Recycling of NdFeB and production of complex new MIM-magnets

MIMplus Technologies Webinar Series 2021

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Webinar Team

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MIMplus Technologies has great knowledge of innovative manufacturing and assembly with a special focus on high-tech materials.

We are a member of OBE Holding GmbH with production sites in Germany and China

>100y
of precision engineering experience

500
employees worldwide

25k
square metre production floor

Key facts MIMplus

- Over 25 Mio. parts and assemblies per year
- Customers from different industries such as medical, aerospace, automotive and luxury
- In house tool shop
- In house machine construction and automation
- Research and development with well equipped laboratory
- Network of leading suppliers
- Certified according to ISO 9001:2015
- Certified according to IATF 16949
- Certificate in preparation ISO 13485:2016
- Certified according to EMAS and ISO 14001

WEBINAR 4

Recycling of NdFeB and production of complex new MIM-magnets

Speaker 1: Prof. Dr. Carlo Burkhardt

Rare Earth as Critical Elements for the Energy Sector

Carlo Burkhardt, Pforzheim University

SUSMAGPRO has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821114.

Pforzheim University

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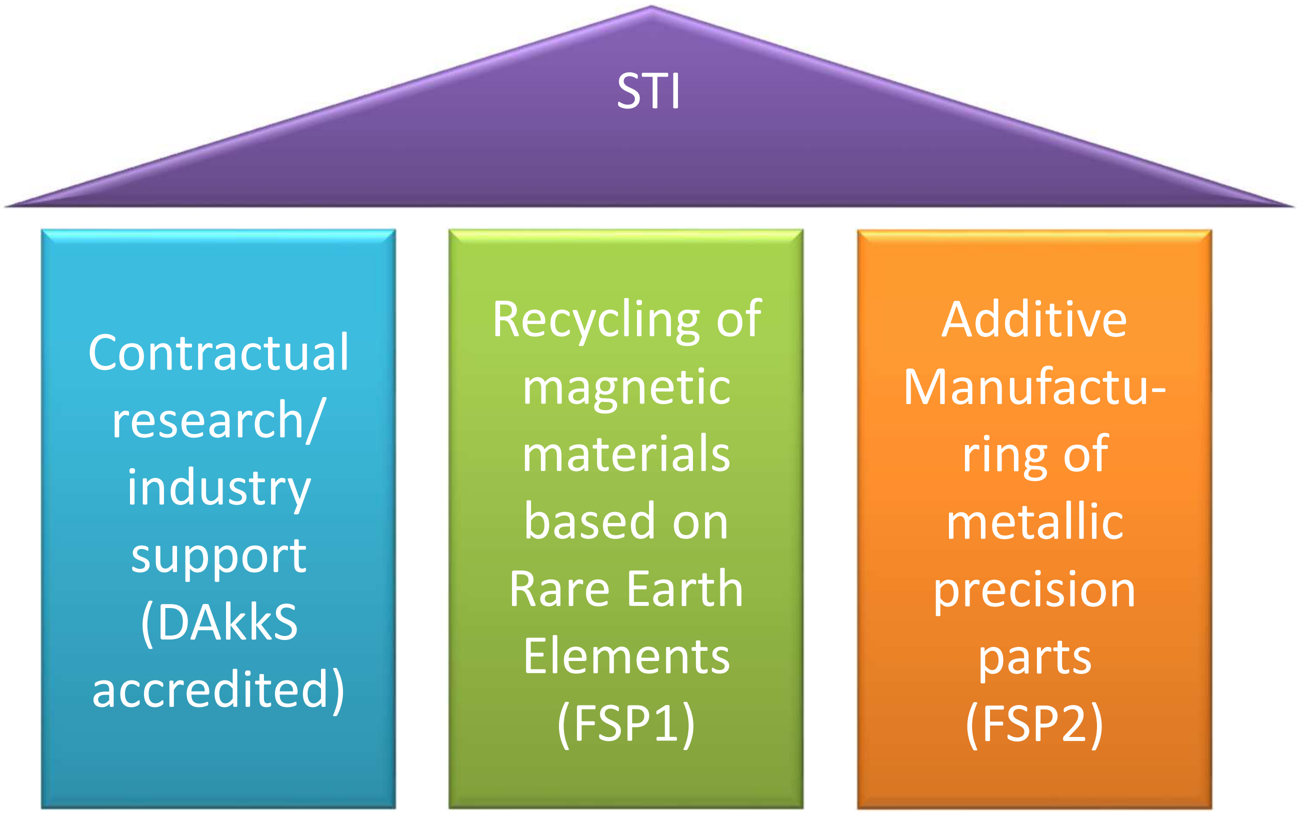

Institute for Precious and Technology Metals (STI)

- 14 employees, incl. 4 PhD students
- 5 national and 3 European research projects with a total budget of >26 Mio. €

Sources: www.energyandpolicy.org; www.earthtimes.org; www.wind-energy-the-facts.org; www.homepower.com; www.cleantechnica.com

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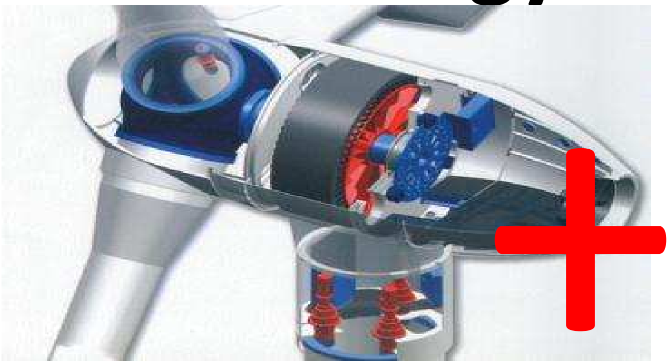
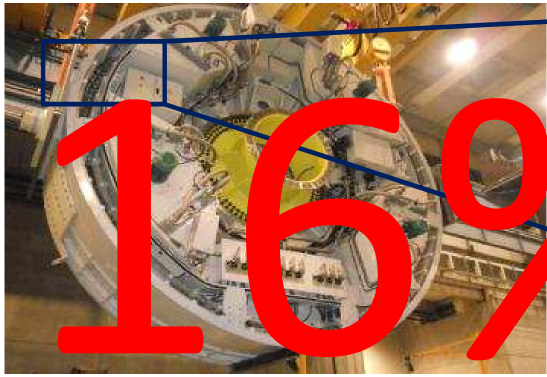
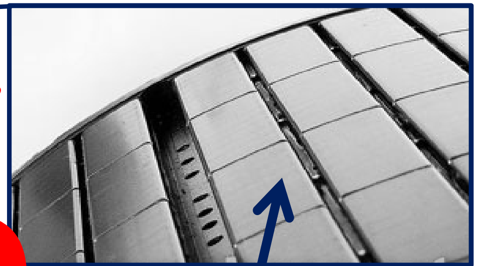
Green energy comes with a material revolution







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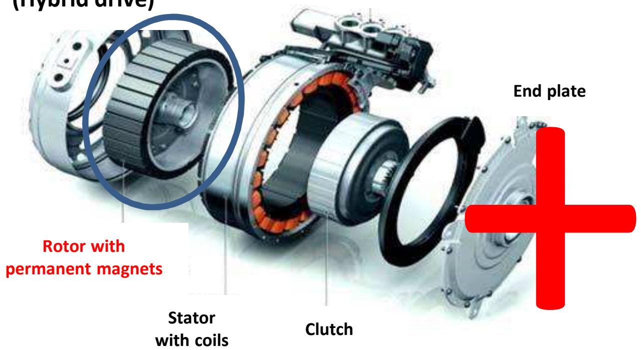

+ 20%

Sources: www.energyandpolicy.org; www.earthtimes.org; www.wind-energy-the-facts.org; www.homepower.com; www.cleantechnica.com

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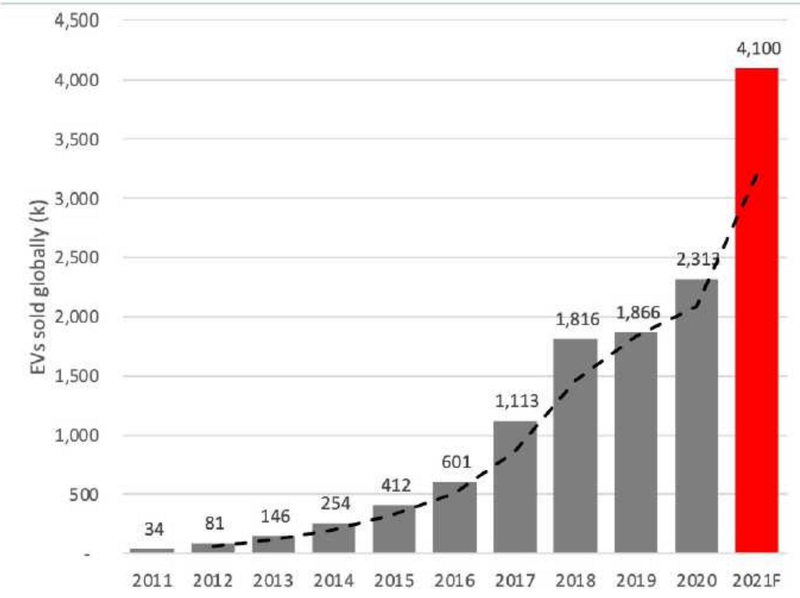
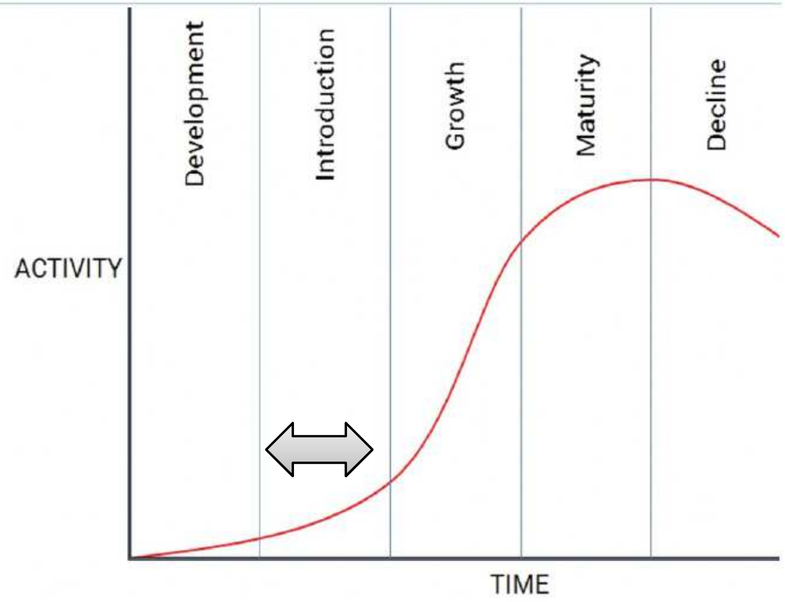
REE are in the centre of this material revolution

Newly registered EVs from 2011 to 2021 (E)





