Recent advances in isotropic melt-spun Nd-Fe-B magnetic powders for automotive applications

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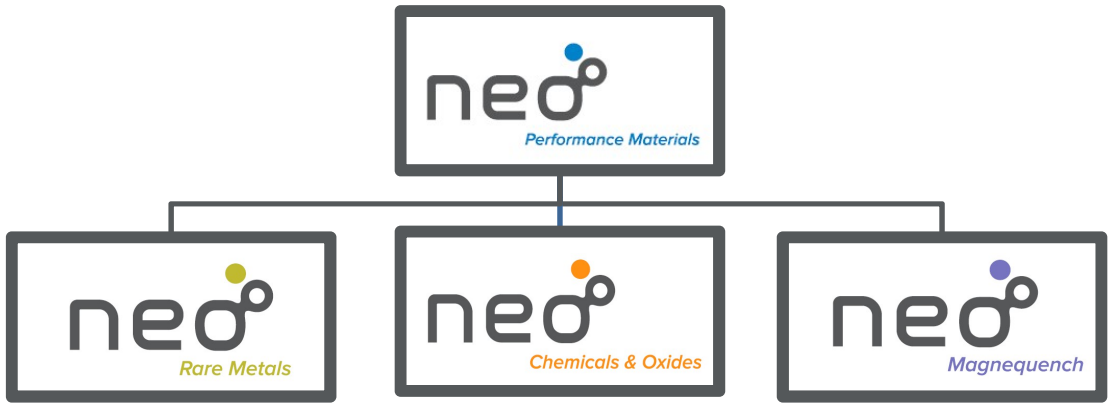
Outline

- Company overview --- Neo Performance Materials
- Latest developments from MQ:
  - Advanced Quenching technology and AQ grade products
  - Expanded Automotive High Temperature Product Line
  - New MQP-14-14 powder
- Application case study with AQ product

Neo Performance Materials Overview



- Privately held company with over 35 years of experience and leadership in the rare earth and rare metals industries
- 3 Business Units which serve global and distinct high technology supply chains
  - **Rare Metals:**
    - Acquired in 2009-2011
    - Produces, Reclaims, and Refines high value niche metals for high tech turbine, solar, and other markets
  - **Chemicals & Oxides**
    - Established in 1993
    - Manufactures broad range of light and heavy rare earth engineered products with facilities both inside and outside of China
  - **Magnequench:**
    - Founded in 1986 by General Motors, which invented bonded NdFeB magnets
    - Industry leader in the production and technologies of bonded rare earth magnetic materials and their applications

Neo Performance Materials Overview

Legend

- Production Facilities
- Reserarch & Development
- Corporate Offices

Sales & Liaison Offices

Abington, UK
Beijing China
Blanding, Utah
Greenwood Village, Colorado
Pendleton, Indiana
Osaka, Japan
Sagard, Germany
Seoul, South Korea
Singapore
Tokyo, Japan
Toronto, Canada
Tubingen, Germany

Magnequench History

2016

As a result of a financial restructuring of Molycorp, Inc., Neo Performance Materials emerges as a new private company.

2012

Neo Material Technologies, Inc is acquired by Molycorp, Inc., in June

2006

Magnequench merges with AMR Technologies, Inc. (AMR). New company is called Neo Material Technologies, Inc.

1986

General Motors (GM) forms Magnequench as a business unit

Magnequench Overview

MQTJ (Tianjin, China)
- Powder Production
- Process Development
- Product R&D

MQK (Korat, Thailand)
- Powder Production
- Process Development

MQ Magnetic Solutions (Tianjin / Singapore)
- Develop novel compounds & coatings
- Provide magnet processing solutions to magnet makers

