Permanent magnets produced by cold spray additive manufacturing

Lamarre, Jean-Michel; Bernier, Fabrice

NRC·CNRC

Permanent Magnets Produced by Cold Spray Additive Manufacturing

Jean-Michel Lamarre & Fabrice Bernier
Research Officers

Magnetics 2017
Orlando
January 19th 2017

Funded by:
Vehicle Propulsion Technologies
PERD - Natural Resources Canada

Proposed Approach: Cold Spray Additive Manufacturing

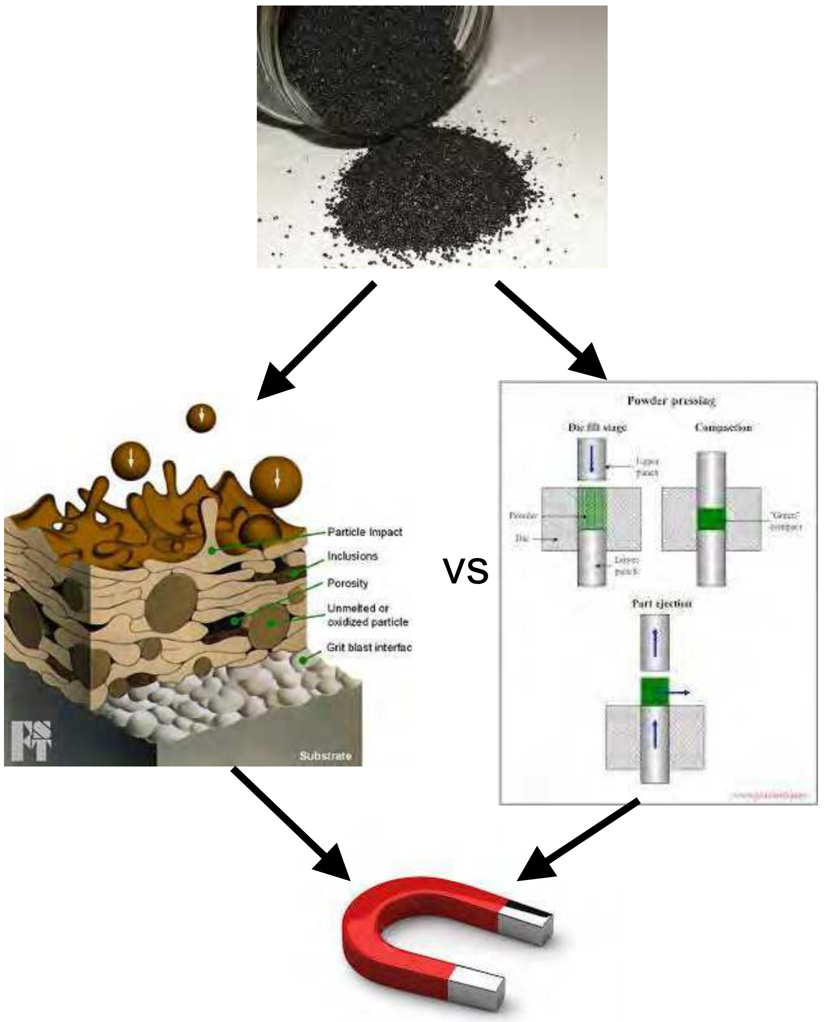
Advantages vs powder pressing :

- Very good control of the microstructure (process vs feedstock)
- Ease to modify geometry
- Reduce costly machining steps
- No assembly

Current magnets are...

1) Complicated to install (glue, screws, grooves) → expensive to install and low design flexibility

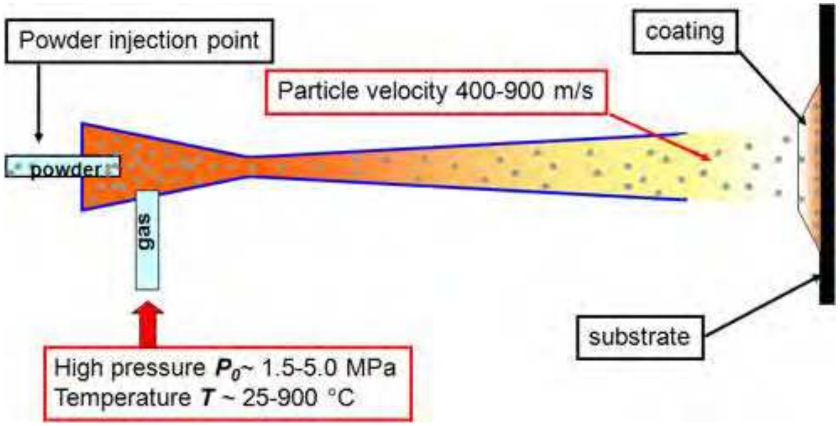
2) Brittle and difficult to machine → low design flexibility



Proposed Approach: Cold Spray Additive Manufacturing

Key features:

- High deposition rate (**several kg per hour** is possible)
- Complex patterns are possible
- Thicknesses from microns to centimeters



M-NdFeB

M: metal

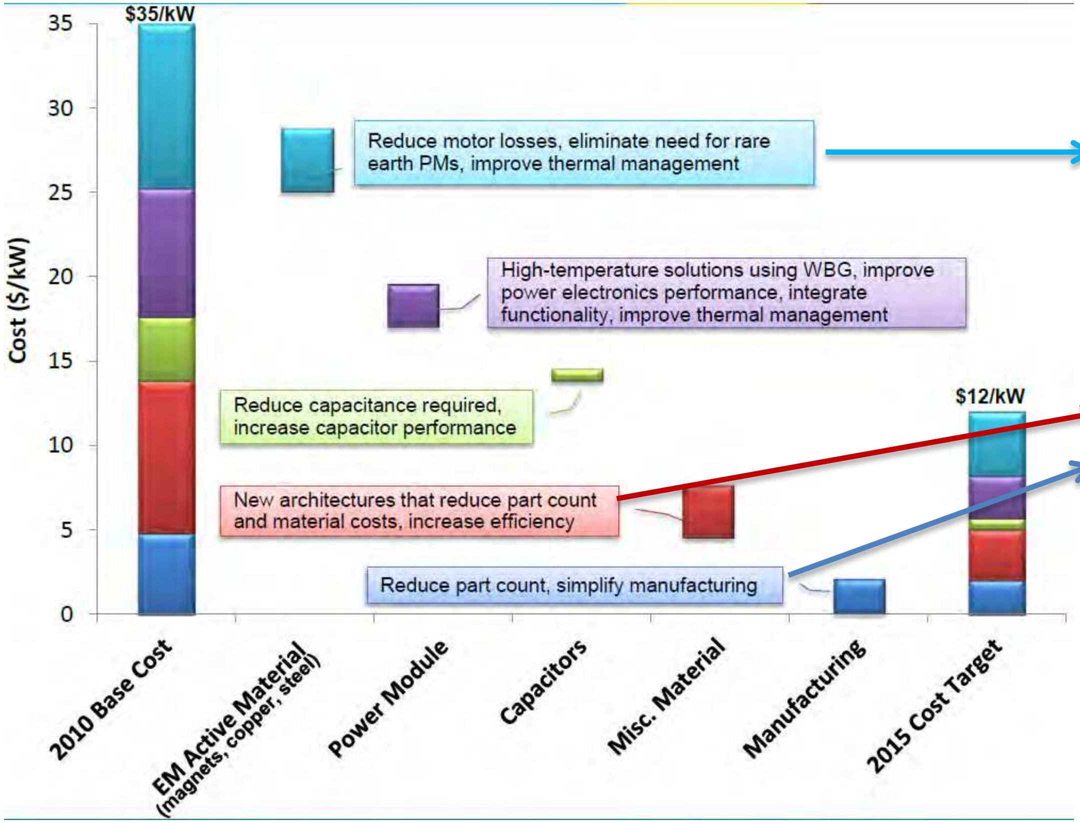
- Increase deposition efficiency
- Good thermal conductivity
- Corrosion/oxidation protection