Source: FD

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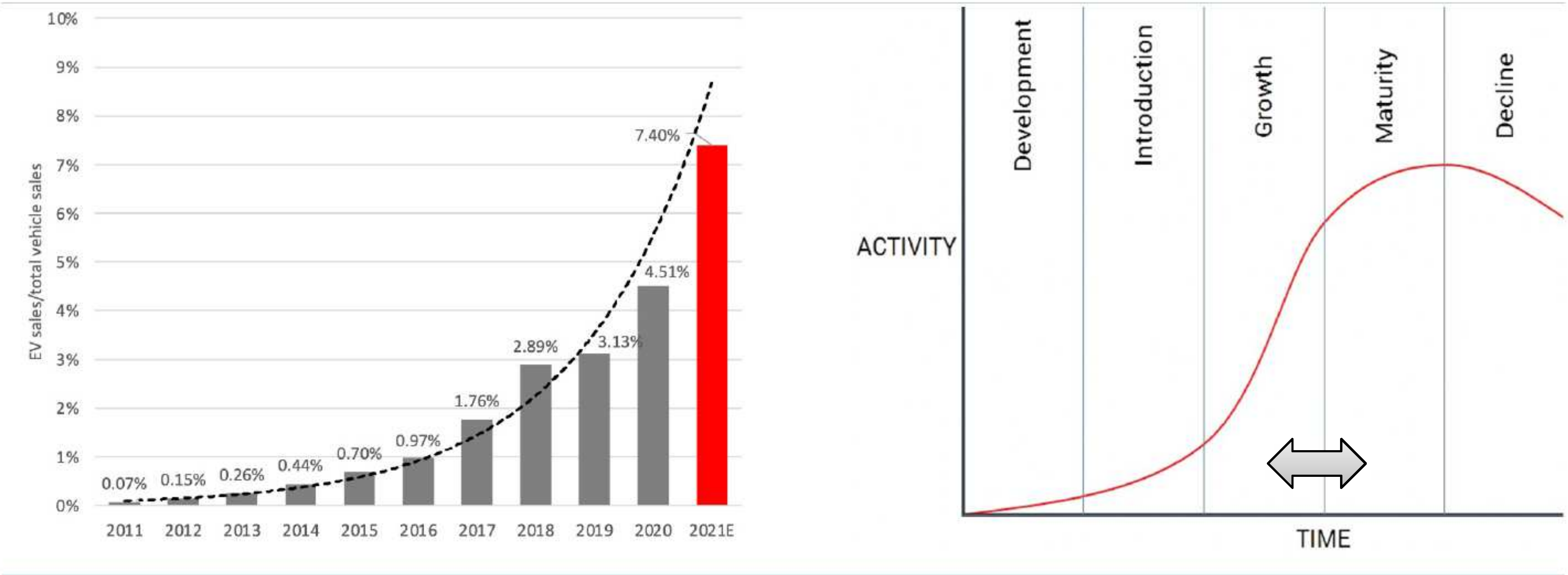

Source: FD

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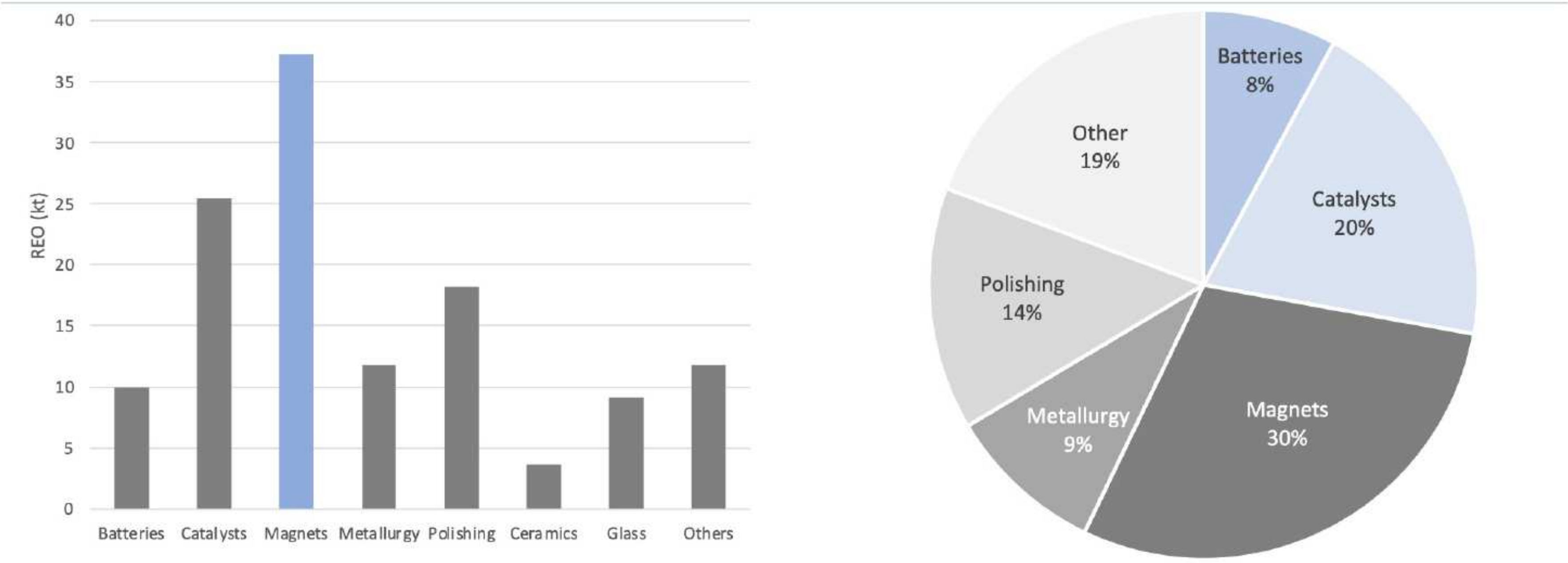
End use REE applications in 2020E



Source: Company reports, FD

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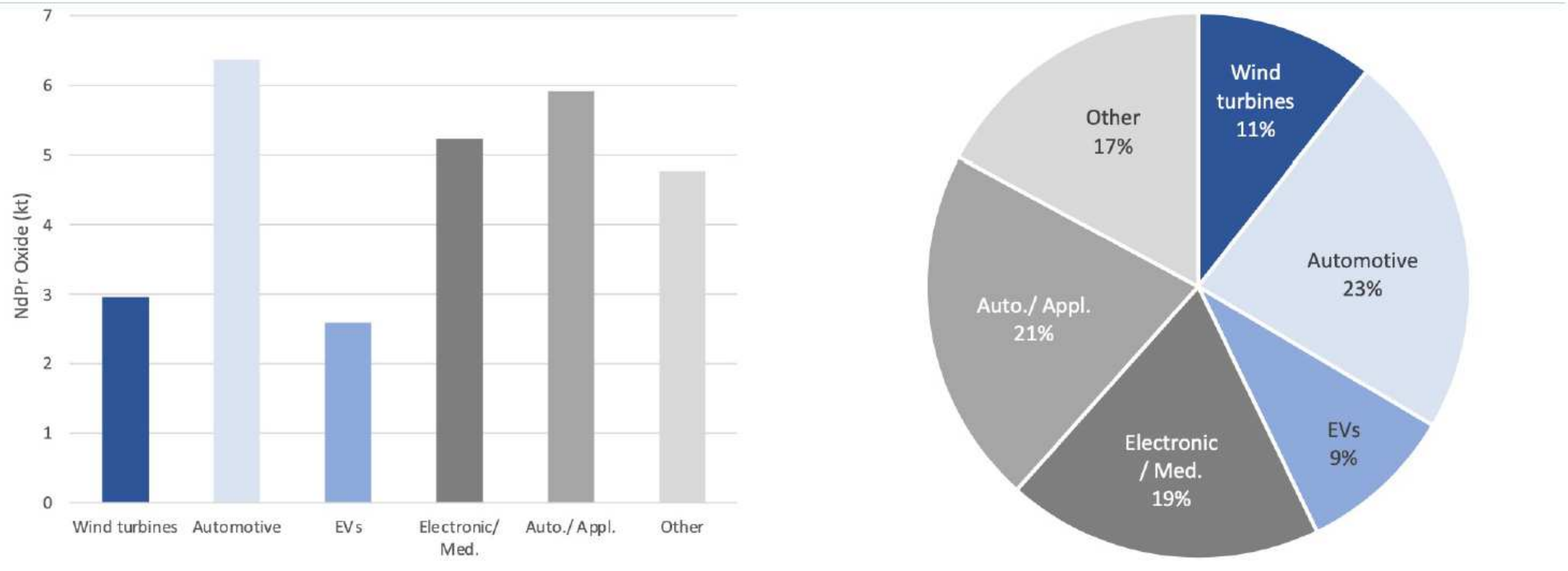
Global demand for NdPr 2020E



Source: Company reports, FD

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- >80% of electric cars sold (globally in 2019) utilised permanent magnet-based motors (PMMs)
- All Chinese EVs use PMMs
- PMMs give higher performance and lower weights compared with their induction competitors (*e.g*. Tesla 3; Munro Associates, 2018)
- Est. ~2,590t NdPr (ave. of two 2020 estimates) used in EVs globally
- European EV sales ~24.8% (NdPr consumption ~903t) of global
- PMM/Induction market share in EVs ~82%

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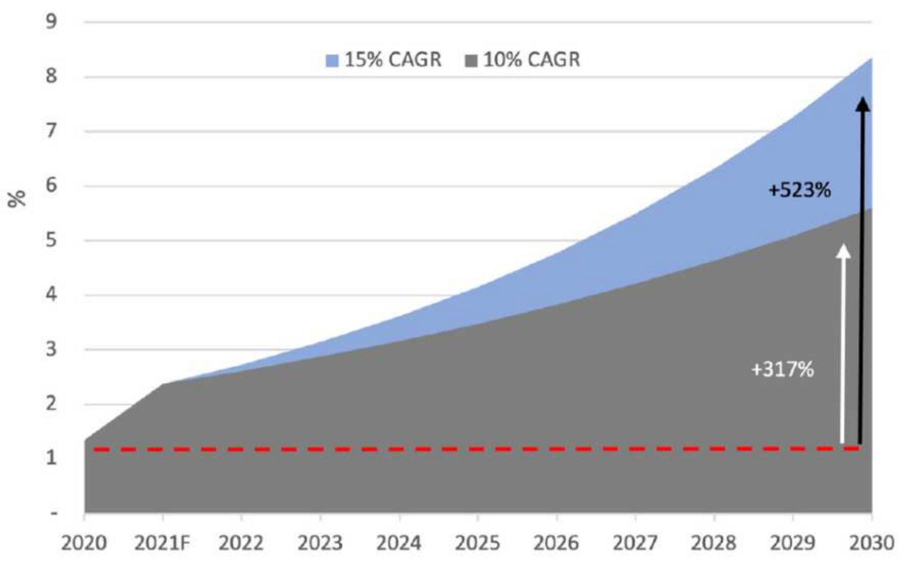
Unit growth rate resulting from EV demand



Source: FD

- EV growth (*ceteris paribus*) will increase global NdPr demand between 2,400% to 3,000% above 2020 levels by 2030!
- Assuming zero growth in every other magnet sector, **EV demand alone will increase overall global NdPr demand ~130% & 190% above 2020 levels**
- **Where is all this additional NdPr supply to come from?**

