Institution: University of Exeter		
Unit of Assessment: UoA 9 Physics		
Title of case study: Reducing the requirement for rare earth metals in high performance magnets for hybrid cars		
Period when the underpinning research was undertaken: 2009-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Professor Gino Hrkac	**Role(s) (e.g. job title):** Personal Chair in Applied theoretical and computational solid-state physics	**Period(s) employed by submitting HEI:** 2012 - Present
Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

A key challenge for manufacturers has been to reduce the requirements for rare earth metals such as neodymium, dysprosium and terbium in the magnets used in electric vehicles as they are expensive and difficult to obtain. Working collaboratively with Toyota and a range of other partners in the EU and Japan, Professor Hrkac's group at the University of Exeter has played a crucial role in the development of magnetic materials which require significantly lower levels of rare earth metals. These materials have been employed in an estimated 6.5 million hybrid vehicles produced by Toyota since 2016, **reducing consumption of rare earth elements by 450 tonnes**, with associated reductions in environmental damage. In addition, the use of the new magnetic materials has contributed to efficiency gains compared to standard hybrid vehicles which have **reduced carbon dioxide emissions from Toyota hybrid vehicles by 11 million tonnes** worldwide since 2016. Professor Hrkac's work also contributed to **cost savings of $108M in production and maintenance costs for hybrid cars** which enhanced job stability at Toyota and generated savings for consumers.

2. Underpinning research

Prof. Hrkac's research group focuses on computational and theoretical magnetism; specifically, the development of models to investigate the complex interface effects on an atomistic scale in nano- and micro-scale materials. Magnetic materials are formed from grains with a distinct magnetic structure. For most applications it is the overall magnetic material properties which are important; these are determined by the interaction between grains, so interfaces and grain boundaries ultimately determine the useful magnetic properties such as the external magnetic field, magnetic flux and magnetic energy density.

Supported by a Royal Society University Research Fellowship (2009-2014), Prof. Hrkac developed *ab initio* simulations of atomic structures and solid-state molecular dynamics to model the behaviour of amorphous and crystalline grain boundaries in neodymium (NdFeB) magnets. In this early work it was shown that for $Nd_2Fe_{14}B$ magnets, containing neodymium (Nd) but without rare earth element dysprosium (Dy), the coercivity was highly dependent upon local anisotropy profiles at grain boundaries **[3.1, 3.2]**. The significance of grain boundaries, highlighted by Prof Hrkac's work, was central to future magnet development. Further research highlighted the importance of Nd-oxides **[3.3-3.5]** and the potential for using structured magnetic materials **[3.6]**.

One of the key challenges in designing high efficiency magnets for use in hybrid and electric vehicles is that they must be able to operate at high temperature, whilst maintaining or improving the efficiency of the electric motors they are used to drive. When neodymium magnets are used at high temperatures, such as in automotive applications, other rare earth elements such as dysprosium or terbium (Tb) are generally added to increase high-temperature coercivity. However, these are rare and expensive metals found in locations with high geopolitical risks. Because of this, considerable efforts have been made to develop magnets that do not use these metals. Although production volumes of neodymium are relatively high amongst rare earth metals, there are concerns that shortages will develop as electric vehicles become increasingly popular in the future. To overcome the issues regarding cost and availability of rare earth metals, Toyota established its Magnetic Materials for High-Efficiency Motors (MagHEM) project in 2012, with the aim of developing technologies that would initially eliminate the use of terbium and dysprosium, and in the longer-term reduce the amount of neodymium used, whilst maintaining the high levels of heat resistance and minimizing loss of coercivity.

As a result of his expertise, Prof. Hrkac played a leading role in the MagHEM project **[5.1]**, providing all the interface materials modelling, with colleagues in Europe and Japan responsible for other elements such as fabrication and testing. The first phase of the research led to the development of magnets requiring very low levels of dysprosium/terbium, which were used by Toyota in its 4th generation Prius, released in December 2015 (Figure 1) **[5.2]**.