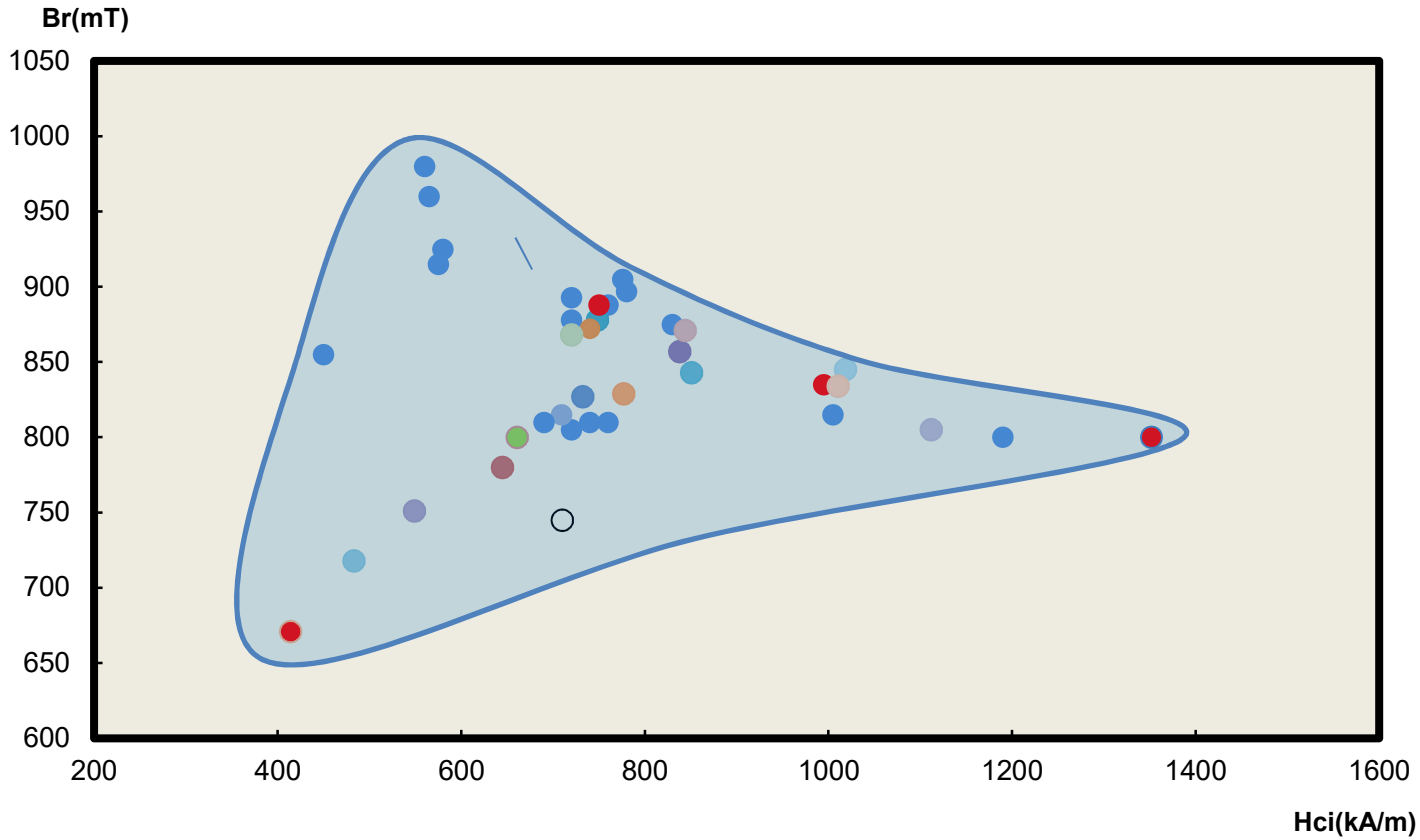
Beijing Office
- Finance
- Admin

Sales and Marketing
- China
- Germany
- USA
- Japan
- Korea
- Singapore

Global Engineering Group
- US
- MQTJ
- MQK

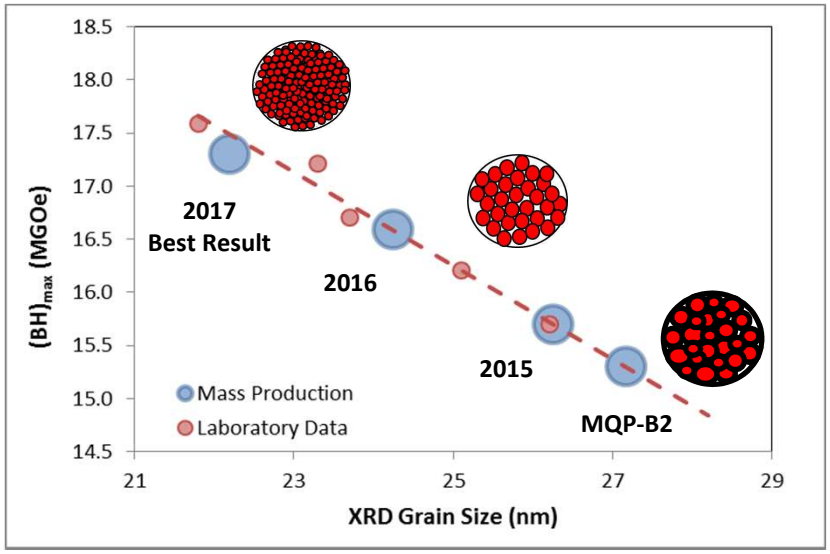
Technology Center (Singapore)
- Product R&D
- Process R&D
- Application engineering

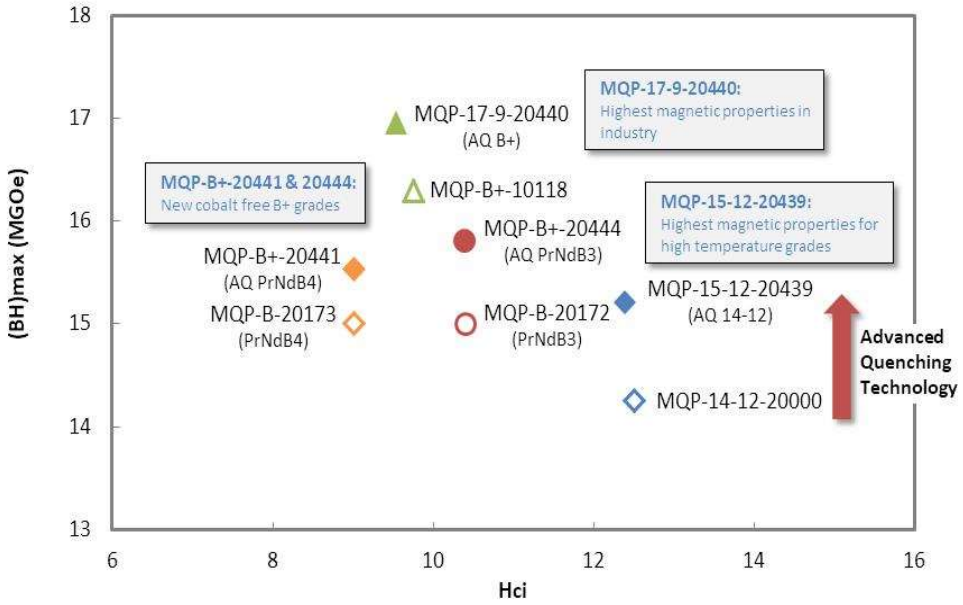
Existing Powder Grades



- MQ offers broad range of powders to meet customers' various needs
- MQ can make any powder with performance within blue area

Latest Development, part 1: Advanced Quenching ("AQ") Technology





- MQ has been continuously working on improving our product's performance
- AQ technology is the results from our past 3 years R&D efforts
- It brings up to 1 MGOe increase in energy product for existing MQP products

AQ Grades Available

Powder Grade		Powder Properties		
		Br mT (kGs)	Hci kA/m (kOe)	(BH)max kJ/m³ (MGOe)
Existing Grade	***MQP-B+-10118***	895-915 (8.95-9.15)	716-836 (9.0-10.5)	126-134 (15.8-16.8)
AQ Grade	***MQP-17-9-20440***	905-915 (9.05-9.15)	745-785 (9.4-9.7)	132-138 (16.6-17.3)
Existing Grade	**MQP-14-12- 20000-070**	820 - 850 (8.20 – 8.50)	940 - 1050 (11.8 – 13.2)	107 - 120 (13.4 -15.1)
AQ Grade	**MQP-15-12- 20439-070**	850 - 860 (8.50 - 8.60)	950 - 1030 (11.9 – 12.9)	118 - 124 (14.8 -15.6)
Existing Grade	***MQP-B-20172 (PrNdB3)***	860-880 (8.60-8.80)	800-860 (10.0-10.8)	116-124 (14.5-15.5)
AQ Grade	***MQP-B+-20444***	875-885 (8.75-8.85)	800-860 (10.0-10.8)	123-129 (15.4-16.2)
Existing Grade	***MQP-B-20173 (PrNdB4)***	883-903 (8.83-9.03)	690-750 (8.6-9.4)	116-124 (14.5-15.5)
AQ Grade	***MQP-B+-20441***	898-908 (8.98-9.08)	700-740 (8.8-9.3)	120-128 (15.0-16.0)

AQ Grades example 1: MQP-17-9 vs. MQP-B+

Powder Grade		Powder Properties		
		Br mT (kGs)	Hci kA/m (kOe)	(BH)max kJ/m³ (MGOe)
Existing Grade	***MQP-B+-10118***	895-915 (8.95-9.15)	716-836 (9.0-10.5)	126-134 (15.8-16.8)
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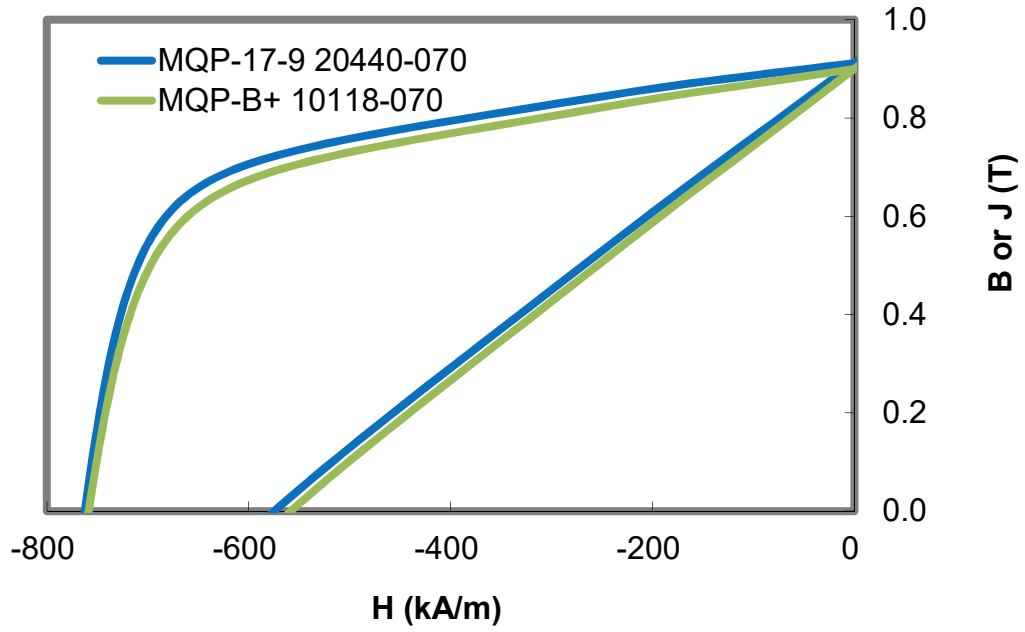

