

Recycling of rare earth permanent magnets for advanced electric drives - Overcoming the criticality and supply risk

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Abstract— Due to the transformation of the automotive industry to e-mobility a rising demand for rare earth permanent magnets for electric traction motors is expected. In this paper, an overview of the worldwide market of rare earth elements, permanent magnets and their supply will be given. To overcome the criticality and supply risks different recycling routes of permanent magnets will be reviewed. Results for recycled Nd-Fe-B sintered permanent magnets via hydrogen based powder metallurgical recycling will be discussed in detail.

Keywords— Nd-Fe-B; criticality; raw material; permanent magnets; recycling; e-mobility

I. INTRODUCTION

The transformation of the automotive industry to e-mobility is currently taking place and is accelerating. Most of the car manufacturers offer fully electric vehicles (or intend to in the near future) and hybrid vehicles. Reasons for this development are political restrictions aiming at a reduction of the CO₂ emissions as well as stricter regulations of urban environmental zones like driving bans for diesel motors in city centers in order to reduce harmful emissions. Also due to the general recognition that a green and eco-friendly energy production and mobility plays a more important role in public awareness, this transition is accelerated.

Due to their excellent magnetic properties, rare earth based permanent magnets (PM) like Nd-Fe-B play a key role in permanent magnet driven synchronous motors for hybrid and fully electric vehicles. Nd-Fe-B magnets are the hard magnetic materials with the highest energy densities (Fig. 1). Since the invention of Nd-Fe-B permanent magnets in 1983 [1] [2] the production processes of this material have undergone constant improvements to optimise properties.

Utilising their high coercivity and high energy density rare earth permanent magnets are also used in a wide range of applications e.g. communication and consumer electronics, loudspeakers, sensors, energy production (wind turbines) or e-bikes. In 2007 38 % of the produced Nd-Fe-B permanent

magnets were used in electric motors, while in 2012 43 % of the magnets were used for this application [3]. Besides the traction motor a huge amount of smaller motors for general functionality, comfort and safety are used in conventional vehicles, too.

Rare earth permanent magnet based motors have some important advantages to other electric motors like (1) higher efficiency, (2) higher power and torque density and (3) better dynamic performance [4]. Other advantages are less maintenance, higher reliability and longer lifetime. Compared to other hard magnetic materials the most important advantage of rare earth permanent magnets is their small size leading to a weight reduction of the motor. The schematic cylinders in Fig. 1 demonstrate the differences of the required magnet size for reaching the same magnetic stray field. For traction motors in electric vehicles a light construction is directly related to lower energy consumption and a higher range.

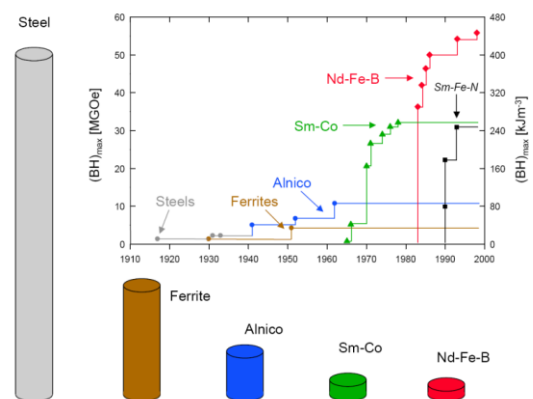


Fig. 1. Development of the energy density $(BH)_{\max}$ at room temperature for hard magnetic materials and presentation of different types of materials with comparable magnetic stray fields [5].

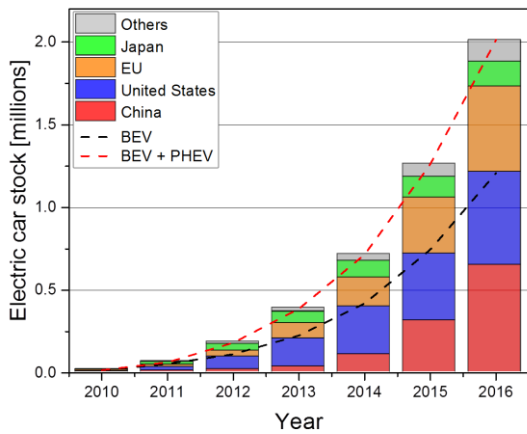


Fig. 2. Development of electric car stock from 2010 till 2016. Over the last six years a continuous increase in electric car stock is observed [6].

