywords: Fe based soft magnetic alloys, Soft magnetic amorphous ribbons, Kerr microscopy, Magnetic field annealing, Magnetic domain imaging

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High Permeability Magnetic Composites with Cement, Asphalt, and Epoxy Binders for Enhanced Performance across Diverse Applications.

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Abstract

This research investigates novel methodologies for creating and evaluating magnetizable composites comprised of cement, asphalt, and epoxy. Two distinct setups are utilized to assess parameters under both low and medium magnetic fields. By manipulating individual parameters such as permeability and losses relative to aggregate sizes, volume fraction, and matrix composition, while maintaining consistent toroid core dimensions, we gain insights into the effects of these variations. Additionally, we compare the impact of varying the matrix while holding volume fraction and aggregate composition constant, aiming to elucidate the influence of the matrix on magnetic composite properties. Our approach to fabricating magnetic composites involves employing ferrites derived from a sustainable recycling process, which entails crushing and sieving magnetic cores sourced from diverse e-waste outlets. The inclusion of epoxy-based magnetic composites for comparison purposes mitigates the influence of pressure fluctuations. The in-depth examination of aggregate size focusing on coarse aggregates and volume fraction within a specified matrix facilitates the production of magnetic composites tailored to specific application requirements. Notably, the magnetic composite denoted as S40, generated through this methodology, has demonstrated significant performance enhancements over powder cores. Further exploration and analysis aim to bridge the performance gap between magnetizable concrete composites and traditional ferrites, offering opportunities for refined customization and application-specific optimization.

Keywords: Magnetic composites, Magnetisable Concrete, Recycled Ferrites

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Development of Double Air-gap PMSM for Ultra High Efficiency and Ultra High Power Operation of eVTOL

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Abstract

In order to use electric energy economically and safely, various technologies are being developed for energy saving and safe operation based on the understanding of the power usage situation in terms of converting electrical energy into kinetic energy in electric vertical take-off and landing (eVTOL). In this study, a double air-gap permanent magnet synchronous motor (PMSM) is selected for energy-saving operation and a safe operation of electric motor application in urban air mobility (UAM). It focused on the ultra-high efficiency and ultra-high power characteristics by preventing demagnetization of permanent magnets by geometric structure were conducted. The torque performance of the motor was analyzed from the economic point of view of the energy efficiency of the motor by the speed, and from the output point of view of the geometry of the rotor consisting of permanent magnet and iron core. All of the above analyzed the performance based on the geometry of the rotor by the pin-bolt diameter for safe operation of the motor. The results of the study provide important information for the optimal selection of double air-gap electric motors and the improvement and effectiveness of energy conversion in the application of various motors such as lift, propulsion, and tilt force so on applicable in eVTOL.

Keywords: double air, gap, eVTOL, PMSM, seamless, UAM

*Speaker

Modelling of Nonlinear Magneto-Thermo-Mechanical Behaviour of Magnetostrictive Materials Subjected to Prestress and Thermal Load

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Abstract

Magnetostrictive material is a type of smart materials by the coupling of magnetic, mechanical and thermal ferroic orders. These materials exhibit the villari effect and conversely joule effect. The nonlinear magnetostrictive material properties are enabling the different applications like sensor, actuator including vibrational energy harvesting applications. Metglas is soft ferromagnetic nonlinear magnetostrive material stands out due to high magnetic saturation point comparing with other magnetostrictive materials, and its low cost which makes the suitable for mass production and cost-effective battery-powered solutions. The nonlinear magnetostrictive material properties, such as magnetization and total strain which comprising of magnetostrictive strain and mechanical strain developed by external magnetic field, prestress and temperature which needs to be characterized effectively for Metglas. Considering that, the present work focuses on investigating these nonlinear magnetostrictive properties of Metglas using combined multiloading of prestress and temperature along with the external magnetic field using finite element method. A three-dimensional magnetostrictive material is adopted and further implemented with user defined nonlinear constitutive relations to investigate the magnetostrive behaviour under magneto-thermo-mechanical loadings using COMSOL Multiphysics. Prior to conduct the present study the analytical nonlinear constitutive models of magneto-thermo-mechanical magnetostrictive material are modelled and validated with good agreement. The results showed that the magnetostrictive strain increases from 39.7 ppm to 45.2 ppm by increasing the compressive stresses from 0 MPa to -40 MPa and 39.7 ppm to -110 ppm by increasing temperature from 0 to 80 respectively. The developed Finite Element Model is used to predict the material parametric and stimulation parametric study to find and optimize the Metglas magnetostrictive material under magneto-thermo-mechanical loading.

Keywords: Magnetostrictive material, Prestress, Metglas

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Polyelectrolyte/silica layer-by-layer assembly on iron powder for soft magnetic composite materials

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Abstract

Powdered ferromagnetic materials with high macroscopic electrical resistivity, also known as SMC, are an excellent resource in the prototyping of electrical machines with non-traditional magnetic flux configurations - for example, axial flux machines. Their use is also increasingly expanding in the mass production of small devices, especially in the automotive sector.
Many research activities still concern the optimization of the performance of materials, aiming to maximize and harmonize their mechanical, energetic and magnetic characteristics.
In this context, play a role a particular process of creating nanometric layers of dielectric material on powder, being the subject of an international patent. The invention allows many degrees of freedom regarding the type of materials used for the construction of the layers. The layers can be of various natures: organic, inorganic and hybrid. Also, the number of layers can be designed and structured. In the proposed activity, we analyze materials produced with a particular formula, containing a polymer and nanometric silica, in which some process parameters are varied, analyzing their influence on the overall performance of the finished material. The samples were measured with a hysteresigraph, to detect the magnetization curve, the relative magnetic permeability and the specific losses at different frequencies. The mechanical properties were measured through transverse rupture strength tests.

Keywords: SMC, layer by layer, materials, powder cores, eddy currents, characterization, hysteresigraph, specific losses

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Modern soft magnetic materials for applications in electric motors

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Abstract

High-induction nanocrystalline materials represent a significant advancement in the field of electrical engineering, particularly in the development of electric motors. This work explores the application and possible benefits of application of this materials in enhancing the performance and efficiency of electric motors.
Nanocrystalline materials are distinguished by their grain sizes, which are typically less than 100 nanometers. This fine-grained structure contributes to their high saturation magnetization and permeability, low coercivity, and minimal energy loss at high frequencies. These properties are crucial for the efficient operation of electric motors, especially those operating under variable speed conditions and high frequencies.

The work is focused on FeCoB based group nanocrystalline materials, focusing on the melt spinning and subsequent heat treatment, which are used to achieve the desired magnetic properties. The influence of various alloying elements, such as niobium and phosphorus, on the magnetic and structural properties of these materials is analyzed. Additionally, the paper discusses the process of tailoring the magnetic properties through controlled crystallization in a presence of magnetic field, which is essential for optimizing the performance of electric motors.