AQ Grade example 2: MQP-15-12 vs. MQP-14-12

Powder Grade		Powder Properties		
		Br mT (kGs)	Hci kA/m (kOe)	(BH)max kJ/m³ (MGOe)
Existing Grade	**MQP-14-12- 20000-070**	820 - 850 (8.20 – 8.50)	940 - 1050 (11.8 – 13.2)	107 - 120 (13.4 -15.1)
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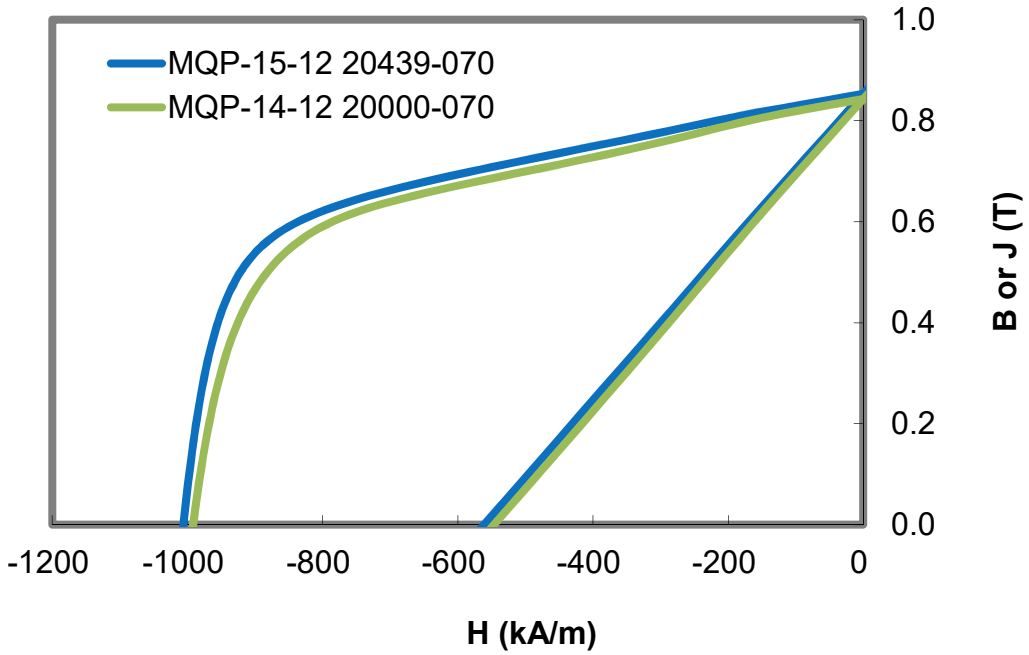
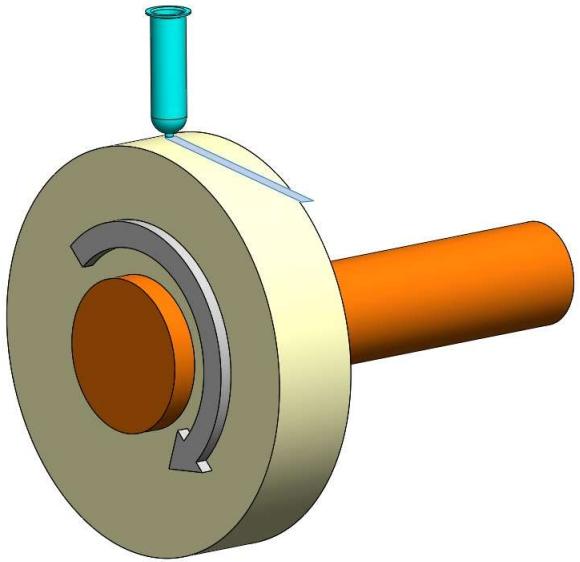
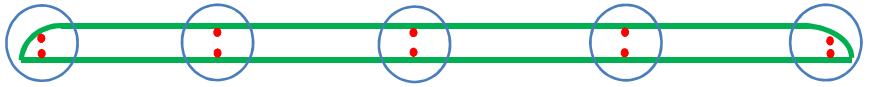
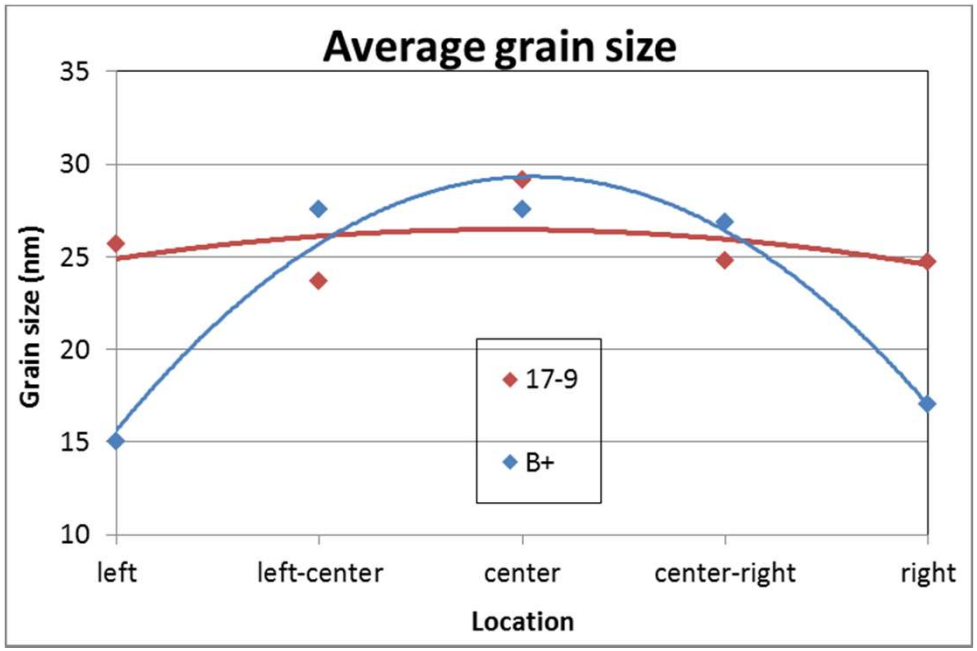


Why do AQ grades have higher Br and (BH)max?
- more uniform microstructure across ribbon width







