A green magnetic cooling device built using upcycled NdFeB magnets

Dimitri Benke[1], Jonas Wortmann[1], Marc Pabst[1], Tino Gottschall[1], Iliya Radulov[1], Konstantin Skokov[1], Oliver Gutfleisch[1, 2]
Davide Prosperi[3], Alex Bevan[3], Stephen Dove[3], Gojmir Furlan[3], Catalina Tudor[3], Peter Afiuny[3], Miha Zakotnik[3]
1 Material Science, Functional Materials, Technische Universität Darmstadt, Germany
2 Fraunhofer Project Group Materials Recycling and Resource Strategies IWKS Hanau, Germany
3 Urban Mining Company, USA

Magnetocaloric devices hold the potential to satisfy the rising demand for cooling in the future. One remaining challenge is to reduce the high ecological footprint of the permanent magnets driving the magnetic cooling cycle. Existing devices use neodymium-iron-boron (NdFeB)-type permanent magnets, which account for more than 50% of the ecological footprint of the appliance. To overcome this hurdle, TU Darmstadt and Urban Mining Company have built the first working magnetocaloric device that uses recycled NdFeB as a magnetic field source. Coupling this with optimisation of the magnets and their geometry, it is possible to further reduce the ecological footprint. Together, these two approaches help to position magnetic cooling as a realistic and sustainable cooling technology.

Introduction

Human activity is steadily warming the planet. Despite being in the midst of a 'refrigeration revolution' there are increasing demands for cooling [1]. Indeed cooling is expected to outpace global demand for heating by 2070 [2] (Figure 1). Cooling could significantly add to climate change unless it is carefully managed. To tackle this problem, better cooling technologies that are more energy efficient than the widely used gas-compression system, must be investigated.

Magnetocaloric and permanent magnet materials are key components for energy conversion technologies that hold a possible answer to more efficient cooling [3, 4]. The Functional Materials (FM) research group, led by Professor Oliver Gutfleisch in Darmstadt, has been investigating both alloys types for several years (www.mawi.tu-darmstadt.de/fm/funktionale_materialien).

The principle behind magnetic cooling is the so called 'magnetocaloric effect' (MCE). MCE is the temperature rise that occurs in a certain group of materials when a magnetic field is applied to them. At this increased temperature, it is possible to expel the heat and, after removal of the magnetic field, the material is subsequently colder than at the start of the cycle (Figure 2). This makes it possible to build a cooling device which operates without a compressor. In addition, devices relying on MCE for cooling do not require coolants that often display a potential to trap solar radiation that is many tens or even hundreds of times greater than an equivalent volume of CO_2.

However, magnetocaloric technology comes with its own challenges; the materials that show the greatest heating effect during MCE are based on the rare-earth element gadolinium; this magnetocaloric 'benchmark' material shows an isothermal entropy change of ΔS_m = 3 J / kg K and an adiabatic temperature change of ΔT_{ad} = 3 K in magnetic field change of $\mu_0 H$ =1 Tesla. Gadolinium occurs in low abundance in natural ores, and is mixed together with many other elements. It is therefore predicted to become more expensive if global demand substantially increased.

In addition, the high-energy field needed for efficient magnet cooling is usually provided by neodymium iron boron (NdFeB) based magnets which contain rare-earth (RE) elements like neodymium and dysprosium. The environmental costs of mining rare-earth have been well documented [5-6]. These costs mean that a conventional approach to magnetic cooling would result in a larger ecological footprint than that of vapor-compression cooling. Indeed, NdFeB magnets account for more than 50% of the total ecological footprint of a magnetic refrigerator [7]. To solve this problem, FM is developing new eco-friendly magnetocaloric materials and devices and have partnered with Fraunhofer Project Group Materials Recycling and Resource Strategies IWKS and Urban Mining Company (UMC), who both specialise in the recycling of NdFeB [7-13].

Upcycling magnetic material

Production of NdFeB magnets from 'virgin' elements derived from mining creates is environmentally damaging; one ton of refined rare-earth creates 75 m^3 (tons) of acidic waste water, one ton of low-level radioactive waste and releases 10 tons of CO_2 [6]. At the same time OEMs are not willing to pay for sustainable mining of REs.