NdFeB: hard magnetic phase

- Strongest magnets
- Provide coercivity and saturation

Objectives

Producing a low cost *M-NdFeB* composite permanent magnet using cold spray



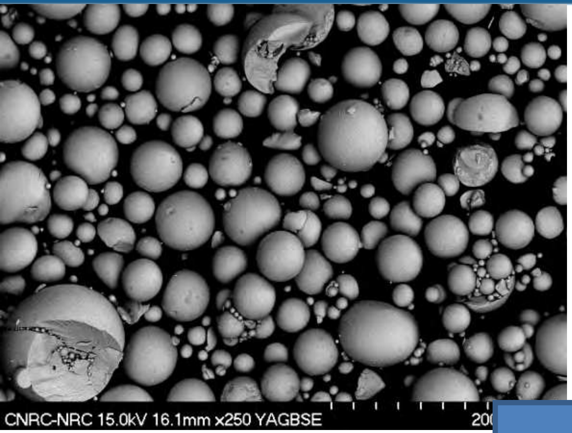
DOE Vehicle Technologies Program

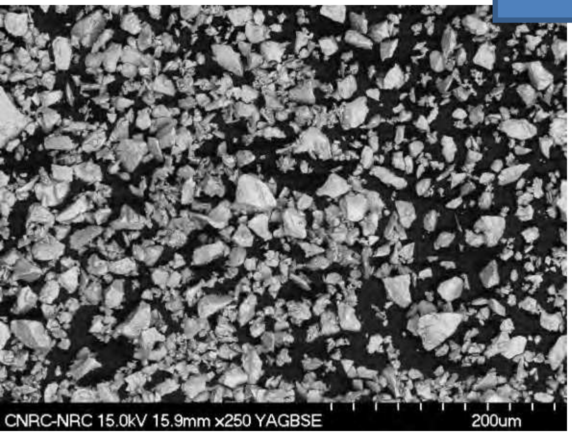
Objectives

- Reduce rare earth quantity
- Improve heat management
- Allow new motor topologies by increasing fabrication geometrical flexibility
- Reduce part number
- Reduce fabrication steps

- Automate fabrication
- Protect magnets from the environment

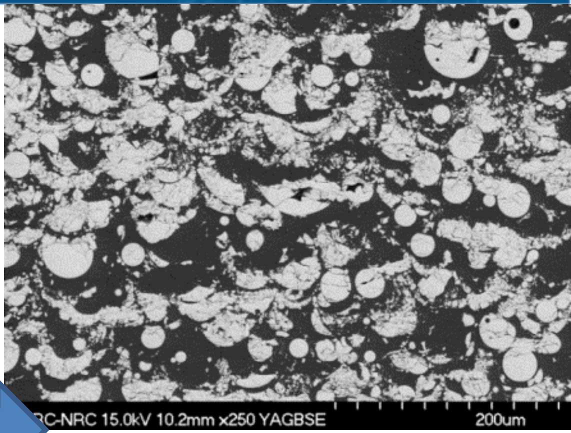
Spray Parameters

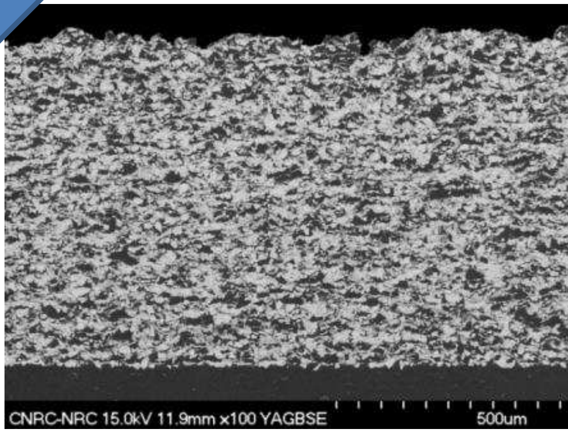




Magnetic powder:
MQFP-B, 15 µm, irregular
MQFP 14-12, 15 µm, irregular
MQP-S-11-9, 25-75 µm, spherical
Aluminum powder:
Valimet 5 µm, 15 µm, spherical

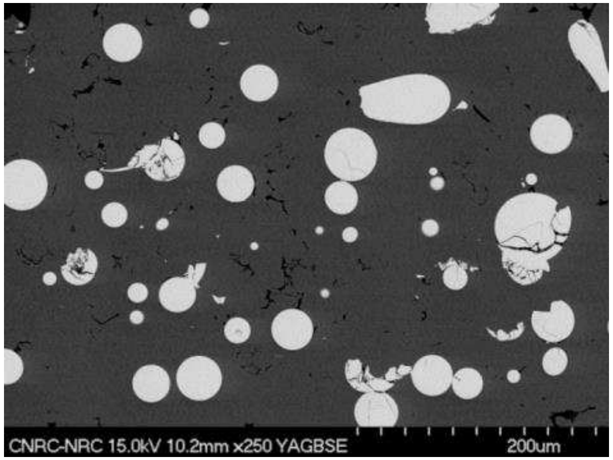
Spray parameters:
Plasma Giken 800
3 to 4.9 MPa
20 to 300 mm/s
400 to 800°C





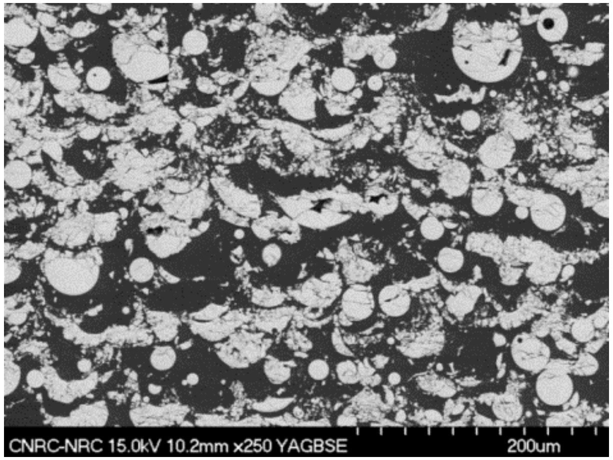
Coating
Adhesion/ cohesion: > 9000 psi
Dense: negligible porosity.
Thick: > millimeters deposited.
F_v NdFeB: 30-65%