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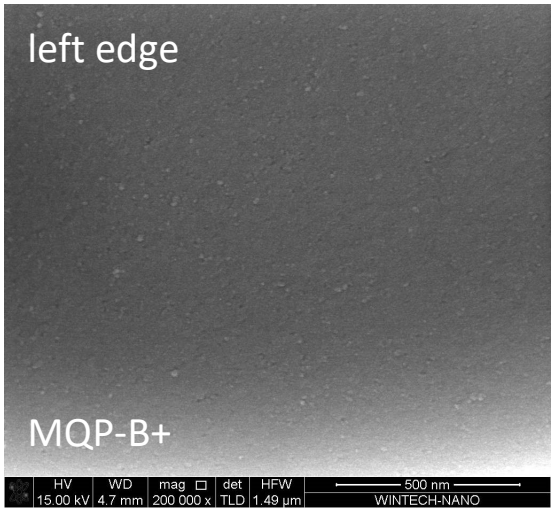
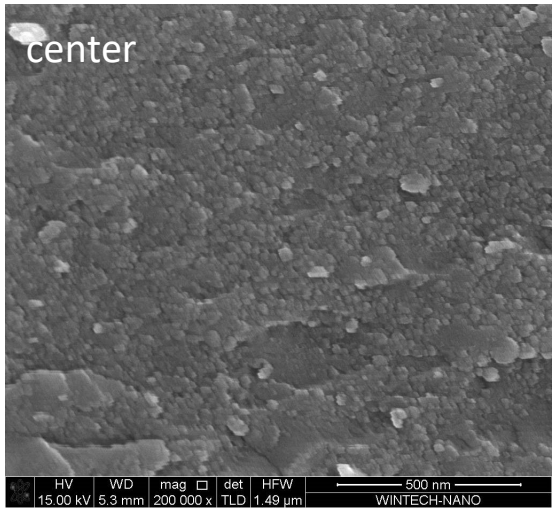
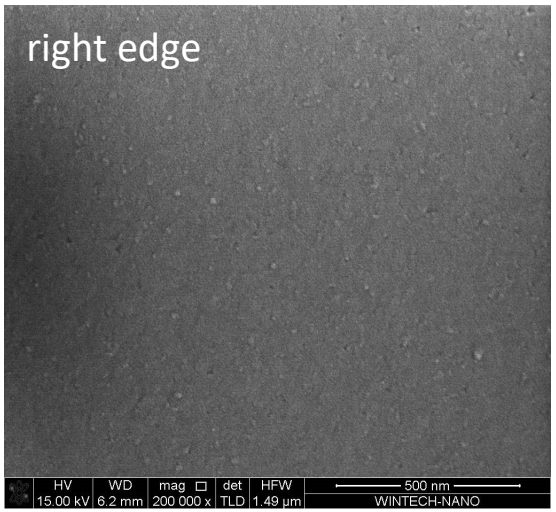
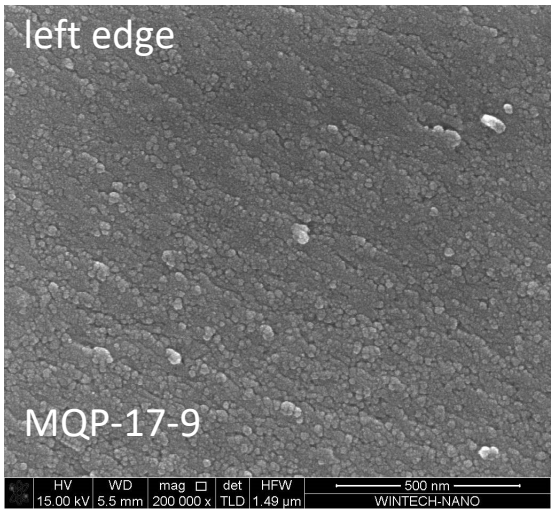
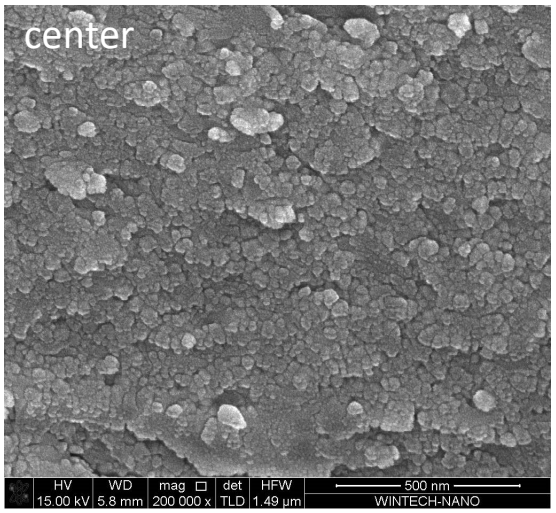
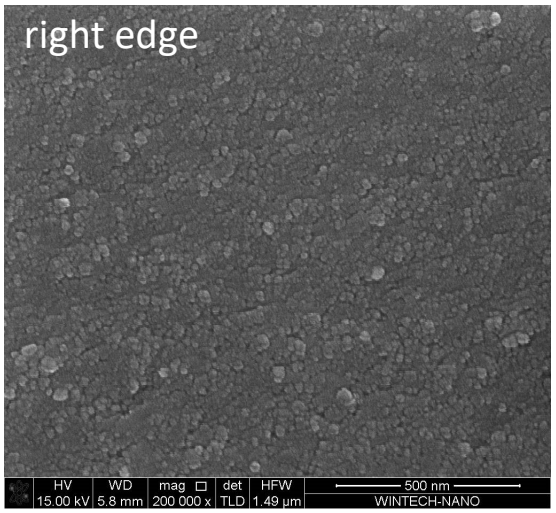






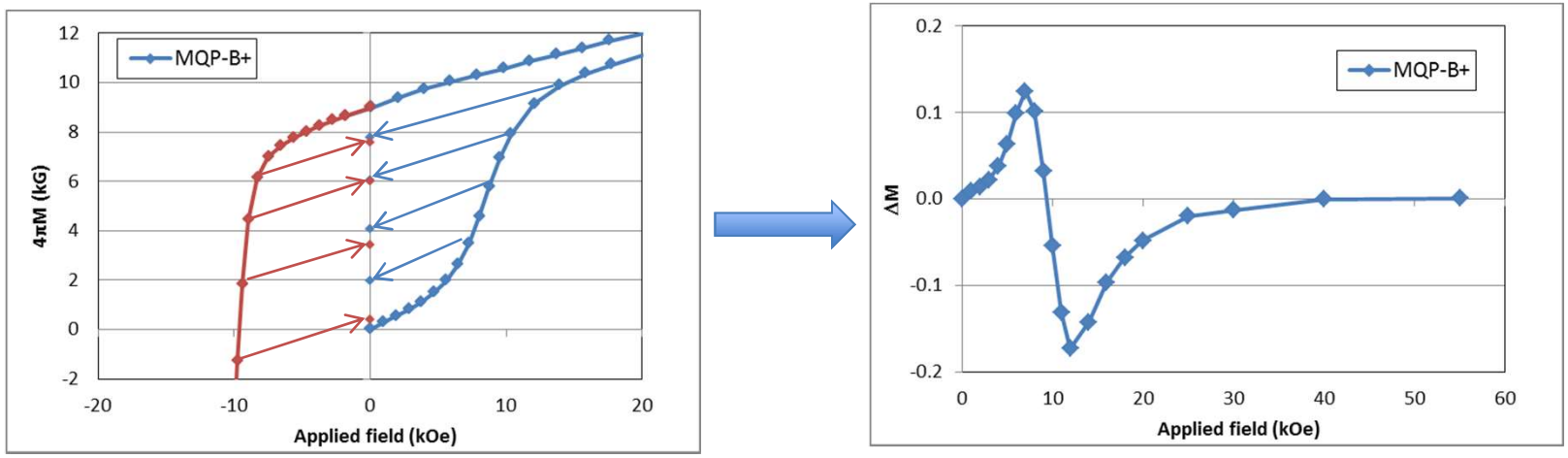






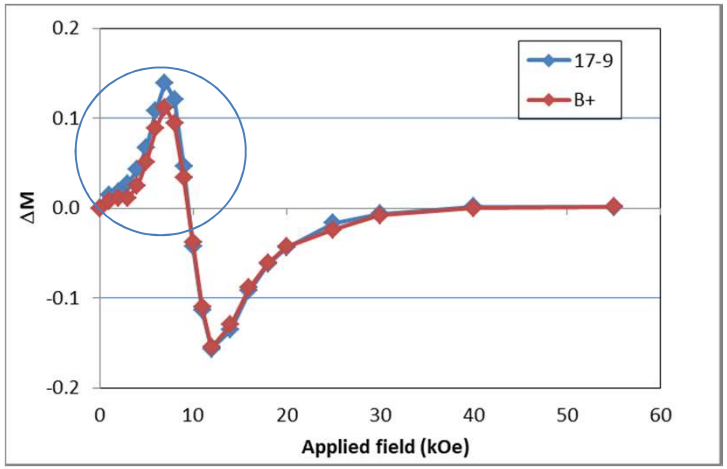
Why do AQ grades have higher Br and (BH)max? - stronger exchange coupling among grains