A response to this dilemma is to create technologies to keep reusing the REs already extracted from the ground. Lead by Dr Miha Zakotnik, Urban Mining Company has obtained funding

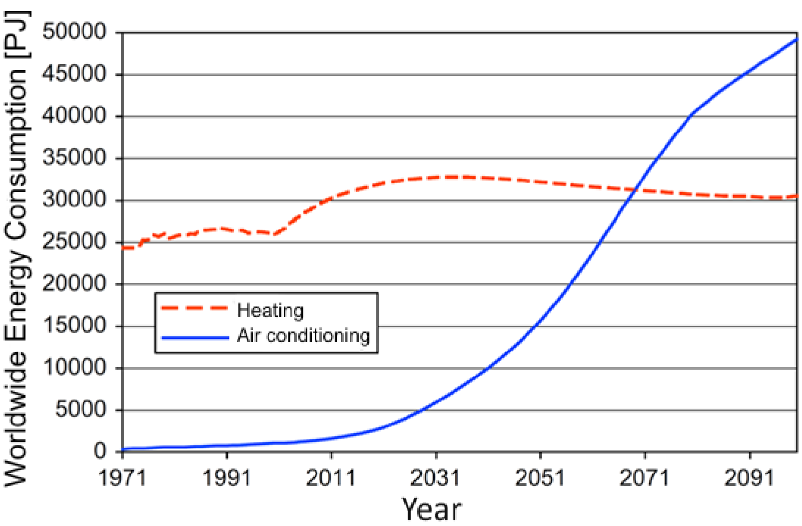

Figure 1 Predicted global energy demand for cooling and heating [2].

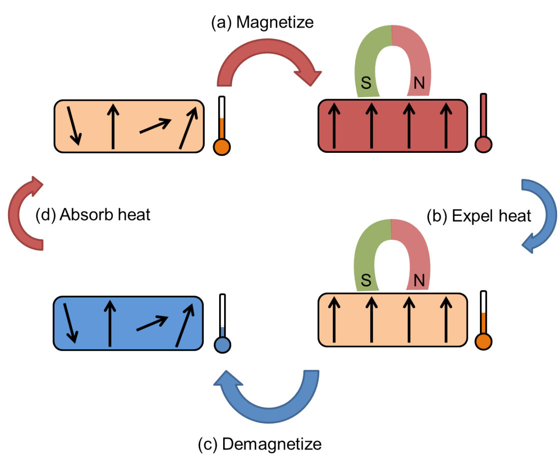

Figure 2 The 4-step magnetic cooling cycle [4].

to build an NdFeB recycling plant and a research center in Austin, Texas (see www.urbanminingco.com). Lead by Prof Oliver Gutfleisch, Fraunhofer Project Group Materials Recycling and Resource Strategies IWKS has built a pilot plant in Hanau (www.iwks.fraunhofer.de).

Recycling NdFeB magnets is more sustainable because it eliminates the environmentally damaging aspects of production; including ore mining, acid leaching, and solvent extraction. The problem with merely recycling is that the magnetic properties of the NdFeB material gradually decrease with each cycle of reuse; as oxidation and contamination take their toll. This limits the potential of a system that merely retains the NdFeB materials' original magnetic properties.

UMC's Magnet-to-Magnet (M2M™) upcycling process, discussed herein, showcases how scrap NdFeB-based magnets can be reused and their physical and magnetic properties maintained or even specifically enhanced. This makes the process powerful; because magnets can now realistically be recycled many times using M2M™.

Briefly, NdFeB is harvested from MRI machines, hard disk-drives, electric motors, or loudspeakers. The waste NdFeB and a proprietary alloy are then mixed and the two materials milled into very fine powders. The two mixed powders are then pressed into loose block shapes in a mould under enormous pressure in a magnetic field (Figure 3). During this stage, each tiny grain of magnetic crystal orientates itself in the magnetic field so that all the grains are aligned. These loose blocks are then given a series of heat treatments that allows the proprietary alloy to coat and glue the particles of the magnetic alloy together (see Figure 3). Fully dense blocks of NdFeB made by M2M™ have:

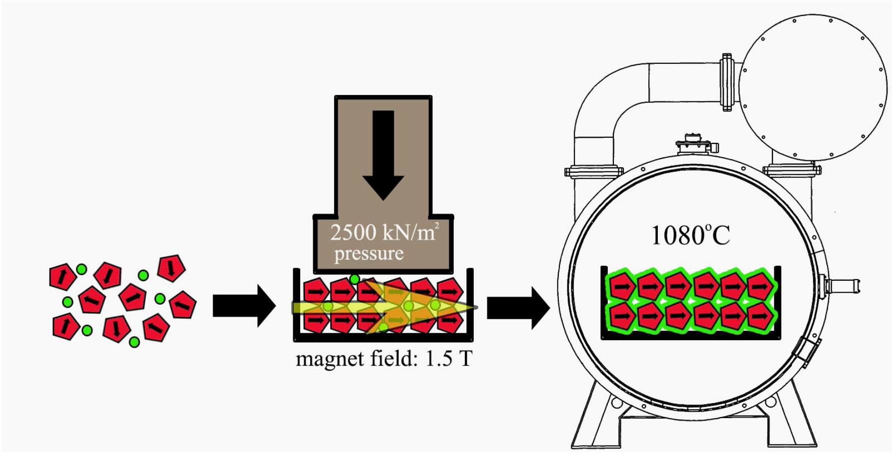

Figure 3 The Magnet to Magnet recycling system [9]. Waste NdFeB is depicted in red and the proprietary alloy in green.

- The same or better magnetic properties as starting materials; properties can be tailored to customer requirements.
- Better resistance to high temperatures; all NdFeBs lose magnetic performance at higher temperatures. The upcycled magnets show improved temperature coefficients.
- Better resistance to corrosion; NdFeB type magnets are very susceptible to attack by water and air and particularly the grain boundary phase can be made chemically more noble.

The M2M™ process is not confined to a laboratory but has been tested in real production facilities at industrial scale.

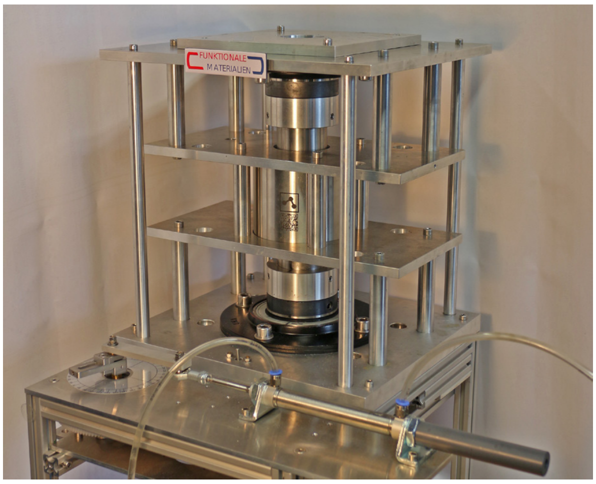

Figure 4 MCE demonstrator at TU Darmstadt in a testing rig.

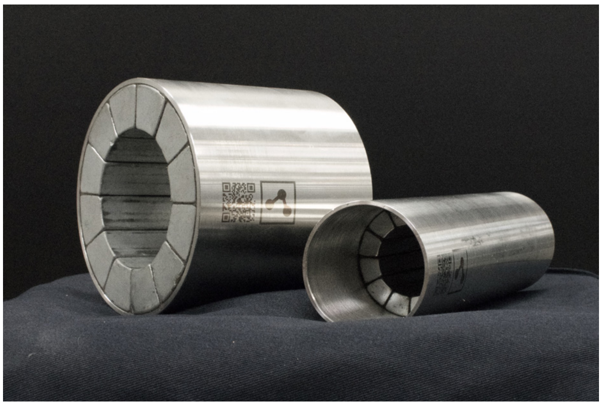

Figure 5 A magnetocaloric demonstrator consisting of nested Halbach arrays made from recycled permanent magnets.

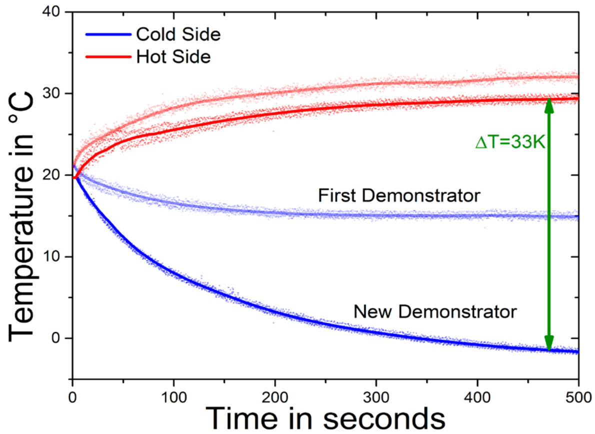

Figure 6 Build-up of the temperature span between cold and hot sides in the magnetic cooling device.

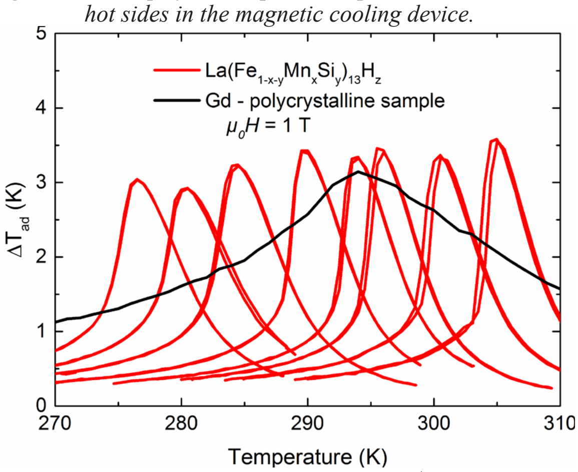

Figure 7 Adiabatic temperature change of ΔT_{ad} of Gd and $La(Fe_{1-x}Mn_xSi_y)_{13}H_z$ in magnetic field change of $\mu_0 H = 1$ T. The Mn content allows precise tuning of the working temperature and decreases here from left to right.

In addition, independent work by Purdue University has demonstrated that the M2M™ process utilises only 50% of the energy required by traditional manufacture; this drops to even further if mining is included. CO_2 emissions are therefore reduced by around 10 tons for every ton of recycled magnets produced. Hence recycled magnets have a greatly reduced environmental footprint compared to conventionally manufactured NdFeBs.

Magnetic cooling array

To prove the viability of recycled magnets, FM and UMC have developed the first prototype magnetocaloric cooling engine (Figure 4) that uses recycled permanent magnets (see Figure 5). In this device, the geometry of the magnetic assembly was optimised such that the amount of magnetic material required was reduced whilst also enhancing performance.

FM and UMC used the M2M™ process to produce customised magnets for a magnetic cooling device. The magnets were shaped into the arrays shown in Figure 4 and coated with an anticorrosion layer.

Magnetic refrigeration

The performance of the upcycled Halbach array was investigated in our demonstrator by implementing a powder bed regenerator made from Gadolinium spheres that is put into the active volume of the magnetic array. Using this array the resulting temperature span (Figure 6) can reach 33 °C, exceeding the first demonstrator by 16 °C while significantly decreasing the amount of permanent magnets used in the device. Also the volume which is exposed to the magnetic field change is larger and so a longer regenerator can be used, resulting in a further increase in thermal span. These developments together mean that this demonstrator can achieve the amount of cooling that is necessary for an actual product. Recent investigations show that our early stage of development already provides a cooling power of up to 76 W / kg which is in the middle range of power compared to similar machines.

We went one step further and replaced Gd with abundant and non-toxic $La(Fe,Si)_{13}$-type compounds which can provide even larger relative cooling power (ΔS_m = 10 J / kg K and ΔT_{ad} = 3.5 K in $\mu_0 H$ =1 T, see Figure 7). Its inherent brittleness we overcame with our patented metal bonding process [14] and the composite magnetocaloric materials can be shaped in heat exchangers with planar channel and / or porous body geometry [15].

In summary, we demonstrated that by combining resource efficient material development for the magnetic refrigerant, upcycling of permanent magnets and materials and device building expertise, TU Darmstadt and Urban Mining built an optimised magnetic cooling device that has a better performance and a lower ecological footprint than former conventional cooling devices.

References

[1] R Gauss, G Homm, O Gutfleisch, *The resource basis of magnetic refrigeration*, J of Industrial Ecology, DOI: 101111/jiec12488 (2016)

[2] M Isaac and D P van Vuuren (2009) *Modeling global residential sector energy demand for heating and air conditioning in the context of climate change*, Energy Policy 37(2): 507–521

[3] R Gauss and O Gutfleisch, *Magnetische Materialien - Schlüsselkomponenten für neue Energietechnologien*, in Rohstoffwirtschaft und gesellschaftliche Entwicklung, ed P Kausch und J Matschullat, März 2016, Springer Spektrum Heidelberg, Springer-Verlag GmbH, ISBN 978-3-662-48854-6, pp 99-118

[4] O Gutfleisch, JP Liu, M Willard, E Brück, C Chen, SG Shankar, *Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient (review)*, Advanced Materials 23 (2011) 821–842

[5] M Zakotnik, C O Tudor, L Talens Peiro, P Afiuny, R Skomski, G P Hatch, Environmental Technology & Innovation Vol 5, pp 117- 126 (2016)

[6] Keith Bradsher, *Mitsubishi quietly cleans up its rare-earth refinery*, New York Times, 9 March 2011, p B4

[7] R Gauß, O Diehl, E Brouwer, A Buckow, K Güth, O Gutfleisch, Verfahren zum, *Recycling von seltenerdhaltigen Permanentmagneten*, Chem Ing Tech 87 no 11 (2015) 1477-1485, DOI: 101002/cite201500061

[8] O Gutfleisch, K Güth, TG Woodcock, L Schultz, *Recycling Used Nd-Fe-B Sintered Magnets via a Hydrogen-Based Route to Produce Anisotropic, Resin Bonded Magnets*, Advanced Energy Materials 3 (2013) 151-155

[9] M Zakotnik and C O Tudor, *Commercial-scale recycling of NdFeB-type magnets with grain boundary modification yields products with 'designer properties' that exceed those of starting*

materials, Waste Management, Volume 44, Pages 48-54, October 2015
[10] US patent 14/307,267
[11] J Hongyue, P Afiuny, T McIntyre, Y Yih, J W Sutherland (2016) LCA, *Analysis for magnet to magnet recycling*, Procedia CIRP, 48, 45-50
[12] A Lixandru, I Poenaru, K Güth, R Gauß, O Gutfleisch, *A systematic study of HDDR processing conditions for the recycling of end-of-life Nd-Fe-B magnets*, J of Alloys and Compounds 724 (2017) 51-61
[13] A Lixandru, P Venkatesan, C Jönsson, I Poenaru, B Hall, Y Yang, A Walton, K Güth, R Gauß, O Gutfleisch, *Identification and recovery of rare-earth permanent magnets from waste electrical and electronic equipment*, Waste Management, 68 (2017) 482
[14] I A Radulov, K P Skokov, T Gottschall, M Kuz'min, O Gutfleisch, *Preparation process of a magnetocaloric powder and a composite with magnetocaloric powder*, German patent application 10 2015 119 1032, 6 November 2015
[15] I A Radulov, D Y Karpenkov, K P Skokov, A Y Karpenkov, T Braun, V Brabänder, T Gottschall, M Pabst, B Stoll, O Gutfleisch, Acta Materialia 127 (2017) 389

Determination of the cutting influence on soft magnetic material and its effect in electrical machines

Part 1: Spatial distribution of soft magnetic properties

Mathias Lindner, IAV GmbH, Auer Str. 54, 09366 Stollberg, Germany (mathias.lindner@iav.de)
Marc Hauck (belgradista@yahoo.de)

The influence of cutting on the soft magnetic properties of electrical steel sheets is a well-known effect and has been demonstrated in numerous studies. However, most findings are hardly applicable in the calculation of electrical machines because of complex geometries, unaddressed impacts on the magnetization curve as well as a lack of data due to strong dependencies on the material and the manufacturing method. This work suggests a simple approach, based on standardized tests of soft magnetic properties in ring specimen, to identify material characteristics depending on the cutting edge distance. Such a representation is much more suitable for magnetic circuit calculations than the common averaged probe behaviour. In subsequent articles, the procedure of core calculation will be demonstrated on two methods: the novel analytical sector model and the numerical layer model. Measurements on different core geometries will proof the capability of such approaches. Finally, an automotive induction machine will be simulated in a transient FEA within JMAG® considering the cutting influence and verified against test data.

Introduction

Electrical machines with soft magnetic cores are established since the 19th century. Since those years the vast majority of cores is manufactured from iron sheets in order to suppress eddy currents and power loss. For this process the iron alloy becomes melted, casted, rolled, surface coated and coiled-up at the steel maker. Afterwards, the machine manufacturer cuts the sheets to the desired cross-sectional geometry, axially compresses, stacks and joins them, sometimes grinds the resulting surface and presses the core into a case or onto a shaft. During all those steps mechanical and thermal stress are induced into the soft magnetic material resulting in degraded magnetic properties. However, the biggest influence usually results from the cutting process [1], [2]. The cutting can be done by multiple methods. Stamping (resp. shear cutting) and laser cutting are the dominant ones in modern production processes. In contrast to some other approaches, as waterjet cutting or eroding, one of their biggest drawbacks is the strong material degradation along the cutting edges [3].

Nevertheless, with conventional standard motors the cutting effect is not a huge issue. Those machines typically feature generous magnetic cross-sections, since high efficiencies, low harmonics and low priced materials are in main focus. Thus, the proportion of degraded edge material is relatively low. Furthermore, the cutting influence is empirically known, the calculations are well calibratable on measurements.

In automotive applications different circumstances are given. With a developing e-mobility more serious requirements arise for electrical traction machines. Higher performances, smaller dimensions and more pole-pairs lead to narrow magnetic flux paths and a high proportion of degraded edge material. Additionally, most applications can not rely on long-term series experiences and with that an empirically corrected calculation. In contrast, a low time-to-market demands only few prototypes and accurate calculation results in the first place. Another issue is the difference in control method. Standard motors often run in speed control with a measured feedback signal and an underlying current control loop. Torque drops due to material degradation are compensated by the control loop. Traction motors however run in torque control with a current feedback only and an open-loop torque prediction. Nevertheless, very low torque deviations

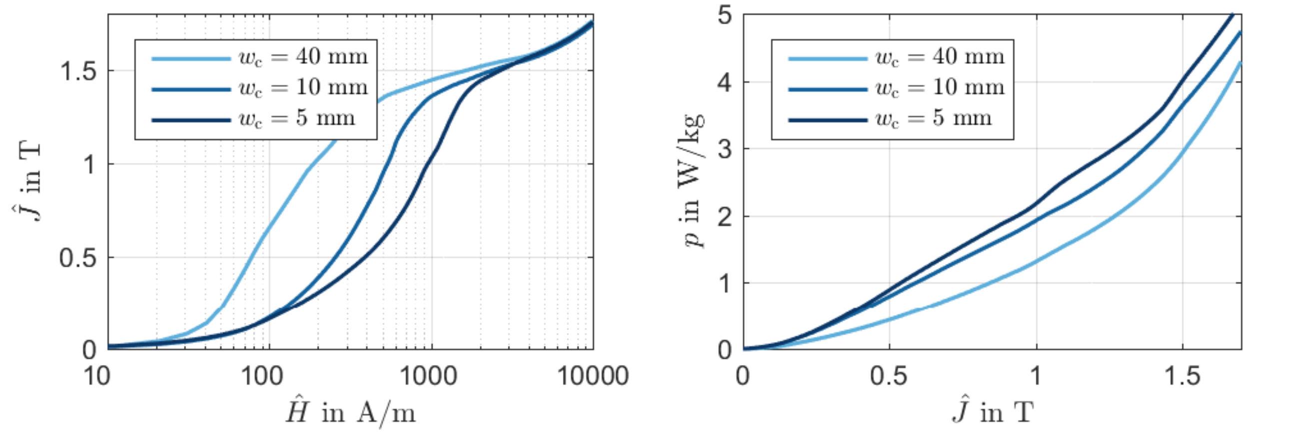

Figure 1 Magnetisation curves and specific core loss in ring specimen of different core widths. Measured on laser-cut M270-35A material at 50 Hz.