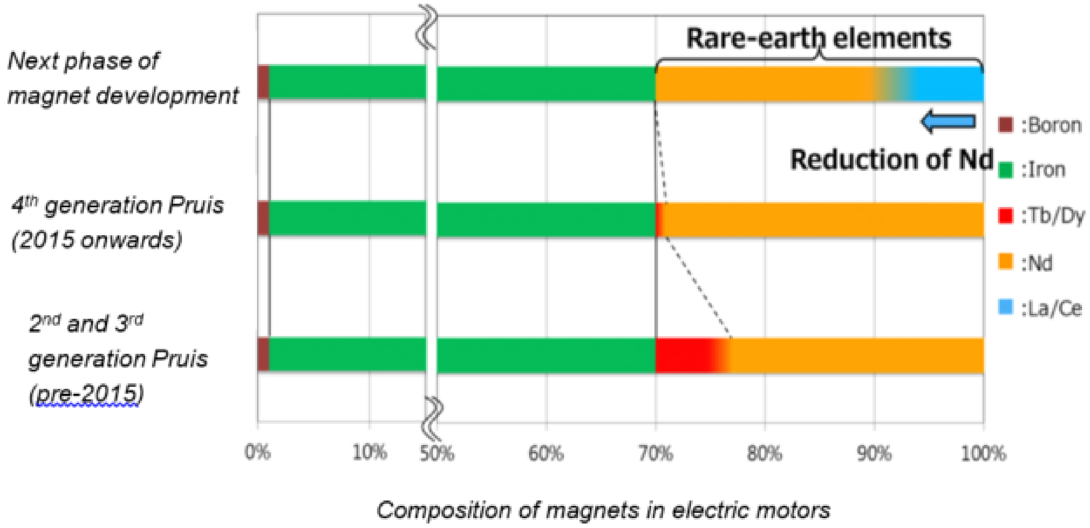

Figure 1: Reduction of Tb/Dy from 3rd generation to 4th generation Prius. Figure adapted from ***[5.2].***

The next phase of the work focused on reducing the neodymium content required, through the combination of three new technologies, all of which were dependent on Prof Hrkac's modelling:

I. Magnetic grain refinement – high coercivity can be retained at high temperatures through the reduction of the size of the magnet grains to one-tenth or less of those found in conventional neodymium magnets and the enlargement of the grain boundary area. This is shown in Figure 2 **[5.2]**, where the performance of the neodymium-reduced magnet (solid red line) is seen to out-perform the conventional neodymium magnet (black line, squares) at higher temperatures. Moreover, simply reducing the amount of neodymium, without changing the grain size significantly, reduces the magnet performance (black line, diamonds);

II. Two-layered high performance grain surface – neodymium can be used more efficiently by increasing its concentration on the surface of the magnet grains and decreasing the concentration in the grain core, which results in a reduction in the overall amount of neodymium required whilst maintaining high levels of coercivity;

III. A specific alloying ratio of lanthanum and cerium – normally, alloying neodymium with lanthanum and cerium results in a significant decline in its key properties of heat resistance and coercivity. However, by evaluating a range of alloy ratios, Toyota identified a specific ratio at which the deterioration of properties was minimised.

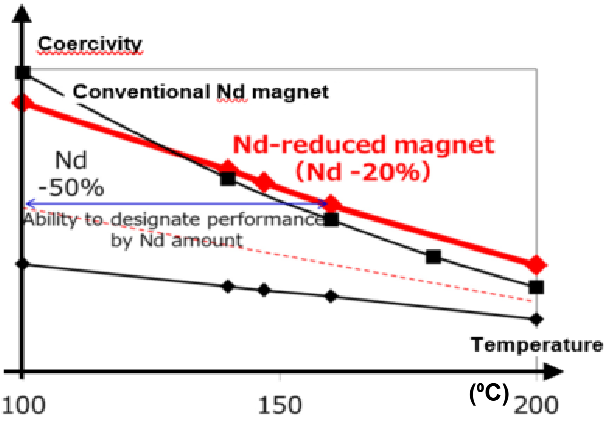

Figure 2: Variation in coercivity with temperature for four different magnetic materials. These are: conventional Nd magnetic material (black line, squares); 20% reduced Nd using magnetic grain refinement (red solid line, squares); 50% reduced Nd using magnetic grain refinement (red dashed line); Nd-reduced magnet without magnetic grain refinement (black line, diamonds). Adapted from ***[5.2].***