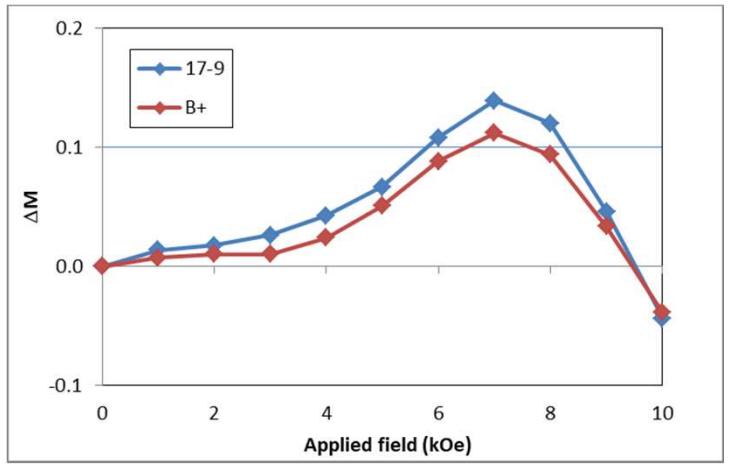
- Intergranular interactions can be investigated by Henkel ΔM plots
  - E. P. Wohlfarth, J. Appl Phys, 29 (1958) 595
  - O. Henkel, Phys. Status Solidi, 7 (1964) 919
- $\Delta M(H) = m_d(H) - [1-2m_r(H)]$
  - m_d is the reduced demagnetization remanence
  - m_r is the reduced magnetization remanence
  - $\Delta M = 0$ $\Rightarrow$ no interaction among grains
  - $\Delta M > 0$ $\Rightarrow$ exchange coupling among grains (moment are parallel aligned)
  - $\Delta M < 0$ $\Rightarrow$ dipolar coupling among grains (moment are anti-parallel aligned)
- Positive ΔM (for H up to H_{ci}) is shown in all MQP powders, suggesting presence of exchange coupling among the nano-grains



Why do AQ grades have higher Br and (BH)max? - stronger exchange coupling among grains

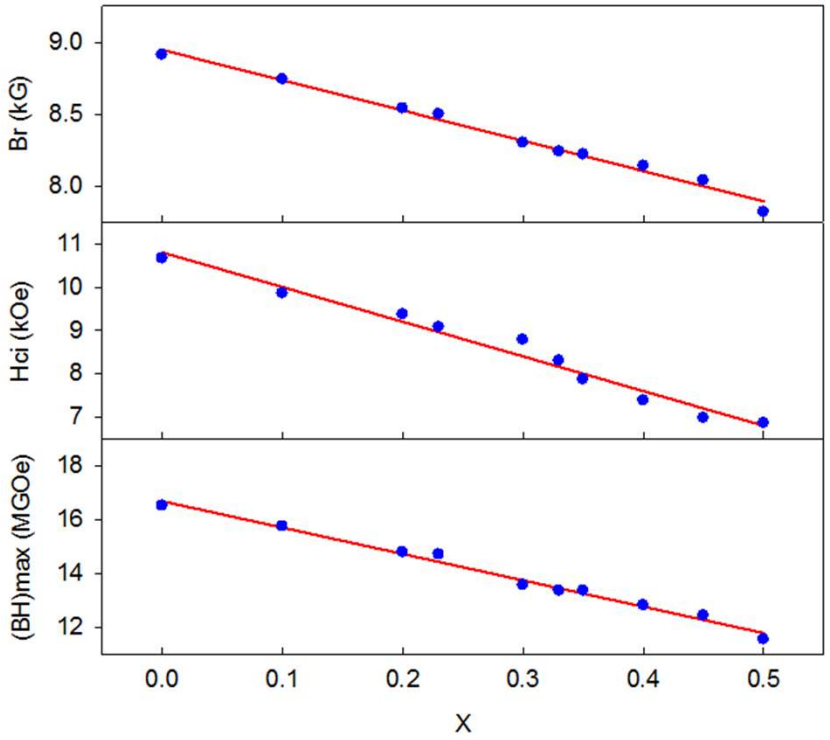
- ΔM peak is slightly higher in 17-9 than in B+ as shown below
- This means an enhanced exchange coupling between grains in 17-9, which leads to higher Br and better squareness in demagnetization curve





Latest Development, part 2: Fundamental studies on Ce substitution

$[(Nd_{0.75}Pr_{0.25})_{1-x}Ce_x]_{11.65}Fe_{82.75}B_{5.6}$



Ce substitution amount (X=Ce/TRE)	T_c (°C)	α (%/°C)	β (%/°C)
X = 0	311	-0.13	-0.39
X = 0.1	297	-0.14	-0.39
X = 0.2	284	-0.15	-0.38
X = 0.23	281	-0.15	-0.38
X = 0.3	270	-0.17	-0.37
X = 0.35	263	-0.17	-0.37
X = 0.4	251	-0.18	-0.36
X = 0.45	243	-0.19	-0.36
X = 0.5	236	-0.20	-0.35

- Br, Hci and (BH)max decrease linearly with increasing Ce substitution
- Curie temperature decreases linearly with Ce substitution
- Temperature coefficient of remanence (α) increases with Ce substitution
- However, temperature coefficient of coercivity (β) decreases with Ce substitution

Development of Ce-contained Powder for automotive applications

Powder Name	Ce (%)	B_r		H_{ci}		BH_{max}	
		mT	kG	kA/m	kOe	kJ/m^3	MGOe
MQP-10-8.5HD 20180	Ce60	722	7.22	687	8.6	82	10.3
MQP-12-10HD-20352	Ce30	791	7.91	819	10.3	99	12.4
MQP-11.5-12HD-20369	Ce30	761	7.61	969	12.2	93	11.7
MQP-10.5-12HD-20379	Ce40	727	7.27	960	12.1	86	10.8
MQP-10-11HD-20402	Ce50	713	7.13	862	10.8	81	10.2
MQP-10-9.5HD-20403	Ce50	723	7.23	753	9.5	82	10.3
MQP-9-8.5HD-20404	Ce70	682	6.82	686	8.6	72	9.0

- Low-cost Ce-contained powders have been developed, with Ce content up to 70% of TRE

