NREL
Transforming ENERGY

An Assessment of Additively Manufactured Bonded Permanent Magnets for a Distributed Wind Generator

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Photo by Dennis Schroeder, NREL 55200

Small and Distributed Wind Turbines: Some Challenges and Trends

Next decade in U.S. → capacity growth of 144 GW is expected.

Challenged by:

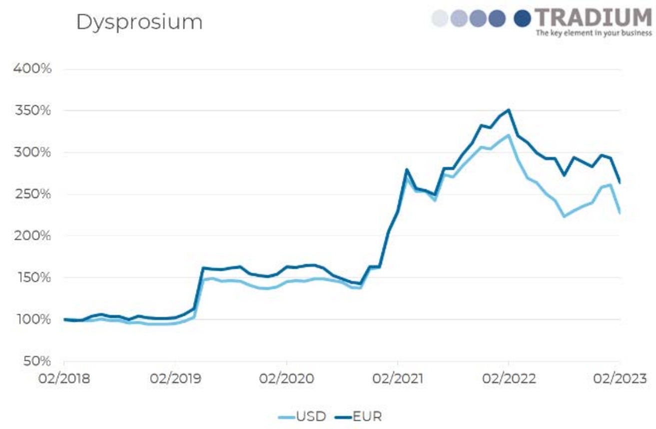
- Increasing costs of manufacturing
- Cost uncertainties of permanent magnets (PMs).

Original equipment manufacturers predominantly use direct-drive permanent magnet synchronous generators (PMSGs)

- PM mass typically between 5 and 15 kg
- The costs to manufacture these generators have risen nearly twofold (Bergey 2021).

March 30, 2017 - A photo of a Bergey excel 15 wind turbine. *Photo from Bergey Windpower*

December 14, 2010 - Primus WindPower Air 40 wind turbine. *Photo from Primus WindPower*



Volatile cost increase dysprosium. *Graph from Strategic Metals Invest (2023)*

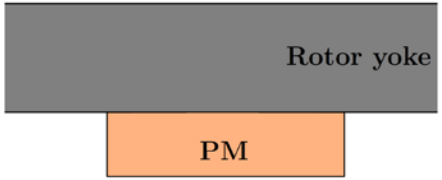
Key goals for OEMs and our approach

- Improving generator efficiency
- Lower material costs from magnets
- Cost-competitive manufacturing.

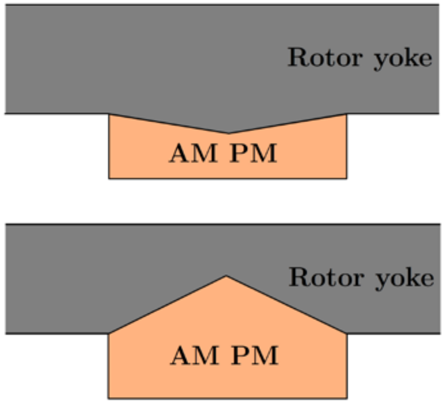
Goal: Lower the generator's fabrication cost by at least 25% (NREL 2021).

Our approach:

- To investigate Additive manufacturing (AM) of magnets for Bergey Windpower Co.'s 15-kW turbine system
- Explore alternative magnet shapes that are more expensive to manufacture (tooling costs, machining)



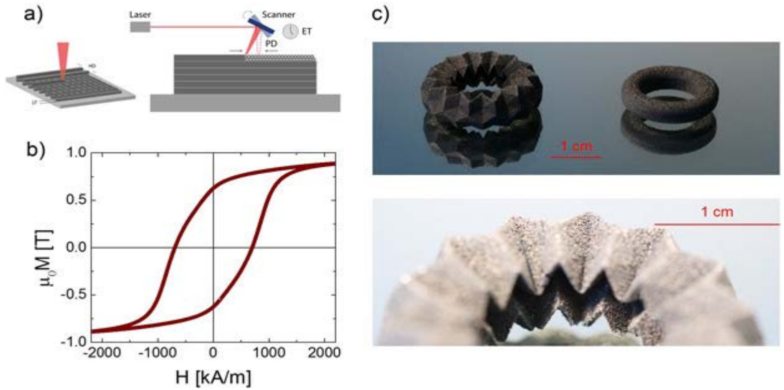
Baseline conventional arc-shaped magnet.



Alternative magnet shapes realized by additive manufacturing.

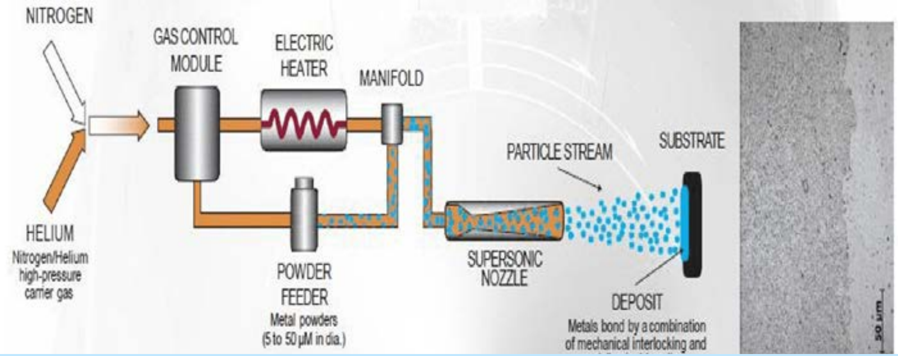
Recent Trends in Magnet AM

Laser additive



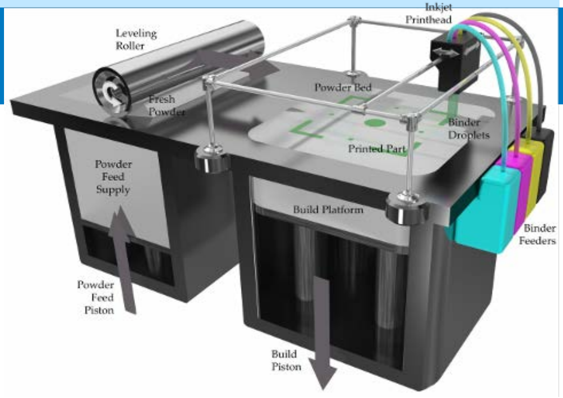
Spherical particles are needed – isotropic NdFeB – low energy product