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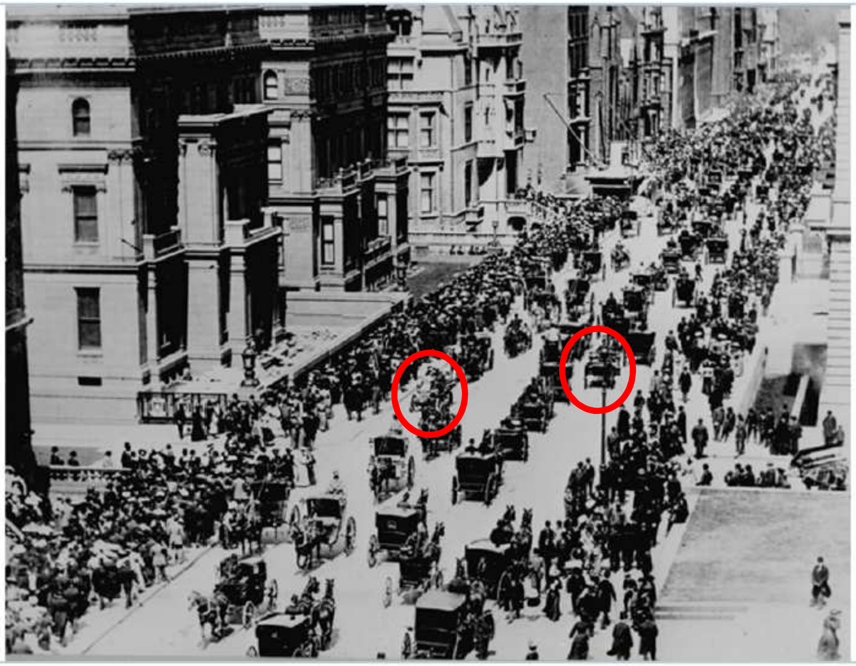
REE are in the centre of this material revolution

Photograph from 1900 shows New York's Fifth Avenue on Easter morning with only two cars visible



Easter morning 1913. Spot the horse?

Source: U.S. National Archives and Records Administration, George Grantham Bain Collection

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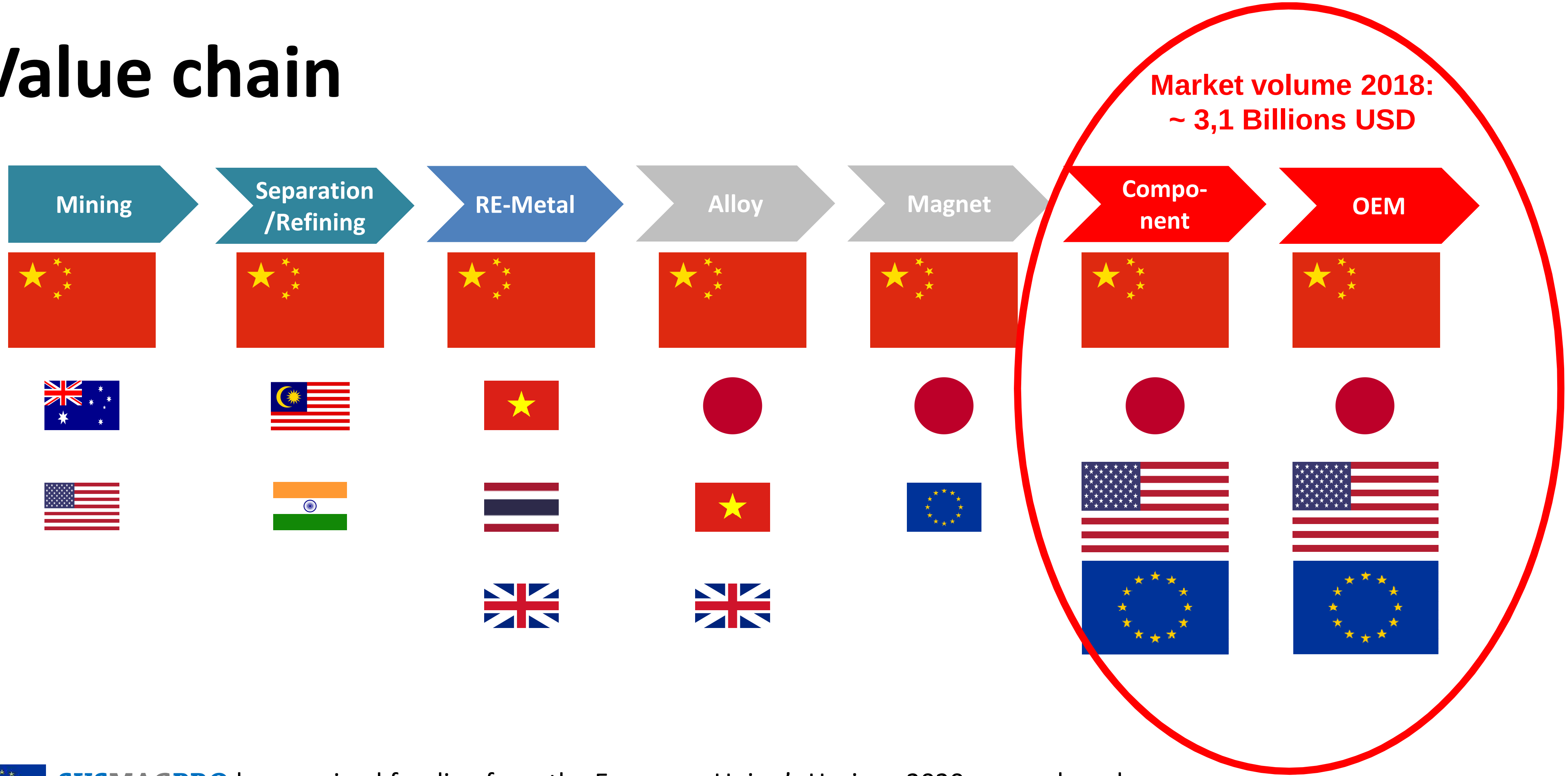
Value chain



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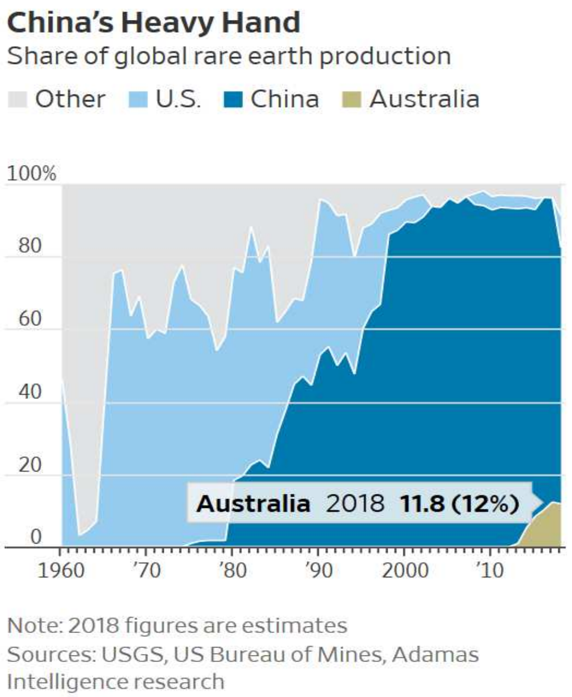
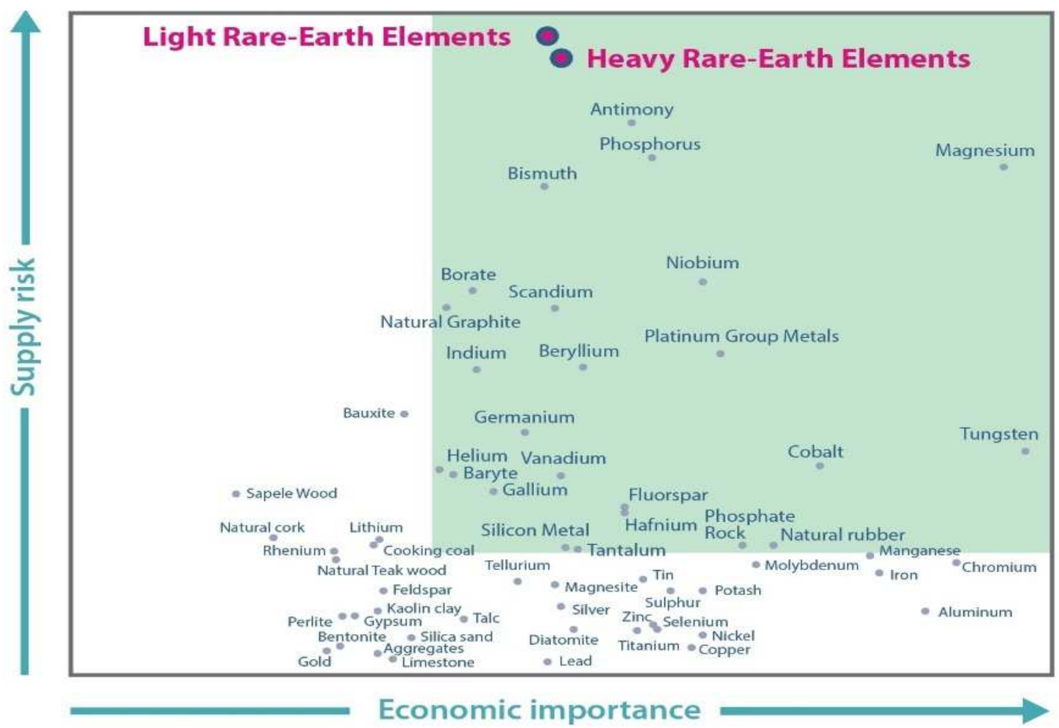
REE are in the centre of the material revolution





Source: https://ec.europa.eu/growth/sites/growth/files/critical-importance-risk.jpg

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REE are in the centre of the material revolution

- Recycling of RE-materials is a must
- Other technology metals (Ag, Pt, Pd) have recycling rates of 30%
- Recycling rate of Nd currently ~1%

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Issues with magnets recycling

- EOL magnets come in a wide variety
    - SmCo, Ferrites, NdFeB…
    - Sintered, polymer bonded…
    - Different coatings (Zn, Ni, …) & glue
    - Different state of corrosion

Source: https://Thinklink.com

- Take-back schemes and overall will to recycle are not sufficient
- Magnet content in the products is often low
- Recycling methods do exist, but up-scaling is expensive and for the stakeholders a large risk

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SUSMAGPRO is an industrialisation project **developing and demonstrating innovative pilot plants at TRL 6-7 for the clean and sustainable recycling of permanent magnets from secondary EoL sources in Europe**