This programme of research and development led to the production by Toyota in 2018 of the world's first neodymium-reduced, heat resistant magnet, which uses no terbium or dysprosium (Figure 2). This new magnet has a wide range of potential applications in motors that require relatively high output; Toyota indicated that the magnets would be used in electric power steering motors for cars in the early 2020s, with plans for further development to enable their application in high performance electrified vehicle drive motors within the next 10 years (i.e. by 2028). **[5.2]**

3. References to the research

[3.1] T. G. Woodcock, Y. Zhang, **G. Hrkac**, G. Ciuta, N. M. Dempsey, T. Schrefl, O. Gutfleisch, and D. Givord, *"Understanding the microstructure and coercivity of high performance NdFeB-based magnets,"* Scr. Mater. 67, 536–541 (2012). DOI: 10.1016/j.scriptamat.2012.05.038

[3.2] S. Bance, H. Oezelt, T. Schrefl, G. Ciuta, N. M. Dempsey, D. Givord, M. Winklhofer, **G. Hrkac**, G. Zimanyi, O. Gutfleisch, T. G. Woodcock, T. Shoji, M. Yano, A. Kato, and A. Manabe, *"Influence of defect thickness on the angular dependence of coercivity in rare-earth permanent magnets,"* Appl. Phys. Lett. 104, 182408 (2014). DOI: 10.1063/1.4876451

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[3.5] S. Bance, B. Seebacher, T. Schrefl, L. Exl, M. Winklhofer, **G. Hrkac**, G. Zimanyi, T. Shoji, M. Yano, N. Sakuma, M. Ito, A. Kato, and A. Manabe, *"Grain-size dependent demagnetizing factors in permanent magnets,"* J. Appl. Phys. 116, 233903 (2014). DOI: 10.1063/1.4904854

[3.6] S. Bance, H. Oezelt, T. Schrefl, M. Winklhofer, **G. Hrkac**, G. Zimanyi, O. Gutfleisch, R. F. L. Evans, R. W. Chantrell, T. Shoji, M. Yano, N. Sakuma, A. Kato, and A. Manabe, *"High energy product in Battenberg structured magnets,"* Appl. Phys. Lett. 105, 192401 (2014). DOI: 10.1063/1.4897645

4. Details of the impact

Electric vehicles are an important element in meeting global goals on climate change, with hybrid vehicles fulfilling a key role in the transition period whilst charging infrastructures are put in place. This was re-emphasised in February 2020 when the UK government announced a ban on petrol and diesel cars by 2030. In 2019, just over 5.4 million hybrid and electric cars were sold worldwide, with a total market value of ~$160Bn. The market value is forecast to increase to almost $540Bn by 2024 **[5.3]**. Toyota Motor Corporation is a leading manufacturer of hybrid electric cars. In 2019 over 99.9% of Toyota's electric vehicle sales were hybrids **[5.2]**. In the same year, Toyota sold 1.9 million hybrid vehicles worldwide (35% of the total market) **[5.2]**.

A key challenge for manufacturers has been to reduce the requirements for rare earth metals such as neodymium, dysprosium and terbium in the magnets used in electric vehicles, as they are expensive and difficult to obtain. As a key member of the MagHEM project, Prof Hrkac's group at the University of Exeter has played a crucial role in the development of magnets which require significantly lower levels of rare earth metals, resulting in the major environmental and economic benefits detailed below and summarised in Figure 3.

