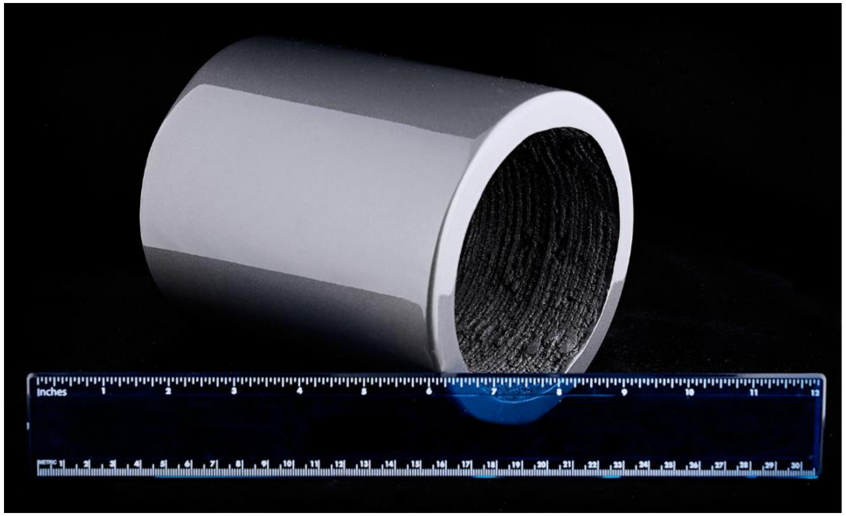
Extrusion Based Additively Printed Magnets Outperforming Traditional Injection Molded Magnets

M. Parans Paranthaman
Materials Chemistry Group
Chemical Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6100
Email: paranthamanm@ornl.gov
Tel. (865) 386-9030 (cell)



This work was supported by the Critical Materials Institute, an Energy Innovation Hub funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office

CMI Critical Materials Institute
AN ENERGY INNOVATION HUB

OAK RIDGE National Laboratory

Acknowledgement

Ling Li, Brian Post, Vlastimil Kunc, Orlando Rios, Amy Elliott, Uday K. Vaidya, Ahmed A. Hassen, S. Suresh Babu, Niyanth Sridharan, Ryan R. Dehoff, Jason Pries, Michael McGuire, Brian Sales **(ORNL)**

Ikenna Nlebedim, Helena Khazdozian, Kinjal Gandha, Tom Lograsso **(Ames)**

Scott McCall **(LLNL)**

Jim Herchenroeder **(Neo Magnequench)**

James Bell, Dereck Harrison, Mark McPherson **(Aichi-Steel/Tengam)**

John Ormerod, Robert Fredette **(Magnet Applications Inc.)**

Aaron Williams **(Arnold Magnetic Tech.)**

Zaffir Chaudhry, Jagadeesh K. Tangudu **(UTRC)**

Rick Spears **(Tru-design Inc.)**

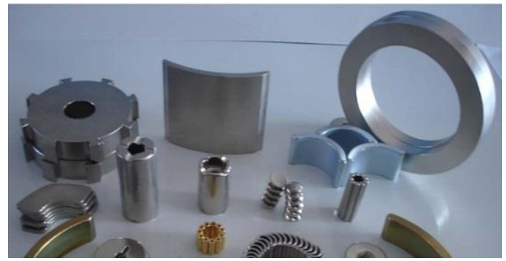
Preston Bryant **(Momentum Technologies)**

Critical Materials Institute
AN ENERGY INNOVATION HUB

Oak Ridge National Laboratory

Rare Earth Permanent Magnet Applications

- PM are widely used in automobiles, hard disk drives, motors, sensors, wind power generators, transducers, loudspeakers, etc.

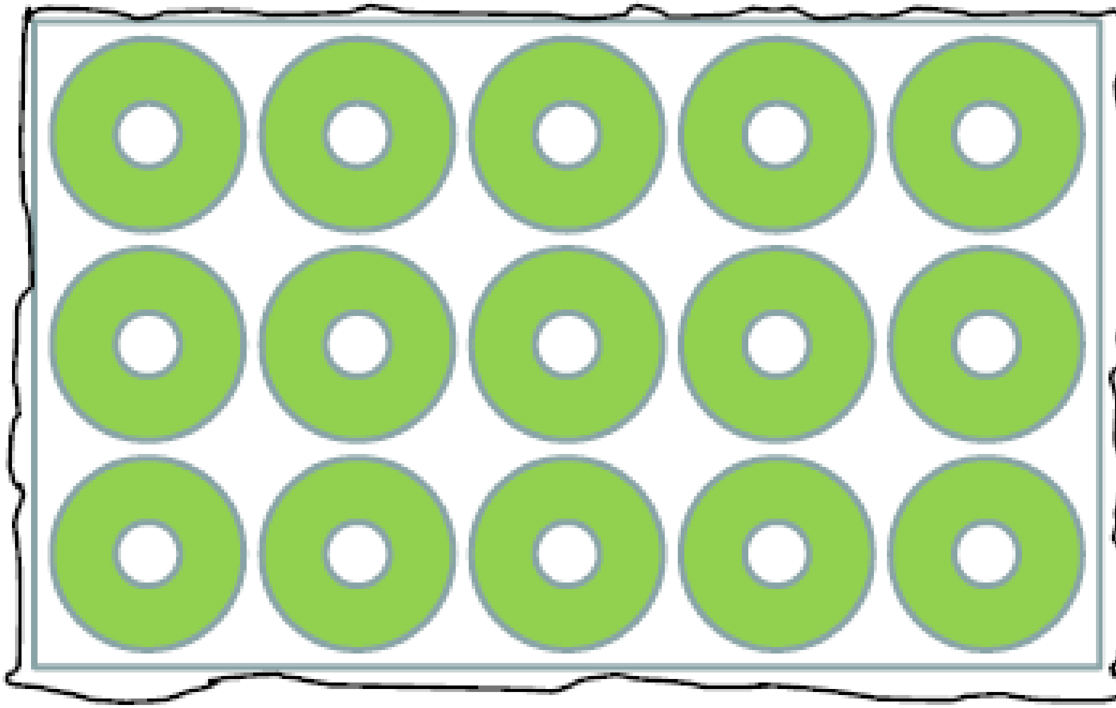


Critical Rare Earths	Rare Earth Magnets	Automobiles
Permanent Magnets Nd (Dy)-Fe-B Sm-Co Global production: 140 tons (2020) Global market: $ 1-2 Billion	Permanent Magnets Nd (Dy)-Fe-B Sm-Co Global market: $ 41.41 Billion (2022) $ 21 Billion (2016) (62% NdFeB)	More than 25+ types of magnets used; Electric and hybrid cars contain 20-25 lbs. of rare earths. Global market: $ 1.7 Trillion (2015)

Present: 90% rare earth world supply – China

10 million tons of RE needed for 2050 (Prof. M. Sagawa)

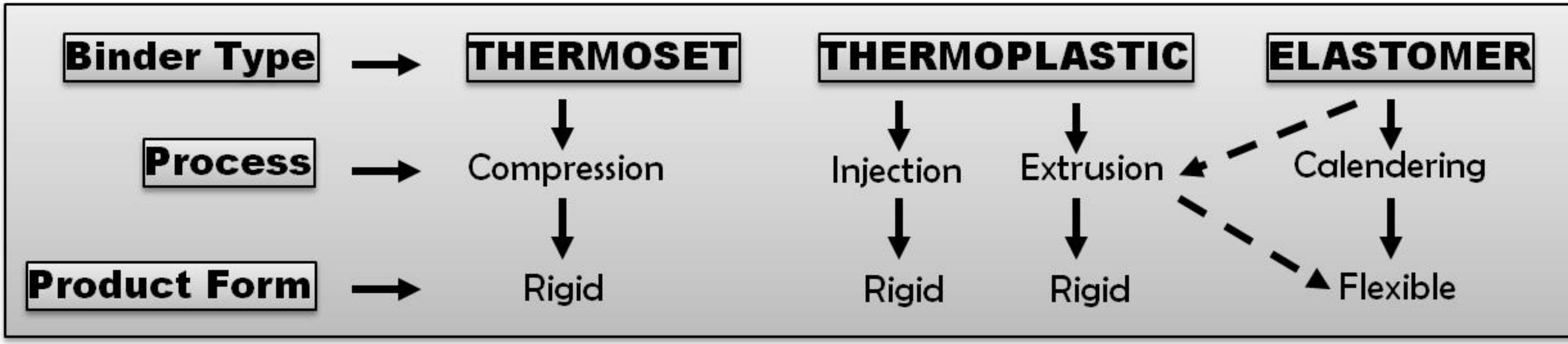
Sintered Magnets – Materials Yield Low



Cored Centers

Utilization – 52%

Bonded Magnets



Processing Type	Vol. Fraction	Br	(BH)max
	Loading	% of sintered alloy	% of sintered alloy
Explosive compaction	81%	81%	65.6%
Compression Bonded	79%	79%	62.4%
Extruded	75%	75%	56.3%
Injection molded, polyamide	65%	65%	42.3%
Injection molded, PPS	61%	61%	37.2%

$(BH)_{max} \sim f^2$

Source: Ormerod, J. & Constantinides, S., J. Appl. Phys. 81, 4816–4820 (1997)

CMI Critical Materials Institute
AN ENERGY INNOVATION HUB

OAK RIDGE National Laboratory

Injection Molded Magnets

Magnetic Materials

- Ferrites
- Nd-Fe-B
- Blends of magnetic materials (Nd-Fe-B; SmFeN)

Binder Types

- Nylon 6 and 12
- PPS (Polyphenylene sulfide)
- Polyamide

Advantages/Disadvantages

- Simple or complex shapes
- Operating temperatures: -40 °C to >180 °C
- No post-finishing is required
- Magnet loading: ~ 65 vol %;
  BH_{max} (injection) < BH_{max} (compression)
- Anisotropic or isotropic – wide range of magnetic alignment possible
- High tooling costs: high volume manufacturing
- Mechanical properties: > sintered magnets

Compression Bonded Magnets

Magnetic Materials

- Nd-Fe-B
- SmCo
- Different grades of materials

Binder Types (thermoset)

- Epoxy (compatible with solvents and automotive fluids)

Advantages/Disadvantages

- Simple shapes (cylinder, rectangular, arc)
- Operating temperatures: -40 °C to >165 °C
- Magnet loading: ~ 80 vol %; BH_{max} (compression) > BH_{max} (injection); but < BH_{max} (sintered)
- Low tooling costs: modest volume manufacturing
- Coated with epoxy to reduce corrosion after shaping
- Mechanical properties: > sintered magnets

Good characteristics of a magnet

- Flux density (B_r); Energy Product (BH_{max})
- Resistance to demagnetization (Hcj)
- Usable temperature range; Magnetization change with temperature (RTC)

- Demagnetization (2nd quadrant) Normal curve shape
- Recoil permeability
- Corrosion resistance; Physical strength

- Electrical resistivity' Magnetizing field requirement
- Available sizes, shapes, and manufacturability
- Material availability and product cost

Physical Properties	Sintered NdFeB	Compression Bonded NdFeB	Injection Molded Bonded NdFeB
Density	7.5-7.8 g/cm^3	5.6-6.0	4.5-5.5
Compressive Strength	850-1050 MPa	80-120	--
Young's Modulus	150-160 GPa	0.7-1.0	--
Tensile Strength	--	37	25-40
Electrical Resistivity	1.2-1.6 μΩm	10-30	40-70
Specific Heat	440 J/(Kg.°C)	400	--
Thermal Conductivity	9 W/(mK)	2	

Source: Steve Constantinides, Arnold Magnetic Technologies

BONDED MAGNETS – Additive Printing

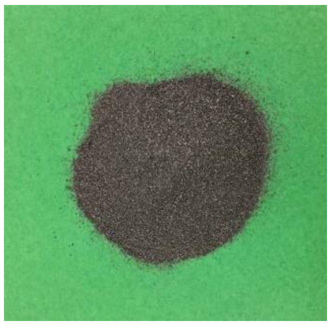
- **Goal:** To fabricate near-net shape NdFeB magnets and to minimize the generated waste associated with magnet manufacturing and reduce the overall cost.

  - One of the ways in which we can achieve this goal is by using additive manufacturing (AM) techniques to create complex shapes and geometries of bonded magnets from a computer aided design which requires little or no tooling and post-processing thus reducing the amount of waste generated.
  - Rapid prototyping: Reduced time to market for new magnet/motor designers.

Magnet Powders: Magnequench MQP and MQA NdFeB (Iso and Anisotropic); Aichi-Steel Dy-free NdFeB Magfine; Sm-Co; SmFeN
Polymers: Nylon; PPS

Schematic Illustration of the BAAM Process

MQP isotropic powder



+

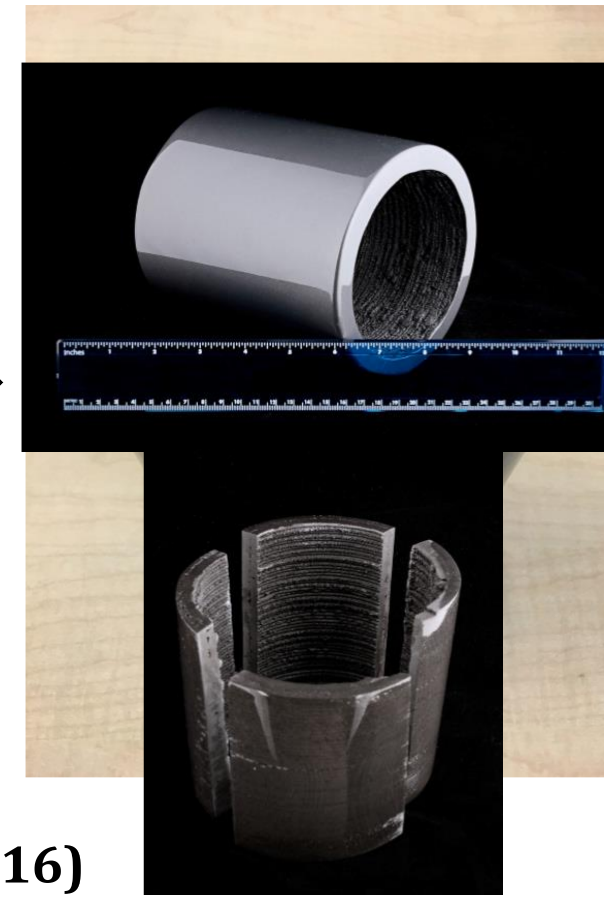
Nylon-12

Mix, melt and extrude

Composite pellets:
65 vol % MQP+ Nylon

BAAM 3D printing

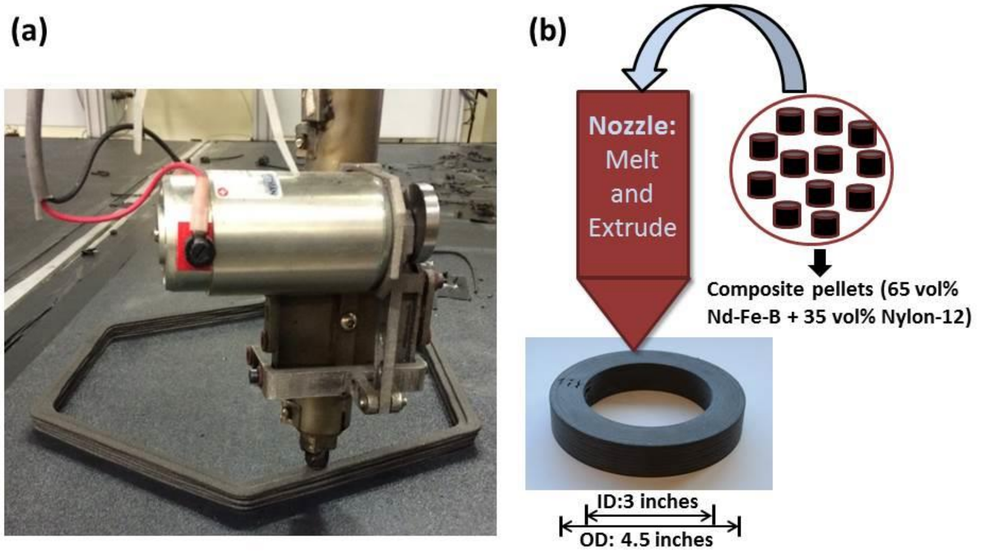
Additively printed NdFeB bonded magnets

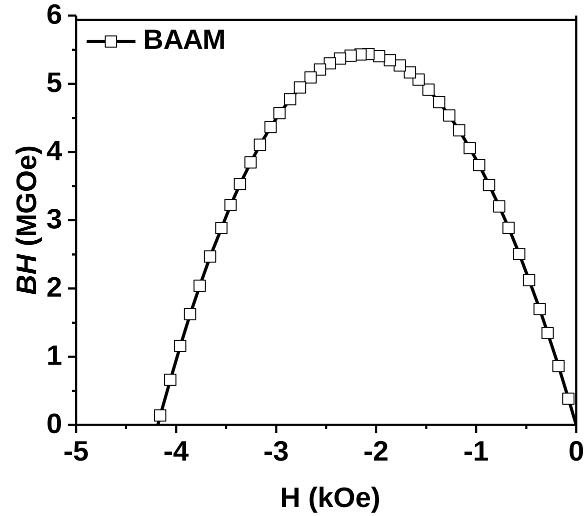


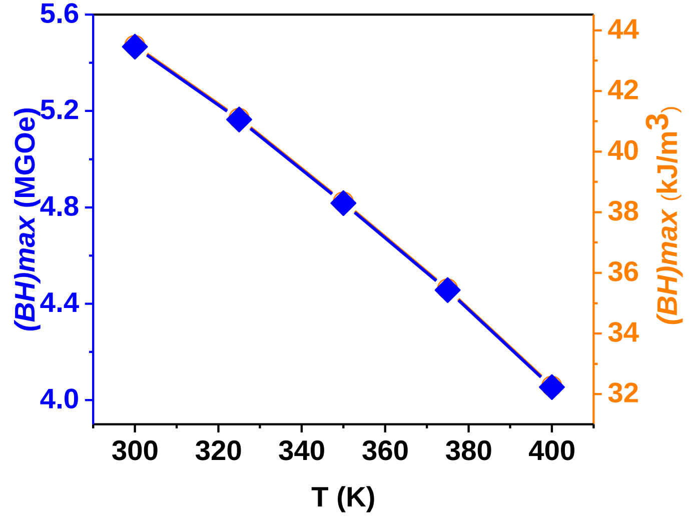
Li, L. *et al., Sci. Rep.* 6, 36212 (2016)

Magnetic Moments, The Economist, Nov. 19, 2016

Big Area Additive Manufacturing (BAAM) of Isotropic NdFeB Nylon Bonded Magnets







Why AM?

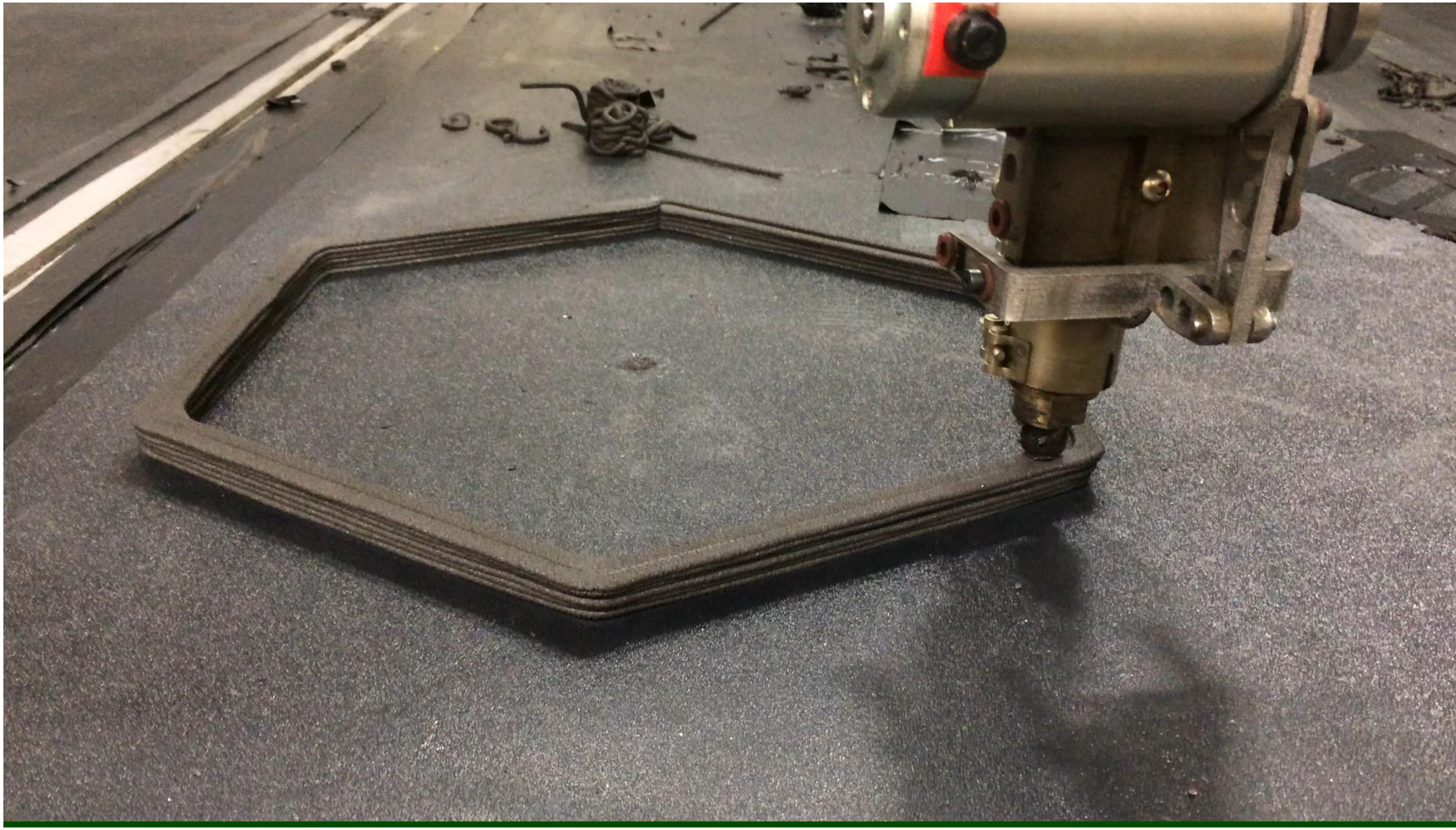
- No tooling required, cost effective
- Minimum critical material (rare earth) waste
- Rapid prototyping
- No limitation in sizes and shapes
- (BH)max = 5.31 MGOe; Density = 4.9 g/cm^3

Critical Materials Institute
AN ENERGY INNOVATION HUB

Li, L. *et al., Sci. Rep.* 6, 36212 (2016)

Oak Ridge National Laboratory

Big Area Additive Manufacturing (BAAM)



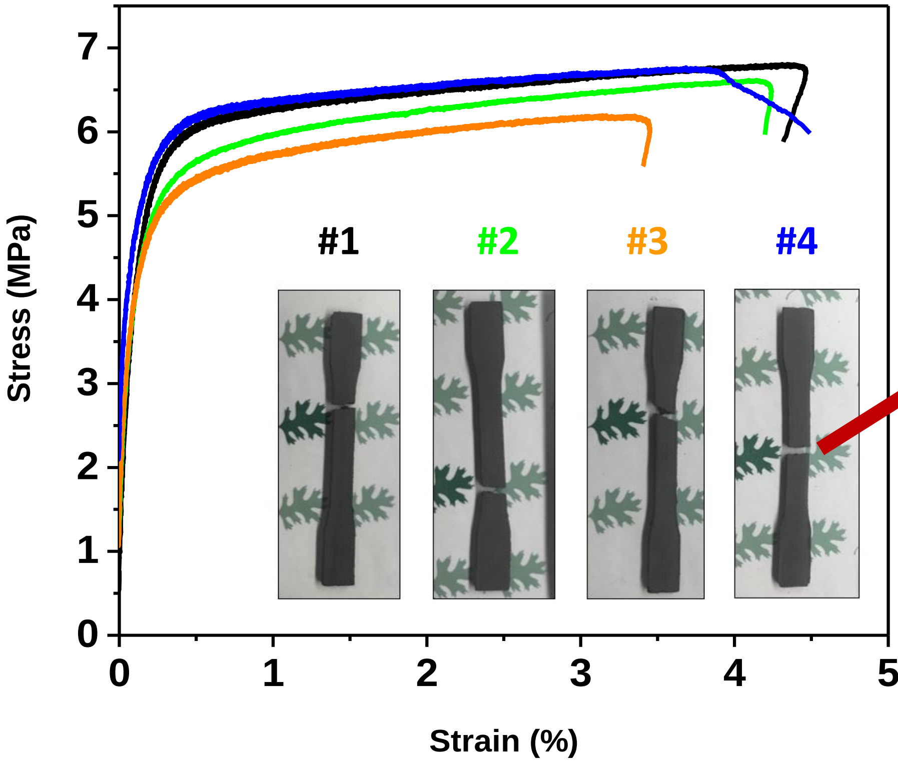
Source: Ling Li, Angelica Tirado, I.C. Nlebedim, Orlando Rios, Brian Post, Vlastimil Kun, R.R. Lowden, Edgar Lara-Curzio, Robert Fredette, John Ormerod, Thomas A. Lograsso, and M. Parans Paranthaman, "Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets," *Nature: Scientific Reports* (2016).

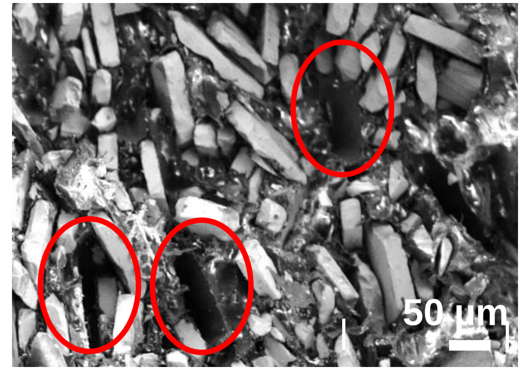
CMI Critical Materials Institute
AN ENERGY INNOVATION HUB

MDF Manufacturing Demonstration Facility

OAK RIDGE National Laboratory

BAAM magnets – Mechanical properties





Fracture is primarily related to the debonding of the magnetic particles from the binder.

Young's Modulus (GPa)	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain
4.29	6.6	4.18%

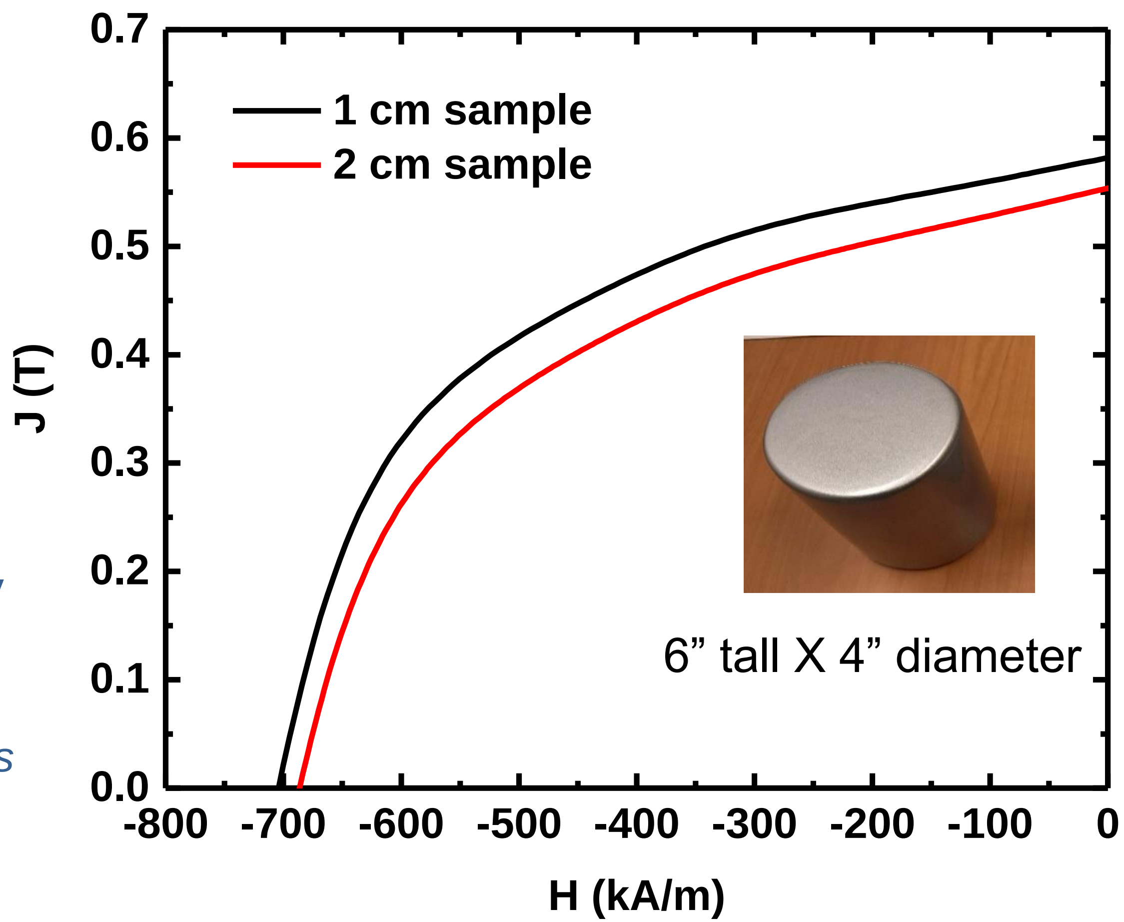
BAAM Magnets Outperformed Injection Molded Magnets with High Magnet Loading in a Polymer

Achievement:

Big Area Additively Manufactured (BAAM) NdFeB bonded magnets with 70 vol % magnets compared to 65 vol % magnets using traditional injection molding in nylon.

Research Details:

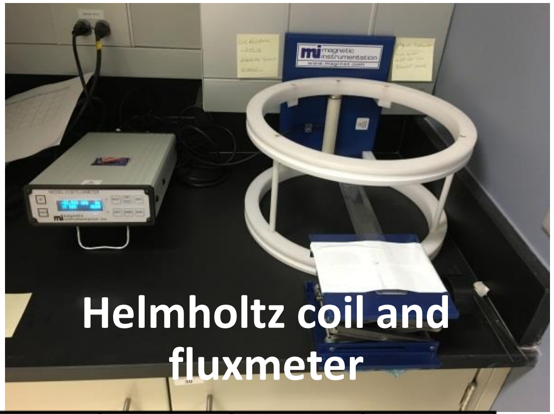
- BAAM magnet has density of 5.15 g/cm^3; intrinsic coercivity *Hci* = 704.2 kA/m; remanence *Br* = 0.58 T; energy product (*BH*)max = 57.7 kJ/m^3 (7.252 MGOe).
- *5% Porosity is present between layers*