As a result of the transformation in the automotive sector to e-mobility the demand for rare earth permanent magnets for motor applications will further increase in the near future. Fig. 2 gives an overview of the market development from 2010 to 2016 for electric vehicles. In 2006 only 1690 electric vehicles (BEV: Battery Electric Vehicle and PHEV: Plug-in Hybrid Electric Vehicles) were sold or registered worldwide. Ten years later in 2016 the level of two million electric cars was exceeded. From 2014 to 2016 the market share of electric vehicles to all vehicles has doubled from 0.54 % to 1.1 %. [6].

Against this background it is important to know the supply reliability of the required resources (REE: rare earth elements) and to have an overview of the rare earth market. To overcome the criticality of these important raw materials metallurgical recycling processes can be used to create an alternative source for REE from scrap magnets.

II. CRITICALITY AND SUPPLY RISK OF RARE EARTHS

A. Geological availability and supply

The rare earth elements are a group of 17 elements and can be divided into Light Rare Earth Elements (LREE) with La, Ce, Pr, Nd, Pm, Sm, Eu, Gd and Heavy Rare Earth Elements (HREE) with Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc, Y. The most important elements for permanent magnet production are Pr, Nd, Sm, Tb, and Dy. Rare earth elements are relatively common in the Earth's crust, whereby discovered minable concentrations are only available in a small number of states [7]. The world reserves in 2016 amount to 120 million tons. The biggest reserves are located in China (44 million tons), Brazil and Vietnam (each 22 million tons) and Russia (18 million tons). In the same year the world mine production amounts to 126.000 tons. The biggest extractors are China (105.000 tons), Australia (14.000 tons) and Russia (3.000 tons) [8]. Fig. 3 illustrates the total mine production of rare

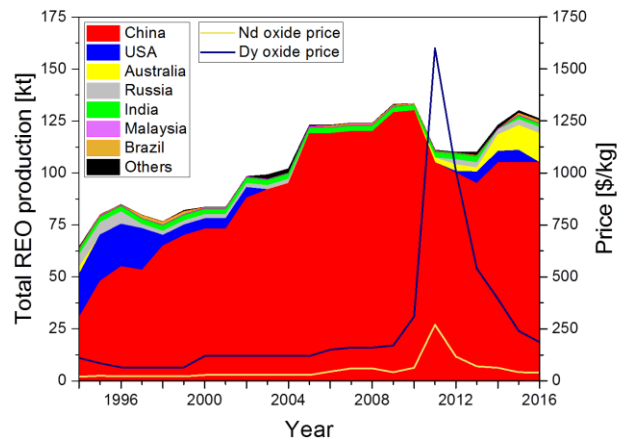


Fig. 3. Total mine production of REO and price development of Nd and Dy between 1994 and 2016. The market domination of China results in the so called rare earth crisis with a dramatic price increase in 2011 [9] [10].

earth oxide (REO) and prices of Nd and Dy from 1994 to 2016 [9] [10]. 83 % of the rare earths are actually mined in China, giving China a monopoly position on the world market. The price volatility for rare earths can be seen as a consequence of the Chinese monopoly. In 2011 China announced export quotas for rare earth elements. This caused a dramatic price increase (see Fig. 3) and resulted in the so called “rare earth crisis”. Due to the crisis different exploration for REE organized worldwide and the Mountain Pass mine in the US restarted the production of rare earth oxides after 10 years. In the years after the crisis the materials prices for REE decreased again and made the mining of rare earths difficult and unprofitable in western countries, like shown in the bankruptcy of Molycorp Inc. the operator of the Mountain Pass mine in 2015 [11]. In June 2017 Mountain Pass were sold for 20.5 million dollar to MP Mine Operations (MPMO) – a Chinese-led consortium [12].