Duration	1.6.19-30.05.23
Total budget	14,741,539 €
Funding	12,977,446 €

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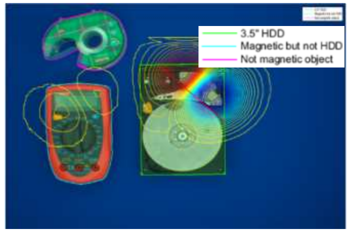
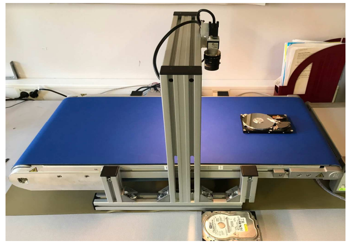
Concept and Approach

- Applications containing Nd-Fe-B magnets are identified, the components containing Nd-Fe-B magnets are separated from the waste stream
- After separation, the magnets are removed from the housings, glues, mechanical fixtures and coatings
- The magnets are recycled using the IP-protected HPMS short cycle processing route (extracting and re-processing the Nd-Fe-B as an alloy), leading to significant energy and cost savings compared to chemical or pyrometallurgical recycling
- The recycled material is re-processed into new magnets by four different manufacturing routes





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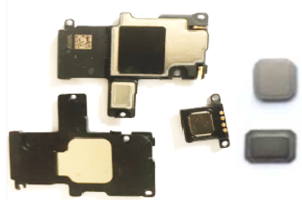
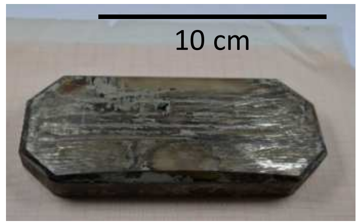
Assessment of scrap

- So far, over 80 applications have been dismantled and analysed for re-cyclability

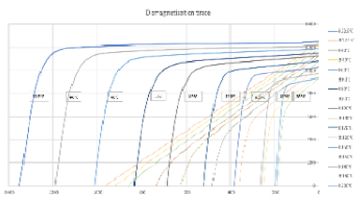
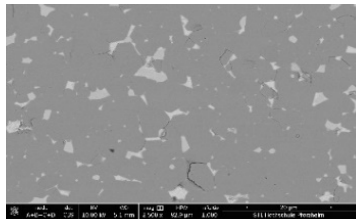




- Parameters I: Accessibility, fixation, contaminations […]

- Parameters II: Magnetic properties, microstructure, coatings, chemical composition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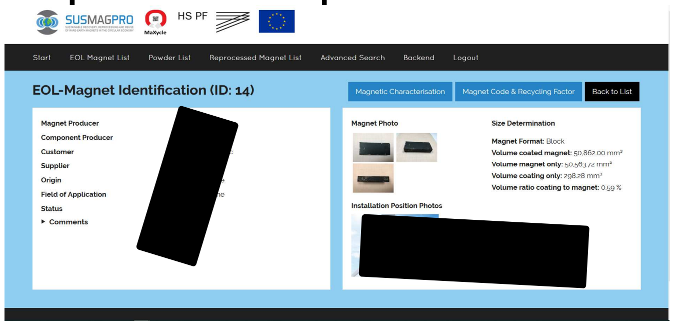
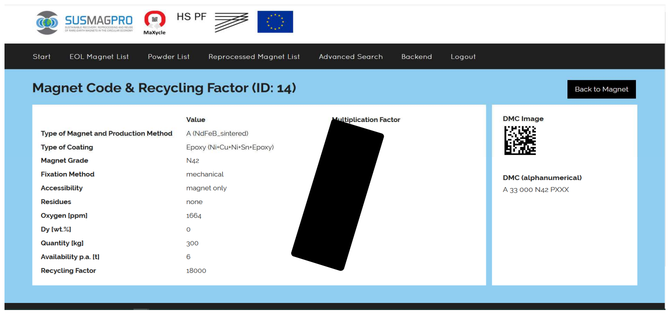
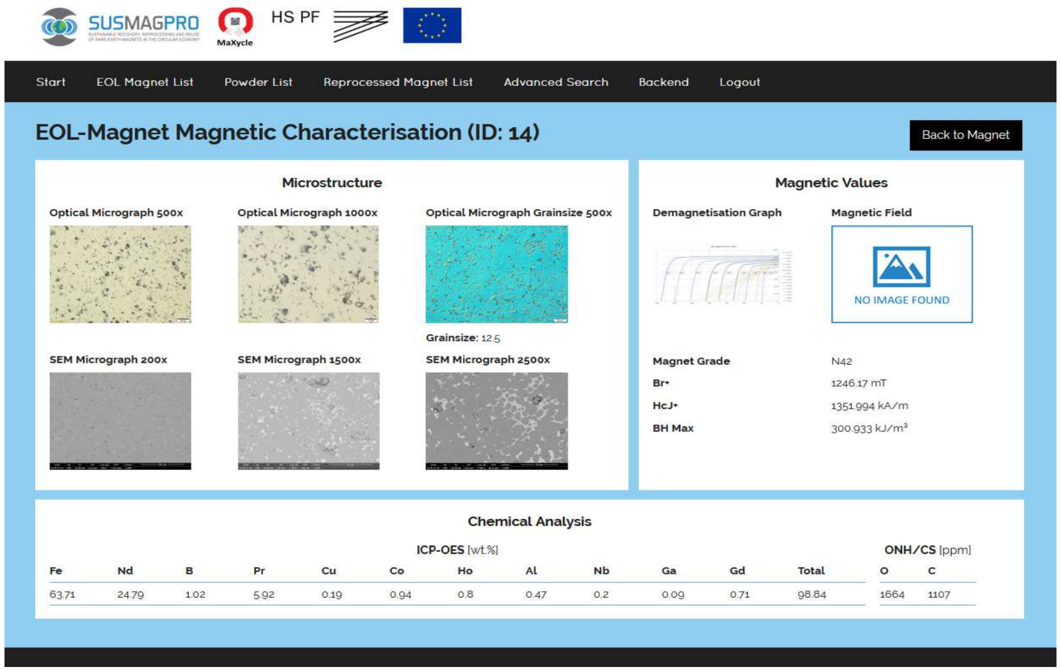
Assessment of scrap

- Setup of a comprehensive database







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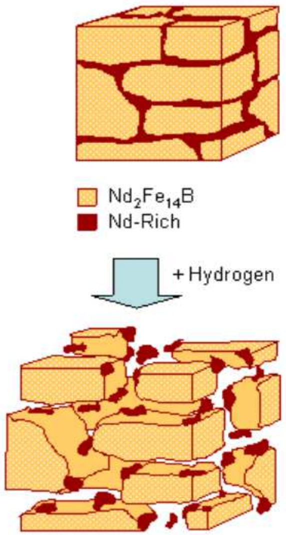
Processing

The HPMS short cycle recycling route



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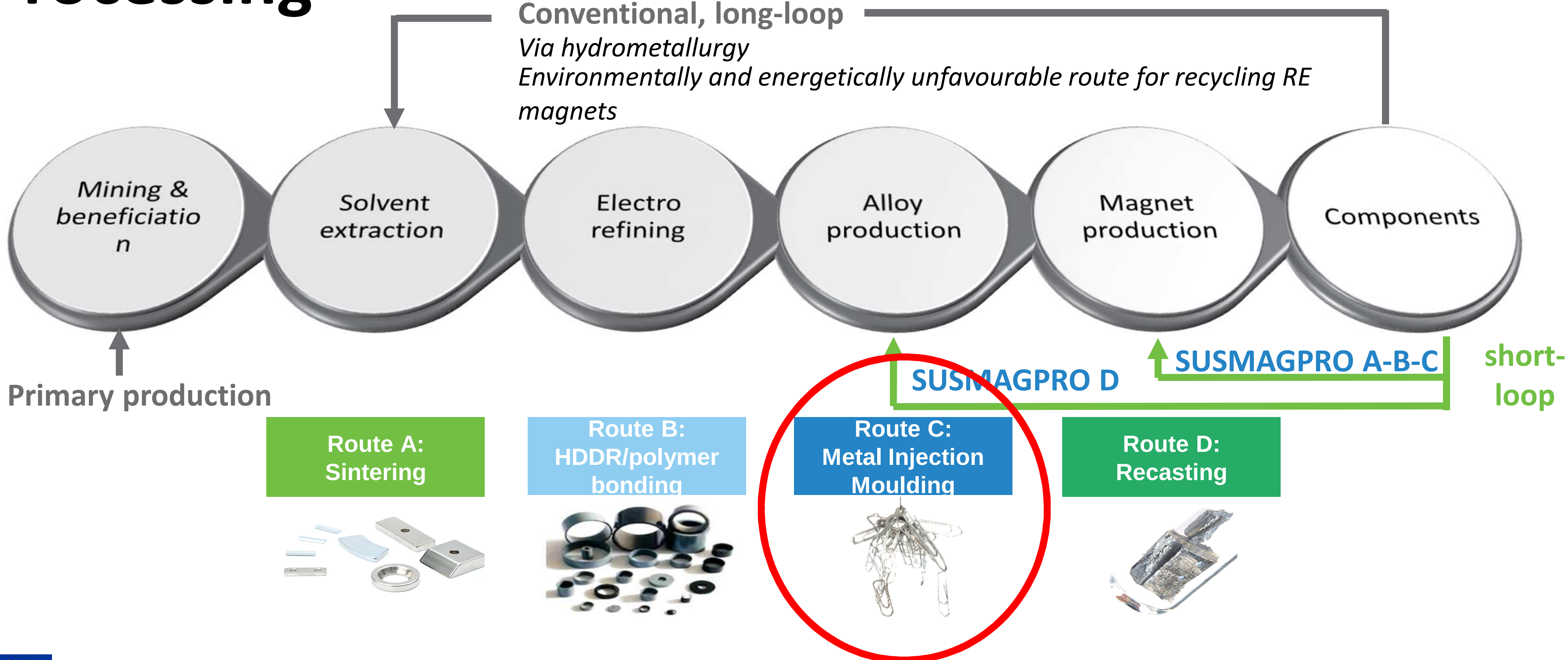
Processing