A comparative analysis of nanocrystalline materials highlights the superior energy efficiency and performance of nanocrystalline materials due to their lower core losses and high magnetic flux density.
The application of high-induction nanocrystalline materials in electric motors offers considerable advantages in terms of energy efficiency, performance, and size reduction. The ongoing advancements in the synthesis and processing of these materials hold the promise of wider adoption in the electric motor industry, contributing to the development of more sustainable and efficient electric motor technologies.

Keywords: Soft magnetic materials, electric motor applications

*Speaker

Transformation of 2:17 phase to 2:14:1 phase in the NdFeCuMoCuB system: A comprehensive in-situ TEM study

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Abstract

In the recent decades, there has been a major focus on improving the magnetic properties of Nd-Fe-B magnets through microstructural engineering. It is aimed to obtain a refined microstructure of Nd2Fe14B grains with ultra-thin (nanoscale) grain boundary Nd-rich phase surrounding the hard magnetic grains. The latter magnetically decouples the Nd2Fe14B grains, preventing the propagation of reverse magnetic domains, leading to a coercivity enhancement. The usual techniques to obtain fine microstructures are rapid solidification (melt spinning) and hydrogen gas-solid reaction (HD – hydrogen decrepitation and HDDR – hydrogenation, disproportionation, desorption and recombination), each with its own set of pros and cons. In a recent work, with the hindsight of Fe-Nd phase diagram, fine-grained Nd2Fe14B magnets was produced by solid state transformation of Nd2Fe17 precursor containing Mo, Cu, and Co. High coercivity is obtained without the need of advanced powder metallurgical processes as for conventional Nd-Fe-B magnets (1). In order to understand the transformation path of 2:17 to 2:14:1 which is the basis for the increase in coercivity, we conducted an in-situ transmission electron microscopy (TEM) experiment from room temperature up to 1075 ◦C. Our TEM results conducted at room temperature, including high-angle annular dark field imaging, show that the 2:17 precursor sample is made of 2:17 and 1:5 phases, while precipitates of Mo, Nd, and Cu are also present in the nanostructure. At 300 ◦C, although the 2:17 structure showed no change, fine grains of a secondary phase appears within the 2:17 grains. These small grains seem to be rich in Fe and Co, and more dilute in Nd, when compared to the matrix. As the temperature was increased, these grains became more frequent throughout the sample. At 600 ◦C, Fe,Co- and Fe,Mo-rich precipitates appear and further grow with increasing temperature. Our results show that the 2:17 phase only transform to 2:14:1 at 750 ◦C, yielding a very fine nanostructure. Further increase in temperature leads only to grain growth of the existing phases. (1) L. Schafer, K. Skokov, F. Maccari, I. Radulov, D. Koch, A. Mazilkin, E. Adabifiroozjaei, L. Molina-Luna, O. Gutfleisch, A novel magnetic hardening mechanism for Nd-Fe-B permanent magnets based on solid-state phase transformation, Adv. Funct. Mater. 33 (2022), 2208821.

Keywords: TEM, 2:17, 2:14:1, NdFeB magnets, Transformation

*Speaker

Study on the shape characteristics of ferrite permanent magnet rotor for small wind power generators

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Abstract

Most recently developed generators and electric motors are synchronous machines using rare earth permanent magnets. As the name suggests, rare earth permanent magnets are expensive because they are distributed in small quantities on Earth. In addition, because mining is concentrated in specific areas, price fluctuations are large. Accordingly, research has recently been actively conducted to develop generators using low-cost ferrite permanent magnets in order to provide a stable supply of permanent magnet generators and reduce their prices.
However, using ferrite permanent magnets in wind power generators has two major disadvantages. First, ferrite magnets have a lower magnetic flux density than rare earth permanent magnets, so a large amount of permanent magnets must be used. Second, ferrite magnets have a lower coercive force compared to rare earth permanent magnets, so the voltage fluctuation rate is large.

So, I first studied a small wind power generator that uses a spoke-type rotor that can use a lot of permanent magnets. The 500W capacity generator achieved the target output voltage and output current by increasing the size by about 20% compared to the rare earth permanent magnet generator. However, a very large voltage fluctuation rate was found due to the low coercive force of ferrite and magnetic flux leakage in the z-axis direction.
Therefore, in this study, I propose a SPM (Surface Permanent Magnet) type permanent magnet generator structure that can reduce the voltage fluctuation rate while using ferrite permanent magnets, and compare the characteristics with the existing spoke type through computer simulation. Additionally, I would like to verify whether the voltage fluctuation rate of the proposed model was actually reduced through production.

Keywords: small wind generator, ferrite magnet, low cost, rotor, stator

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3D microstructure characterization and micromagnetic model development for permanent magnets

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Abstract

Development of high coercivity Dy-free Nd-Fe-B magnets or alternative systems such as SmFe12 requires a precise understanding of the correlation between microstructure and magnetization reversal process. Traditional analysis based on 2D SEM or TEM images and micromagnetic simulations on models with simple grain shapes and homogeneous grain boundary have been employed to link microstructure and coercivity. However, the 2D microscopy data and oversimplified models cannot capture the complexity of a real 3D multicomponent material. Therefore, advanced 3D characterization methods such as FIB-SEM and XMCD tomography (1) have been used to gain deeper insight into the magnetization reversal mechanisms and the influence of defects. In this study, we aim to extend current capabilities by combining FIB-SEM tomography, up-to-date image processing, and micromagnetic simulation. We show that the detailed statistical information from the 3D imaging data not only provides valuable insights into the distribution of the main and secondary phases but also becomes a foundation for true-to-life micromagnetic models for identifying weak links and hypothesis testing.

The FIB-SEM tomography data was obtained for a sintered Nd-Fe-B magnet. Image preprocessing included brightness and contrast adjustment, drift correction, and denoising using OpenCV and SciPy libraries. Processing of volume data included semantic segmentation (phase composition) and instance segmentation of Nd-Fe-B grains (information on individual grains). For semantic segmentation we used k-means and U-Net-like model, for instance segmentation – NISNet3D (requires pre-training) and modified Segment Anything (no pre-training required) models (2,3). Postprocessing included analysis of phase composition, grain surrounding, grain size distribution, connectivity, etc. As a result, a complete volumetric information on the phase distribution and individual Nd-Fe-B grains was obtained and used to build a finite element model. The micromagnetic simulations were conducted to identify nucleation sights and to reveal the role of secondary phases in coercivity. We believe that the proposed workflow for developing realistic multiphase finite element models will be particularly useful for multiphysics simulations (4).