Magnet Data

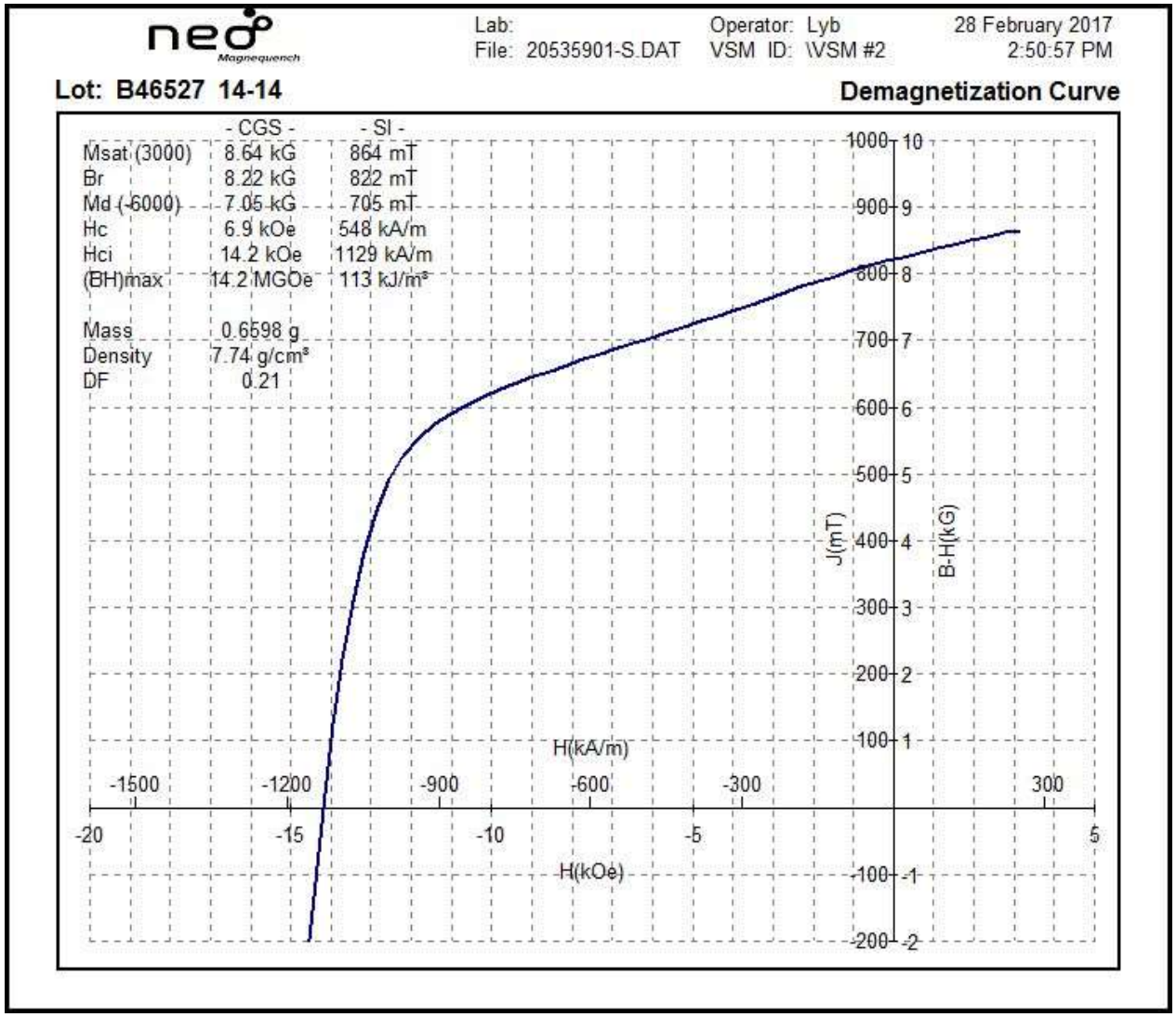
Powder Name	Ce (%)	B_r		H_c		H_{ci}		BH_{max}		PC=2 Magnet
		mT	kG	kA/m	kOe	kA/m	kOe	kJ/m^3	MGOe	120°C Aging (%) @1000hr
MQP-10-8.5HD-20180	Ce60	580	5.80	378	4.8	676	8.5	55	6.9	-4.2
MQP-12-10HD-20352	Ce30	640	6.40	422	5.3	792	10.0	67	8.4	-4.5
MQP-11.5-12HD-20369	Ce30	610	6.10	406	5.1	957	12.0	61	7.7	-3.9
MQP-10.5-12HD-20379	Ce40	574	5.74	382	4.8	941	11.8	55	6.9	-4.3
MQP-10-11HD-20402	Ce50	569	5.69	374	4.7	850	10.7	53	6.7	-4.5
MQP-10-9.5HD-20403	Ce50	583	5.83	384	4.8	747	9.4	56	7.0	-4.0
MQP-9-8.5HD-20404	Ce70	539	5.39	349	4.4	673	8.5	47	5.9	-6.4

- Good thermal stability and suitable for applications up to 120°C
- Good candidate for most automotive applications

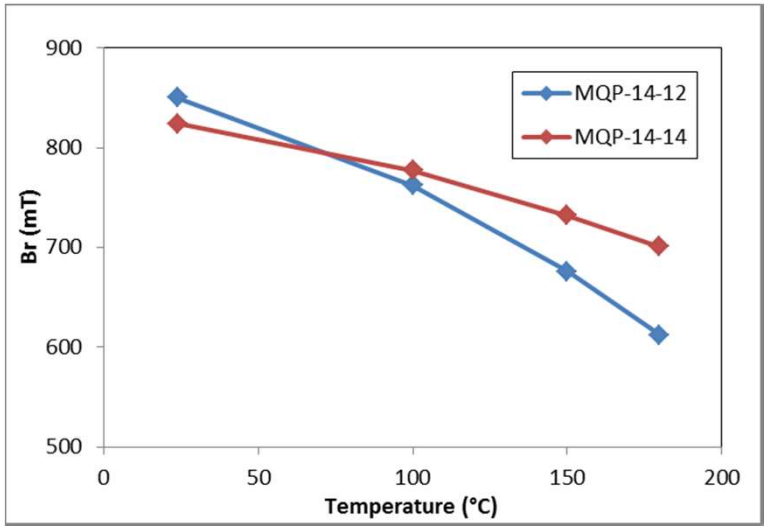
Latest Development, part 3: Developing MQP-14-14 for higher Br at 150°C

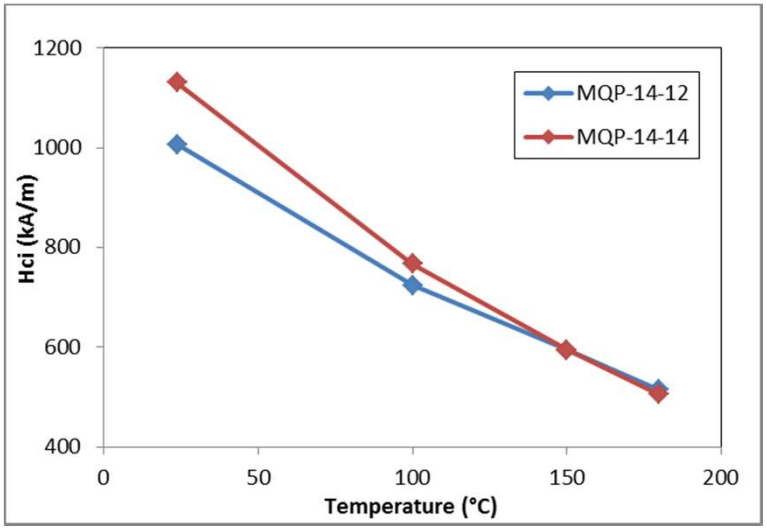
- MQ has developed a new MQP-14-14 powder for 150°C applications, in response to customer's needs
- The new MQP-14-14 is developed from MQP-14-12 by introducing Co and increasing Nd content
- Compared with MQP-14-12, the new MQP-14-14 has:
  - Higher Br at 150°C
  - Same Hci at 150°C