Decreased environmental damage through reduced use of rare earth metals – reduction of 450 tonnes dysprosium since 2016: The mining of rare earth metals used in conventional hybrid motors negatively impacts the environment and surrounding communities, creating toxic waste and damaging the surrounding environment **[5.9]**. Furthermore, global supplies are limited, and demand is exceeding supply, with reserves expected to run out in the next five years. By using the newly developed low-dysprosium magnet in its 4th generation Prius and other hybrid electric vehicles since 2016, Toyota has reduced consumption of dysprosium by an estimated 450 tonnes*, reducing the carbon footprint and the environmental damage associated with production of these vehicles. In the short term, this work has freed up the limited dysprosium supplies for use in other vital applications such as wind turbines. In the longer term, it has made a lasting difference by demonstrating that it is possible to use alternatives to the rare earth metals traditionally used in electric vehicles.

In addition, by bringing magnet production in-house during the joint development project, Toyota has been able to instigate a recall programme aimed at recycling electromotors and recovering rare earth materials to further limit environmental impact in the future **[5.10]**.

> ** The estimated 450 tonnes saving is calculated from an 84% reduction (Figure 1) in dysprosium, i.e. from 83g per car [see Hoenderdaal, et al. (2013), Energy Vol. 49, Pages 344-355] to 13g per car. Scaling the saving by 6.5 million cars produced since 2016 gives the estimated figure.*

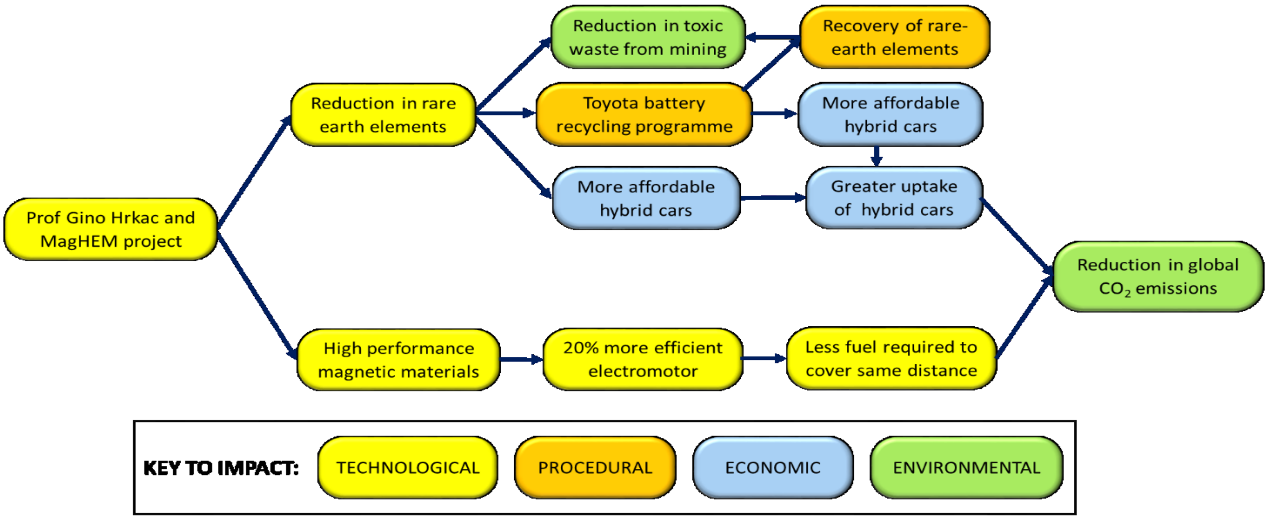

Figure 3: Summary of impacts from new magnetic materials in hybrid cars.