(1) Takeuchi M. et al. NPG Asia Mat. (2022) 14:70

(2) Wu L. et al. Sci. Rep. 13 (2023) 9533

(3) Kirillov A. et al. arXiv:2304.02643 (cs.CV) (2023)

(4) Sun Z. et al. JMMM 589 (2024) 171555

Keywords: microstructure characterization, FIB, SEM, deep learning, micromagnetic simulation

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Machine Learning Assisted Optimization of SmFe12-based Alloys

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Abstract

SmFe12-based alloys with ThMn12-type crystal structure (1:12) are among the most intriguing hard magnetic materials (1), whose remarkable intrinsic magnetic properties ($\mu 0Ms$ = 1.64 T, $\mu 0Ha$ = 12 T, and Tc = 555 K for SmFe12 (2)) are difficult to convert into good extrinsic magnetic performance of the bulk magnets – high coercivity and remanence. The main obstacle comes from the instability of the SmFe12 phase, which requires multiple substitutions, *e.g.*, (Sm,Zr)(Fe,Co)12-xMx, where M are nonmagnetic elements such as V, Ti, Mo, and others. Sophisticated optimization is needed to design a composition with minimized loss of magnetization and magnetic anisotropy. Machine learning on large DFT-based datasets has recently been employed to accelerate this optimization (3). However, there are other critical factors that should also be considered during the optimization – phase composition, separation of 1:12 grains with an intergranular phase (4), crystallographic texture, *etc.* To control these synthesis-related factors, in this work we conducted machine learning on an experimental dataset. The dataset comprised 908 samples collected from articles and our own experiments on the SmFe12-based alloys which were obtained either by mechanical alloying or by melt-spinning followed by heat treatment. The descriptor of each sample consisted of the chemical composition and synthesis details. The importance of the features and their correlations were analyzed, then two gradient boosting regressors were trained to predict coercivity and remanence as the main targets. Next, a large feature space of (Sm,Zr)x(Fe,Ti,V)100-x melt spun samples with annealing temperatures ranging from 923 to 1373 K (≈57,000,000 candidates in total) was examined to define a Pareto front of the competing targets. Finally, we proposed a list of the most prospective alloys for an experimental validation, the results of which will be reported, as well as other details of the machine learning on the SmFe12-based isotropic alloys.

References

(1) P. Tozman, H. Sepehri-Amin, and K. Hono, Scr. Mater. 194 (2021) 113686.

(2) Y. Hirayama, Y.K. Takahashi, S. Hirosawa, and K. Hono, Scr. Mater. 138 (2017) 62.

(3) D.N. Nguyen, H. Kino, T. Miyake, and H.C. Dam, MRS Bull. 48 (2023) 31.

(4) X. Tang, J. Li, A.K. Srinithi, H. Sepehri-Amin, T. Ohkubo, and K. Hono, Scr. Mater. 200 (2021) 113925.

Keywords: Machine learning, SmFe12, hard magnetic materials

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Shifted Inductances Axes Hybrid Excited Synchronous Motors: Exploitation of the Degrees of Freedom of PM Synchronous Machines for Torque and Energy Densities Improvement

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Abstract

This contribution introduces a tool crafted specifically to explore the efficiency maps of shifted inductances axes hybrid excited synchronous motors (SIAHESMs), presenting it for the benefit of readers. Rooted in a solid foundation laid by previous research, which predominantly centered on the power capabilities of synchronous machines (1)-(4), this study extends the scope to delve deeper into the power capabilities of shifted inductances axes hybrid excited synchronous motors (3). This tool can both used for design and analyses purposes. To validate this advancement, classical permanent magnet or hybrid excited synchronous machines are treated as particular cases of SIAHESMs, and serve as benchmarks. Validation entails a meticulous comparison of the power capabilities and efficiency maps of SIAHESMs with those of classical HESMs and other PM machines, leveraging both the newly devised and previously established modeling tools. Furthermore, this contribution goes beyond validation, exploring the influence of specific design parameters on efficiency maps and power contributions, enriching the suite of design tools available to engineers and researchers in the field. Through this comprehensive approach, a deeper understanding of the intricacies of SIAHESMs and their performance characteristics is achieved, laying a robust groundwork for future advancements in electric machine design.

(1) Y. Amara, S. Hlioui, H. B. Ahmed and M. Gabsi, "Power Capability of Hybrid Excited Synchronous Motors in Variable Speed Drives Applications," in IEEE Transactions on Magnetics, vol. 55, no. 8, pp. 1-12, Aug. 2019, Art no. 8204312, doi: 10.1109/TMAG.2019.2911599.

(2) Yacine Amara, Hamid Ben Ahmed, and Mohamed Gabsi, Hybrid Excited Synchronous

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Machines: Topologies, Design and Analysis, London, U.K.: Wiley-ISTE, 2022.

(3) H. Diab, S. Asfirane and Y. Amara, "Torque Capability of Shifted Inductances Axes Hybrid Excited Synchronous Machines," 2022 International Conference on Electrical Machines (ICEM), Valencia, Spain, 2022, pp. 1211-1217, doi: 10.1109/ICEM51905.2022.9910835.
(4) H. Diab, S. Asfirane and Y. Amara, "Analysis of Efficiency Maps of Synchronous Machines," in IEEE Transactions on Magnetics, vol. 59, no. 11, pp. 1-5, Nov. 2023, Art no. 8101805, doi: 10.1109/TMAG.2023.3285856.

Keywords: Permanent magnet, Sycnhronous motors, Electromagnetic modeling, Equivalent circuits, Motor drives, Variable speed drives, Efficiency maps

Additive manufacturing of heavy rare earth free high-coercivity permanent magnets

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Abstract

Laser powder bed fusion (PBF) is a promising additive manufacturing process for the manufacturing of NbFeB permanent magnets with versatile complex shapes. The weak performance (usually, low coercivity) of the additively manufactured magnets as compared with the sintered counterparts currently hinder their withspread application. In this study, we demonstrated a proof-of-concept of PBF of heavy rare earth free NdFeB magnets featuring technologically attractive coercivity values. The additively manufactured NdFeB magnets exhibit one of the highest (among additively manufactured magnets without heavy rare earth metals) coercivity values reaching $\mu 0H\mathrm{c} = 1.6$ T. The NdFeB magnets were synthesized by PBF of a mixture of the NdFeB and the low-melting eutectic alloy powders. The essential role of the eutectic alloy in the manufacturing process is (i) binding of the NdFeB particles and (ii) coercivity improvement of NdFeB by the *in-situ* grain boundary infiltration. The fundamental understanding of the magnetization reversal processes in these 3D-printed magnets leads to the conclusion that the excellent performance of the additively manufactured NdFeB magnets can be achieved through the delicate control of the intergrain exchange interaction between the grains of the Nd2Fe14B phase.

Keywords: Additive manufacturing, NdFeB

*Speaker

Poster Session - Functional Materials (TU Darmstadt)

Wednesday 18th September

FUNKTIONALE MATERIALIEN

Welcome to the Poster Session III!