The “Deutsche Rohstoffagentur” (DERA) classifies raw materials into three risk groups (group 1: *low*; group 2: *moderate*; group 3: *high*). In the actual report from 2016 [13] the REE are categorized into the highest risk group 3. For classification the Herfindahl-Hirschman-Index (HHI) and Worldwide Governance Indicators (WGI) are important. The WGI consist of six indicators like political stability and absence of violence or control of corruption. The HHI is defined as the sum of the squared share value of all market participants. If there is a monopoly on market, the HHI will be 1. In this study the HHI of mined REE is 0.79 and of refined REE 0.88 which indicates a highly concentrated market. The list of critical raw materials 2017 of the European Commission [14] also defines all REE as critical raw material. According to this study the main importers of REE to the European Union (EU) (average value from 2010 to 2014) were China (40 %), USA (34 %), and Russia (25 %). The dependence of the EU to imports of REE is given by 100 %.

Although the price volatility and big reserves in other countries the world market is still dominated by China. Reasons for the reluctance of mining rare earths in other

countries are the difficulty of ore processing, environmental regulations and possible environmental impacts.

B. Environmental impact of mining RE

In rare earth ores the oxides of the different elements are mixed with each other. Due to their similar chemical and physical properties a separation to the single REO is difficult. After ore mining and processing the REO has to be extracted with concentrated sulfuric acid followed by separation of the different rare earths according to their physical and chemical properties like solubility, partition coefficient, ion exchange coefficient or constant of complex formation. Due to the similarity of the properties the separation procedures have to be repeated several times [7]. These preparation processes causes significantly environmental impacts, due to the high amount of chemicals and energy needed for the separation [15].

For the conditioning of the RE containing ore a dry or wet fusion are established processes. The enrichment of REE through dry fusion takes place by mechanical processes. The ore is cracked, milled, sieved and suspended. For the suspension a high quantity of water is used, whereby the fine milled gangue can flush at the heap. The settling basins bear the risk of leakage of mixed mud that is often contaminated with radioactive elements like Thorium and Uranium. The more problematic process is the wet fusion, especially the in situ leaching of RE. Boreholes in mines with porous stone are filled with diluted sulphuric acid or a solution of ammonium sulfate. The advantage of this process is the avoidance of high amount of gangue, but a serious problem is the contamination of groundwater [7] [16].

Another environmental impact is caused by the mentioned radioactive elements Th and U which are often concentrated in RE deposits with quantities up to 700 ppm Th and 250 ppm U in the geographic dependence of the ore origin [15]. This is particularly critical with a very long half-life of $1.4 \cdot 10^{10}$ years. Due to strict environmental regulations these elements can complicate mining projects to a large extend. In cause of such regulations the Australian Lynas Corporation, which is the owner of Mount Weld mine, prepare their RE concentrates in Malaysia. [7] [17] [18].

Nowadays environmental impacts can be minimized with strict regulations and environmental-friendly technology to a very low level. A further decrease could be achieved through the use of recycled magnetic materials. Taking into account the whole lifetime of a rare earth based magnet from mining of the elements and production of the Nd-Fe-B product as well as its use and disposal about 90 % of total energy consumption is needed for the mining and refining of the elements. This includes the steps mining, beneficiation, extraction, separation, and reduction [15]. Moreover about 50 % of the material is lost in tailings during these processes. In circular economy End-of-Life products like scrap magnets can be used as sources for recycling, and hence reducing the impact of the mining and reeving on a product level. This smaller “environmental footprint” would be beneficial especially in the sector of e-mobility or renewable energies.

III. RECYCLING OF RE PERMANENT MAGNETS

Like illustrated in Fig. 4 the recycling process of permanent magnets can be divided into three different routes: (1) direct re-use of magnets, (2) recycling of permanent magnet alloys (functional recycling), and (3) the recovery of the REEs (elemental recycling) [19].

The direct re-use of scrap magnets may seem as the best solution in terms of ecology and economy. Due to aging processes during lifetime of the magnets, properties like alloy composition (impurities through oxidization) and characteristic magnetic values can change. For a direct re-use it is difficult to achieve specific magnetic properties which are required for the targeted application. This recycling route will be practicable only in individual cases [19] [20]. In addition a non-destructive dismantling of the less accessible magnets and the absence of irreversible damages, especially corrosion, are required. Furthermore for an easy dismantling a design for recycling of the e.g. traction motors is needed.