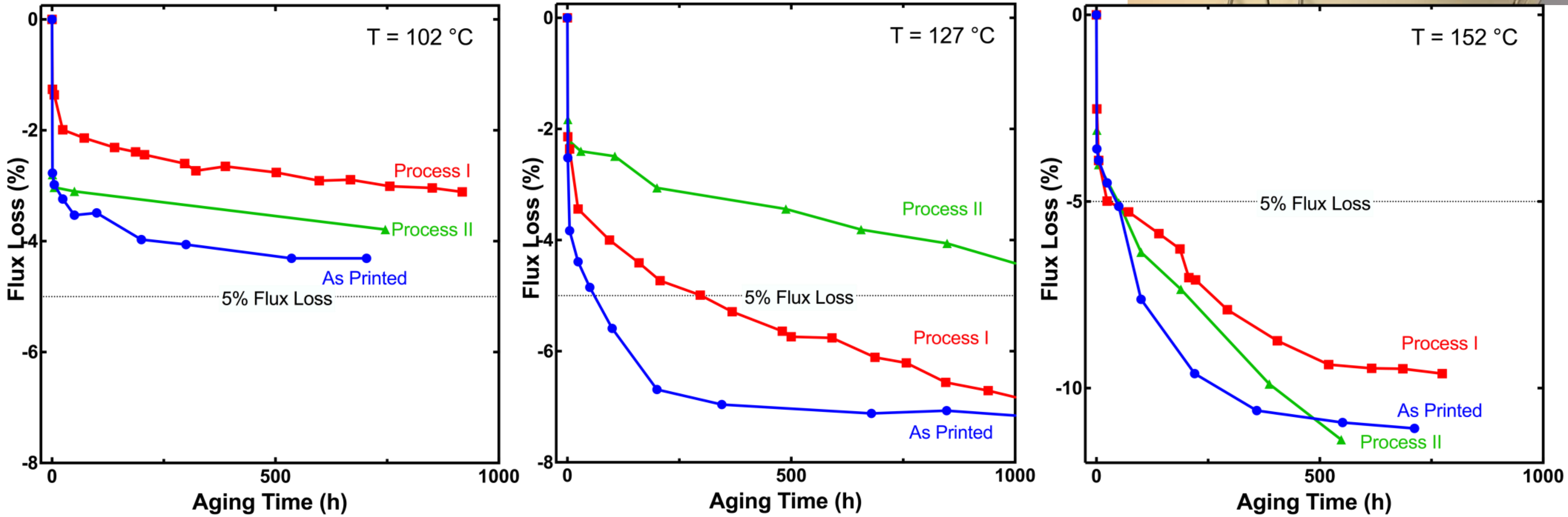


Additive manufacturing can now be applied to produce high energy product magnets

Li, L. *et al., Additive Manufacturing (2018)*

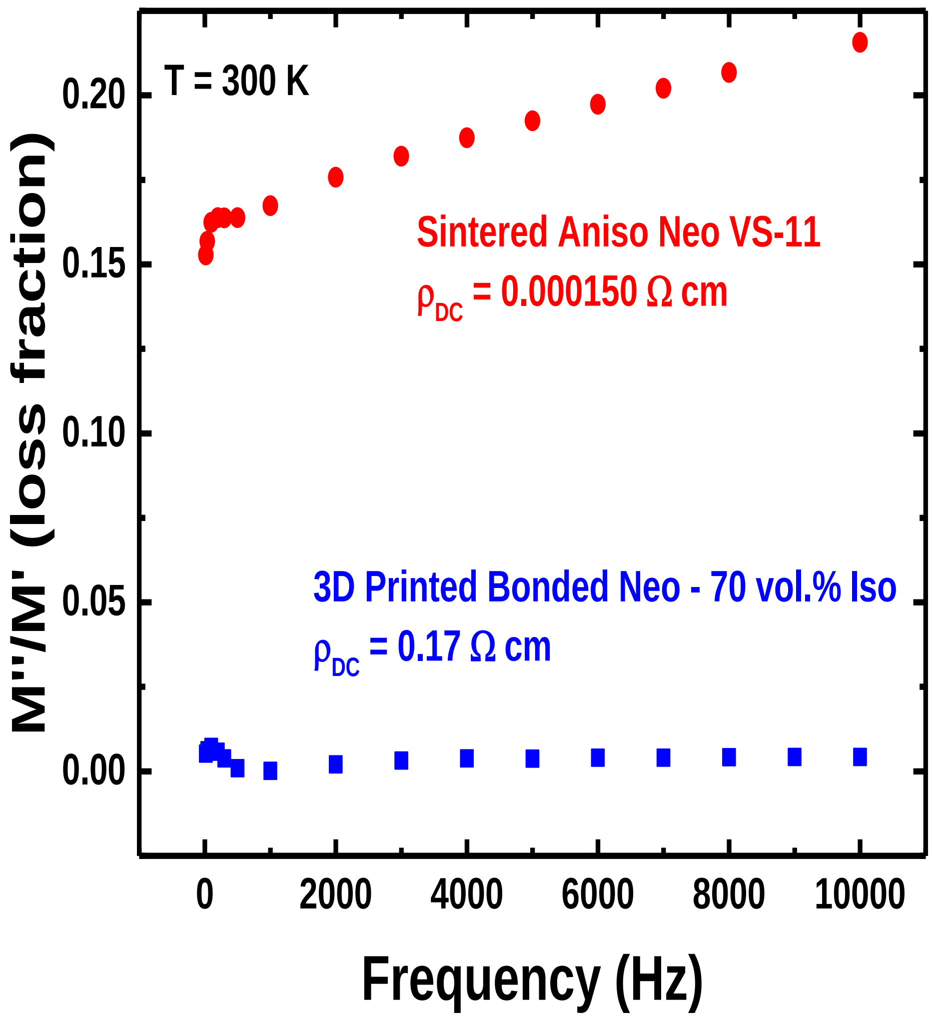
Thermal Stability and Flux Aging Loss of 70 vol% BAAM NdFeB Magnets – Flux Loss





- Stable flux loss for 1000 hours at 77 and 102 °C
- Resin coatings improved the thermal stability and also increased the operation temperature to 127 °C
- Higher temperature stability is limited by the starting magnet composition

AM magnets outperformed Sintered NdFeB magnets with Reduced Eddy Current Loss and Improved High Resistivity

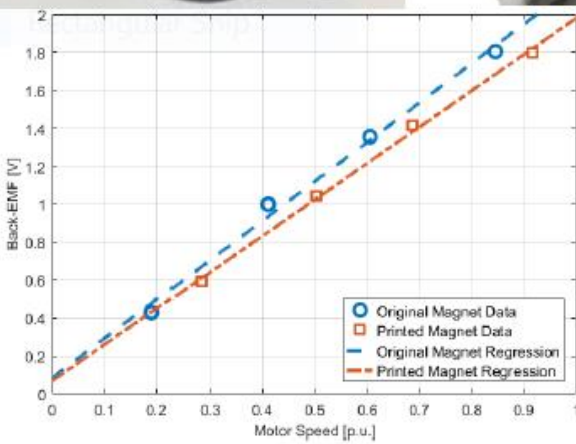


- Eddy current heating in large motors with permanent magnets can be significant
- Often eddy current heating is reduced by slicing the permanent magnets into smaller pieces
- Demonstrated the potential of using additively printed NdFeB magnets instead of standard magnets in motors where we can approximately achieve 1000 times less eddy current loss

Successful Demonstration of AM Printed NdFeB Magnets in a DC Motor Configuration

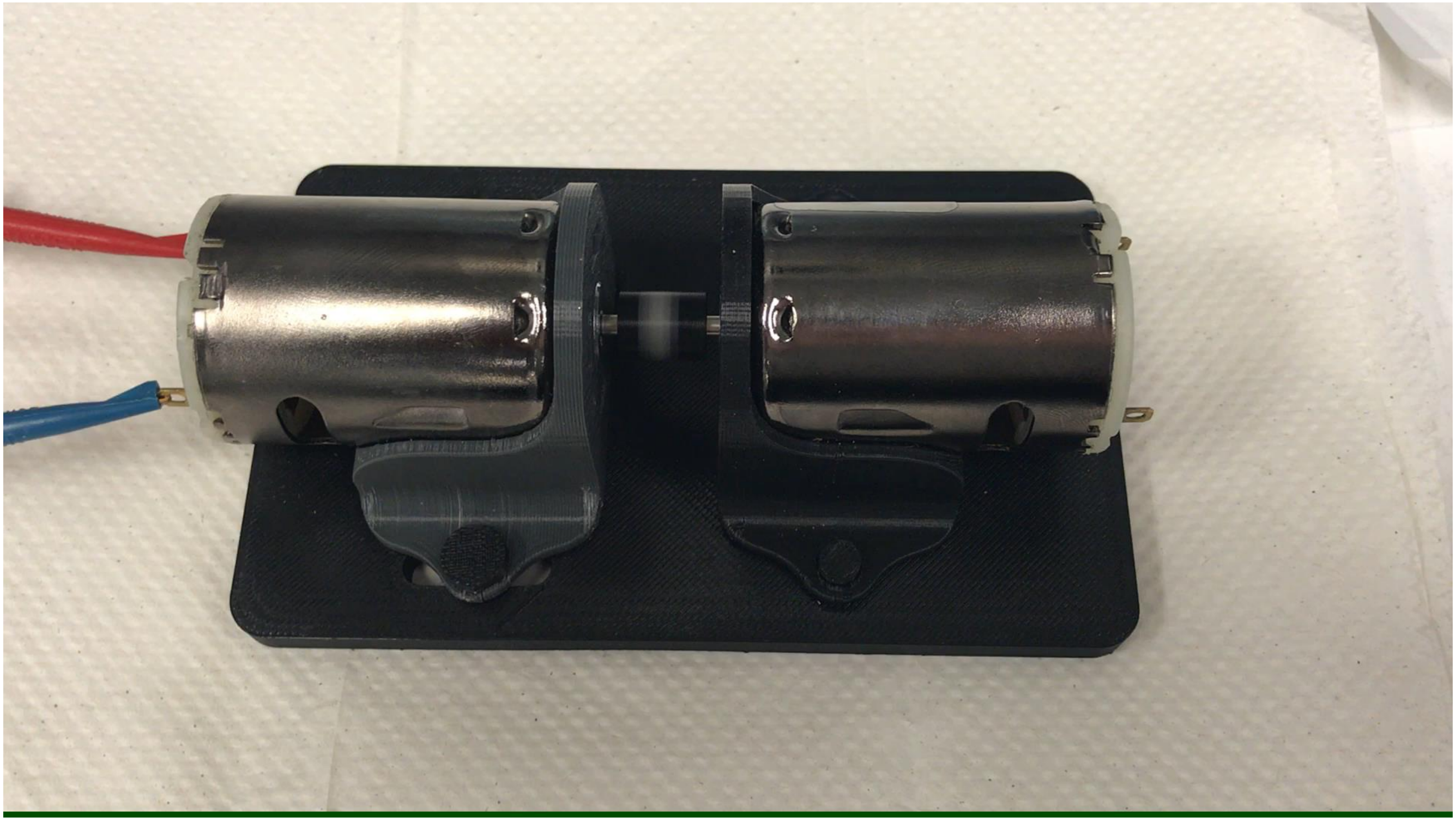
Printed Magnet Motors

- Replace sintered ferrite with printed NdFeB
- 3D printed small mounting plates for back-to-back testing

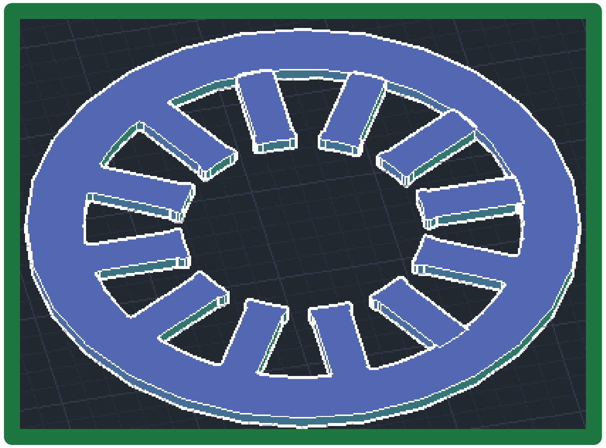


This work has demonstrated the potential of using additively printed NdFeB magnets instead of sintered ferrite magnets in motors

Applications – AM NdFeB Magnets in a DC Motor Configuration



Prototyping and Printing Stators and Rotors for Electric Motors and Induction Rotors



CAD Model

Binderjet Printed Stators
(Cu infiltrated Steel)

BAAM NdFeB Magnets

Moonshot: AM Motors (stators and rotors)

Summary

- Big Area Additive Manufacturing (BAAM) has been successfully used to fabricate near-net-shape isotropic NdFeB bonded magnets.
- Magnetic and mechanical characterizations demonstrate that the BAAM fabricated magnets can compete with or outperform the injection molded magnets.
- Additive manufacturing offers significant advantages such as cost effectiveness (no tooling required), fast speed (simple procedure), and capability of producing parts of unlimited in sizes and shapes.
- Effect of binder type, loading fraction of the magnetic powder, anisotropic particles, and processing temperature on the magnetic and mechanical properties of the printed bonded magnets will be investigated.