On the Improvement of Magnetic Loading



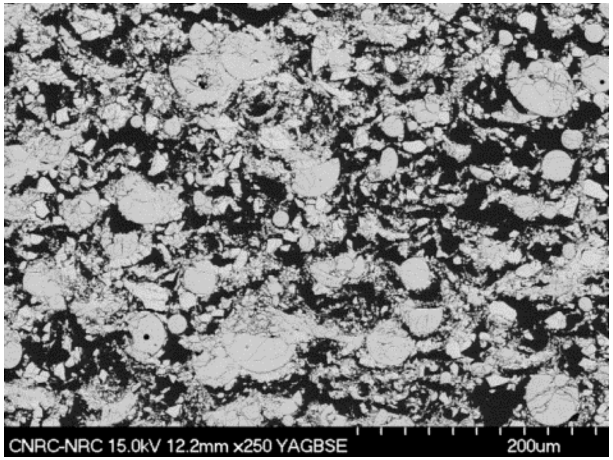
Fall 2013

Base powder and parameters



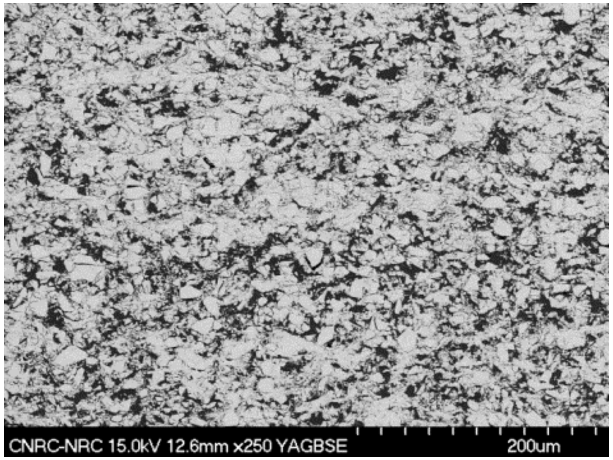
Spring 2015

Improved process parameters



Fall 2015

Optimized magnetic powder granulometry and optimized magnet/binder ratio

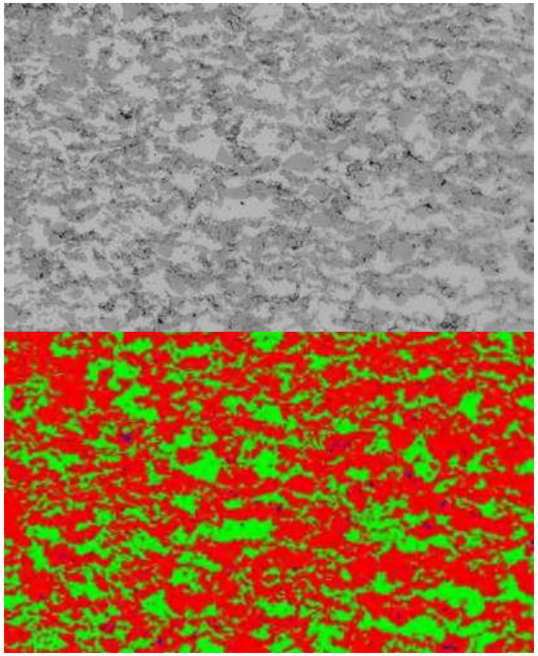


Winter 2017

Improved metallic binder granulometry and improved process parameters

Magnetic Characterization

Powder type	Composition	Size d_{50}, µm	Morphology	B_r, mT	H_c, kA/m
MQP-S-11-9	Nd-Pr-Fe-Co-TiZr-B	49.8	Spherical	745	710
MQFP-B	**Nd-Pr-Fe-B**	**10.2**	**Angular**	**880**	**752**
MQFP-1412	**Nd-Fe-Nb-B**	**10.7**	**Angular**	**817**	**961**
H15	Aluminium	15	Spherical	-	-

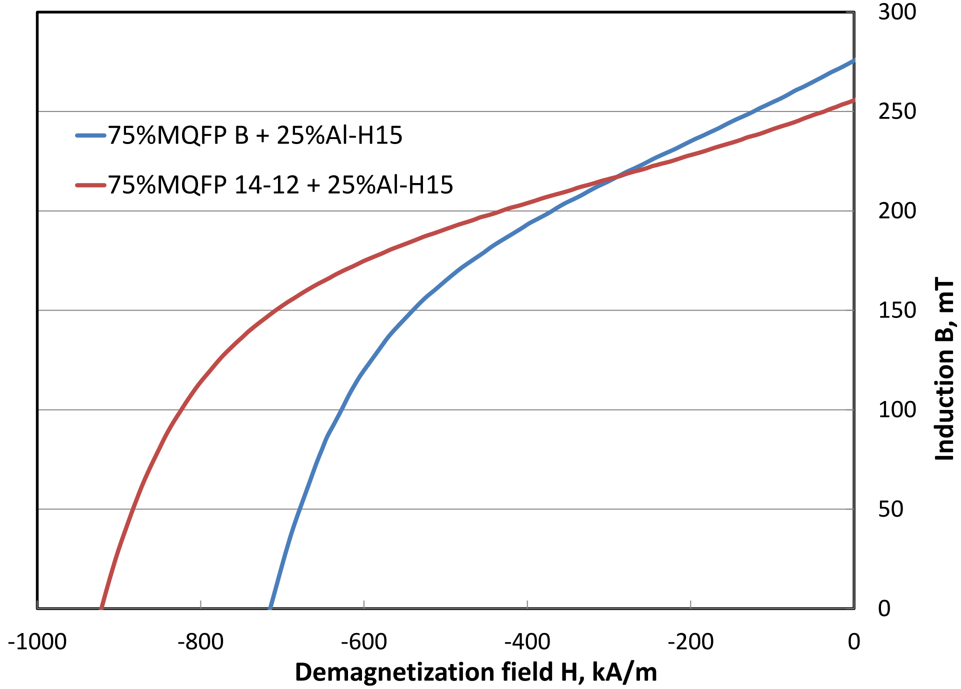


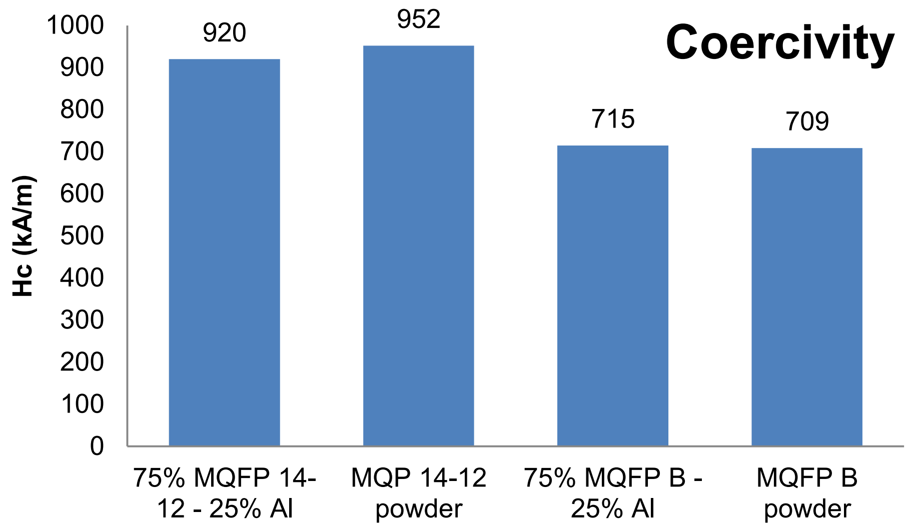
Content of FeNdB:
SEM image analysis to determine volume fraction of FeNdB in coating