Cold-spray additive



Spherical particles are needed – isotropic NdFeB – low energy product

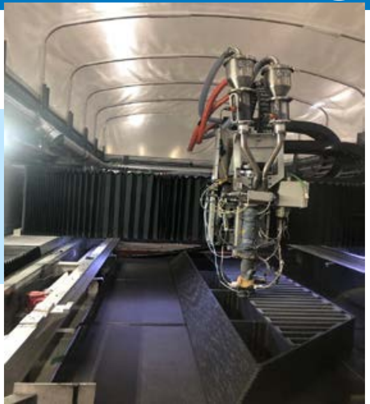
Binder Jetting



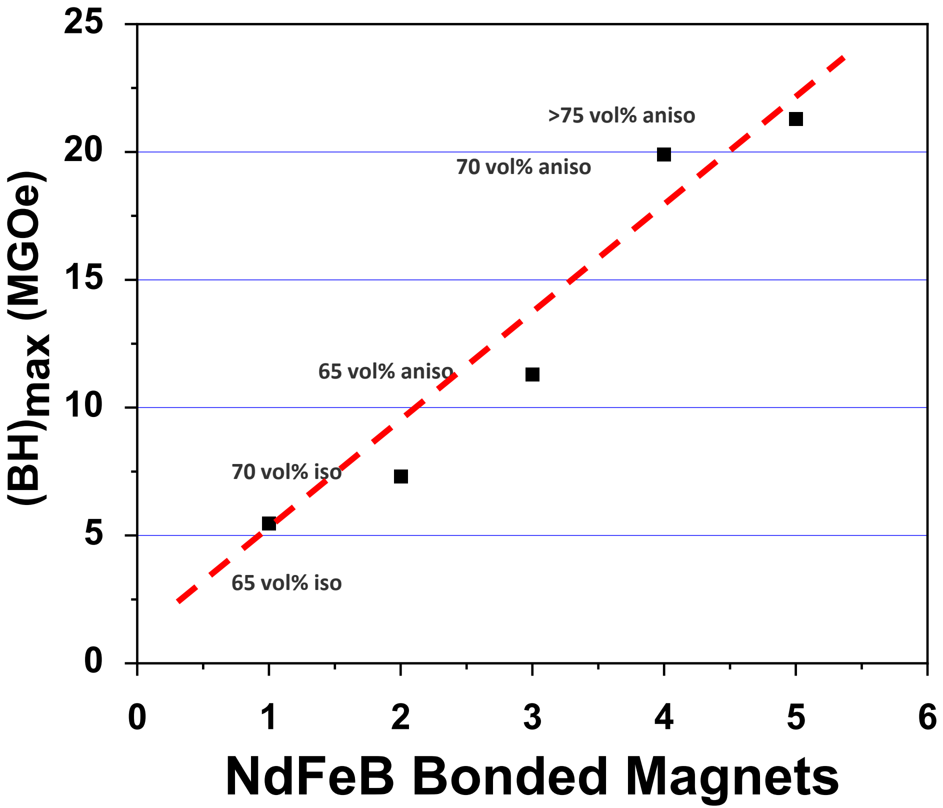
No shape preference, achieving full density with permanent magnets has been difficult

Fused deposition modeling

Highest energy product (24MGOe)
Only polymer bonded magnets
ORNL-BAAM system



BAAM Magnets demonstrated gap magnets with highest energy product with post-annealing (Aniso with >70 vol% magnet loadings)



Kinjal Gandha, Ikenna Nlebedim, Parans Paranthaman et al., Scripta Materialia (2020); Xubo Liu et al. (in preparation)

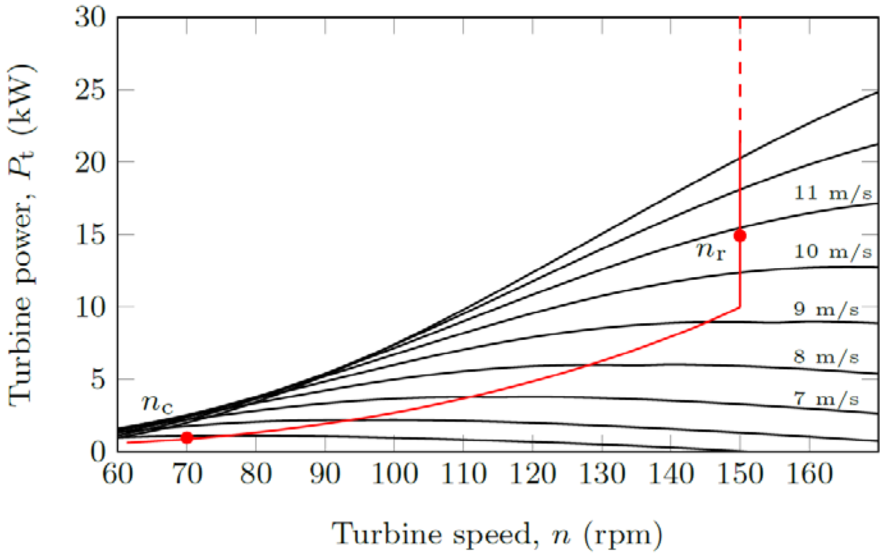
- ✓ Additively printed magnets outperformed injection molded magnets and approaching compression molded magnets
- ✓ High resistivity (3X sintered magnets)
- ✓ Eddy current loss (1000↓ sintered magnets)
- ✓ 100% recyclability
- ✓ Improved corrosion resistance
- ✓ Mechanical properties
- Lower energy product

Utilize BAAM-manufactured bonded magnets

Generator design for the Bergey Wind Turbine Specification

Operating points:

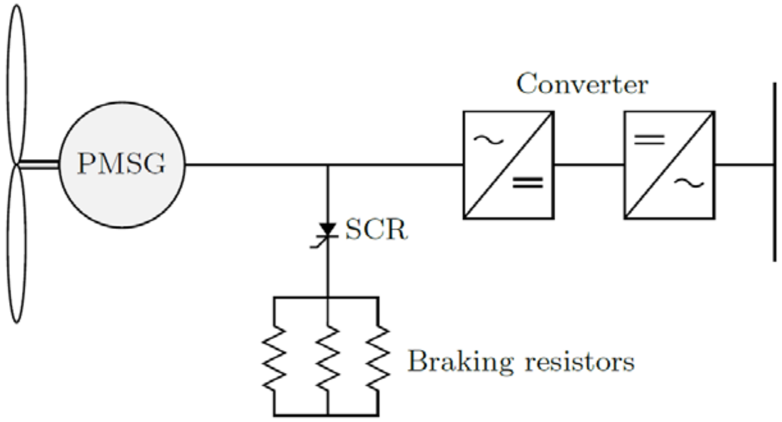
- Rated operation, 15 kW, at turbine speed of 150 rpm and wind speed ≈ 11 m/s
- Minimum stalling power of 40 kW for electromagnetic braking.



Turbine power versus speed curves with specified operation.

Drivetrain Specification

- The designed generator is assumed to be connected to grid via back-to-back full rated frequency converter.
- The original system uses a diode bridge rectifier with a grid-tie converter.



Direct-drive PMSG wind energy system with active control and passive electric braking (Illustration by NREL)

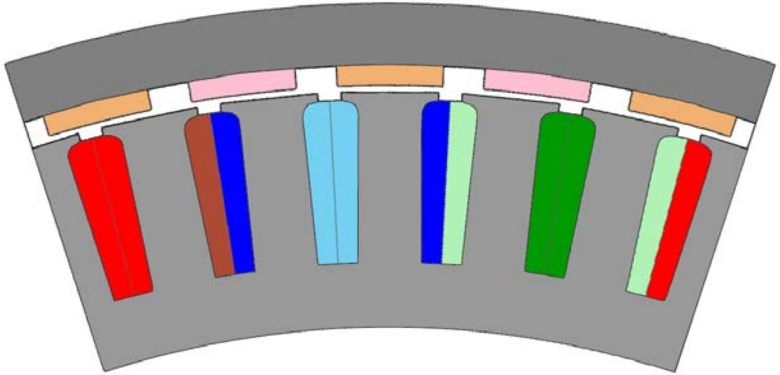
Baseline Generator Design

PM Wind Generator

- Radial-flux topology
- Outer rotor
- Surface-mounted permanent magnets on the rotor
- Fractional-slot concentrated winding.

Slot-pole combination

- 60 slots – 50 poles.

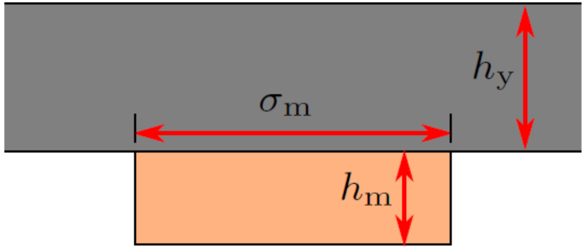


Baseline 15-kW Bergey Windpower Co. outer-rotor surface-mounted PMSG.

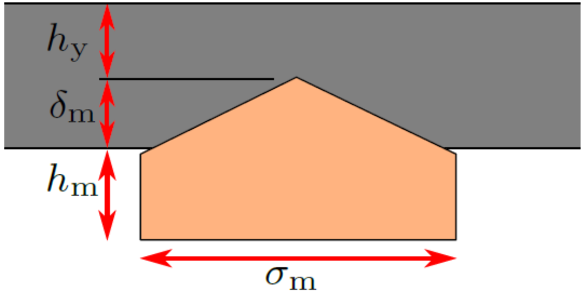
Magnet Shaping

- Retain the stator design of the baseline generator
- Alter the rotor yoke and the PM dimensions.

Designs optimized on paper:



Arc-shaped magnet



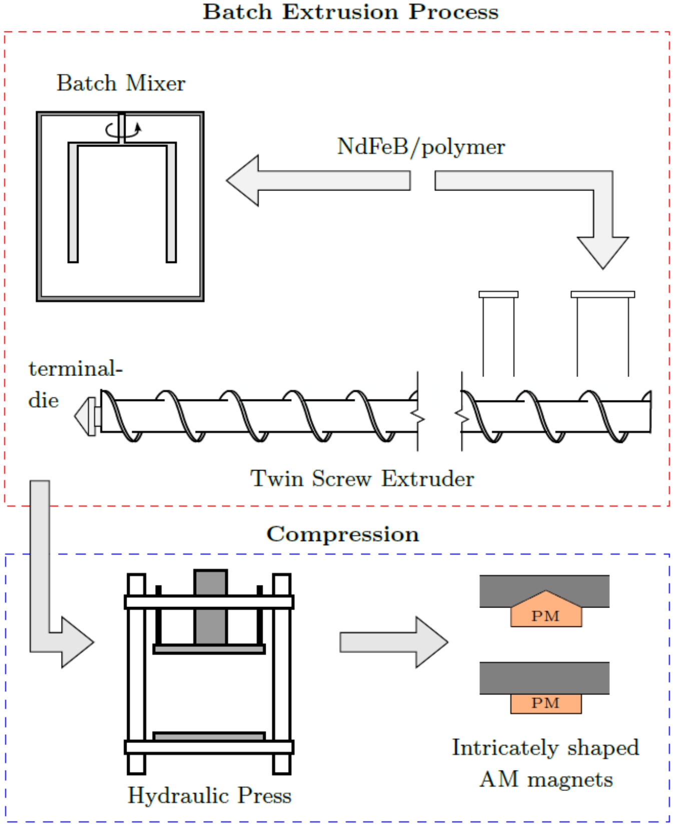
Crown-shaped magnet

→ Investigate N48H and 75 vol% AM magnets for both shapes.

Additive Manufacturing for the proposed shapes

- Near-net magnet shapes compressed onto rotor using a 3D-printed mold (*indirect additive manufacturing*)
- Followed by post-magnetic annealing process.

Raw samples of an AM 75 vol% NdFeB-SmFeN magnet used to measure B-H curves.



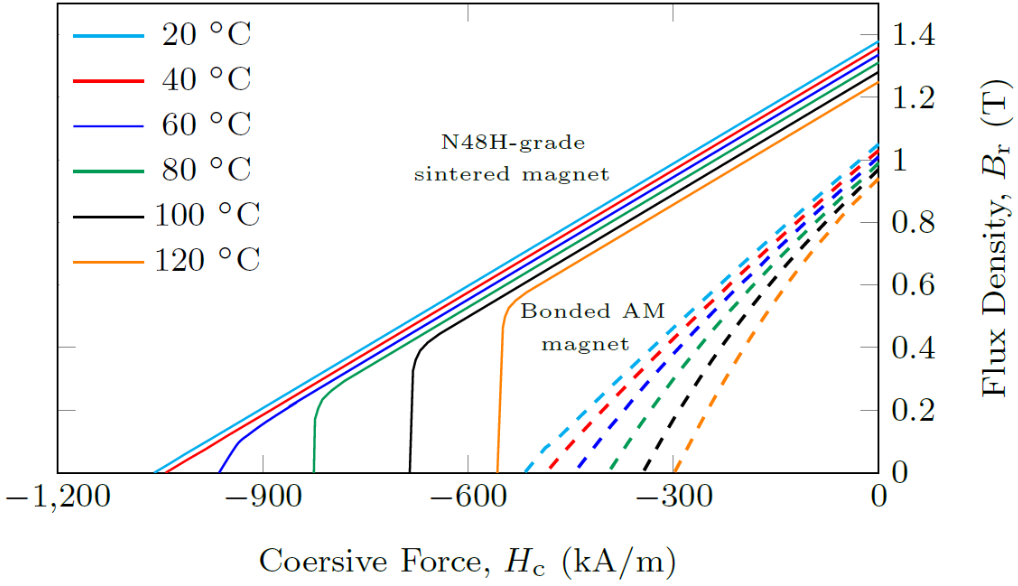
A comparison of demagnetization curves

N48H neodymium magnets:

- Used in baseline generator
- High-energy product
- Low demagnetization knee point.

AM bonded magnets:

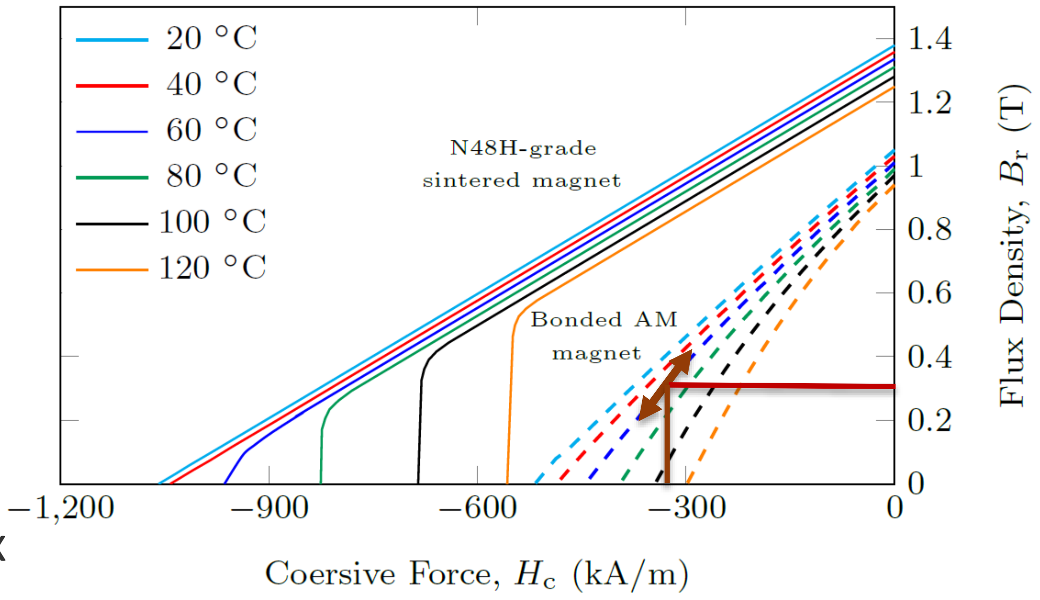
- “Linear” like curves – **NO clear knee**
- 75 vol% Magfine NdFeB-SmFeN in nylon polymer binder magnets.



Demagnetization curves for N48H NdFeB magnets and 75 vol% NdFeB-SmFeN printed bonded magnets.

Demagnetization Threshold for AM Magnets

- Assume steady-state magnet temperature will not exceed $\boldsymbol{T_{PM} = 60}$ ^{0}C
- Knee point between $\boldsymbol{B_r = 0.2}$ T and $\boldsymbol{0.4}$ T.



Minimum allowable remnant flux density in AM magnets:

$$\boldsymbol{B_{r-min} = 0.3} \text{ T}$$

Demagnetization curves for N48H NdFeB magnets and 75 vol% NdFeB-SmFeN printed bonded magnets.

A comparison of AM bonded magnet with sintered magnet

- Weaker compared to N48H grade NdFeB

  (superior to commercially available bonded magnets).
- Much higher resistivity
- Lower mass density

N48H and 75 vol% NdFeB-SmFeN AM magnet properties at 313.15 K

	N48H NdFeB	75 vol% NdFeB-SmFeN
B_r, (T)	1.36	1.03
H_{ci} (intrinsic), (kA/m)	1,200.0	859.4
H_c (normal), (kA/m)	1,041.7	485.9
BH_{max}, (MGOe)	45	20
Density, (kg/m^3)	7,600	6,150
Resistivity, (Ω·m)	1.5×10^{-6}	0.0258

These properties were used to model the magnets in commercial magnetic FEA tool

Optimization Approach

Global response surface method (GRSM) used for the optimization

Objective function:

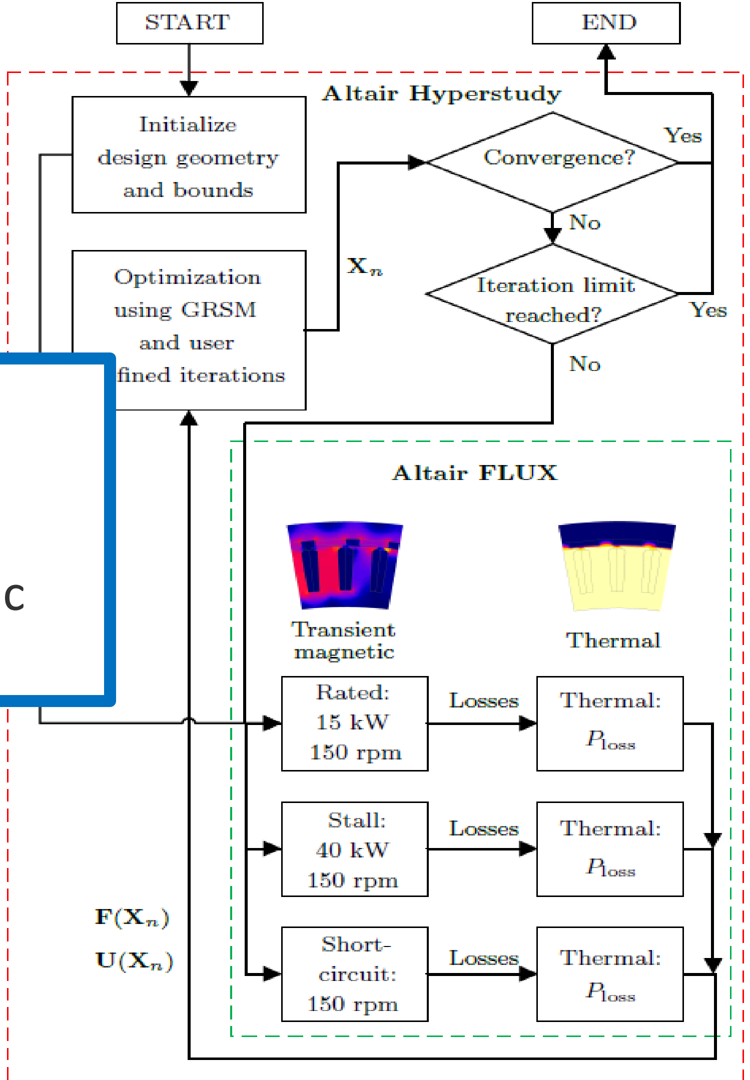
- Minimize PM mass

Solved for:

- Rated operation
- During stalling
- Three-phase symmetric short-circuit fault

Constraints:

- *Rated power*
- *Efficiency*
- *Stalling power*
- B_{r-min} *(stalling/SC)*
- *Winding temperature*
- *Cogging torque*



Results: PM Material Cost

Estimate cost with per-unit (p.u.) values:

- N48H NdFeB = 1 p.u.
- 75 vol% AM = 0.55 p.u.

Material		N48H NdFeB		75 vol% NdFeB–SmFeN	
Magnet shape	Baseline	Conv.	Crown	Conv.	Crown
h_m (mm)		3.0	3.0	5.62	5.89
σ_m (p.u.)		0.69	0.689	0.658	0.658
h_y (mm)		15.09	16.48	14.4	10.8
δ_m (mm)		-	-0.21	-	-0.626
M_{PM} (p.u.)	1.0	0.59	0.56	0.85	0.84
C_{PM} (p.u.)	1.0	0.59	0.56	0.47	0.46
P_{rated} (kW)		15.0	15.0	15.0	15.0
η (%)		96.9	96.1	97.1	97.1
P_{stall} (kW)		40.0	40.0	40.0	40.0
$B_{r\text{-}min}$ (T)		0.456	0.453	0.302	0.304
T_{Cu} (°C)		73.6	73.4	74.2	74.5
τ_{cog} (Nm)		24.8	24.7	24.1	24.0
				0.005	0.005
				168.2	165.7
				110.6	115.3
				265.5	271.1
				0.87	0.85
				1.46	1.47
				48.5	48.8
				156.5	155.2

Results:

- Optimized designs with N48H-grade magnets use between 24% and 30% less PM material.
- 13% reduction of PM material cost is possible when using AM magnets.

Comments on Performance

AM magnet designs use more magnet material:

- Expected result
- Same performance
- Negligible eddy current losses in the magnets.

Material		**N48H NdFeB**		**75 vol% NdFeB–SmFeN**	
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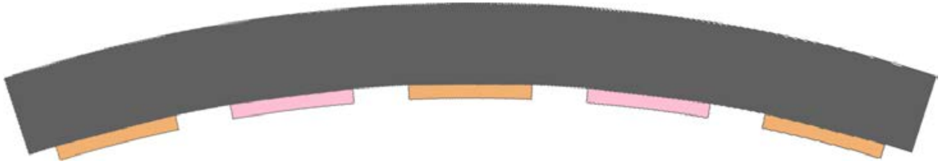
η (%)		96.9	96.1	97.1	97.1
P_{stall} (kW)		40.0	40.0	40.0	40.0
$B_{r\text{-}min}$ (T)		0.456	0.453	0.302	0.304
T_{Cu} (°C)		73.6	73.4	74.2	74.5
τ_{cog} (Nm)		24.8	24.7	24.1	24.0
Loss breakdown:					
- P_{PM} (W)		54.5	55.4	0.005	0.005
- P_{Stator} (W)		249.2	239.1	168.2	165.7
- P_{Rotor} (W)		110.2	122.4	110.6	115.3
- P_{Cu} (W)		171.0	180.1	265.5	271.1
B_g (T)		1.02	1.11	0.87	0.85
I_{peak} (p.u.)	1.0	1.17	1.20	1.46	1.47
T_{PM} (°C)		54.5	55.4	48.5	48.8
$T_{Cu\text{-}SC}$ (°C)		208.0	196.9	156.5	155.2

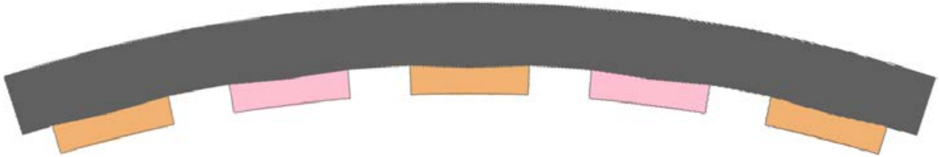
Crown-Shaped Design

Slight mass reduction possible using crown-shaped design:

- *Negative crown height.*



Optimized crown-shaped magnet for N48H-grade magnet rotor



Optimized crown-shaped magnet for 75 vol% AM magnet rotor

Conclusions

PM material cost reduction is possible using AM bonded magnets.

- *Similar performance possible at lower costs*
- *More compelling for generator manufacturers.*

Crown-shaped magnets resulted in magnet mass-reduction advantage.

- Possible with design freedom of AM
- Could further improve with more intricate AM magnet shapes.

Thank You.

Questions?

www.nrel.gov

NREL/PR-5000-86192

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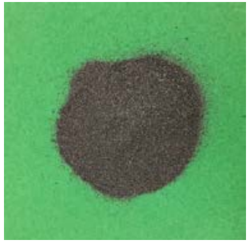
Big Area Additive Manufacturing (BAAM) Process

MQA anisotropic powder

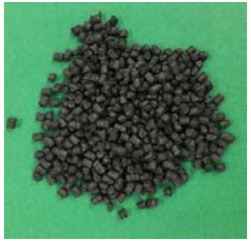


+

Nylon-12

Mix, melt and extrude

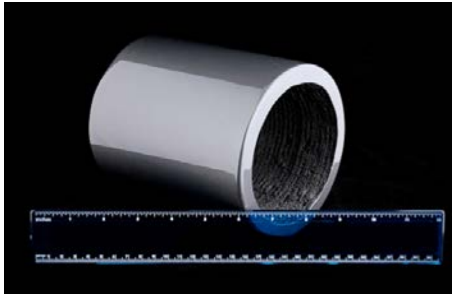
Composite pellets:
70 vol % MQA+ Nylon

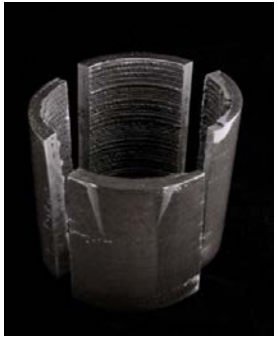


BAAM printing

R&D 100

Additively printed NdFeB bonded magnets

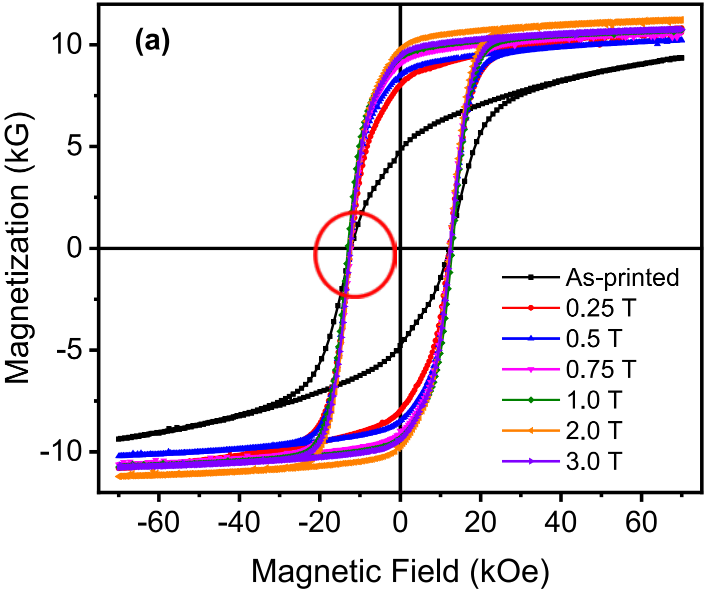




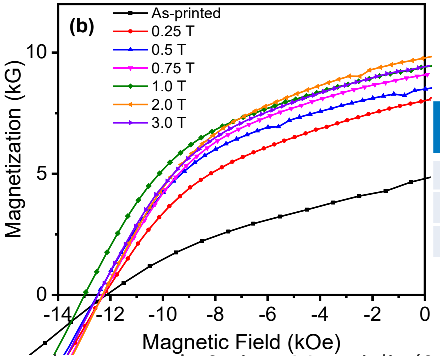
https://web.ornl.gov/sci/manufacturing/mdf/

Li, L. *et al., Sci. Rep.* 6, 36212 (2016); *Additive Manuf.* 21, 495 (2018)
Magnetic Moments, The Economist, Nov. 19, 2016; K. Gandha et al., J MMM (2019); Scripta Materialia (2020)
Frontiers of Materials Research 2019 (National Academy of Sciences; p.2-26)

Post-annealing of printed NdFeB bonded magnets under magnetic fields improve remanence and energy product



Alignment Field (T)	B_r (kG)	Hc (kOe)	$(BH)_{max}$ (MGOe)
As-printed	4.8	12.1	4.4
0 .25	8.0	12.2	12.6
0.5	8.5	12.5	14.8
0.75	9.0	12.3	16.6
1.0	9.4	13.0	17.6
2.0	9.8	12.3	18.6
3.0	9.4	12.5	17.5



@ 0.75 T

Samples	Hc (kOe)	Br(kG)	$(BH)_{max}$ (MGOe)
Sample # 1	12.2	10.1	19.9
Sample # 2	12.3	9.7	18.4
Sample # 3	12.3	9.0	16.6

- Reversible temperature coefficients of remanence, α (−0.09%/K), and the reversible thermal coefficient of coercivity, β (−0.53%/K).
- These parameters represent the rate of change in B_r and H_c, respectively, with temperature

Kinjal Gandha, Ikenna Nlebedim, Parans Paranthaman et al., Scripta Materialia (2020)

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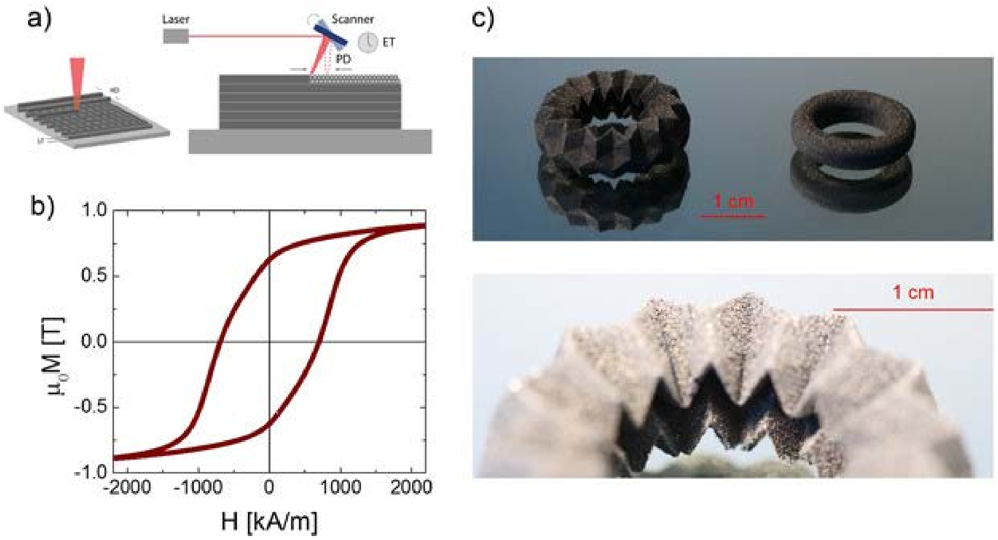
Directed Energy Deposition

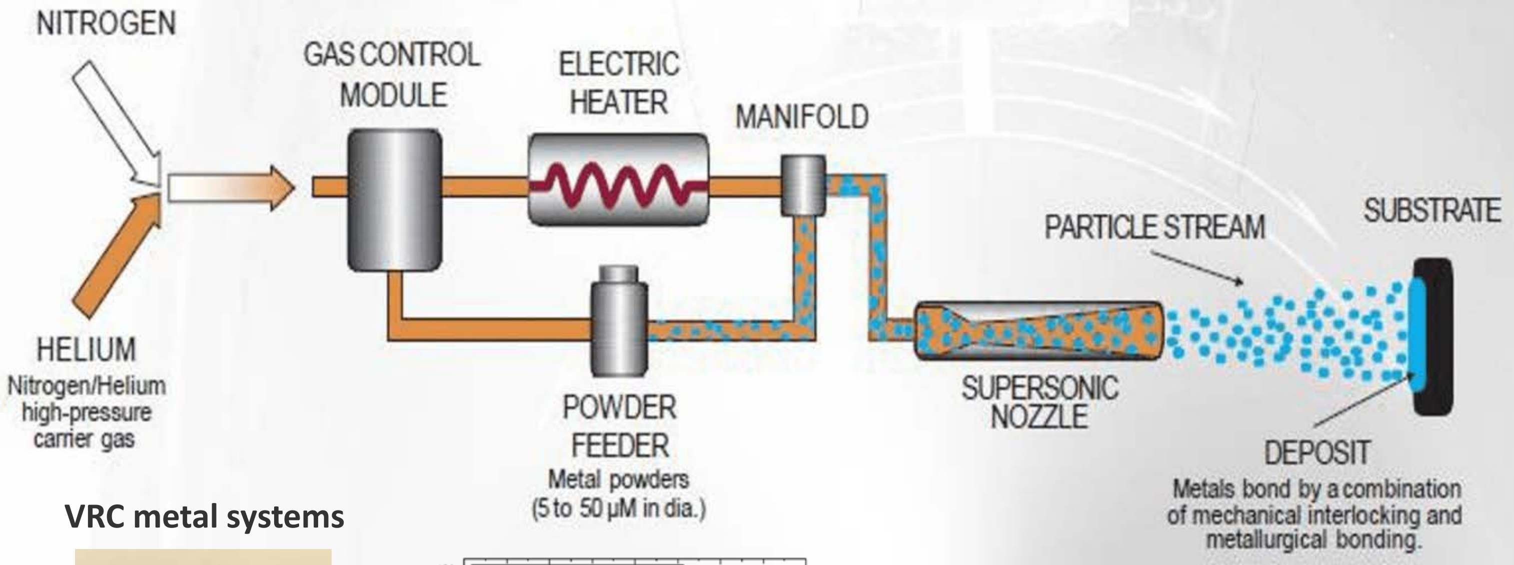


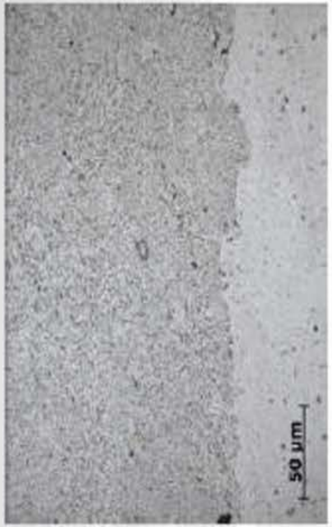
(a) Schematic illustration of the 3D printing method of magnet fabrication.
(b) Full magnetic hysteresis loop for a 3D printed brick like sample ($10 \times 10 \times 10$ mm^3) with H_c = 695 kA m^{-1} and B_r = 0.62 T, at room temperature.
(c) Photograph of printed magnets of various shapes. The left object has an internal channel that adds a novel functionality (cooling channel) to the hard magnets (see zoom on bottom right part of figure). The complexity of the object is just an illustration of the geometric potential of SLM of NdFeB.