In terms of the elemental recycling of REEs, specific elements or chemical compounds are dissolved out of the magnet alloy and then used for established industrial routes or processes. Main research here focuses on pyro- and hydrometallurgical methods as well as gas phase extractions [19]. Hydrometallurgical methods like liquid-liquid extraction or selective precipitation, consume a lot of energy and large amounts of acids. Another possible route for element extraction is the so-called bioleaching process that uses the ability of microorganisms to selectively extract solids into solutions using natural metabolic processes. This process is already well established on large scale for the primary extraction of copper [21] [22].

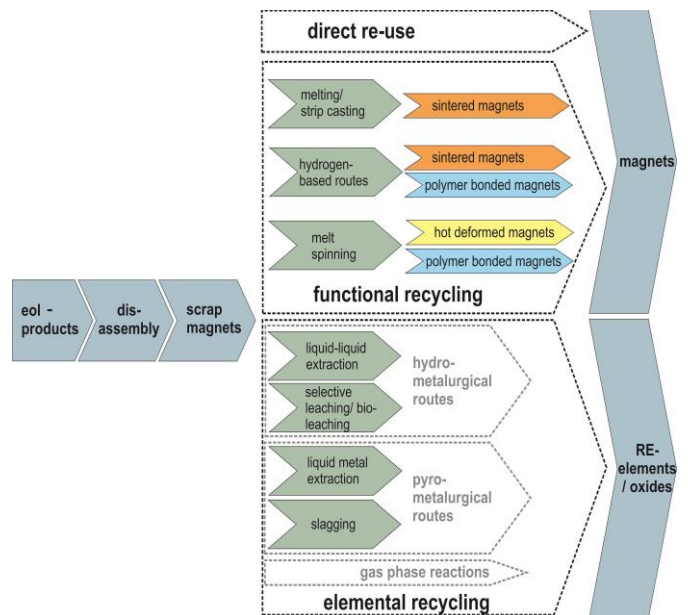


Fig. 4. Potential routes for recycling of permanent magnets from End-of-Life (EOL) products: (1) direct re-use, (2) functional recycling, and (3) elemental recycling [23].

The functional alloy recycling has the big advantage to retain the 2-14-1 structure of Nd-Fe-B during the recycling process. To adapt the chemical and physical properties to the target values of the new application the alloy can be adjusted through addition of additives or changing of microstructure. A further advantage is the possibility to change dimensions and shape of the recycled magnets relatively easy for specific demands. This recycling can further be divided into three processing routes starting with strip-casting, hydrogen treatment or melt-spinning of the scrap magnets like shown in Fig. 4.

Besides the technical requirements for recycling six barriers have to be overcome for an effective recycling: (1) insufficient and non-selective collection rates, (2) lack of information about the quantity of REE materials available for recycling, (3) dissipative use, (4) presence of contaminants (5) price volatility for scrap and products and (6) shipping of waste [15]. A study from 2014 [24] showed that due to the absence of such a closed recycling loop many of these alloys and critical elements disperse in the scrap metal after End-of-Life (EOL) of their products. In 2017 the recycling quote in the EU of LREE and HREE of all RE containing products amount to 3 % and 8 % respectively [14].

A. Hydrogen based route

The hydrogen decrepitation (HD) process plays a fundamental role in the production of high power sintered magnets [25]. The absorption of hydrogen into the treated material leads to an increase of brittleness and finally the pulverization of this material. Therefore the HD process is used for the production of sintered magnets on an industrial scale as a pre-crushing step before jet-milling. Additionally, in the hydrated powder a differential and anisotropic lattice expansion of the different phases leads to an improved milling behavior in the jet-mill [26]. A schematic description of the HD-process for a Nd-Fe-B magnet is shown in Figure 5.

For the recycling purpose the scrap sintered Nd-Fe-B magnet is exposed to hydrogen atmosphere (Figure 5a), the Nd-rich intergranular phase absorbs more hydrogen than the matrix phase, leading to differential volume expansion and efficient pulverization of the magnet (Figure 5b). Finally, the powder of the once sintered magnet consists of single crystalline particles (Figure 5c). The HD process is both temperature- and pressure-dependent and the hydrogen absorption reactions of the Nd-rich phase as well as the 2-14-1 phase are strongly exothermic, leading to a self-propagating reaction around room temperature and low H_2 -pressure (< 1 bar) [27] [28].