RT demagnetization curve



Br & Hci vs. Temp for powder samples

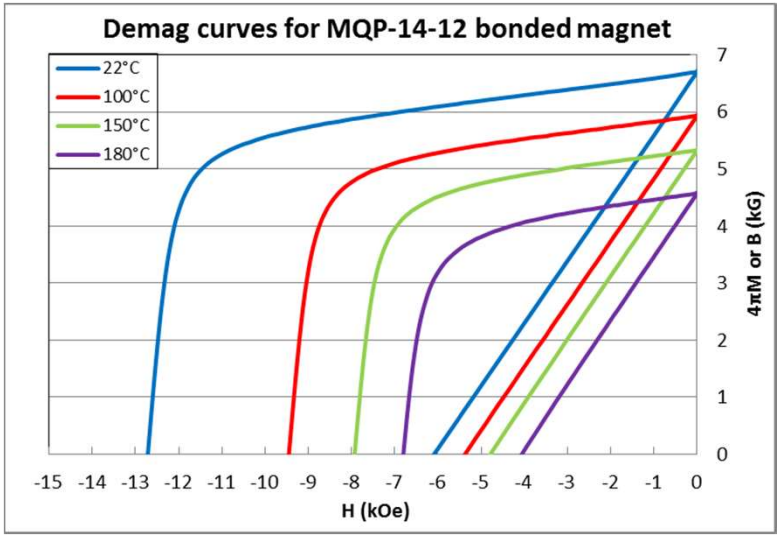


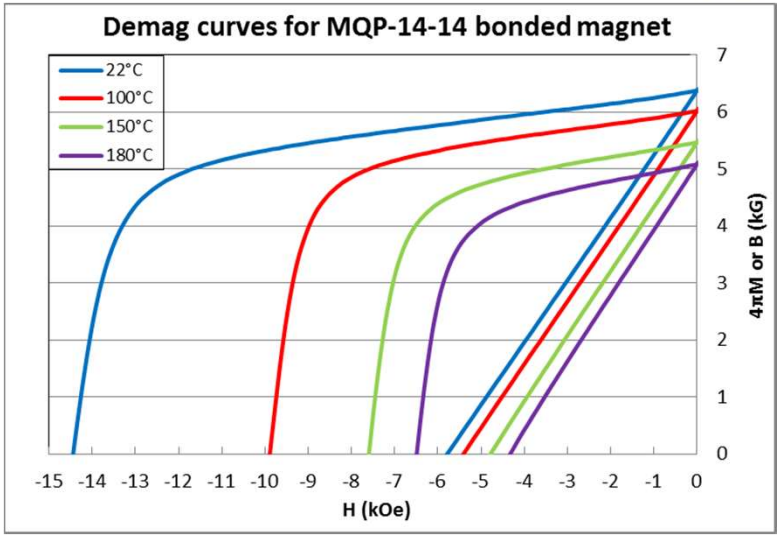


Sample ID	Temp (°C)	Br (mT)	Hci (kA/m)	(BH)m (kJ/m^3)	α (%/°C)	β (%/°C)
MQP-14-12 A0218996	23.7	850	1007	121		
	100	762	724	94	-0.14	-0.37
	150	676	595	72	-0.16	-0.32
	180	612	514	58	-0.18	-0.31
MQP-14-14 B46527	23.8	824	1131	114		
	100	777	767	98	-0.07	-0.42
	150	732	595	84	-0.09	-0.38
	180	701	505	74	-0.10	-0.35

- 14-14 powder has higher Br (than 14-12) at elevated temperatures (≥100°C)
- Hci in 14-14 is higher at temp from RT up to 150°C

Magnetic properties from bonded magnets

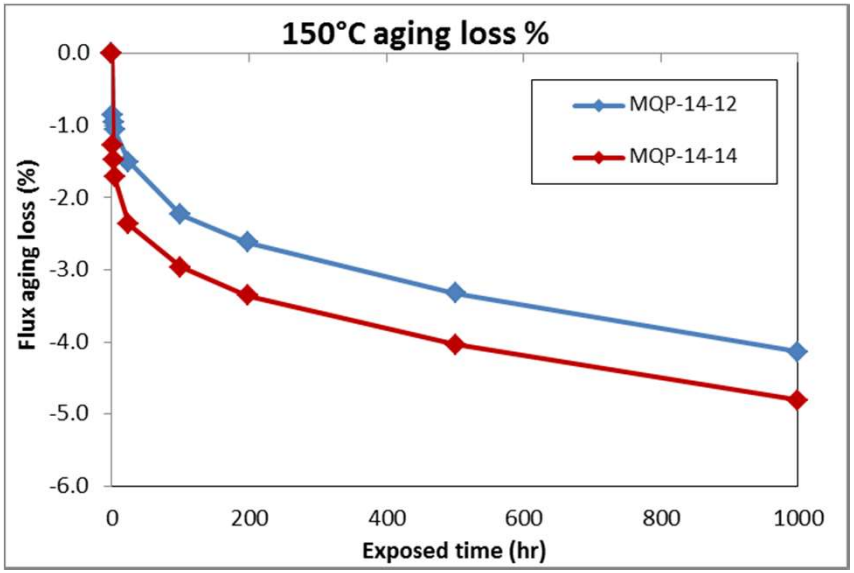




Alloy ID	magnet density (g/cc)	Temp (°C)	Br (mT)	Hc (kA/m)	Hci (kA/m)	(BH)m (kJ/m3)	α %/°C	β %/°C
MQP-14-12 A0218996	6.04	22	671	484	1012	81		
		100	594	428	752	64	-0.15	-0.33
		150	534	381	631	51	-0.16	-0.29
		180	458	323	541	37	-0.20	-0.29
MQP-14-14 B46527	6.08	22	638	461	1149	73		
		100	602	431	787	65	-0.07	-0.40
		150	547	381	604	53	-0.11	-0.37
		180	509	344	516	45	-0.13	-0.35

- 14-14 bonded magnet has higher Br (than 14-12) at elevated temperatures (≥100°C)
- Straight B-H line up to 180°C

150°C flux aging loss in bonded magnets



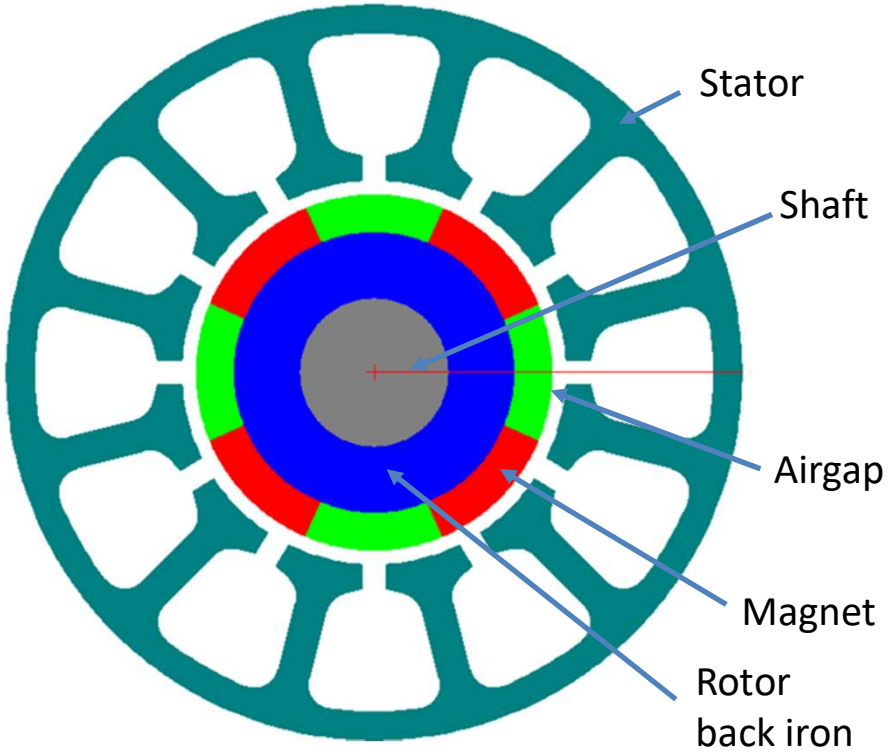
- 14-14 bonded magnet (PC=2) has 4.8% flux aging loss after 150°C/1000hr
- This is slightly higher than that of MQP-14-12 (4.1%)

Automotive Accessory Motor Redesign with AQ grade powder/magnet

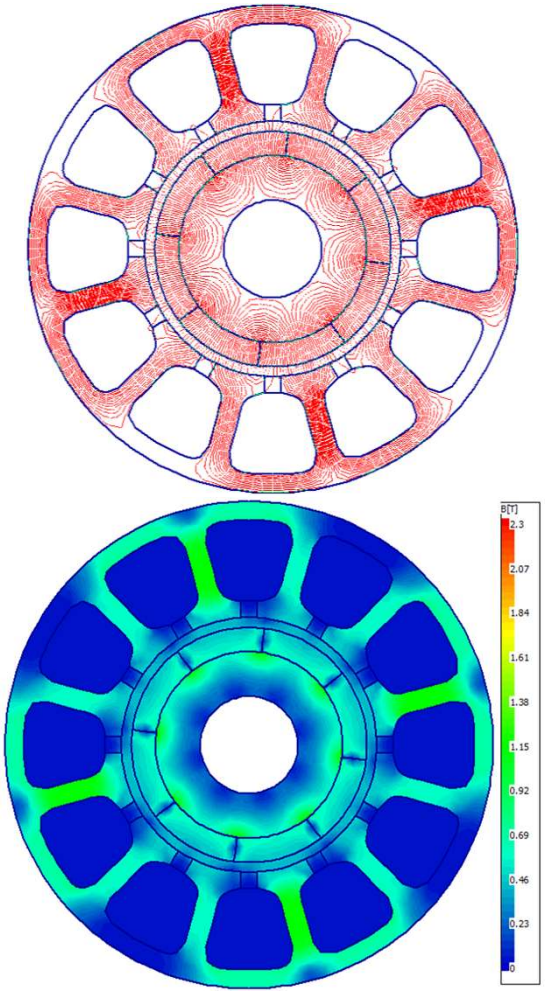
- An automotive accessory motor has been redesigned for two magnet type for the same size
  - Magnets from MQP-14-12 and MQP-15-12
- The advance quenching technique has helped in achieving finer grain size for MQP-15-12 powder
  - 1.2% increase in magnet B_r over the magnets from MQP-14-12
- As the motor was designed to avoid working in deep saturation of soft magnetic components (e.g. Stator back iron and rotor back iron), the increase in B_r translated to similar increase in the active airgap flux leading to an improved performance.