Grain boundary engineering and recycling

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Abstract

Nd-Fe-B magnets have the highest room temperature energy product (BH)max and therefore are vital for various industries having allowed the development of the most energy efficient electric motors and generators for applications like electric and hybrid vehicles and wind turbines. However, appliances containing Nd-Fe-B do have a significant environmental footprint caused by the usage of rare earth metals, most importantly Nd, Pr, Dy, Tb. These materials are becoming increasingly problematic due to environmental, economic as well as geopolitical concerns related to China which is the main global exporter. Lowering the criticality and increasing the sustainability of rare earth permanent magnets are challenges which have to be solved for an environmentally friendly and carbon neutral future.
In this work we exploit two strategies to advance the development towards resource-efficient Nd-Fe-B magnets: (i) reduction of heavy rare earth elements (HREs) and (ii) production of recycled magnets directly from end-of-life scrap material.
Reduction of HREs is achieved by optimizing the grain boundary diffusion (1) process as well as strategic selective hardening of areas in the magnet that are the most susceptible to demagnetization, such as corners or edges. The latter approach becomes especially important considering the advent of additive manufacturing which has the potential to realize such tailored local magnetic hardening based on specific application requirements.
Different Nd-Fe-B permanent magnet recycling strategies are investigated and compared. The so-called hydrogen-based (2) magnet-to-magnet route is optimal in terms of energy consumption since no elemental separation or re-melting of the alloy is necessary. Instead the matrix remains in the Nd2Fe14B phase throughout the processing steps. In addition, we have also investigated recycling via the nanocrystalline hot pressing – hot deformation route as well as production of polymer bonded magnets by additive manufacturing.

(1) T. Helbig, A. Abel, S. Sawatzki, T. Gröb, I. Dirba, S. Ener, O. Gutfleisch, Anisotropic grain boundary diffusion process in textured sintered and hot-deformed Nd-Fe-B magnets, J. Alloys Compd. 992 (2024) 174490.
(2) O. Gutfleisch, K. Güth, T. G. Woodcock, and L. Schultz, Recycling Used Nd-Fe-B Sintered Magnets via a Hydrogen-Based Route to Produce Anisotropic, Resin Bonded Magnets, Adv. Energy Ma-ter., vol. 3, no. 2, pp. 151–155.

Keywords: NdFeB, recycling, grain boundary diffusion, rare earths

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Challenge Brown's paradox by searching for the "perfect defects"

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Abstract

Permanent magnets play a pivotal role in various aspects of our daily lives, serving as essential components in countless electronic devices, medical equipment, motors, and generators. Their ability to generate a constant magnetic field with no external power source makes them indispensable for modern technology, enabling the global implementation of electric mobility and wind energy. Nonetheless, a significant constraint of any magnets arises from its coercive field. This property is essential as it prevents the demagnetization of the magnet during application and is typically reaching only 25% of the theoretically attainable value, a phenomenon recognized as Brown's paradox.

Permanent magnets derive their properties from a complex interplay of composition and phase distribution, spanning multiple length scales. Each phase serves as a fundamental building block with its own intrinsic properties. Gaining a deep understanding of the interactions between these phases is crucial for deciphering the origins of magnetic performance. This knowledge can facilitate the development of advanced magnets by enabling the design of "ideal defects" that either enhance domain wall pinning or suppress the nucleation of reverse magnetic domains, thereby improving overall magnetic performance. Thus, the main goal of permanent magnet fabrication processes is to create an ideal microstructure (or "ideal defects") that maximizes both the coercivity and the remanence, resulting in the highest energy density.

In this talk we will explain the concept of "ideal defects" and show several examples of how can we challenge Brown's paradox identifying and tailoring the perfect defects for superior pinning centers. We will showcase our latest achievements aimed at finding the ideal microstructural components and features to achieve high coercivity in various materials such as (i) single crystalline $SmCo5$ (1), (ii) sintered Sm(ZrCoCuFe)7+δ (2), (iii) sintered, hot deformed and nanocrystalline Nd(Pr)-Fe-B (3), (iv) MnAl-based alloys (4).

(1) H. Zhang et al., *J. Alloys Compd.* **993**, 174570 (2024) doi:10.1016/j.jallcom.2024.174570.
(2) X. Ye et al., *Adv. Mater.* **33**, 2–8 (2021) doi:10.1002/adma.202006853.
(3) Y. Wu et all., *Acta Mater.* **263**, 119517 (2024) doi:10.1016/j.actamat.2023.119517.
(4) Y. Jia, et al., *Acta Mater.* **245**, 118654 (2023) doi:10.1016/j.actamat.2022.118654.

Keywords: Magnetic hysteresis, Permanent magnets, Coercivity mechanisms, Microstructure

*Speaker

New sustainable Fe-rich Magnet using a predictive Alloy and Microstructure Design Toolbox (Mag-TOOL)

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Abstract

Permanent magnets are crucially important for green technologies, where demand increases constantly to achieve net zero greenhouse gas emissions. Currently, high-performance Nd-Fe-B magnets are widely used for this purpose. However, these magnets require heavy rare earth elements like dysprosium and terbium to operate the magnets at temperatures of over 100∘C. These elements are not only scarce and costly but also pose environmental and supply chain risks. Recently, there has been renewed interest in SmFe12-based compounds as potential candidates for high-performance magnets. These compounds possess the highest Fe content among the 4f-3d compounds and exhibit superior intrinsic magnetic properties, such as saturation magnetization and anisotropy field, compared to Nd2Fe14B (1,2). However, their practical applications are hindered due to their phase instability and the challenges associated to obtain optimum microstructure.

The key to finding a solution is performing composition engineering in Sm(Fe,M,X,Z)12 by using multiple alloying elements, each contributing differently to phase stability, the formation of intergranular phase and consequently, the magnetic properties. However, the vast number of potential combinations makes pinpointing the optimal composition challenging, requiring extensive experiments and characterization. To accelerate this process, we are developing in my **new ERC Starting Grant project Mag-TOOL** an advanced toolbox that integrates experimental techniques with modern machine-learning algorithms, reducing the dependency on trial-and-error methods and streamlining the development process.

To address these challenges, our current research interest on employing data-driven approaches to reassess the Sm-Fe-V phase diagram, with particular emphasis on the 1:12 phase and its coexisting phases (3). The objective is to adapt these methods for unknown Sm-Fe-M phase diagrams. Initially, data from existing literature were digitized and analyzed using techniques such as random forest, k-nearest neighbor (KNN), Neural Network - Multi-Layer Perceptron (NN-MLP) and label propagation. These methods help predict missing parts of the phase diagram and identify the most uncertain regions. Experimental samples are then synthesized from these uncertain areas. Finding an equilibrium between 1:12 phase and low melting point in the phase diagram, while maintaining high magnetization, is key to developing the desired microstructure.

(1) P. Tozman, et al, *Scr. Mater,* vol. 194, pp.113686, 2021.
(2) P. Tozman,et al, *Acta Mater.,* vol. 232, p.117928, 2022.
(3) P. Tozman, et al *Acta Mater.,* vol. 258, pp. 119197, 2023.