The pulverized scrap magnets can be further processed into recycled permanent magnets [29]. For this the conventional sintering route for the production of rare earth permanent magnets can be pursued. Oxygen and carbon contamination from the scrap magnets or due to the powder processing can lower the magnetic properties of the recycled magnets. Moreover the remanence of the recycled magnets may be

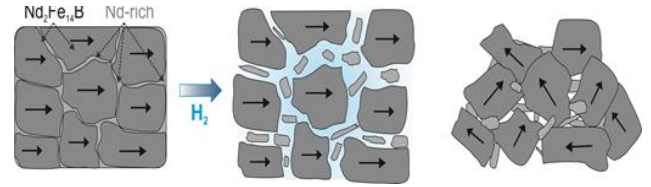


Fig. 5. Scheme of hydrogen decrepitation (HD) process; the hydrogen reacts with the Nd-rich grain boundary phase between the $Nd_2Fe_{14}B$ matrix grains which lead to a pulverization into a isotropic powder; the black arrows marks the alignment direction of the grains [23].

slightly decreased, which could be a hint for a different behavior of recycled and fresh powder during alignment [30].

One important advantage of the hydrogen based recycling route is the combination of the pulverization and demagnetization of magnetic material and the separation from non-magnetic material in one process. With this procedure permanent magnets from electric motors can be pulverized without an additional manual disassembly step. The avoided disassembly step can be very time- and cost consuming. On the lab scale this method has been demonstrated successfully for previously shredded hard disc drives [31].

Besides these benefits a hydrogen based recycling routes has some drawbacks as well, especially in case of corroded material. The oxygen content of the scrap material will stay constant during HD process or even increase [32]. Therefore a cleaning of the scrap magnet surface with sand blasting might be necessary before the feedback into the materials cycle via the HD process.

B. Re-melting and strip-casting route

The recycling of Nd-Fe-B permanent magnets can be performed by processes established in the commercial production of sintered Nd-Fe-B magnets. Therefore the scrap magnets are melted i.e. by using an induction furnace. Due to the oxidation sensitivity the melting procedure has to be carried out under inert atmosphere. The liquid melt is then cast into a copper mold. The slow cooling of casted bars or ingots leads to a segregation of α -Fe which is detrimental to the magnetic properties and has to be reversed by a time intensive homogenization tempering step [33].

To avoid the occurrence of α -Fe, Nd-Fe-B alloys are produced by using the Strip Casting Process, nowadays. Thereby the molten alloy is casted on a water cooled copper wheel. The wheel speed is about 1 – 3 m/s which results in a lamella microstructure of the resulting strip cast flakes and flake thicknesses of about 300 μm . The strip cast flakes are embrittled by hydrogen decrepitation and afterwards milled in a jet-mill. The resulting powders are compacted in a magnetic field and sintered afterwards to fully dense magnets [34] [35].

In comparison to the hydrogen route the oxygen content of the processed material can be lowered during the melting, since oxygen is bound in the slag [23]. Also an accurate addition of alloying elements and rare earth can easily be done to design the resulting alloy to fulfill the alloy requirements. The

disadvantage of this route is the manual and often difficult disassembly of the magnets which has to be done before melting on the one hand and the additional energy intense process step of strip-casting on the other hand.

C. Melt-spinning route

Another type of magnets are nanocrystalline hot-deformed Nd-Fe-B magnets. Starting material for these magnets are flakes produced via melt spinning [36]. The material is inductively melted in a crucible and then pressed through a nozzle and casted on a water-cooled copper wheel rotating with high speed (~10 times higher than strip-casting). The melt solidifies rapidly with cooling rates up to 10^6 K/s, and as a result of this very fast solidification the material is in the shape of flakes at the macroscopic level and forms a nanocrystalline or even amorphous structure with grain sizes of 5 - 50 nm at the microscopic level [37].

These rapid solidified flakes are milled to a coarse powder that can be used for the production of polymer bonded or hot-pressed magnets [33] [38]. Through hot-pressing the isotropic powder is pressed in an isotropic magnet and the grain size is increased slightly up to 80 - 100 nm. The subsequent hot-deformation process creates a texture in the direction of the material flow and as a result the magnet shows anisotropic behavior. The grain size of hot-deformed magnets is about 300 nm [37]. Concerning hot-deformation on an industrial scale die-upsetting and backward extrusion are the prevailing techniques [39]. Feeding this production route with scrap magnets is possible in general [40], but for an upscaling it needs to be considered that the alloy composition has to be adjusted and optimized for the deformation process, since the biggest share of scrap material origins from sintered magnets with composition not suitable for hot-deformation.

IV. EXPERIMENTAL

In the following the recycling of scrap-magnets from End-of-Life motors is demonstrated using the hydrogen decrepitation process to produce recycled sintered magnets. For this purpose scrap magnets were hydrogenated at 2 bar hydrogen pressure and room temperature for 90 min and subsequently dehydrided at 500 °C in vacuum. The produced HD-powder was then jet-milled with a classifier wheel speed of 5000 rpm using a 6 bar nitrogen milling pressure with a feed rate of 0.5 kg/h to obtain a fine grained sintering powder with particle size in the range of 5 μ m. The received material was mixed with varying amounts of NdH₂ and DyH₂ to compensate expected losses in remanence due to oxygen contamination or other impurities of the recycled material during production process. For mixing of the recycled material with hydride additives a mixer mill was used. The mixed powders were aligned at an external magnetic field > 2 T and pressed with approximately 0.5 kN with the alignment perpendicular to the pressing direction. The anisotropic green compacts were sintered at 1080 °C for 4 h and annealed at 500 °C for 2 h under vacuum up to $3 \cdot 10^{-7}$ mbar. In case of the magnets with 4 wt.-% and 6 wt.-% DyH₂ the sintering

program had to be adjusted. Here the sintering temperature was raised to 1090 °C for 5 h and 8 h respectively. To prevent oxidation through production process all steps were done under argon atmosphere or vacuum. The composition of the scrap magnets as well as the sinter powder was analyzed with inductively coupled plasma optical emission spectrometry (ICP-OES). The densities of sintered magnets were measured by Archimedeian principle in ethanol three times for each sample to calculate an average density. For the magnetic characterization of the samples a permagraph system (MAGNET-PHYSIK Dr. Steingroever GmbH) with a maximum magnetic field of about 2000 kA/m was used. Magnets with higher coercivities than 2000 kA/m at room temperature were measured at 80 °C or 125 °C, respectively.

V. RESULTS AND DISCUSSION

A. Composition of scrap magnets

The chemical composition of the scrap magnets by ICP-OES showed a composition of Nd_{21.8}Pr_{0.1}Dy_{8.58}Fe_{65.5}B_{1.07}Co_{2.31}Cu_{0.21}Ga_{0.17}Ti_{0.12}Al_{0.38} (wt.-%). Such high HRE content like 8.58 wt.-% of the particularly critical Dy is typical for magnets used for electric traction motors. The HRE leads to an increase in coercivity due to the higher magnetocrystalline anisotropy [41] [42] [43], which is needed for high temperature applications to withstand demagnetization.

B. Density and microstructure of recycled magnets

The measured densities of the magnets are shown in Fig. 6. The 100 % recycled magnet with no further additives shows a density of 7.54 g/cm³. With increasing amount of NdH₂ the density also increases up to 7.56 g/cm³ for the sample with 2 and 4 wt.-% NdH₂ and 7.58 g/cm³ for 6 wt.-% NdH₂ addition. However, all recycled magnets do not reach the ideal density of the original scrap magnet of 7.71 g/cm³. All magnets of the NdH₂ series are produced under the same conditions and

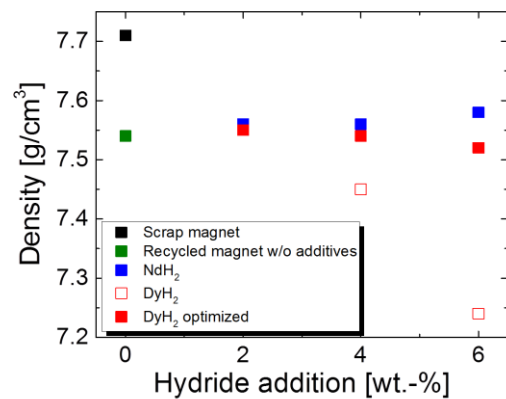


Fig. 6. Densities of recycled magnets with NdH₂ and DyH₂ addition; NdH₂ addition leads to a slight increase while DyH₂ causes a decrease in density; through rising sintering temperature comparable densities are reached.

sintered with the same temperature profile. The increasing density with increasing amount of NdH_2 is due to the compensation of oxidized REE with free neodymium. The oxidized REE have higher melting points and therefore do not contribute to liquid phase sintering.