Redesign Motor: Configuration

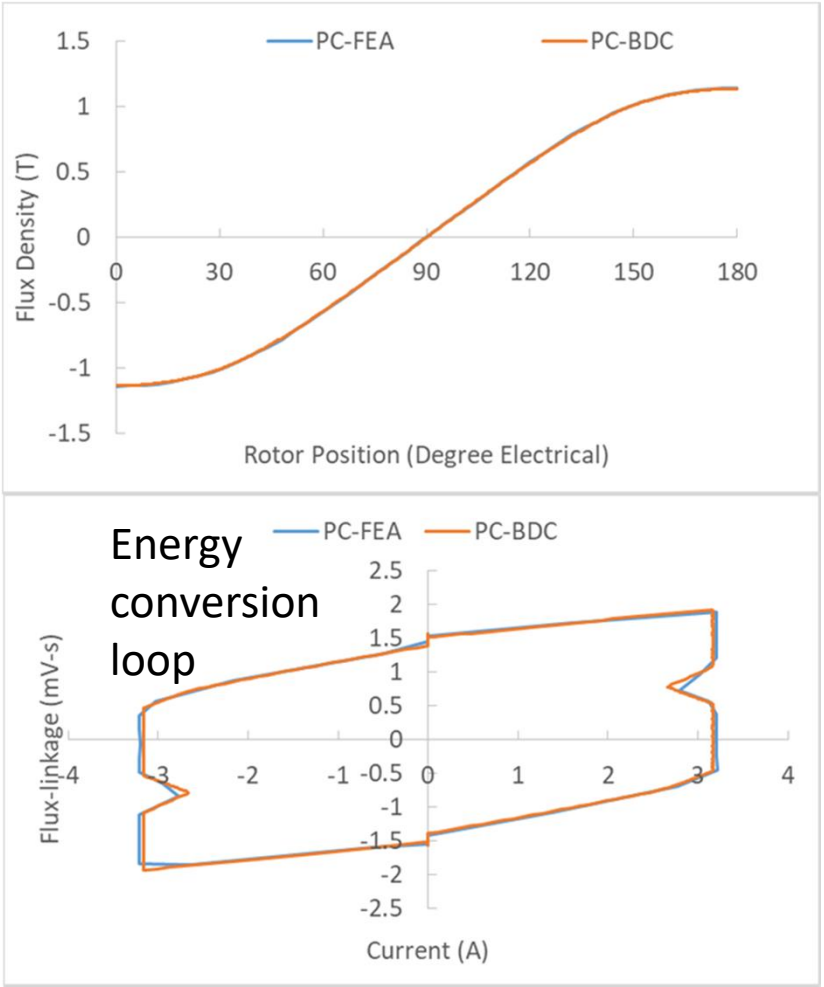
- Permanent Magnet Brushless DC Motor
  - Three Phase, 8-Pole, 12-Slot configuration
  - Concentrated winding
  - Radially magnetized magnet
  - Rectangular current drive



Redesigned Motors: Finite Element Analysis

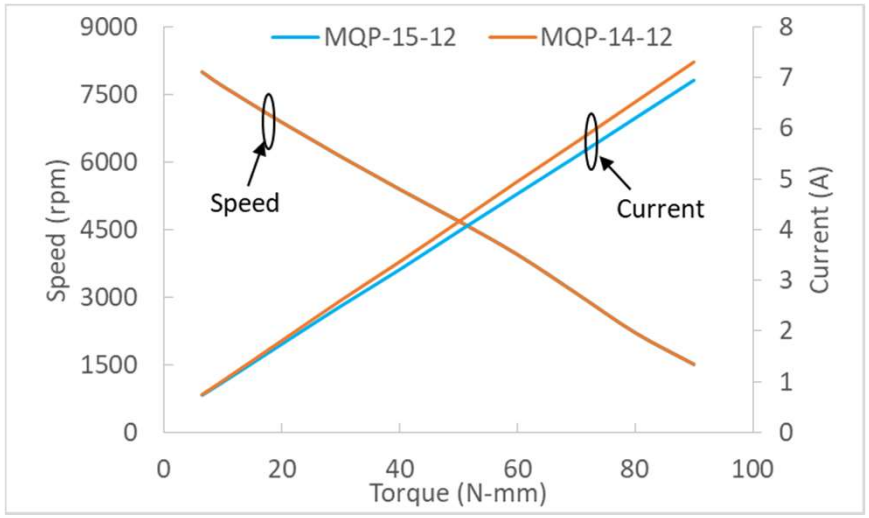


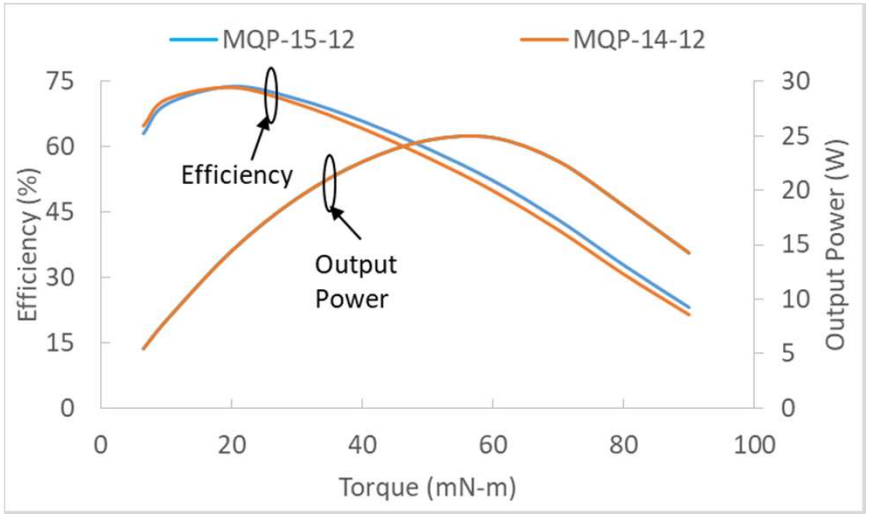
No-load flux density distribution in a motor with magnet from MQP-15-12



Close match between the Analytical design and FE Analysis

Redesigned Motors: Performance Comparison





Motor performance comparison for two MQ1 magnets

- The magnets from AQ process will help in improving the motor performance.
  - Useful for applications needing the reduction in motor envelop without sacrificing the performance or improving the performance from the same envelop

Summary

- AQ technology has enabled AQ grade products
  - More uniform microstructure & enhanced exchange coupling
  - Higher Br and (BH)max
  - Applicable to all existing MQP products
- Ce-contained powders have been developed for automotive applications
  - Ce content up to 60% of TRE
  - Good thermal stability at up to 120°C, suitable for most automotive applications
- A new MQP-14-14 powder has been developed
  - Higher Br at 150°C than MQP-14-12
  - Same Hci at 150°C
- Magnets from AQ grade powder can help in meeting the challenging motor performance requirement (e.g. improved efficiency, increase in torque density etc.)