Keywords: Phase diagram, Magnetic properties, Machine learning

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Rare-earth free and compositionally complex magnets

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Abstract

The demand for high performance magnetic materials for green energy applications is growing rapidly. From a hard magnetic materials perspective, traditional rare earth transition magnets dominate high power applications. However, they are composed of highly critical elements and raise concerns about supply chain, cost and environmental impact. For this reason, the search for alternative materials has been motivated.
Among the alternative rare earth-free magnetic materials, Mn-based and Fe-based material systems are promising candidates. The Mn-Al system shows potential for "gap magnet" applications where a moderate energy product is required. The
tau-phase of MnAl offers relatively high coercivity and moderate magnetization values, making them suitable candidates as permanent magnets (1). On the other hand, the α"- Fe16N2 phase exhibits high magnetization values with reasonable anisotropy which limits the practically achievable coercivities (2). For both of these materials the phase stability is an issue. The approach of compositionally complex alloy design helps us to tackle these stability challenges with tuning the additional secondary functionalities. By coupling the experimental studies with digital materials science approaches in different length scales we search for solutions to these problems (3).
Complimentary, soft magnetic materials (SMMs) also play a key role in electrical applications and sustainable energy systems by allowing magnetic flux to change in response to variations in the applied magnetic field with minimal energy loss. Contrary to hard magnets, reducing coercivity is desired since it decreases these losses and improve its efficiency. However, achieving low coercivity alone is not enough; SMMs used in electrical engines must also withstand significant mechanical stresses, requiring alloys that possess both high strength and ductility. This poses a significant materials design challenge in terms of both composition and microstructure, as many methods that enhance strength tend to introduce stress fields that can lock magnetic domains, increasing coercivity and hysteresis losses. By adopting the high entropy alloy approach, the balance between mechanical properties and magnetic performance can be optimized, offering a higher degree of freedom in designing novel materials with multi-functional properties through a wide range of chemical compositions and microstructural engineering. (4-5)

(1) PASSENGER Project - https://passenger-project.eu/
(2) I. Dirba, O. Gutfleisch et al., Acta Mater. 123, 214-222 (2017).
(3) CoCoMag Project - https://cocomagproject.eu/
(4) L. Han, F. Maccari, O. Gutfleisch, D. Raabe, et al., Nature 608, 310–316 (2022).
(5) L. Han, F. Maccari, O. Gutfleisch, D. Raabe, et al., Adv. Mater. 2021, 33, 2102139.

Keywords: rare, earth free, permanent magnet, sustainable materials

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Development of alternative iron-based magnetic nanoparticles for biomedical applications

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Abstract

The advancement of biomedical applications such as magnetic fluid hyperthermia, magnetic separation and targeted drug delivery relies on engineering of magnetic nanoparticles with tailored magnetic properties. Typically, superparamagnetic iron oxide nanoparticles, e.g., γ-Fe2O3 (maghemite) or Fe3O4 (magnetite) are used as they are chemically stable, show low toxicity and their pathways of metabolism are known. However, because of their ferrimagnetic nature the saturation magnetization remains moderate which limits the performance since susceptibility scales as Ms2. This is particularly important for applications where the concentration is very low. Therefore, we are developing alternative iron-based materials (1) with optimized magnetization, susceptibility and anisotropy.

To investigate the effect of particle morphology, we have successfully synthesized various shapes of Fe3O4 nanoparticles (nano-cubes, nanospheres, nano-hexagons, and nanorods) using adjusted solvothermal process. The specific absorption rate indicates that spherical particles show the best heating performance. Moreover, spherical core/shell iron/iron oxide nanoparticles benefit from combined features of the iron magnetic core providing high magnetization and a passivating oxide with good biocompatibility as demonstrated from cellular uptake by endothelial cells (2).

The most challenging task is to develop novel advanced materials that consist of cheap, abundant and non-toxic elements. We have conducted a case study based on the Fe-N system were FeN/Fe4N nanoparticles with average size of 13.5 nm and saturation magnetization as high as 162 A·m^2/kg were prepared by thermal decomposition process. This is significantly higher than Fe3O4 (92 emu/g in bulk) and suggests that Fe-N nanoparticles could offer alternative to the conventional iron oxide nanoparticles in biomedical applications.

(1) I. Dirba, C. K. Chandra, Y. Ablets, J. Kohout, T. Kmječ, O. Kaman, O. Gutfleisch, J. Phys. D: Appl. Phys. 2023, 56, 025001.

(2) K. Riahi, I. Dirba, Y. Ablets, A. Filatova, S. N. Sultana, E. Adabifiroozjaei, L. Molina-Luna, U. A. Nuber and O. Gutfleisch, Nanoscale Adv., 2023,5, 5859-5869.

Keywords: nanoparticles, biomedical applications, iron oxides, iron nitrides

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Exploring multi- and magnetocaloric materials

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Abstract

In the quest for advancing energy-efficient cooling technologies, the study of magnetocaloric and multicaloric materials has emerged as a promising frontier. Magnetocaloric cooling leverages the magnetocaloric effect, where the temperature of a material changes in response to an applied magnetic field, offering a pathway to reduced energy consumption and more environmentally friendly cooling solutions (1). Complementarily, multicaloric materials, which exhibit coupled caloric effects-such as magnetocaloric, electrocaloric, and mechanocaloric effects-can further enhance cooling performance by leveraging multiple stimuli to induce phase transitions associated with large caloric effects (2).
Ni-Mn-based Heusler alloys, showing first-order magnetostructural matertensitic transformations, have demonstrated notable multicaloric effects under magnetic fields and uniaxial stress. Our investigations have shown that microstructure design like grain refinement, doping, precipitation formation and texture significantly impact the caloric responses and enhance the cyclic stability (3). In Ni-Co-Mn-Ti all-d Heusler alloys, we achieve sharp phase transitions and significant magnetocaloric effects that can be fine-tuned through heat treatments (4) and compositional adjustments (5). Going beyond Heusler alloys, the pressure-assisted magnetocaloric effect of low-cost and low-critical La0.7Ce0.3Fe11.6Si1.4 compounds is investigated, revealing large isothermal entropy changes originating from their field-induced first-order itinerant-electron metamagnetic transition (6). Focusing on second-order phase transition materials, single step reactive hot-pressed Fe2AlB2-type MAB phases show moderate magnetocaloric performance, though substantially reduced cost and criticality compared to high-criticality and high-cost benchmark material Gd (7). Complementing to our experimental work, high-throughput computational studies have yielded valuable insights into how doping and structural modifications can further optimize the performance of Heusler and MM'X alloys (8,9). Collectively, these efforts give a good overview of the opportunities, challenges and a deeper understanding of solid-state caloric cooling, paving the way for more efficient and sustainable cooling technologies.