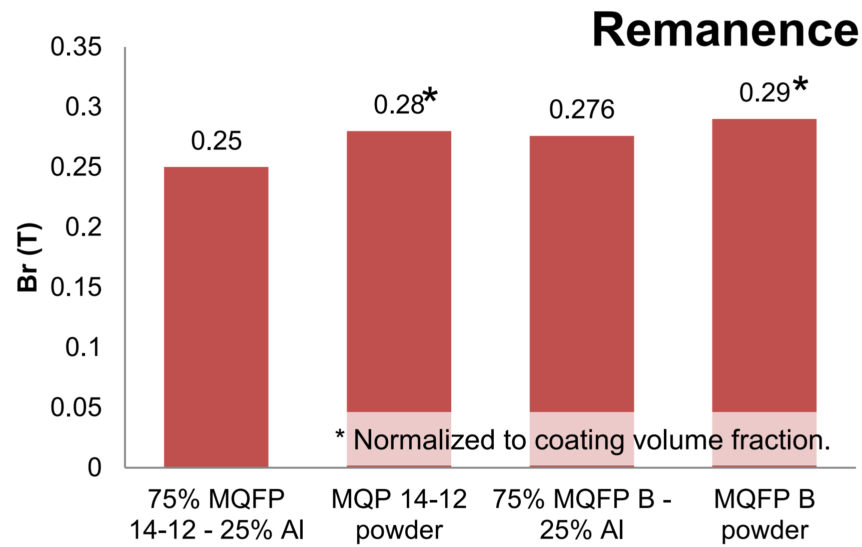
Magnetic Characterization:
Hysterisigraph Permagraph L from Magnet Physics Specimen: 10-25 mm diameter and 4 mm thickness, Provide: B_r, H_c and BH

NRC·CNRC

Effect of Powder Composition







The process does not significantly degrade the magnetic properties!

- Coating remanence is 5 to 10 % lower than the calculated value.
- Coating coercivity is 3 to 5% lower than the reference value.

NRC·CNRC

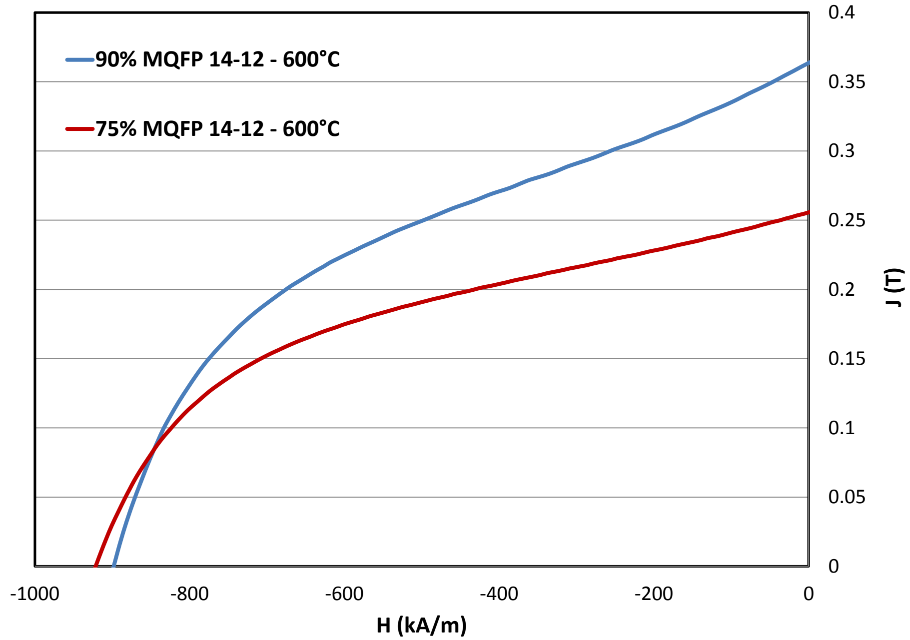
Effect of Magnetic Loading

Mélange	Carrier gas (°C)	H_c (kA/m)	B_r (T)	$B_{rcoating}/B_{rdata}$	F_v*
90%MQFP 14-12 - 10%Al H15	400	917	0.337	39.8	43.1
	600	**898**	**0.364**	**43.0**	**47.3**
75%MQFP 14-12 - 25%Al H15	**600**	**930**	**0.257**	**30.3**	**33.1**
MQP 14-12 - Data		952	0.847		

* Measured by image analysis

Increasing the NdFeB content in the starting mixes from 75% to 90%

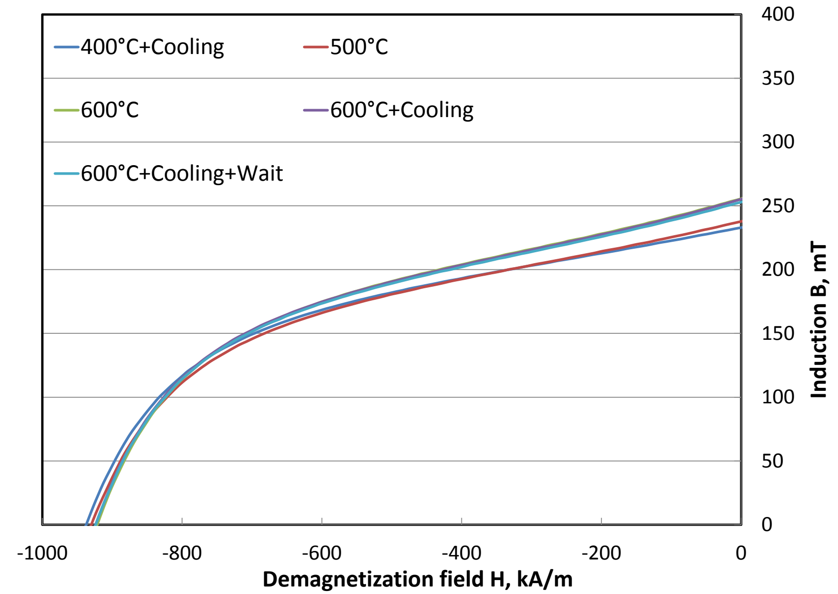
1) Increases volumetric fraction and hence remanence by 40%.
2) Does not significantly decreases H_c (3%).