In case of DyH_2 addition the densities of sintered magnets rapidly decrease with increasing Dy content. 2 wt.-% of Dy leads to a density of 7.55 g/cm^3 comparable to Nd addition. A further increase of 4 and 6 wt.-% decreases the densities to 7.45 and 7.24 g/cm^3 respectively. To compensate these low values the sintering temperature of both samples were raised up from $1080 \text{ }^\circ\text{C}$ to $1090 \text{ }^\circ\text{C}$ for 5 h (4 wt.-% DyH_2) and 8 h (6 wt.-% DyH_2). Raising the sintering temperature and remaining time increases the densities of the magnets to 7.54 g/cm^3 and 7.52 g/cm^3 , shown as the optimized curves in Fig 7.

For a further increase in density of NdH_2 and DyH_2 samples a further sintering and annealing optimization has to be done. Thereby it is important to hit the optimum temperature interval. On the one hand a too high sintering temperature leads to the growth of giant grains in the microstructure of the magnets which deteriorate the magnetic properties like remanence or coercivity. A too low sintering temperature results in not fully dense samples with comparable weak magnetic properties. All density values are summarized in Tab. 1.

C. Magnetic Properties

Fig. 7 shows the measured demagnetization curves of the recycled magnets with addition of NdH_2 (Fig. 7 top) and DyH_2 (Fig. 7 down). Due to the high coercivities at room temperature the magnets with NdH_2 addition were measured at $80 \text{ }^\circ\text{C}$ and with DyH_2 addition at $125 \text{ }^\circ\text{C}$. The obtained values are also summarized in Tab 1. The scrap magnets used for the recycling have a remanence B_r of 1.11 T, a coercivity of 1838 kA/m and a maximum energy product of 243 kJ/m^3 at $80 \text{ }^\circ\text{C}$. With no further additives, the recycled magnet loses 6 % in remanence and 15 % in coercivity. This decrease of magnetic performance may be caused by contamination with oxygen during processing and sintering. For an increase in remanence the temperature program for sintering and annealing can be further optimized. Even a small amount of impurities like oxygen or changes in alloy composition influences the optimal sintering program. For the recycling of different or unknown scrap magnet materials this is a general challenge. The addition of 2 wt.-% NdH_2 to the recycled powder induces an increase in coercivity of the recycled magnet of 9 % to 1699 kA/m while remanence stays constant. The added NdH_2 compensates the oxidized rare earth elements of scrap alloy and enlarges the Nd-rich grain boundary phase between the $\text{Nd}_2\text{Fe}_{14}\text{B}$ grains, which leads to higher coercivities through improved magnetically decoupled grains. A further increase of the NdH_2 content leads to a decrease in coercivity and remanence to values below those for the sample without NdH_2 .