Decreased CO_2 emissions due to increased fuel efficiency – 11 million tonnes less CO_2 since 2016: The use of newly developed magnetic materials contributed to reductions in the size of the motor (35%) leading to improvements in motor efficiency of 20% **[5.4]**. Together with other design refinements, this enabled Toyota to reduce CO_2 emissions in its 4th generation Prius by 21% **[5.2].** Assuming similar levels of efficiency savings on their other hybrid vehicles, this has led to estimated savings in carbon dioxide emissions of 11 million tonnes since 2016. This saving in CO_2 is equivalent to the average yearly emission associated with more than 1.8 million homes **[5.5].** Efficiency savings from these new magnetic materials are also projected to be more significant in the future in applications such as robotics and fully electric cars **[5.1]**.

Decreased production costs leading to increased confidence in the market, greater job stability at Toyota and savings for consumers*:* The reduced use of rare earth metals results in significant reductions in production costs: for example, the decreased levels of dysprosium used since 2016 has resulted in estimated cost savings of $108M (estimated from the 450 tonnes saving, see above, and the $240/kg market value of dysprosium **[5.6]).** This will translate into cheaper access to electric vehicles for consumers as well as increased confidence for automotive manufacturers that they can acquire the resources needed for future production of electric vehicles. Furthermore, the newly developed magnets have improved durability, leading to reduced maintenance costs over the lifetime of the vehicle, another positive benefit for consumers. Toyota has benefitted in other ways as well: by moving the development and production of magnets in-house (Prof Hrkac has also worked closely with Toyota on this project and has trained Toyota engineers in simulation techniques); it has acquired intellectual property rights in this area **[5.7];**

and has security over future production. This has contributed to job stability and sustainability at the company.

Wider implications for neodymium reduced magnets: This case study has focused on the impacts that have been delivered to date by Toyota through the use of improved, low-dysprosium magnets in its hybrid and electric vehicles (Figure 2). However, in 2018 and as noted above, further development based on Prof Hrkac's research has also led to the production by Toyota of the world's first neodymium-reduced, heat resistant magnet, which uses no terbium or dysprosium (Figure 1). Toyota indicated that the magnets would be used in electric power steering for cars in the early 2020s, with plans for further development to enable their application in high performance electrified vehicle drive motors within the next 10 years (i.e. by 2028) **[5.2]**. In addition to applications in hybrid and electric vehicles, the magnets will have wider potential use in robots and other household appliances, a huge and growing market: the household robots market is expected to grow from $3.3Bn in 2019 to $9.1Bn by 2024 **[5.8].**

Summary statement: Working collaboratively with Toyota and a range of other partners in the EU and Japan, Prof Hrkac has played a crucial role in modelling and development of new magnetic materials which require significantly lower levels of rare earth metals. These novel materials have been employed in an estimated 6.5 million hybrid vehicles produced by Toyota since 2016. This has reduced the consumption of rare earth elements by 450 tonnes, with associated reductions in environmental damage, reduced CO_2 emissions from Toyota hybrid vehicles by 11 million tonnes and contributed to efficiency gains which have led to cost savings of $108M

5. Sources to corroborate the impact

[5.1] Dr Kato, A., Grand Master, Advanced Materials Engineering Div. Toyota Motor Corporation (03/03/2020) *Private comment: REF Impact Case Study Exeter University statement about our work* [email]. Available as PDF.

[5.2] Toyota Press releases: Toyota Media (20th February 2018) *Toyota develops new magnet for electric motors, aiming for 50 percent reduction in use of critical rare-earth elements* [online] Available as PDF. Global Toyota, *Sale, Production, and Export Results* [online] Available as PDF. Toyota Blog (17th November 2015) 2016 Toyota Prius MPG and CO2 revealed [online] Available as PDF.

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[5.6] Statista (2019) *Rare Earths*. [online] Available as PDF.

[5.7] Sakuma et al. (2016) *Production method of rare earth magnet*. US Patent US9520230B2. Available as PDF.

[5.8] Markets and Markets (June 2019) *Household Robots Market by Offering (Products, Services), Type (Domestic, Entertainment & Leisure), Application (Vacuuming, Lawn Mowing, Companionship, Elderly and Handicap Assistance, Robot Toys and Hobby Systems), and Geography - Global Forecast to 2024* [online] Available as PDF.

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