Effect of Temperature

Mélange	Carrier gas (°C)	H_c (kA/m)	B_r (T)	$B_{rcoating}/B_{rdata}$	F_v*
75%MQFP 14-12 - 25%Al H15	**400 + cooling**	**937**	**0.233**	**27.5**	**28.5**
	500	930	0.238	28.1	30.7
	600	**920**	**0.25**	**29.5**	**33.5**
	600 + cooling	924	0.255	30.1	32.9
	600 + cooling and wait	924	0.253	29.9	32.9
MQP 14-12 - Data		952	0.847		

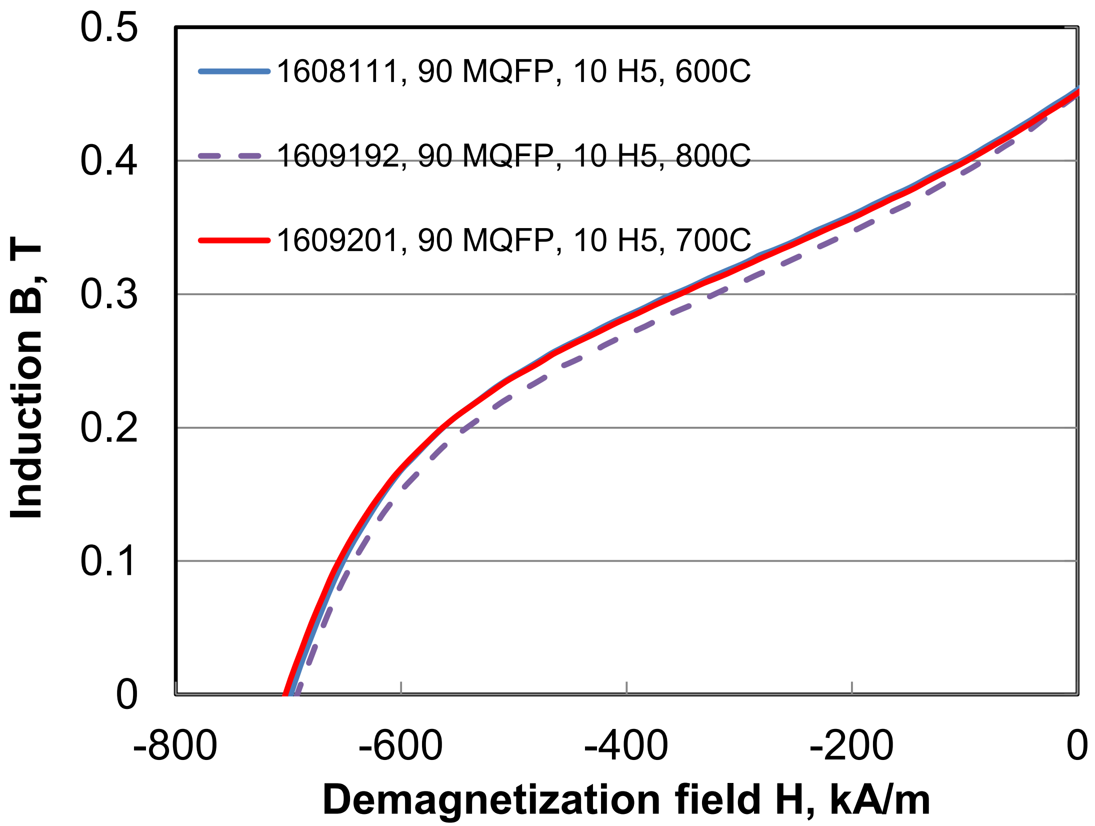
* Measured by image analysis



Increasing gas temperature from 400°C to 600°C

1) Increases volumetric fraction and hence remanence by 10%.
2) Does not significantly decreases H_c (2%).
3) Cooling of substrate and waiting period between passes had no significant effect.

Effect of Temperature



Increasing gas temperature from 600°C to 700°C

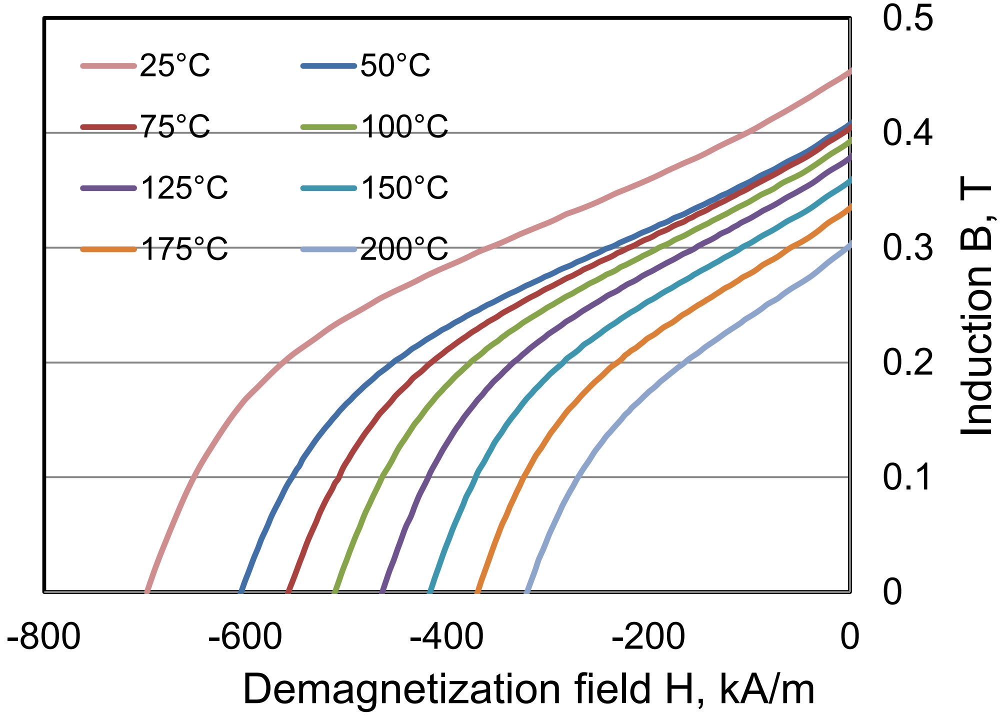
Does not alter the magnetic content hence magnetic properties are unchanged.