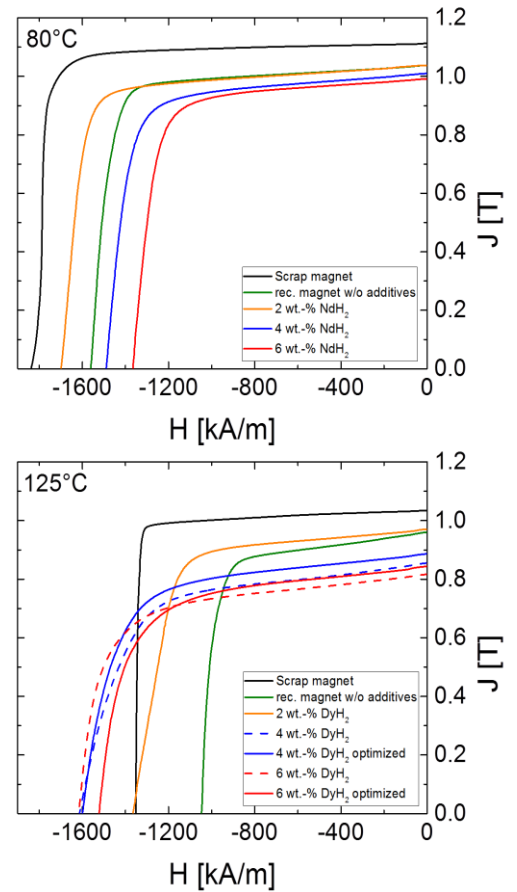


Fig. 7. Demagnetization curves of recycled magnets with NdH_2 (top) and DyH_2 (down) addition and reference samples. The addition of RE hydride results in an improvement of coercivity.

The slight losses in remanence with higher hydride contents can be explained with an increase of paramagnetic Nd rich grain boundary phase which does not contribute to remanence.

For DyH_2 addition the coercivity shows an increase of 30 % for 2 wt.-% and 53 % for 4 wt.-% compared to the 100 % recycled magnet without additions. While coercivity is improved, remanence decreases up to 7 % and 12 %, respectively. The higher influence of the HRE Dy compared to the LRE Nd is due to a substitution of Nd atoms in the $\text{Nd}_2\text{Fe}_{14}\text{B}$ matrix phase through Dy. The resulting $(\text{Nd,Dy})_2\text{Fe}_{14}\text{B}$ grains have a higher magnetocrystalline anisotropy than the pure $\text{Nd}_2\text{Fe}_{14}\text{B}$ matrix phase. This leads to a higher resistance against demagnetization which is reflected in a higher coercivity. On the other hand Dy atoms couple antiferromagnetically with Fe which leads to the decrease in remanence [44]. The magnet with 6 wt.-% DyH_2 addition shows lower coercivity and remanence as the 4 wt.-% sample, but the values are still improved to the original ones without additions. Through optimization of sintering program of 4 and 6 wt.-% DyH_2 samples, the remanence could be increased for both samples about 3.5 % while the coercivity could be also improved.

VI. CONCLUSION

Due to the high energy densities of rare earth permanent magnets and excellent properties of hard magnetic driven electric motors a rising demand of RE permanent magnets is expected with further expansion of e-mobility. One way to overcome the criticality and unsure supply chain of these crucial materials is the recycling of RE containing products. Besides the direct re-use of such products and elemental recycling, the alloy recycling has some big advantages like retaining the 2-14-1 structure with relatively less new process steps. At the alloy recycling processes three different routes are distinguished: (1) hydrogen based routes, (2) re-melting and strip-casting and (3) melt-spinning. Compared to the melting technologies a manual disassembly of the magnets, which is very time and cost consuming, is not required with the hydrogen based process. With this process scrap magnets from electric motors were recycled through hydrogen decrepitation and sintering under vacuum. The magnetic values of the recycled magnets are slightly lower than the original values for the scrap magnets. An improvement of remanence can be reached with pressing additives or further optimized sintering parameter. While remanence is decreased, density and coercivity has been increased through addition of NdH₂ and DyH₂ to higher values than the original scrap magnet.

Table 1. Summary of magnetic properties and densities of all recycled magnets.

Sample	T [°C]	B _r [T]	H _{cj} [kA/m]	(BH) _{max} [kJ/m ³]	ρ [g/cm ³]
scrap magnet	80	1.11	1838	243	7.71
no additives		1.04	1561	206	7.54
2 wt.-% NdH ₂		1.04	1699	206	7.56
4 wt.-% NdH ₂		1.01	1489	194	7.56
6 wt.-% NdH ₂		0.99	1365	188	7.58
scrap magnet	125	1.03	1352	209	7.71
no additives		0.96	1047	169	7.54
2 wt.-% DyH ₂		0.97	1365	177	7.55
4 wt.-% DyH ₂		0.86	1613	134	7.45
4 wt.-% DyH ₂ opt.		0.89	1599	147	7.54
6 wt.-% DyH ₂		0.82	1617	124	7.24
6 wt.-% DyH ₂ opt.	0.85	1523	132	7.52	

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