Jacimovic, Jacim, et al. "Net shape 3D printed NdFeB permanent magnet." Advance Engineering Materials 19 (8), 1700098.

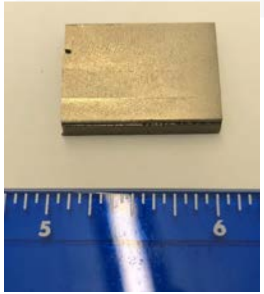
Spherical particles are needed – isotropic NdFeB – low energy product

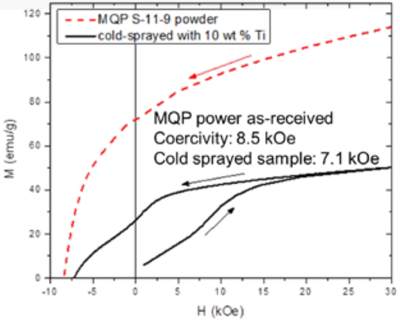
Cold spray



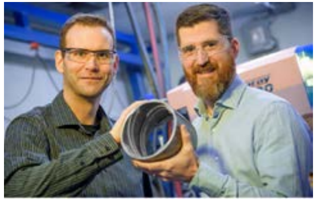


VRC metal systems





Successfully fabricated NdFeB metal composite magnets



NRC, Canada

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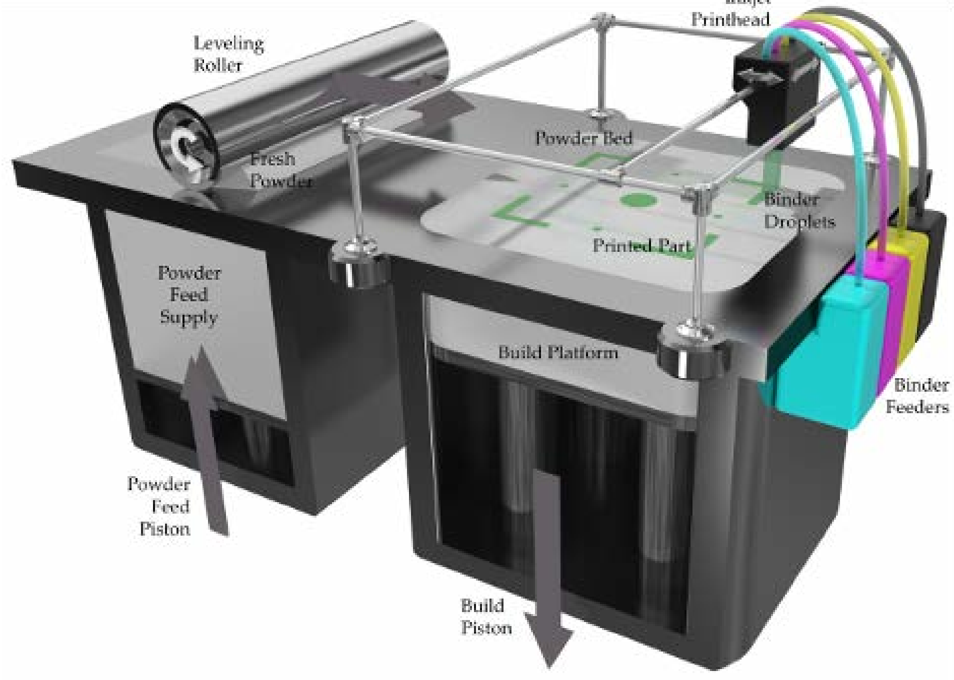
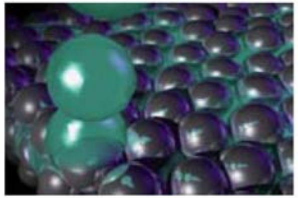
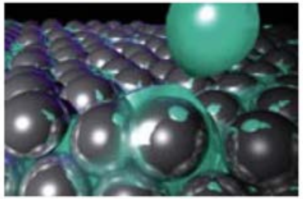
Spherical particles are needed – isotropic NdFeB – low energy product

Binder jetting works by selectively depositing binder into a powder bed via inkjet





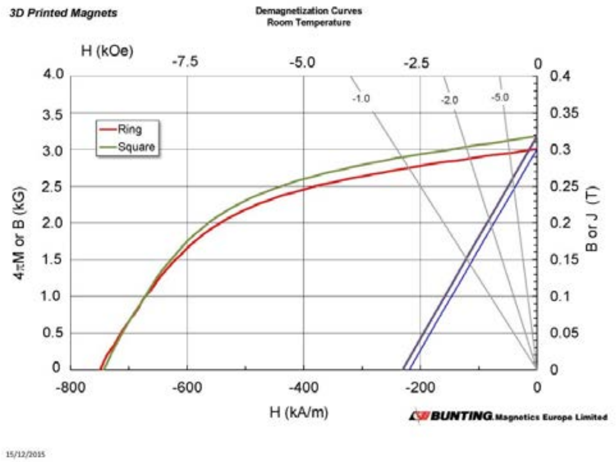


Printing is followed by curing, depowdering, sintering and infiltration

Paranthaman, M. P. *et al.*, *JOM* 68, 1978–1982 (2016)

Successful printing of MQP NdFeB magnets using ExOne Binder Jet process

1 x 1” Neo square/ring magnets
(bonded magnet; sintered magnet)



Successfully printed several near-net shape magnets followed by a polyurethane clear coat to achieve a smooth surface with no magnetic property degradation

Bonded magnets produced through this additive process are ~ 45 vol %

Paranthaman, M. P. *et al.*, *JOM* 68, 1978–1982 (2016)

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