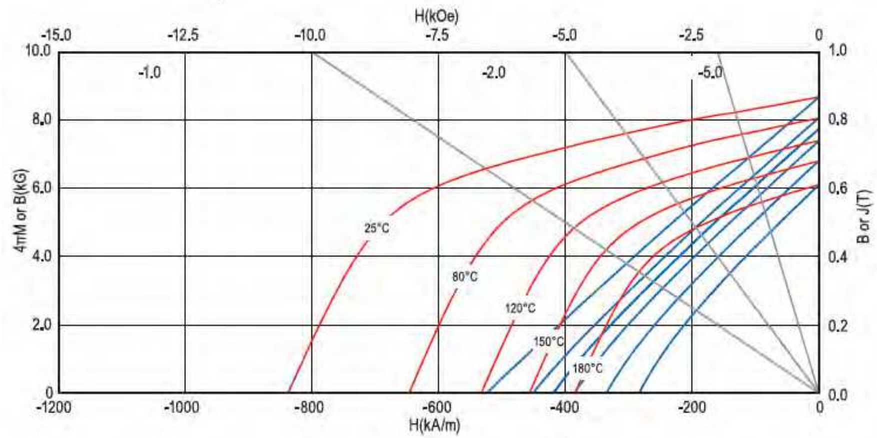
Increasing gas temperature from 700°C to 800°C

Does not alter the magnetic content but magnetic properties are slightly decreased.

Demagnetization Temperature

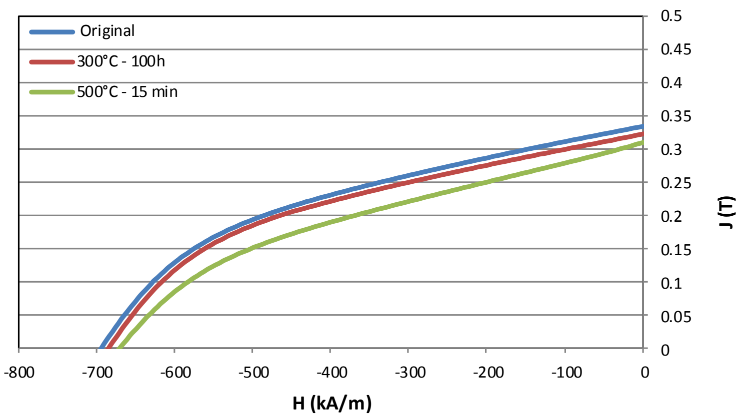
Coating: 90%MQFP-B - 10%Al H5

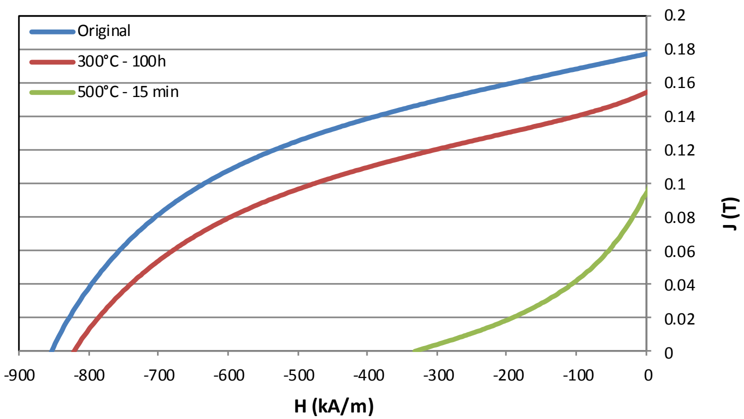




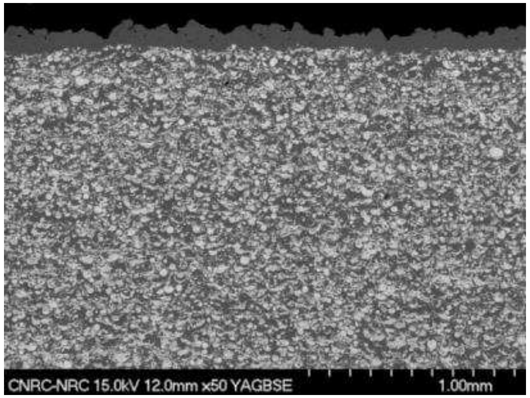
Powder datasheet

Others Characterization Techniques



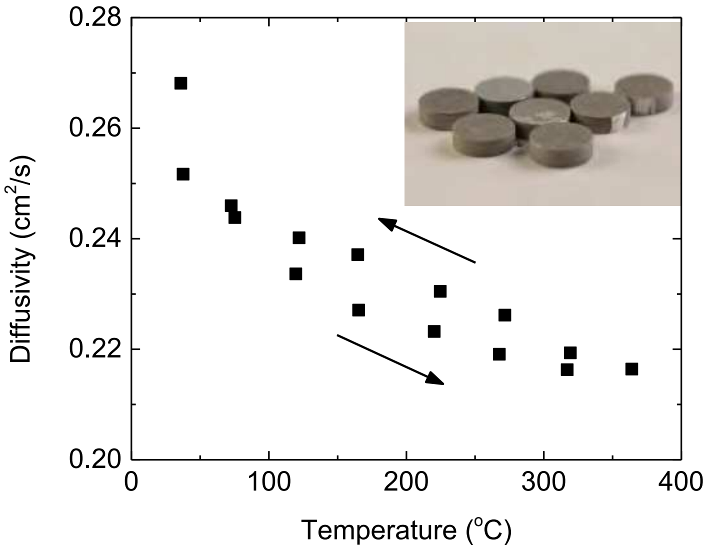


Aging: Effect of aging treatment on magnetic performance for a) MQP-S-11-9 and b) MQFP-14-12 NdFeB powder.



Protective layer: SEM image showing a 2 layer-structure. Bottom layer is a composite NdFeB-Al while top layer is Al.