(1) F. Scheibel *et al.*, Energy Technology 6 (8), 1397-1428 (2018)
(2) T. Gottschall *et al.*, Nature Mater 17, 929–934 (2018)
(3) F. Scheibel *et al.*, J. Appl. Phys. 7, 133 (2023)
(4) A. Taubel & B. Beckmann *et al.*, Acta Mater. 201, 425 (2020)
(5) B. Beckmann *et al.*, Acta Mater. 246, 118695 (2023)
(6) B. Beckmann *et al.*, ACS Appl. Mater. Interfaces 16, 38208 (2024)
(7) B. Beckmann *et al.*, J. Appl. Phys. 133, 173903 (2023)
(8) N.M. Fortunato *et al.*, Chem. Mater. 36, 6765-6776 (2024)
(9) N.M. Fortunato *et al.*, Adv. Sci. 10, 2206772 (2023)

Keywords: multicaloric, magnetocaloric, cooling technology

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Magnetocaloric cooling for natural gas and hydrogen liquefaction

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Abstract

Magnetocaloric refrigeration is an emergent cooling technology. Considered to be potentially 30% more efficient than the gas-decompression one, this on-development refrigeration relies on the magnetocaloric effect, a thermal response of the material due to changes in the applied magnetic field (1). This alternative cooling technology have been mostly developed for room-temperature applications in the past years. However, recent efforts towards using this technology in the cryogenic temperature range were performed, mainly due to the lower efficiency of the Joule-Thomson expansion, and the aim to use liquid hydrogen as energy carrier in a future ideal carbon-neutral society (2). While searching for the best magnetocaloric solid refrigerants for hydrogen liquefaction, a trend is found: the lower the ordering temperature, the higher the magnetocaloric effect (2). The reason for such trend is found as the weaker thermal motion of magnetic moments and the strongly decreasing heat capacity in the cryogenic temperature range. Further, by the comparison between light rare-earth magnetocaloric compounds with their heavy rare earth counterparts, the dilemma concerning criticality and performance is discussed (3). Among all new materials developed for such application, Pr2In is selected here for a case-study of the role of Debbie temperature in the cryogenic magnetocaloric cooling (4).

(1) Liu et al., J. Alloy. Compd. 995 (2024)
(2) Liu at al., Appl. Mater. Today 29, 101624 (2022)
(3) Liu et al., J. Phys: Energy 5, 034001 (2023)
(4) Liu et al., Phys. Rev. B 109 (2024)

Keywords: Magnetocaloric, Cryogenic, Light rare, earth, heavy rare, earth, Hydrogen liquefaction

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Ultimate magnetic characterization for functional materials

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Abstract

Materials undergoing first-order phase transitions are crucial for new solid-state refrigeration methods. External stimuli, like magnetic field, temperature or stress, induce substantial transformations in other subsystems such as crystal lattice, electrical resistivity, sample temperature etc. Understanding the nature of these interactions is vital for optimizing the hysteresis of this material (1,2).

We will present a new pathway to disentangle the interplay between the structural, magnetic and electronic degrees of freedom in such a system. We believe that our approach serves as the next step towards a complete understanding of the driving forces of the transition, together with comprehension of the origin of thermal hysteresis in magnetic phase-change materials (1). Recently, we have built several original experimental setups for simultaneous measurement of macroscopic physical properties (magnetization, magnetostriction, resistivity, temperature change) in isothermal or adiabatic conditions. Based on this, we have recently built the "ULMAG-Ultimate MAGnetic characterization" instrument at the beamline ID12 of the European Synchrotron Radiation Facility (ESRF) (3). It offers a unique possibility to measure under strictly the same experimental conditions the element-specific X-ray absorption spectroscopy (XAS)/ X-ray magnetic circular dichroism (XMCD), high-resolution XRD simultaneously with the measurement of various macroscopic properties (magnetization, volume changes, magnetocaloric properties, resistivity etc.), all as a function of magnetic field (up to 7 T) and temperature (5–325 K) (4).

To fully understand the physics of materials with first-order magnetostructural or magnetoelastic transitions, studying the elastic constants across a wide range of temperatures and magnetic fields is crucial. In our lab, we developed two setups for this purpose (temperature: 10–300K, field: up to 14 T). The first is a stress-strain cell that measures Young's modulus and Poisson's ratio, enabling precise determination of other elastic constants. The second setup measures longitudinal and transverse sound velocity through ultrasonic methods. We used these techniques to investigate elastic property anomalies in La(FeSi) alloys, providing a comprehensive description of their magnetoelastic interactions.

References

(1) K. P. Skokov, et al. Appl. Phys. Rev. 10 (3): 031408 (2023)
(2) D. Yu. Karpenkov et al. Phys. Rev. Applied 13, 034014 (2020)
(3) A. Aubert et al., IEEE Trans. Instrum. and Meas, 71, 1-9, 6002409 (2022)
(4) A. Aubert et al., (under review) J. Synchrotron Radiat. (2024)

Keywords: ultimate, simultaneous, synchrotron, stress, strain, ultrasonic

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Magnetic Domain Imaging

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Abstract

The imaging of magnetic domains has played a crucial role in advancing the understanding of micromagnetic phenomena and on the optimization of magnetic materials. Today, a wide array of modern techniques is routinely employed for magnetic imaging of materials and nanostructures, providing a direct view of magnetic properties at the microscopic scale. By visualizing magnetic domains and its arrangements not only intrinsic properties can be evaluated but also extrinsic characteristics of both soft and hard magnets (1-2). This allows for the correlation of macroscopic magnetic behavior with microstructural features at micromagnetic length scales.
Recent advancements in magnetic imaging techniques, combined with progress in micromagnetic simulations, have significantly deepened our understanding of magnetism at different length scales. Various imaging methods now cover a broad range of spatial resolutions, from milli and micrometer (as seen with Kerr microscopy) to nanoscale precision (as achieved with magnetic force microscopy, MFM). In more advanced techniques, atomic-level resolution can be attained through transmission electron microscopy (TEM) and related methods, providing insights into domain wall and its interaction with crystalline defects. Beyond imaging under static conditions, these techniques can be applied under the influence of external stimuli, such as mechanical stress, temperature variation, and magnetic fields-or even a combination of these factors. This enables the study of magnetic materials under conditions closer to real-world applications, offering deeper insights into critical properties like coercivity, magnetic and magnetostructural phase transitions, and other key behaviors. The flexibility of these imaging methods allows the investigation of a wide range of sample types, including amorphous, nanocrystalline, and microcrystalline materials, whether in thin films or bulk forms (3-4).
The synergy between improved imaging capabilities and computational simulations continues to bridge gaps in the field, linking experimental observations with theoretical models, enabling understanding of magnetism across multiple length scales with increased accuracy, assisting on the optimization and development of new functional magnetic materials.