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WEBINAR 4

Recycling of NdFeB and production of complex new MIM-magnets

Speaker 2: Dr. Johannes Maurath

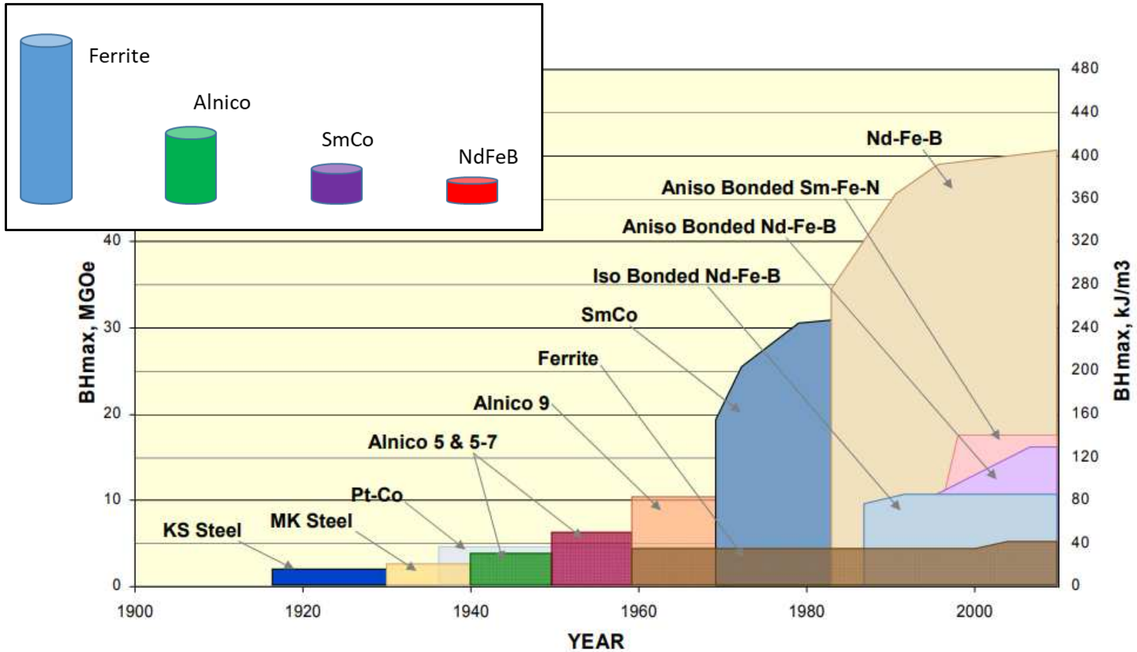
NdFeB Permanent Magnets - Introduction

- NdFeB magnets are based on its volume the strongest currently available permanent magnets
- Developed in the 1980's NdFeB-magnets captured the market due to their high energy product BH_{max} of max. ~ 410 kJ/m³
- High demand in permanent magnets with increasing trend to e-mobility and green energy

Source: Adobe Stock \ ©unlimit3d

Source: Adobe Stock \ ©Prostock-studio

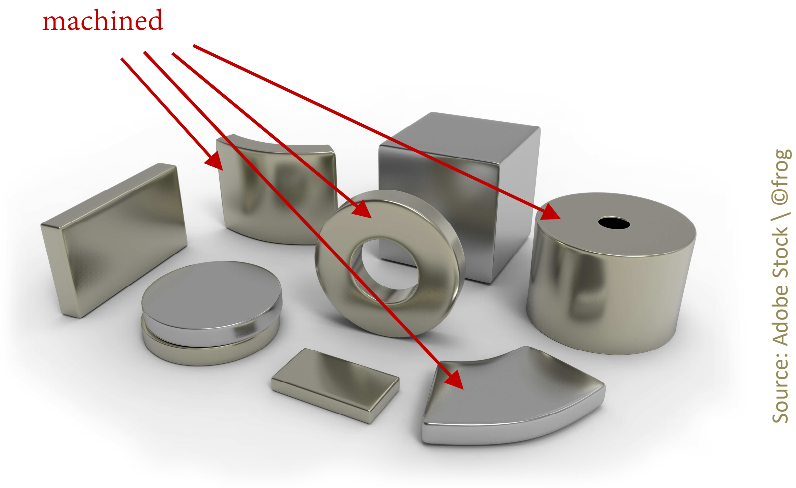
Source: Adobe Stock \ ©Blue Planet Studio



Source: S. Constantinides: The Demand for RE Materials in Permanent Magnets. Arnold Magnetic Technologies, 2012.

Conventional NdFeB Magnets

- Production processes for conventional magnets
  - Pressing and sintering of larger blocks → strongest magnets with maximum BH_{max}
  - Polymer bonded magnets via injection molding or extrusion → complex but low BH_{max}
- Most technical applications require performance of sintered NdFeB
- Sintered NdFeB is brittle and has a high hardness
- More complex sintered magnets require cost-intensive machining (EDM or grinding)



Maximum complexity of contentional sintered magnets

Typical shape of bonded magnets

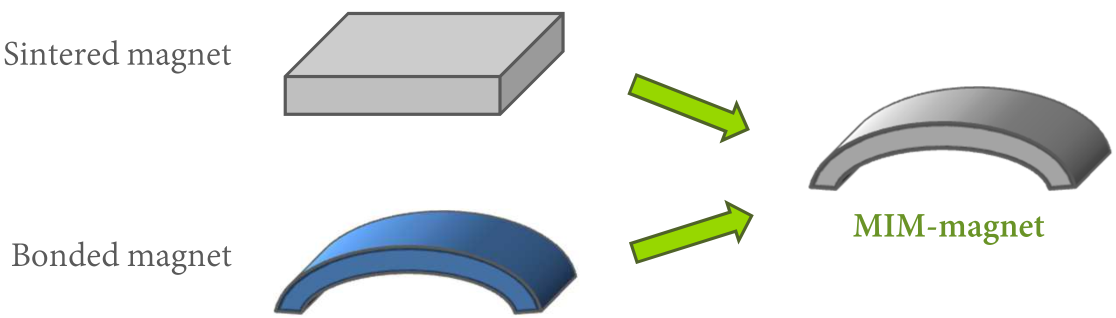
Unique Design Freedom with MIM Magnets

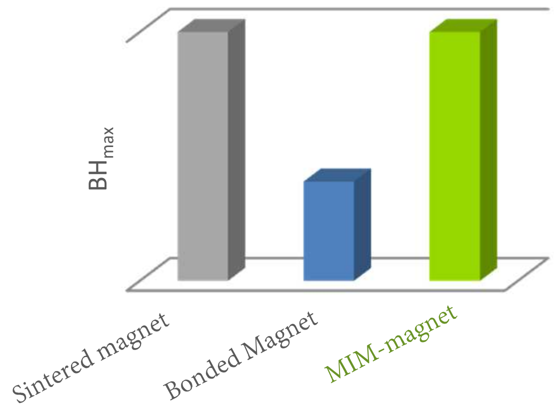
- Metal Injection Molding (MIM) combines advantages of both processes:
  - Sintered magnets: high energy product BH_{max}

    and

  - Polymer bonded magnets: complex geometry and orientation

- MIM magnets are recycling friendly (= sintered magnets)





MIM Magnets vs. Conventional NdFeB Magnets

Sintered magnet

- Low complexity
- High energy product
- Simple magnetization

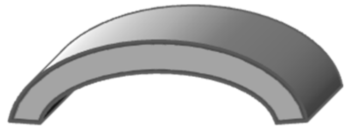
- Sintered NdFeB
- Shaped via pressing

Bonded magnet

- High complexity
- Low energy product
- Complex magnetization

- NdFeB + polymers
- Shaped via extrusion or injection moulding

MIM-magnet

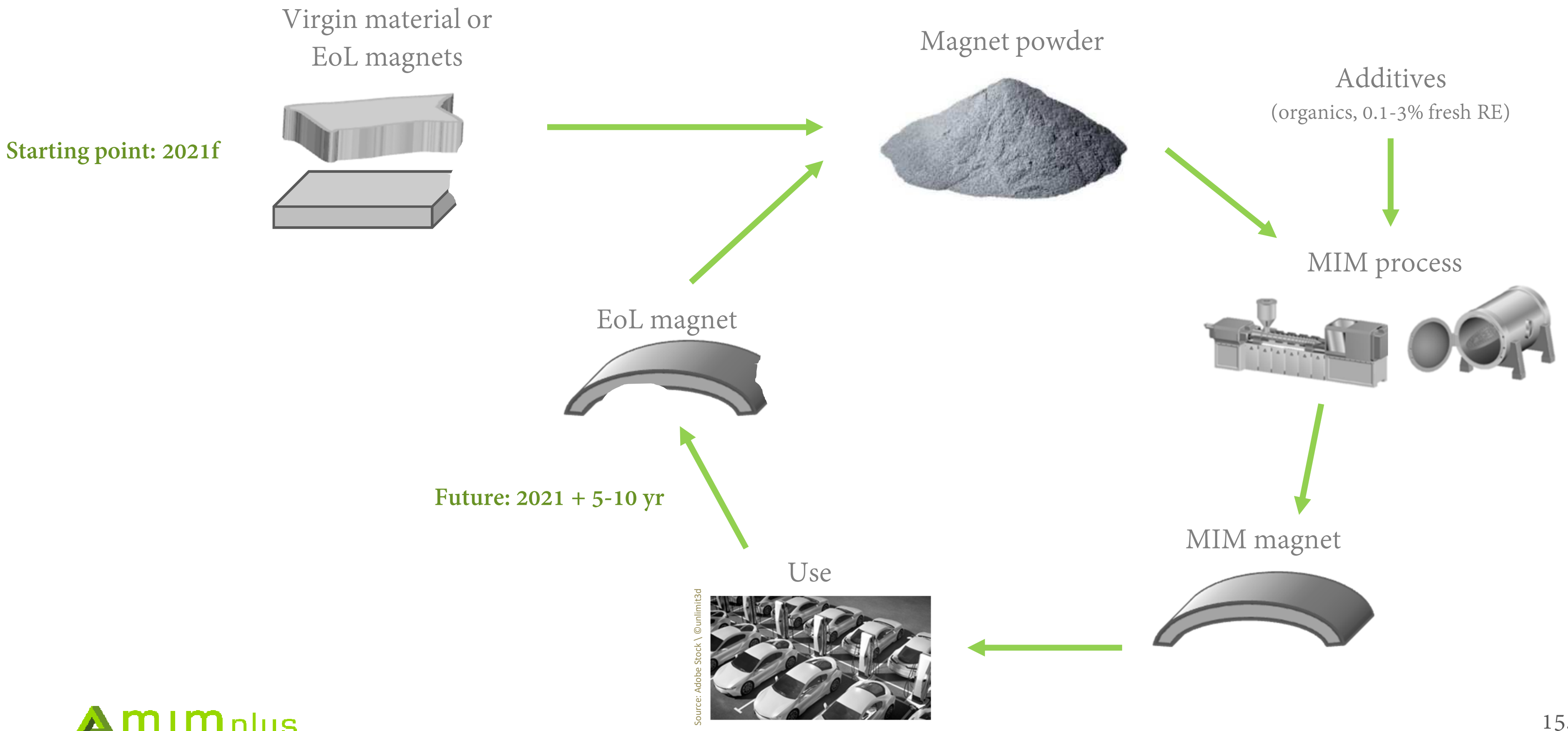


- High complexity
- High energy product
- Complex magnetization

- Sintered NdFeB
- **Shaped via MIM**

Vision: Closed Loop Recycling Process

Production of magnets in a closed loop process



R&D at MIMplus Technologies

- MIMplus focused on the development of a production process for producing complex shaped NdFeB magnets via MIM
- Full process-chain in house
- MIM magnets from virgin material available
- MIM magnets from recycling material available:
  Close-loop process from end-of-life magnets to sintered MIM magnets with similar performance

- Several EU funded R&D-projects in the field of magnet recycling at MIMplus:

2015 - 2018

2018 - 2021

2019 - 2023

Metal Injection Moulding of NdFeB-Magnets - The Process

At the first glance quite similar to conventional MIM…

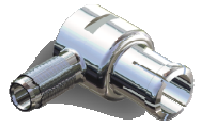
Powder

Compounding

Injection Moulding

Debinding

Sintering



Finished Part

1 — 2 — 3 — 4 — 5 — 6

Metal Injection Moulding of Magnets - The Process

.. reality is challenging:

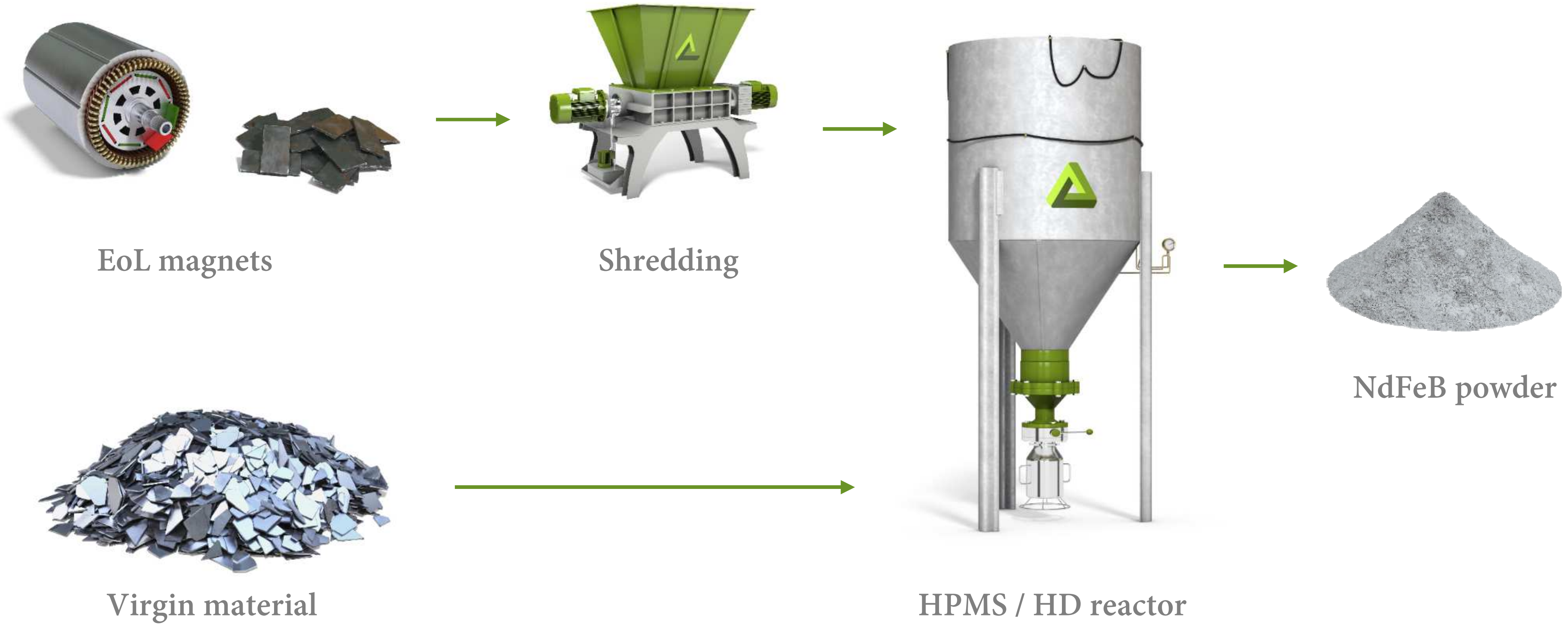
- NdFeB – powder is highly <u>pyrophoric</u> !
- Reactivity of the powder with O, N and especially C (MIM is binder based technology !) has to be handled
- NdFeB alloys often contain hazardous elements like Cobalt

→ Only with special process equipment and process know-how the high reactivity of the sensitive product can be handled

Metal Injection Moulding of NdFeB-Magnets - The Process

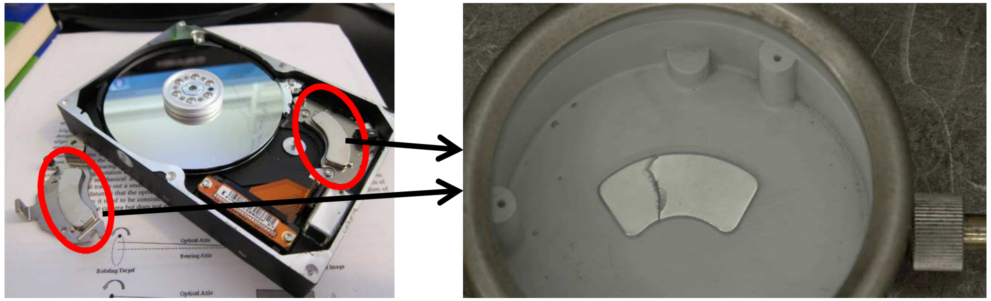
Critical process steps along the whole process chain

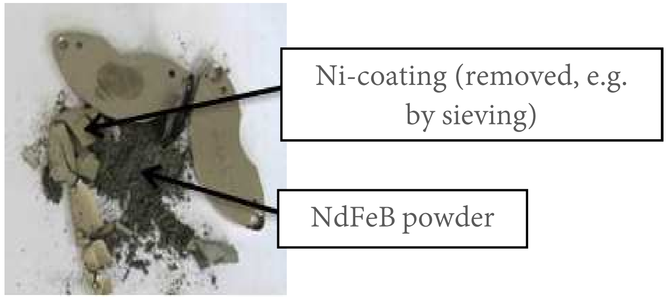
Powder production

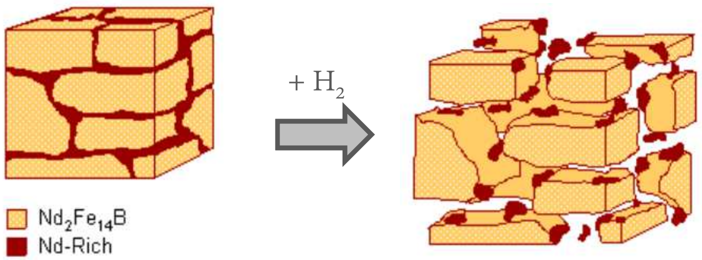


Powder Production - Recycling

Recycling Technology: Hydrogen Processing of Magnet Scrap (HPMS)







- Efficient process for recycling of EOL magnets
- Coatings and residues from resins or glues can be separated
- Clean powder can be directly reused in MIM process

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Source: www.birmingham.ac.uk/research/activity/metallurgy-materials/magnets/index.aspx

Powder Production – Virgin Material

Ingot

Strip cast

- Production process for virgin NdFeB-Material comparable to recycling process (="HD-process")
- Ingot material as well as strip cast material can be used for powder production

Feedstock Production

- Special feedstock compositions are necessary for protecting reactive powder particles
- Appropriate handling technologies important for high quality of final products
- Composition has to ensure low intake of C and O into material → direct impact onto B_r and H_{cJ}
- Final feedstock is overall comparable to state of the art MIM feedstocks

Metal powder
(NdFeB powder)

+

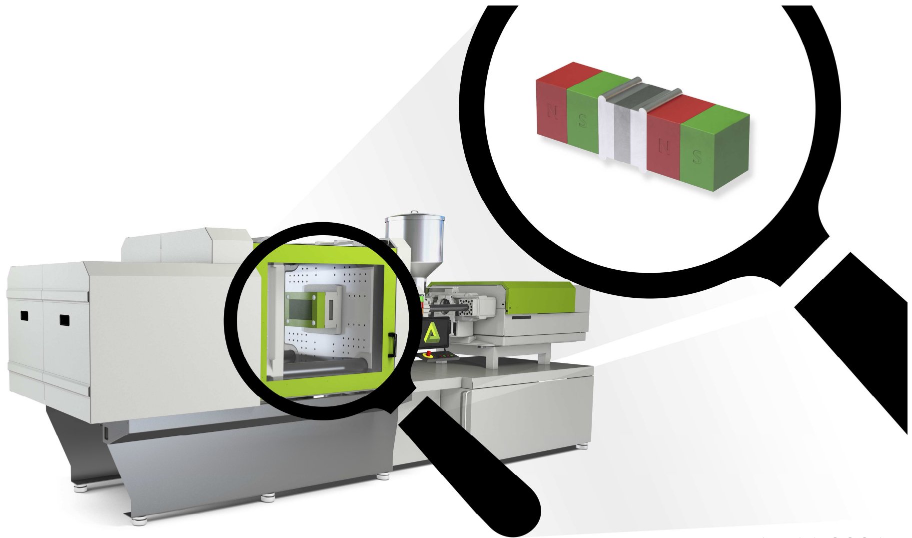
Binder
(polymer mixture)

Mixing, melting and
homogenization

Feedstock

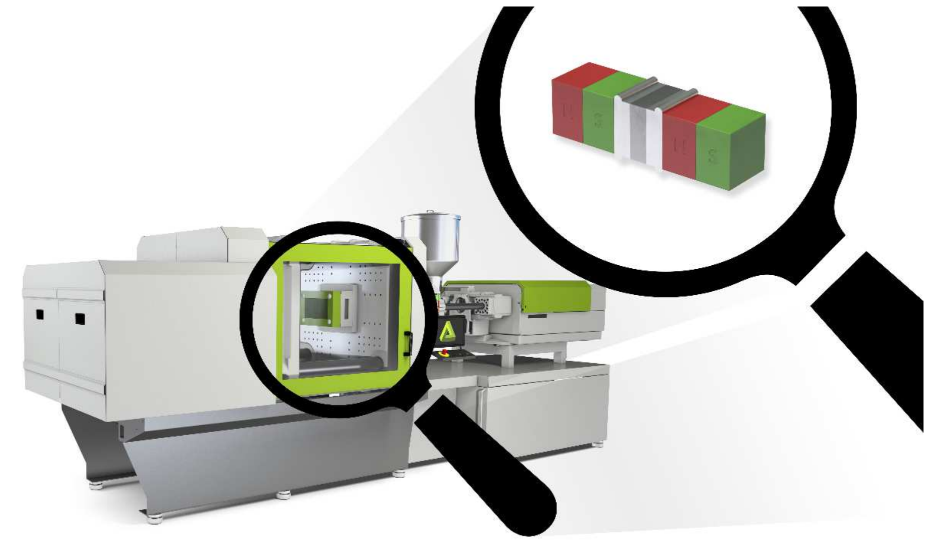
Injection Moulding

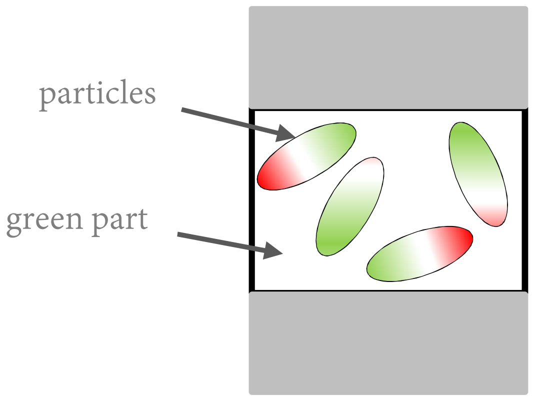
- Conventional state-of-the-Art injection molding machines can be used
- MIM tools for magnets have special requirements:
  - Produced at in-house mold tool shop of MIMplus
  - Mold tool with internal magnetic field for alignment of particles in magnetic field
    → anisotropic magnets for highest performance



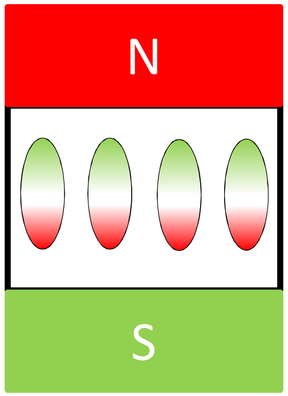
Injection Molding – Alignment in Tool

- Every single powder particle in the feedstock behaves like a single magnet
- Magnetic field in tool allows alignment of particles in the green part
- Strong anisotropic magnets can be produced





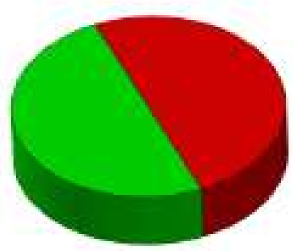
isotropic magnet

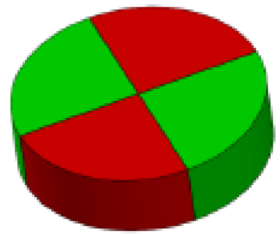


anisotropic magnet

Injection Molding – Alignment in Tool

- Complex magnetizations are possible:
  - Multi-pole magnets: diametrical, radial
  - Halbach arrays

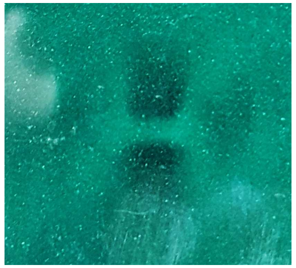


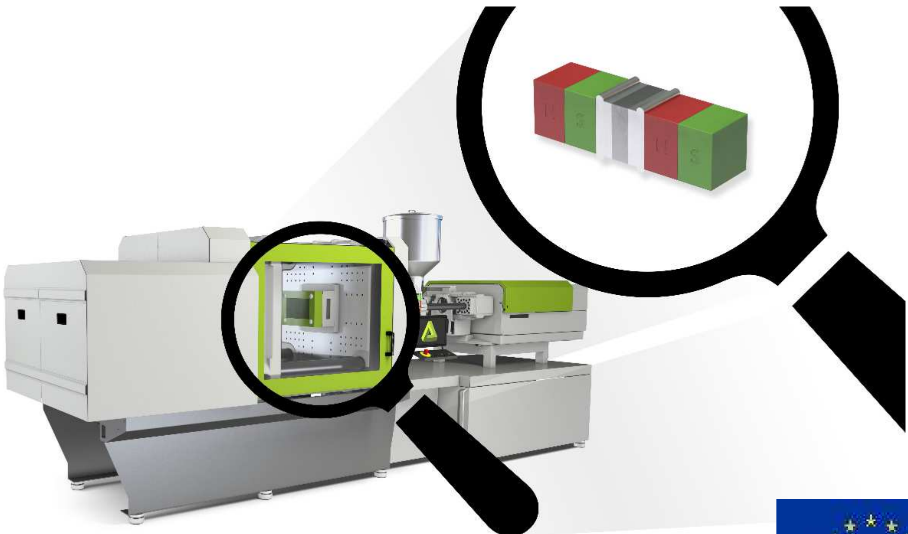


magnetic flux foil

Top view:

Side view:





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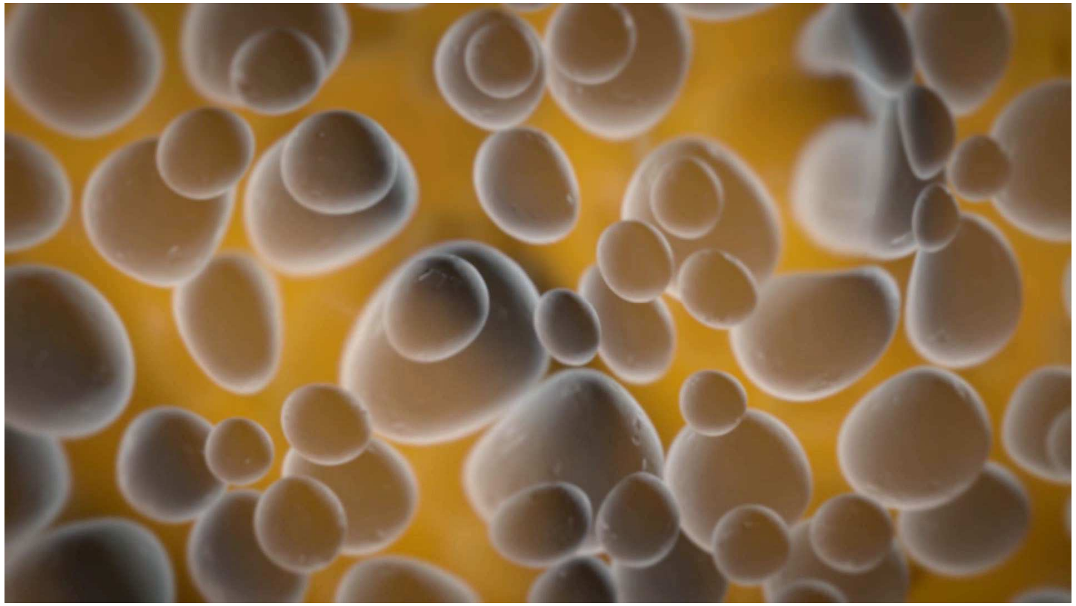
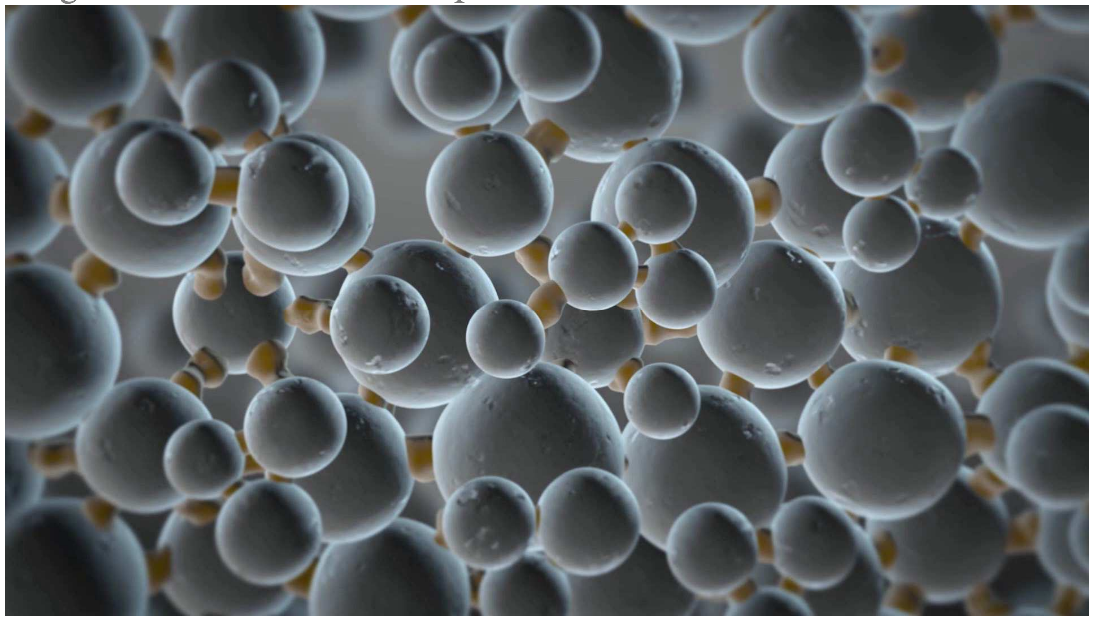
Pre-debinding

- Pre-debinding comparable to conventional MIM
- Solvent debinding allows binder extraction without reaction with powder



Thermal Debinding & Sintering

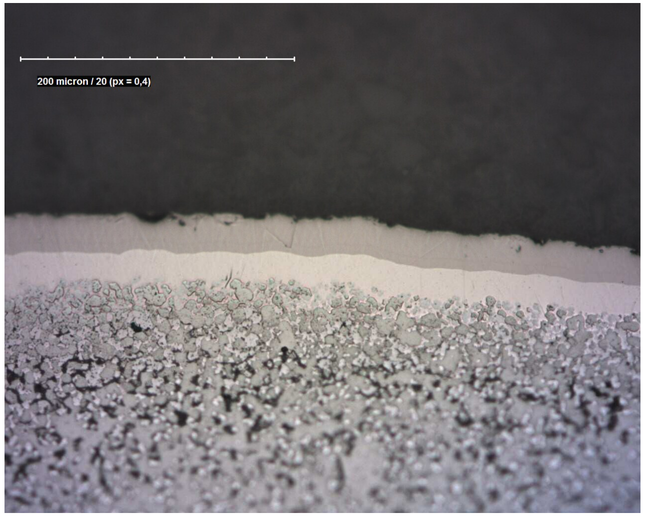
- Thermal debinding: Decomposition of remaining backbone binder
- Adequate thermal debinding is a very critical step
- Sintering: Densification of the porous structure to receive a dense (> 96%) magnet



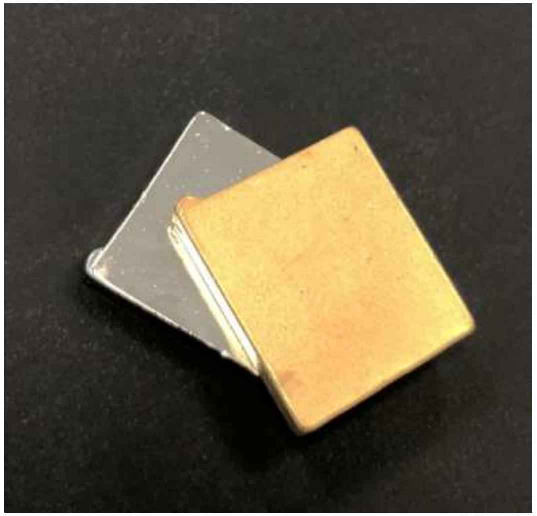
Post-processing

- Sintered NdFeB magnets are then magnetized in pulse magnetizer
- Magnets can be coated with state of the art coating systems for corrosion protection:
- Coating in-house at OBE group as well as at sub-suppliers of MIMplus

Examples:



Sn + Ni



Ni and Ag

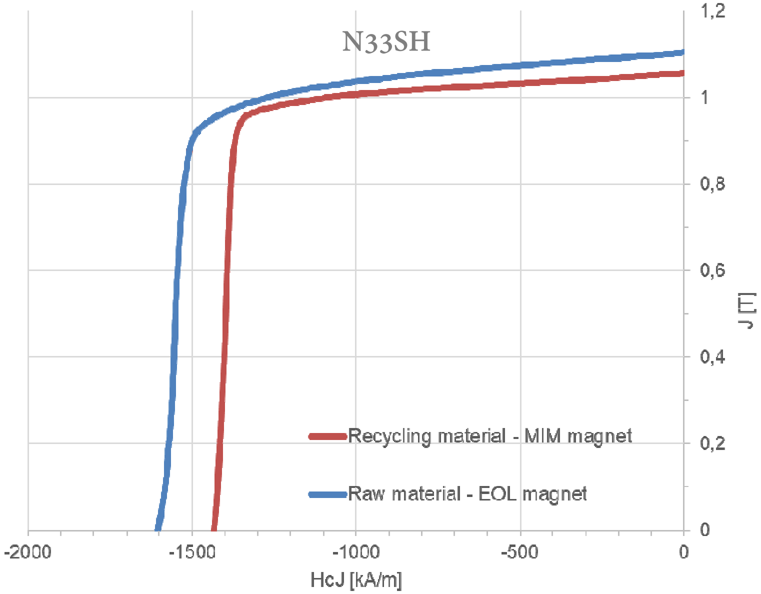
Case Study 1 - Recycling - Out-of-spec Magnets

- MIMplus received out-of-specification magnets from magnet assembly producer
- Magnetic powder was extracted via HPMS process
- Strategy for removal of coating (here: NiCuNi-coating) was selected
- Feedstock composition for the specific powder was developed
- Thermal debinding, sintering and annealing procedure was adapted on chemical composition of powder

SUSMAGPRO has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821114.