Laser flash diffusivity: 75% MQFP, 25% aluminium powder

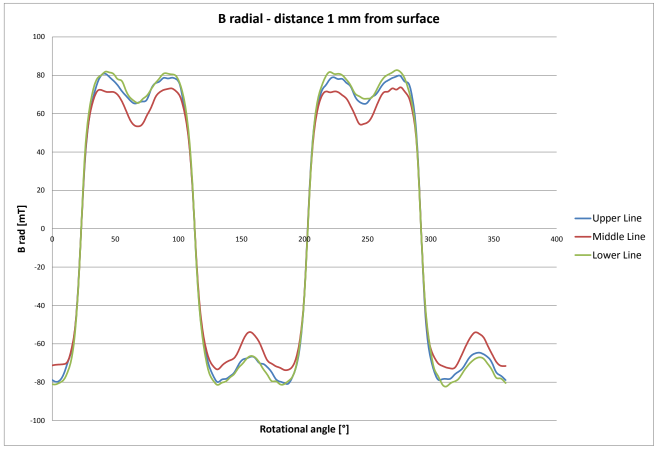


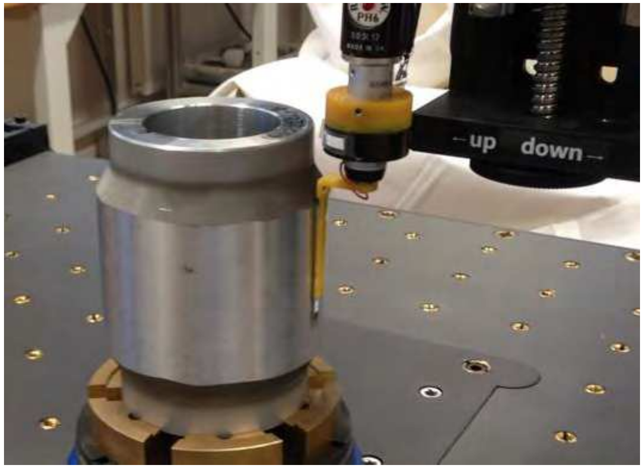
Demonstrator Magnetization Testing

Validate magnetization and performance of an industrial component

Demonstrate machinability

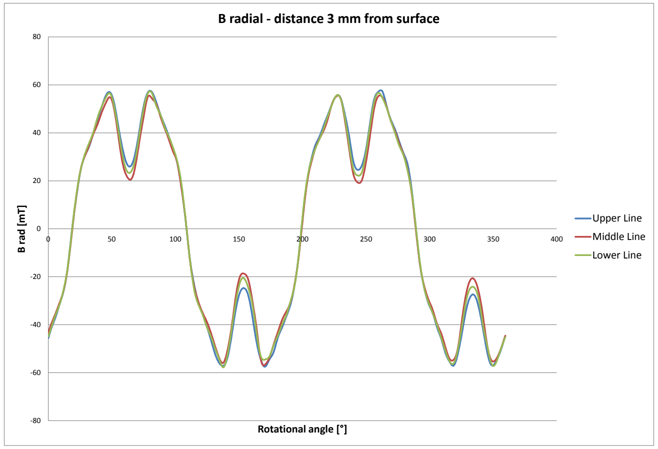
Magnetic mapping for 90% NdFeB magnet on steel





Magnetization and measurement by Magnet-Physics

Magnetic mapping for 90% NdFeB magnet on aluminium



Outer Diameter

Key objectives:

- Deposit thick and wide magnet.
- Optimize spray parameters for fast deposition.
- Evaluate time and cost.

Outer diameter prototype with four strips design, diameter ≈ 17 cm

Complex Inner Diameter

Key objective:

- Use complex robot programming to achieve complex design on inner diameter.

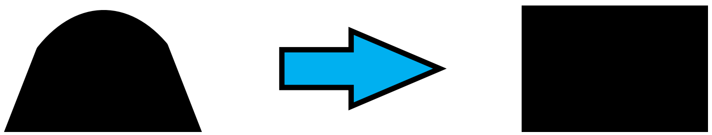
- Develop ability to spray at an angle with high deposition efficiency
- Adapt the spray geometry (gun size, spray distance and angle) to an inner diameter

Vertical Walls

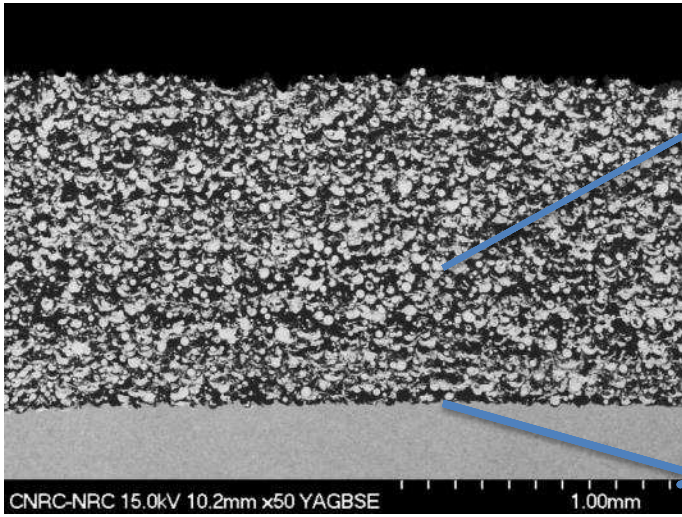
Key objectives:

- Optimize robot programming and process parameters to achieve vertical walls.

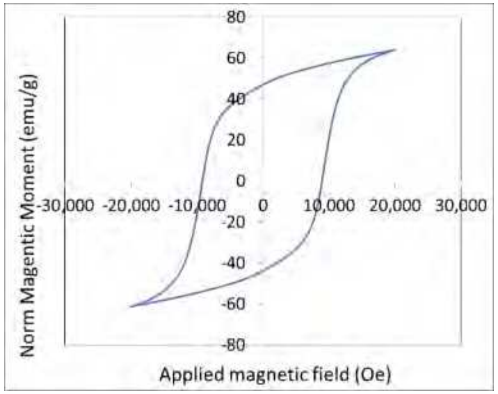
Cross-section optimization



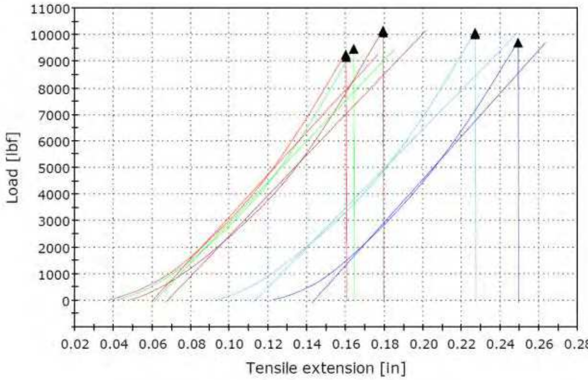
Conclusions

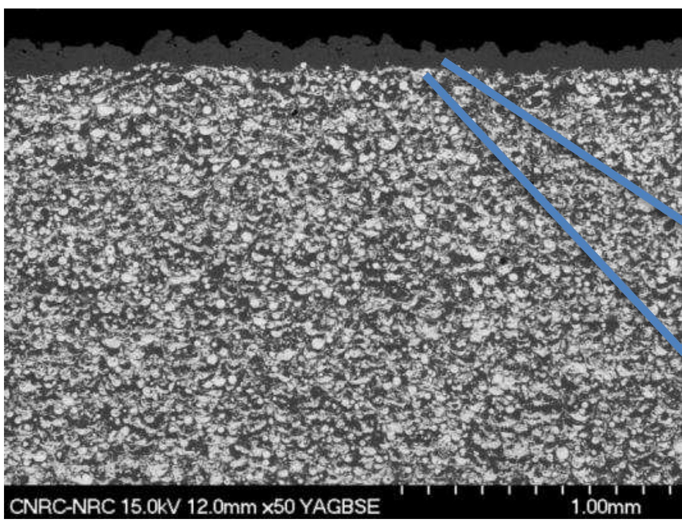


- High density coating with high NdFeB content. Magnetic properties follow mixture law.
- High deposition efficiency.
- Increase heat diffusivity.

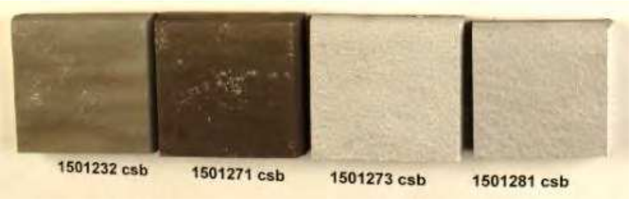


- Interface adhesion exceeding industrial standard (> 65 MPa).