(1) L. Han, F. Maccari, O. Gutfleisch, et al., Nat. Commun. 14, 8176 (2023)
(2) H. Zhang, A. Aubert, O. Gutfleisch, et al., J. Alloys Compd. 993, 174570 (2023)
(3) T. Helbig, S. Ener, O. Gutfleisch, et al., J. Alloys Compd. 992, 174490 (2023)
(4) M. T. Ghahfarokhi, F. Maccari, F. Albertini, O. Gutfleisch, et al., Acta Mater. 221, 117356 (2021)
(5) L. Schäfer, F. Maccari, O. Gutfleisch, et al., Adv. Func. Mater. 33, 2208821 (2023)

Keywords: Magnetic domains, coercivity, magnetic transition, microstructure

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Additive Manufacturing of Magnetic Materials

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Abstract

Additive manufacturing (AM) offers a transformative method for fabricating complex magnetic materials with tailored properties. This includes permanent magnets, magnetocaloric materials, and hard magnetic composites, essential for applications like energy conversion and soft robotics. Unlike traditional methods, which involve complex, multi-step processes, AM allows for greater design flexibility and the direct integration of magnetic components, enabling precise control over microstructure and magnetic properties.

Here we present composites fabricated via laser powder bed fusion, combining hard magnetic powders with polyamide-based polymers. We evaluate the influence of magnetic powder filler fraction, morphology, and particle size on magnetic performance (1). Results show that anisotropic magnetic properties, crucial for enhanced performance, are achievable using elongated powder particles with a crystallography-to-morphology relationship (2). Additionally, localized mechanical properties in flexible hard magnetic composites are achieved by adjusting laser processing parameters, enabling the production of magnetically controllable actuators with precisely tailored properties (3).

We also address the challenge of creating fully dense metallic magnets via laser powder bed fusion, which often results in undesirable microstructural features that reduce coercivity. We demonstrate the development of a beneficial microstructure in Pr21Fe73.5Cu2B3.5 and Nd21Fe73.5Cu2B3.5 alloys, achieved through subsequent heat treatment. The printed Pr21Fe73.5Cu2B3.5 samples achieve a coercivity of 0.75T (4). Other compositions based on Nd16Fe56Co20Mo2Cu2B7 where a heat treatment could lead to hard magnetic properties after the printing process are also under investigation (5).

For the application of magnetocaloric and multicaloric materials, microstructural design and shaping these alloys into heat exchanger geometries are essential. Microstructure design by additive manufacturing can improve the mechanical stability and enable the machinability of brittle magnetocaloric alloys. However, the AM technique and processing conditions effect the first-order transition, microstructure and chemical composition (6). Tailoring of the magnetic and caloric properties requires the investigation of the microstructural and magnetic properties over the entire process chain from gas-atomized powder to post-processed partes. We showed this for Ni-Mn-Sn multicaloric Heusler alloy (7).

(1) K. Schäfer, et al. *Materials Research Bulletin* 158 (2023): 112051. (2) K. Schäfer, et al. *Journal of Magnetism and Magnetic Materials* 583 (2023): 171064. (3) K. Schäfer, et al. *Additive Manufacturing* 79 (2024): 103905. (4) L. Schäfer, et al. *Advanced Functional Materials* 31.33 (2021): 2102148. (5) L. Schäfer, et al. *Advanced Functional Materials* 33.4 (2023): 2208821. (6) F. Scheibel, et al. *Adv. Eng. Mater.* 24 (2022): 2200069 (7) F. Scheibel, et al. *Materialia* 29 (2023): 101783.

Keywords: Additive Manufacturing, Permanent Magnets, Bonded Magnets, Soft Robotics, Heusler Alloys

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Permanent Magnets by Hot Deformation

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Abstract

Since the discovery of the hard-magnetic Nd2Fe14B phase, Hot Deformation of Nd-Fe-B has developed into a commercial alternative alongside the sintered magnet route. The performance relies on nanocrystalline isotropic powders, which are compacted and deformed to obtain textured magnets with high energy-product. Besides the fast processing times and easy handling of the powders, this production route offers important advantages. The possibility to obtain radial texture and, therefore, oriented net-shaped ring-segments by backwards extrusion (1) has been demonstrated. Moreover, the nanocrystalline microstructure gives rise to higher coercivity and temperature stability, which can be further improved by grain boundary diffusion (2).

Driven by the increasing demand for high performance magnets in the e-mobility sector, continuous and energy efficient development of deformation techniques are investigated. Due to fast processing times and upscaling of batch sizes, Field Assisted Sintering Techniques have become a promising alternative to conventional Hot Deformation. High currents pass through the punches and the material, leading to fast heating rates and densification. The experimental results demonstrate similar texture development and comparable magnetic properties to commercial hot deformed Nd-Fe-B magnets (3). Severe Plastic Deformation techniques are promising top-down approaches to obtain magnets with refined and textured microstructure. Especially Rotary Swaging could enable a continuous production of Nd-Fe-B magnets (4). Similarly, High Pressure Torsion at elevated temperature is a promising technique to obtain grain refined microstructures, even for materials with low plasticity (5). These techniques are also interesting for alternative hard magnetic materials such as Mn-Al based compounds (6), which are potential "gap-magnets" between low-cost, low-performance ferrites and the high-cost, high-performance RE-based magnets.

(1) I. Dirba, O. Gutfleisch et al., J. Alloys Compd., vol. 589, pp. 301–306, Mar. 2014
(2) T. Helbig, O. Gutfleisch et al., J. Alloys Compd., vol. 992, p. 174490, Jul. 2024
(3) F. Maccari, O. Gutfleisch et al., Adv. Eng. Mater., vol. 25, no. 18, Sep. 2023
(4) F. Chi, P. Groche, O. Gutfleisch et al., J. Magn. Magn. Mater., vol. 490, p. 165405, Nov. 2019
(5) F. Staab, K. Durst, O. Gutfleisch et al., Acta Mater., vol. 246, p. 118709, Mar. 2023
(6) F. Maccari, O. Gutfleisch et al., J. Mater. Sci., vol. 57, no. 10, pp. 6056–6065, Mar. 2022

Keywords: hot deformation, severe plastic deformation, continous processing, magnet production

*Speaker

Water electrolysis in the presence of magnetic fields

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Abstract

Clean hydrogen is a technology that can accelerate the ongoing energy transition to reach carbon neutrality. Several technologies already exist to produce hydrogen. Water electrolysis using renewable electricity (e.g. solar and wind) is recognized as the most promising and sustainable technological solution for producing "green" hydrogen. The efficiency of the water electrolysis relies mostly on the performance of electrocatalysts. Recently, some studies have reported a positive influence of the magnetic field on the electrolysis efficiency: a strongly enhanced current density in the proximity of a permanent magnet (1,2,3). Literature suggests a decrease in overpotential due to a favoured reaction pathway as a result of the spin polarization (2). This effect is, however, not fully understood as there are many interplaying variables, such as the magnetic state of the catalyst and its electrochemical conditioning. Here, we study systematically Ni-based electrocatalysts in a water electrolysis cell with and without the application of the magnetic field. The role of the magnetic field and well-defined magnetic state on the electrolysis efficiency is discussed.

(1) F.A. Garcés-Pineda et al, Direct magnetic enhancement of electrocatalytic water oxidation in alkaline media, Nature Energy 4 (2019) 519–525.
(2) Ren, X.; Wu, T.; Sun, Y.; Li, Y.; Xian, G.; Liu, X.; Shen, C.; Gracia, J.; Gao, H.-J.; Yang, H.; Xu, Z. J. Spin-Polarized Oxygen Evolution Reaction under Magnetic Field. *Nat Commun* 2021, *12* (1), 2608
(3) Hunt, C.; Zhang, Z.; Ocean, K.; Jansonius, R. P.; Abbas, M.; Dvorak, D. J.; Kurimoto, A.; Lees, E. W.; Ghosh, S.; Turkiewicz, A.; Garcés Pineda, F. A.; Fork, D. K.; Berlinguette, C. P. Quantification of the Effect of an External Magnetic Field on Water Oxidation with Cobalt Oxide Anodes. *J. Am. Chem. Soc.* 2022, *144* (2), 733–739

Keywords: Electrocatalysis, water hydrolysis, green hydrogen, spin chemistry

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SPEED: Machine learning guided high-throughput experimental platform for accelerated development of magnetic materials

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Abstract

Functional materials often involve a multitude of elements to achieve specific functionalities, which can significantly complicate the search for new materials. However, using the traditional way of trial-and-error and expert judgment results with a huge number of experiments, the materials development has been very slow, as reflected by the fact that the up-to-date best room temperature permanent magnet was discovered four decades ago. We focus on sustainable, performance enhanced, and efficient permanent magnets and magnetocaloric materials.

In our to-be-built material platform, we aim to revolutionize materials discovery and optimization by rational design, combining *(1) high-throughput experimental techniques* with *(2) machine learning* and *(3) autonomous experimentation.* With this approach we will expedite the identification of useful materials by at least a factor of 1000, bridging the gap between atomic scale and bulk materials.

High-throughput experimental processes and characterization techniques will be employed to create a reliable dataset using combinatorial sputtering and laser deposition facilities. These methods enable the production of multifunctional alloys with graded compositions for 2D and 3D materials, respectively, generating extensive datasets for machine learning applications. The samples will be analyzed using high-throughput techniques like point-by-point X-ray diffraction (XRD) for crystal structure and Energy Dispersive X-ray analysis (EDX) for chemical composition. As there is no standard method for measuring magnetic properties, this proposal aims to establish a new standard using magneto-optic Kerr microscopy (MOKE).

Data-driven material science speeds up material discovery by using multiple data sources like experiments, simulations, and machine learning. Our project uses different machine learning models to predict virtual materials, understand how elements affect material properties and accelerate novel material development. The concept of deep learning involves complex computing tasks, and all these tasks require choosing a reasonably powerful top-quality Graphics Processing Units (GPU) module with high memory capacity.

Autonomous experimentation will be realized by developing (semi-) autonomous experimental platform for thin film and bulk materials libraries with robotics moving the wafer or 3D built libraries along the different characterization stations for key properties (Structural, composition, transport (thermal/electric) and magnetic properties.

Keywords: high throughput experiment, Machine learning, thin film, additive manufacturing

*Speaker

Understanding resource efficiency in permanent magnets: A conceptual framework for LCA of permanent magnet recycling

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Abstract

Recycling Nd-Fe-B (neodymium-iron-boron) permanent magnets is crucial for promoting a circular, sustainable economy due to replacing energy-intensive extraction processes of rare earth elements, particularly of Nd, and mitigating associated greenhouse gas (GHG) emissions. For the evaluation of the environmental benefits and trade-offs of recycling routes, the LCA method is typically used. LCA enables the environmental assessment throughout the entire life cycle, from raw material extraction to end-of-life-treatment of commercial products. Assessing the recycling of Nd-Fe-B permanent magnets includes two challenges in conducting LCA: 1) there is almost no data on commercial recycling routes; 2) the assessment starts with the end-of-life (EoL) of scrap magnets and ends with the production of new magnets based on recycled materials.

We present a conceptual framework for conducting a Life Cycle Assessment (LCA) of permanent magnet recycling, addressing two key challenges. The framework identifies potential recycling routes and models them into process chains, from scrap magnets to new magnets, within the LCA. These process chains are assessed across three different technology readiness levels (TRL)-from lab to full-scale commercial implementation. To achieve this, primary data from lab and pilot recycling processes is collected, enabling comparison between scales and the deduction of data for broader commercial application.

Keywords: NdFeB, recycling, LCA, rare earths

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In-vivo wireless charging of implantable medical devices using magnetoelectric composites

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Abstract

Active Implantable Medical Devices (AIMDs) are surgically placed in the human body to either diagnose or monitor the functioning of organs and rely on batteries for their continuous operation (1). The discharging of batteries after certain years of operation hinders the functioning of AIMDs and subjects the patient to frequent surgeries for battery/device replacement. Magnetoelectric (ME) composites having an inherent tendency to convert magnetic energy to electrical energy offer a promising prospect for wireless power transfer (WPT) in AIMDs (2). This research study aims at the development and use of self-biased epoxy-free ME composites using electroless and electrodeposition of magnetostrictive layers on the piezoelectric substrate with high piezoelectric coefficient, which allows the elimination of epoxy for composite fabrication, thus imparting long life to the composite (3). The self-biased (inherent magnetic bias field) characteristic, which aids the elimination of cumbersome permanent magnets, will be imparted to the composite assembly by providing a gradient-based magnetostrictive layer with a change in saturation magnetization along the thickness direction. The presence of a gradient-based magnetostrictive layer generates an internal magnetic potential, leading to self-biased behavior (4). Our original and unique approach lies in the deposition of advanced intermetallic compounds with high magnetostrictive properties in the form of FeRh, galfenol, Ni-Mn-In Heusler alloy, LaFeSi, FeCo, and FeNi on the piezoelectric substrate and developing an epoxy-free ME composite-based WPT mechanism for AIMDs. A significant advantage of the ME-based WPT mechanism is its operation in the frequency range of tens of Hz to a few kHz, unlike the electromagnetic induction-based counterparts that operate in a few hundred kHz to MHz range and pose health issues owing to high specific absorption rate (SAR). Thus, this research aims to solve this persistent challenge by developing a prototype of ME-based wirelessly chargeable AIMD.

(1). Joung, Y.H., 2013. Development of implantable medical devices: from an engineering perspective. *International neurourology journal*, *17*(3), p.98.
(2). C.W. Nan, 2008. Multiferroic magnetoelectric composites: Historical perspective, status, and future directions. *Journal of applied physics*, *103*(3).
(3). Kumar, A. and Arockiarajan, A., 2022. Epoxy-free fabrication techniques for layered/2-2 magnetoelectric composite: a review. *Smart Materials and Structures*, *31*(8), p.083001.
(4). J.V. Mantese et al., 2005. Magnetization-graded ferromagnets: The magnetic analogs of semiconductor junction elements. *Applied Physics Letters*, *87*(8).

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