Case Study 1 - Recycling - Out-of-spec Magnets

- Production of recycled MIM magnets was successful:
    - Remanence B_r = 95% of raw material
    - Coercivity H_{cJ} = 91% of raw material
- Reached magnetic performance is sufficient for customer that is in early stage for searching recycling technology → Selling criteria "100% recycled" magnets



EoL magnet:

MIM magnet:

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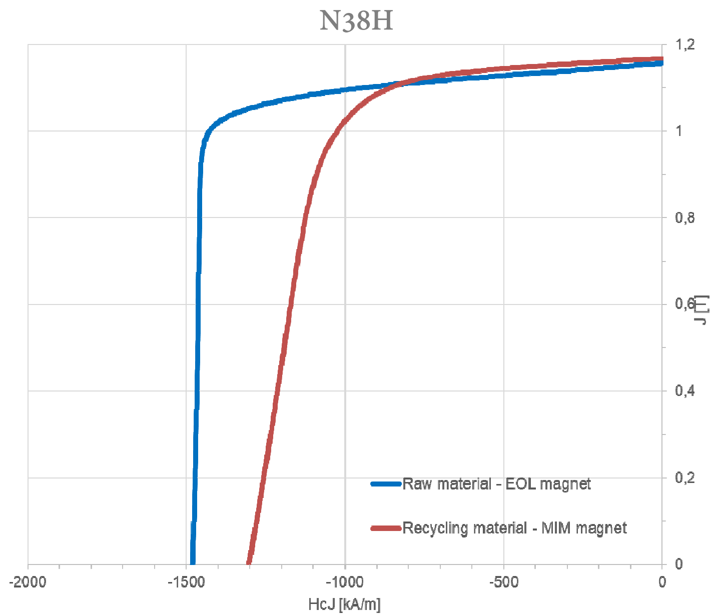
Case Study 2 - Recycling - End-of-Life Magnets

- Scrap magnets received from scrap dealer
- Wind turbine magnets, thermally demagnetized
- Magnetic material was recycled and MIM magnets were produced
- Remanence of scrap magnets was reproduced to 100%: $B_r = 1.18$ T !
- Optimizations on coercivity H_{cJ} ongoing



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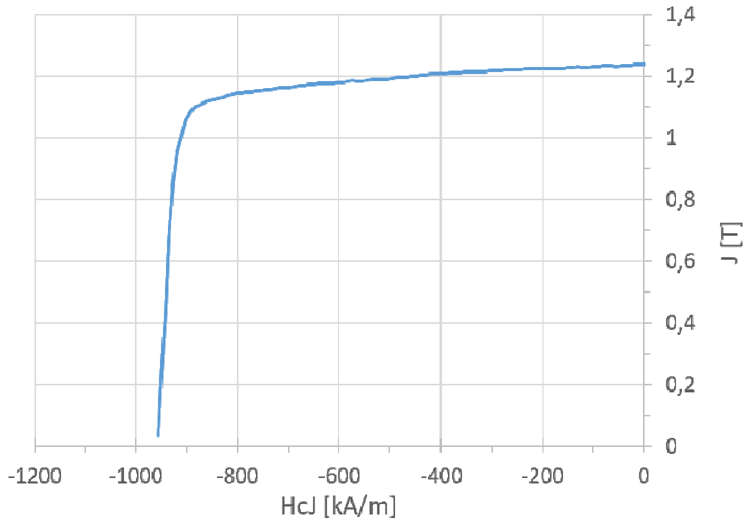
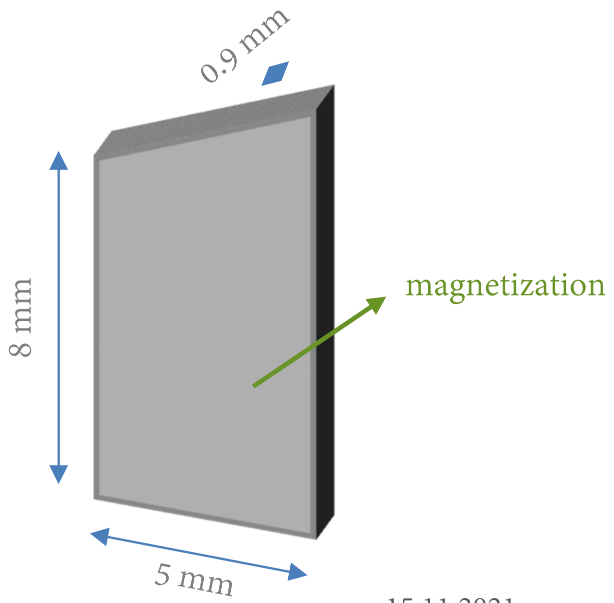
Case Study 3 - Design - Magnet for Electronic Devices

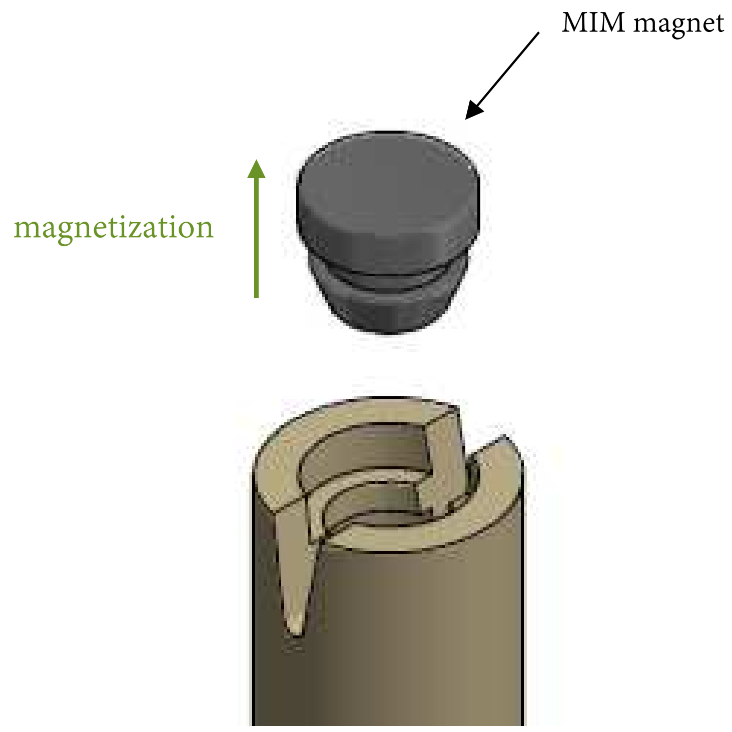
- Magnet for an assembly in electronic devices
- Requirement: virgin material
- Compact assembly needs very thin magnets with high performance
- Final coated magnet with a thickness of < 1 mm
- State of the art production of the part:
  Press & sintering and post-processing via wire cutting → low yield !





Case Study 4 - Design - Holding magnet

- Holding magnet for furniture industry
- Former design needed assembly of 3 different parts:
  - 2x soft magnetic parts
  - 1x rectangular shaped magnet
  - Gluing of the three parts was necessary
- New MIM-magnet: Clip feature integrated into the magnet
- Magnetic holding force of 1.2 kg can be reached with MIM magnet
- State of the art production of the part: not possible
- Cost saving: elimination of magnet holder and bonding process

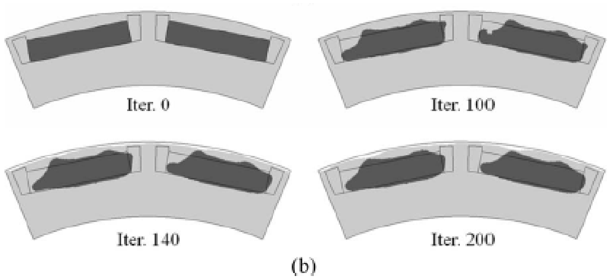


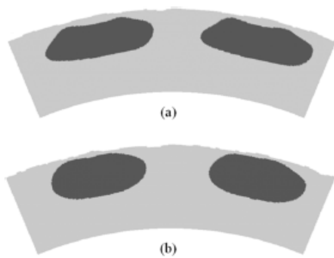
Case Study 5 - MIM-Magnets for E-Mobility

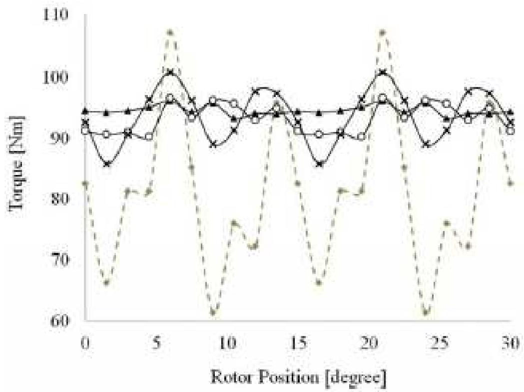
- Almost all designers think in simple shaped block magnets in permanent magnet motors
- The simple rectangular shape of permanent magnets seems to be fixed
- Technical challenges are solved with design changes on other motor components
    - Soft magnetic electric sheets
    - Power electronic & control system
    - Motor design & arrangement magnets
- MIM allows for large scale production of completely new magnet designs with so far unreached potential for motor performance

Example from literature:

Reduction of torque ripple







Source: Lim et. al, IEEE Transactions on Magnetics, Vol. 48, No. 2, February 2012.

MIM-Magnetes from MIMplus Technologies

- Innovative MIM technology for NdFeB magnets allows for production of permanent magnets (NdFeB) in geometries that were not economically before
- MIM magnets allow unique freedom in design
- Magnetic properties equivalent to state of the art sintered magnets
  → no limitation on magnetic grade / chemical composition
- Closed-loop recycling process for NdFeB MIM-magnets possible
  - Recycled MIM magnets available ✓
  - Virging material MIM magnets available ✓
- Unique chances for all sectors: Automotive, medical, aerospace, electronic, consumer industry

MIMplus Webinar Series at one sight

Thank you !

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www.mimplus.com