- Environmental sealing via appropriate top-coat use.
- Improved high temperature resistance.



250°C – 10h

Conclusions

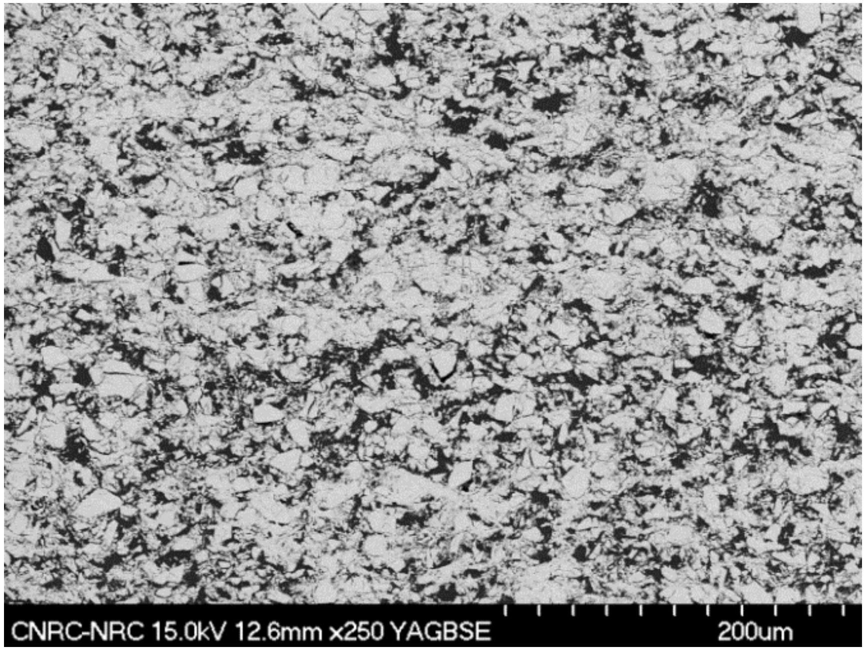
1) Assembled rare earth permanent magnets were fabricated by cold spray

2) Complex shape rotor can be readily fabricated without assembly

Technology Development 2017-2020

Next steps

- Integrate coating permanent magnet technology to actual motor design.
- Explore design possibilities offered by the added manufacturing flexibility.

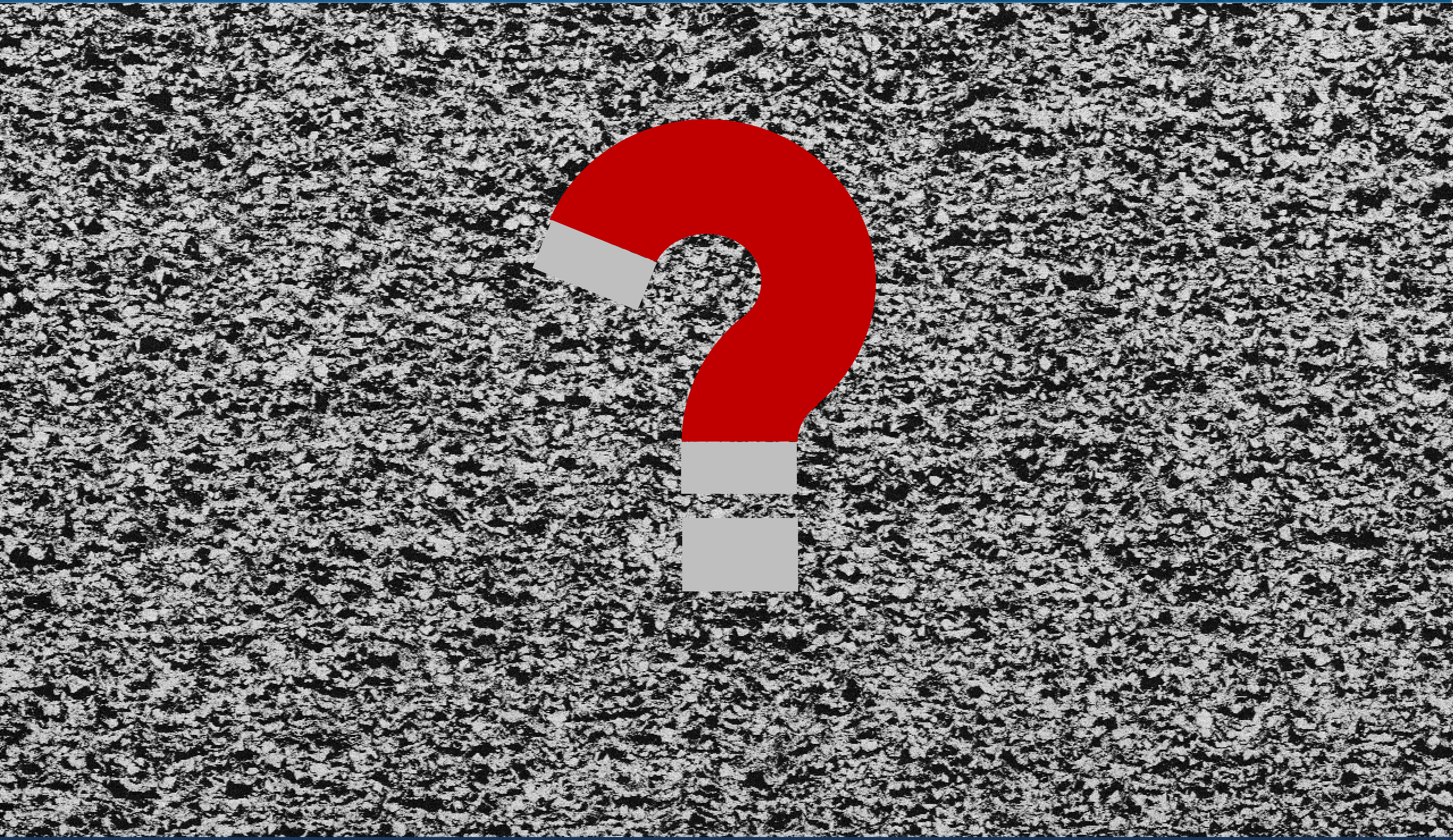


Project Team

Automotive and Surface Transportation Portfolio - Thermal Spray and Powder Forming groups.

- Jean-Michel Lamarre, Project leader.
- Fabrice Bernier, Task leader characterization.
- Thermal spray: J.-F. Alarie, F. Belval, J. Sykes, J.-C. Tremblay.
- Characterization: S. Mercier, D. de Lagrave, D. Simard, K. Théberge.
- Robot toolpath programming: M. Martin.

Questions?



Acknowledgment

The authors gratefully acknowledge financial support for this project from Natural Resources Canada through its Energy Research and Development Program and the National Research Council through its Vehicle Propulsion Technologies Program

Thank you

Jean-Michel Lamarre
Research Officer
Tel: 450-641-5386
jean-michel.lamarre@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca