Bonded Magnets: Current Status and Future Developments

Dr. John Ormerod

Senior Technology Advisor

Magnet Applications, Inc.

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Presentation Outline

- Introduction: who am I and who is MAI?
- What are bonded magnets anyway?
- Is there anything new in magnets (bonded or otherwise)?
- What are the market and application drivers?

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Introduction: John Ormerod

- BSc, MSC and PhD in Metallurgy from the University of Manchester (1972 – 1978).
- Magnetics career began with Philips (UK and Holland) - 1979 – 1990.
    - Developed and commercialized $SmCo_5$, 2:17 and NdFeB magnets
- Joined Arnold Engineering (US) responsible for soft and hard magnetic materials development and GM for permanent magnets (1990 – 2002).
- 2002 - 2014 President of Res Manufacturing in Milwaukee.
    - Metal stamping and value added assemblies to the automotive market (Toyota, GM, Nissan)
    - Major supplier to Tesla Motors for Model S and future Model X
- Recently provided expert testimony on issues of invalidity during the rare earth magnet ITC investigation and currently advising the Rare Earth Magnet Alliance on prior art relative to Hitachi Metals key patents.
- Advisory Board member for Bunting Magnetics, Senior Technology Advisor for MAI and Technology Advisor for Niron Magnetics.
- Founded business and technology consultancy for magnetics and metals related industries in 2015 – JOC LLC (www.jocllc.com).

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Introduction: Magnet Applications, Inc.

- Visit the website at: http://magnetapplications.com.
- A Bunting Magnetics Company: https://buntingmagnetics.com/.
- Largest North American manufacturer of compression bonded NdFeB and injection molded ferrite and NdFeB magnets.
- Supply full range of engineered magnets and magnetic assemblies.
- Located in DuBois, PA – Originally established in UK over 50 years ago – sister company located in Berkhamsted, UK.
- Primary applications are BLDC motors and sensors in the automotive, medical and industrial markets.

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Introduction: Magnet Applications, Inc.

- Pre-production magnetic design services including 3D magnetic modeling.
- Industry leading technical services to optimize the material for the application.
- Investing in R & D for next generation of magnetic materials.
- The backing of strong family ownership – in business for over 55 years.
- ITAR / DFARS registered for Defense Industry.
- ISO-9001 Certified Quality System with continuous improvement.
- Very strong international supply chain for the complete range of permanent magnet materials.

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What Are Bonded Magnets Anyway?

- Bonded magnets are composites of a permanent magnetic powder(s) embedded in a non-magnetic matrix.
- The matrix is typically a thermoplastic or elastomeric binder.
- Common processing techniques are extrusion, injection molding, compression bonding, and calendering.
- Exhibit excellent mechanical properties compared to fully dense rare earth and ferrite magnets.
- End product has good finish and dimensional tolerances requiring no finishing operations.
- Injection molded magnets can be formed into complex shapes and be insert or over molded directly onto other components to produce assemblies.
- The non-magnetic binder lowers the density of the magnet and dilutes the contribution of the magnetic powder.
- They generate less magnetic output per unit volume than fully dense magnets.
- The two most common magnetic powders are isotropic NdFeB and hard ferrite.

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Bonded vs. Sintered

Bonded

- Excellent geometric tolerances with minimal or no secondary operations
- Good mechanical properties
- Complex shapes
- Insert/overmolding of sub assemblies
- Higher electrical resistivity
- Multipole magnetization
- Tailored flux output for given size/shape magnet

Sintered

- Highest flux output
- Higher operating temperature

Isotropic Magnets

- Definition: Isotropy is uniformity in all orientations; equal properties in all directions.
- Some magnets do not have a preferred direction of magnetization; equal flux output in all directions when magnetized.
  - These are referred to as isotropic (or non oriented) magnets.
- Vast majority of bonded NdFeB magnets are isotropic.
  - Individual powder particles consist of numerous randomly oriented crystal grains.
- May be magnetized in any direction with equal output .
  - A rectangular magnet may be magnetized through the width, thickness or length and maintain the same intrinsic properties of magnetization.
  - This is a very useful characteristic for building multi-pole devices out of a single piece of magnetic material.
  - We have developed multipole rings with up to 102 poles at 0.8 mm pole pitch.

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Anisotropic Magnets

- Definition: Anisotropy is exhibiting properties with different values when measured in different directions, as opposed to isotropy, which implies identical properties in all directions.
- Magnets have a preferred direction of magnetization
  - Referred to as an anisotropic or oriented magnet.
  - During manufacture single crystal grains of the material are aligned to maximize the flux density output of the magnet.
  - Requires magnetization parallel to the alignment.
  - Stronger magnetic output than isotropic.
- Vast majority of sintered NdFeB magnets are anisotropic.

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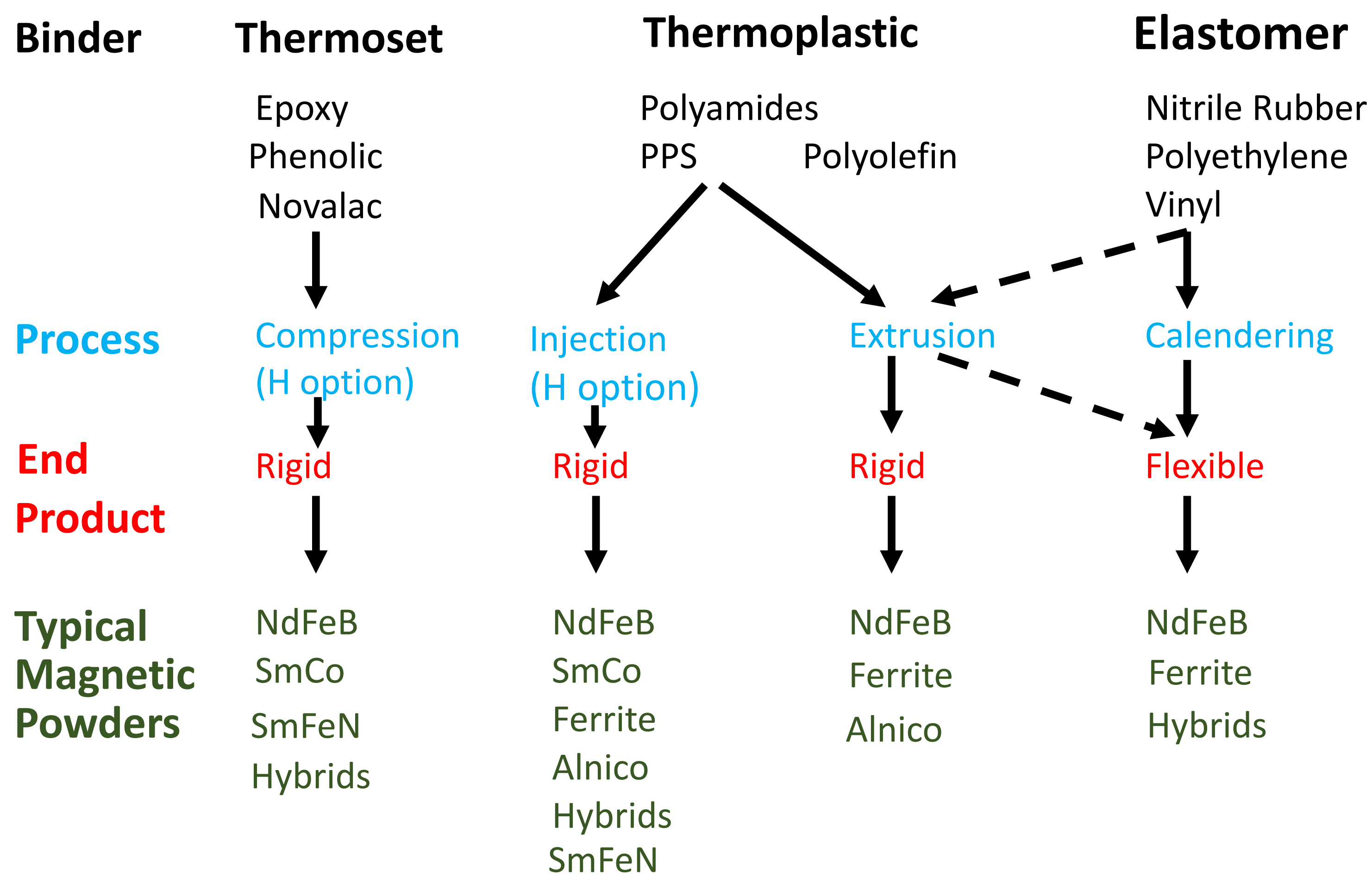
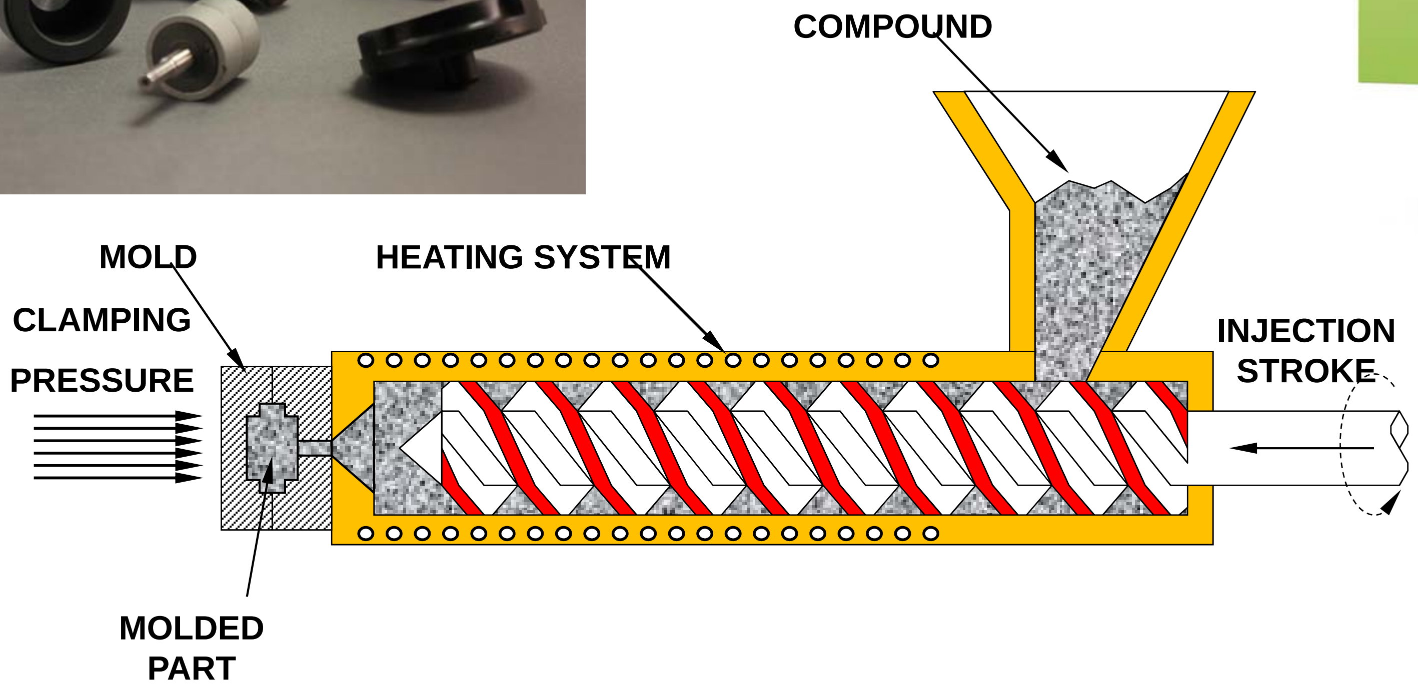
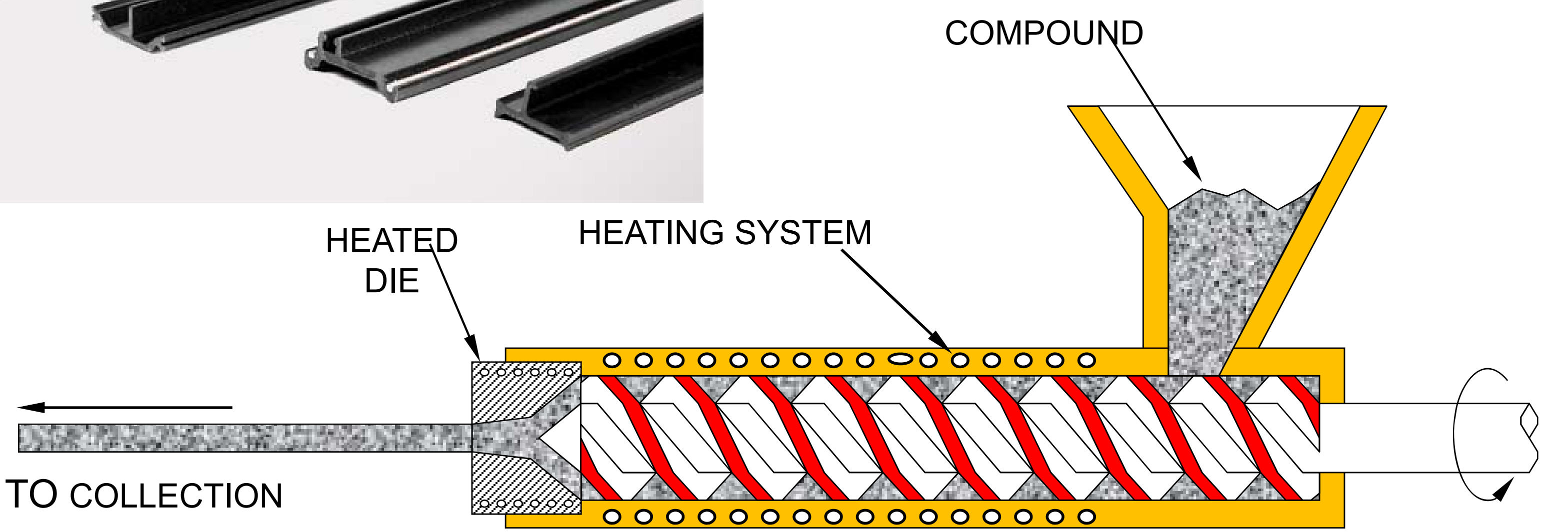
Bonded Magnet Material And Process Options



Injection Molding



Extrusion



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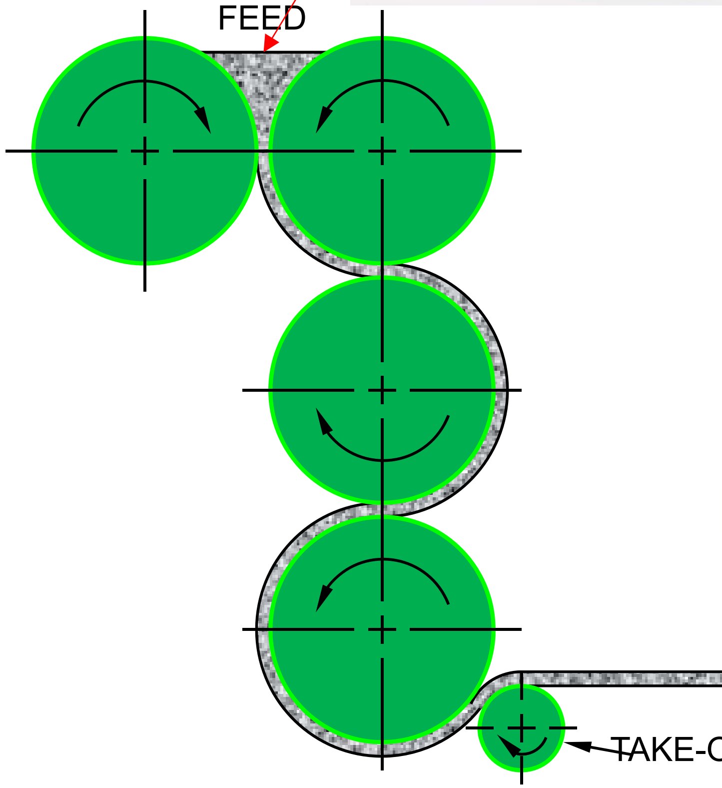
Calendering

Granulated compound



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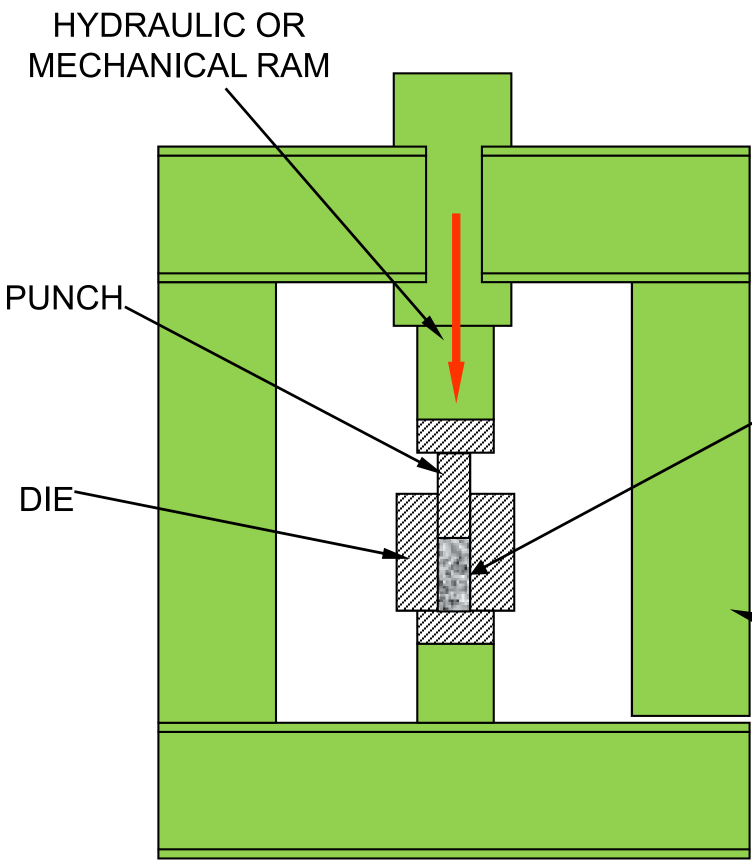
Compression Bonding



Encapsulated powder

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Compression Bonding or Injection Molding?

Injection Molding

- Complex forms with good geometrical tolerances
- Multi-cavity tooling
- Over and insert molding

But

- Expensive tooling
- Lower magnetics (66% volume loading of magnetic powder)
- NdFeB and ferrite

Compression Bonding

- Thin walled large L/D ratio rings
- Simple low cost tooling
- Higher magnetics (75% volume loading of magnetic powder)

But

- Simple geometries
- Value added operations during pressing very difficult
- NdFeB only

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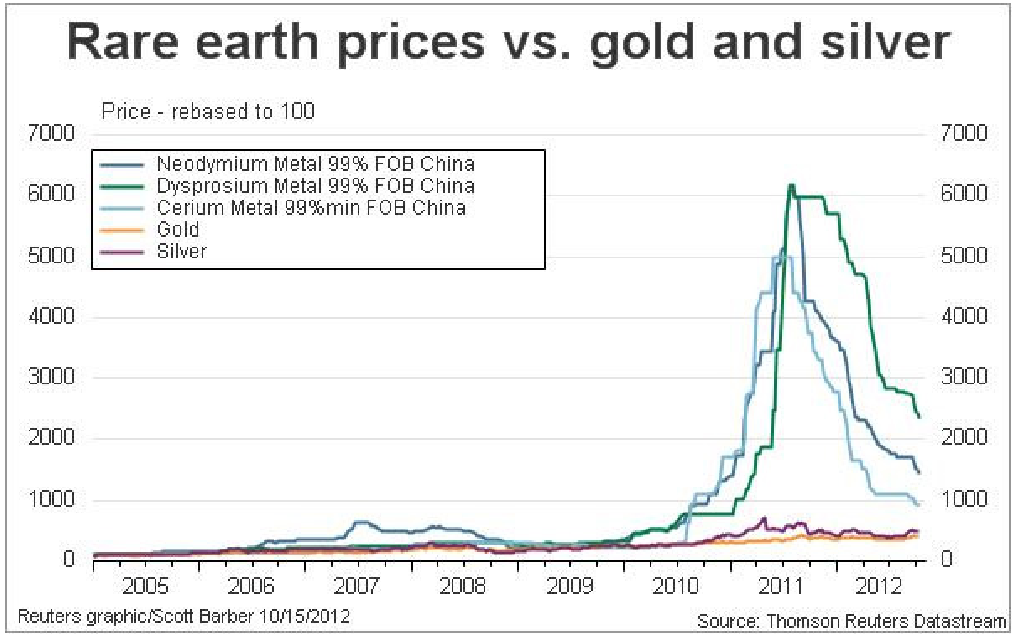
Is There Anything New in Magnets (Bonded or Otherwise)?

- In the summer of 2011, the price of rare earth elements was skyrocketing, blasted upward by uncertainties around sourcing.
- What goes up must come down, and the rare-earth market has done so with a vengeance.



- In 2010, the Chinese government cut the export quota by 40%.
- Customers began doubling and tripling orders, and speculators moved in.
- A widespread misconception in industry holds that the bubble formed because the Chinese government curtailed supply.
- The cut in export quotas was the precipitating event but it was the response of customers and the supply chain that caused the problem, not an absolute limitation in the supply.

Source: K. Lewotosky, MCMA 11/23/2015

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Is There Anything New in Magnets (Bonded or Otherwise)?

- However, it did trigger a Global response to spend mainly other people's money (ARPA-E, DARPA-E, EU-REFREEPM) on the search for a RE-free or reduced RE content magnet.
- So what's new-ish (but not yet commercialized):

Ce-TM	Mn-Bi
Nanocomposite exchange spring	Optimized AlNiCo
Fe-N	Co-Fe-C nanoparticles
Nanocrystalline Mn-Al	Fe-Ni
Hf-Co	etc., etc.

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Recent Development - Mn-Bi

US 20150325349A1

(19) **United States**
(12) **Patent Application Publication**
GABAY et al.

(10) **Pub. No.: US 2015/0325349 A1**
(43) **Pub. Date: Nov. 12, 2015**

(54) **HIGH PERFORMANCE PERMANENT MAGNET BASED ON MNBI AND METHOD TO MANUFACTURE SUCH A MAGNET**

(71) Applicant: **SIEMENS AKTIENGESELLSCHAFT**, Munchen (DE)

(72) Inventors: **Alexander GABAY**, Newark, NJ (US); **George HADJIPANAYIS**, Wilmington, DE (US); **Michael KRISPIN**, Munich (DE); **Venkata Ramarao NEELAM**, Hyderabad (IN)

(73) Assignee: **SIEMENS AKTIENGESELLSCHAFT**, Munchen

Publication Classification

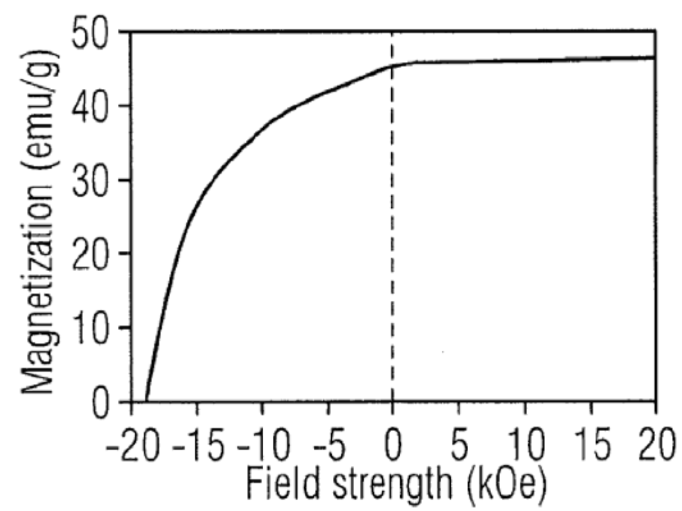
(51) **Int. Cl.**

H01F 1/047	(2006.01)
H01F 1/08	(2006.01)
B22F 9/04	(2006.01)
H01F 41/02	(2006.01)
B22F 3/02	(2006.01)
B22F 3/24	(2006.01)

(52) **U.S. Cl.**
CPC ***H01F 1/047*** (2013.01); ***B22F 3/02*** (2013.01); ***B22F 3/24*** (2013.01); ***B22F 9/04*** (2013.01); ***H01F 41/0266*** (2013.01); ***H01F 1/08*** (2013.01); *B22F 2003/248* (2013.01); *B22F 2009/043* (2013.01)

(57) **ABSTRACT**

FIG 12



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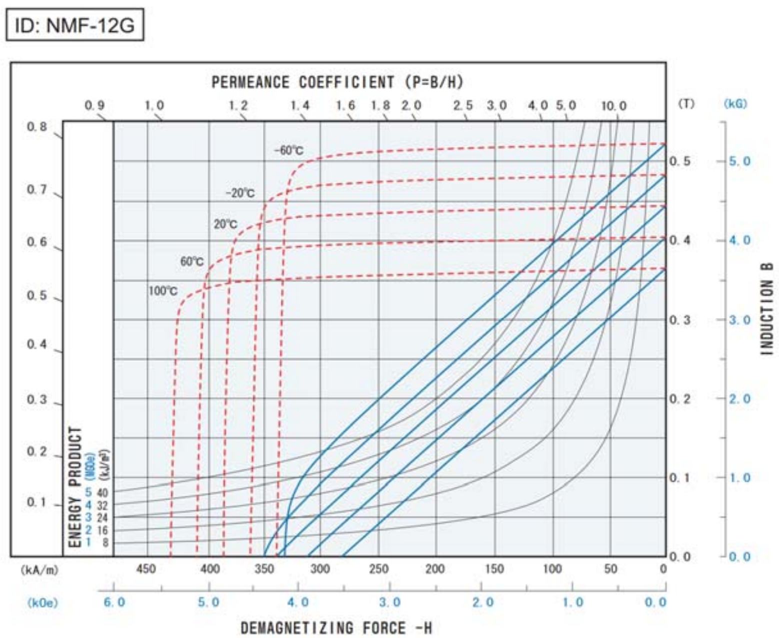
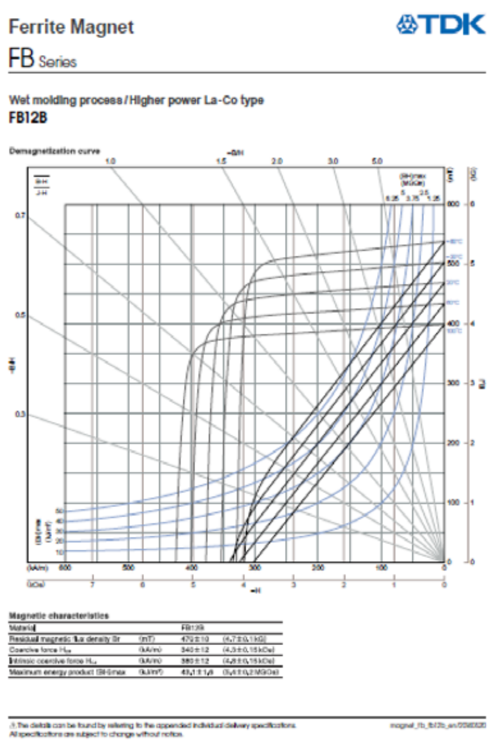
Commercially Important Recent Developments

- Next Generation La-Co doped hard ferrite magnets e.g. HML, TDK



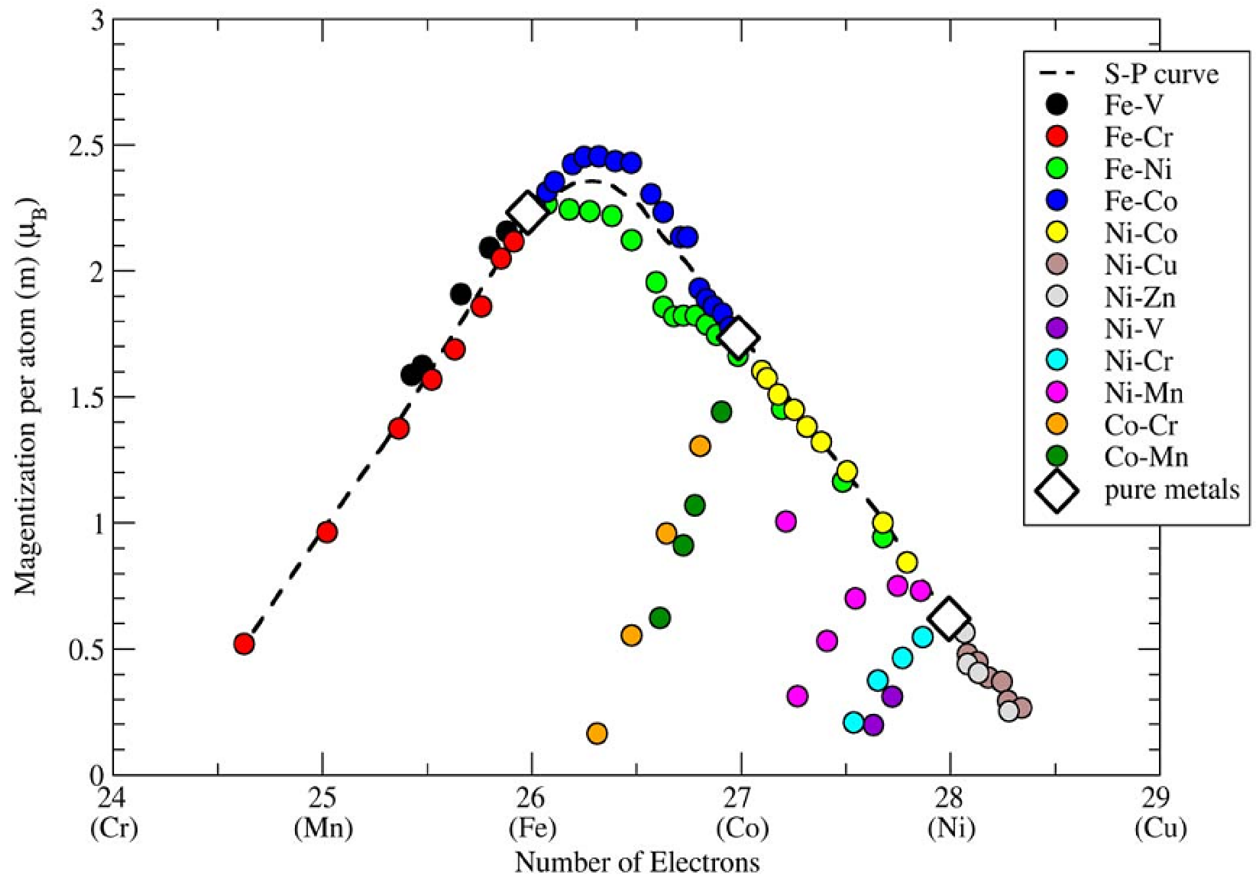


- Dy diffusion processing - Reduced Dy content high operating temperature NdFeB magnets

What's New in Bonded Magnets?

- Rare Earth-Free $Fe_{16}N_2$ based magnets.
- Application of 3D Printing/Additive Manufacturing to Bonded Magnets and Assemblies.
- Higher Energy Product Compression Bonded Isotropic NdFeB magnets.

Some History on Fe16N2; The Slater-Pauling Curve



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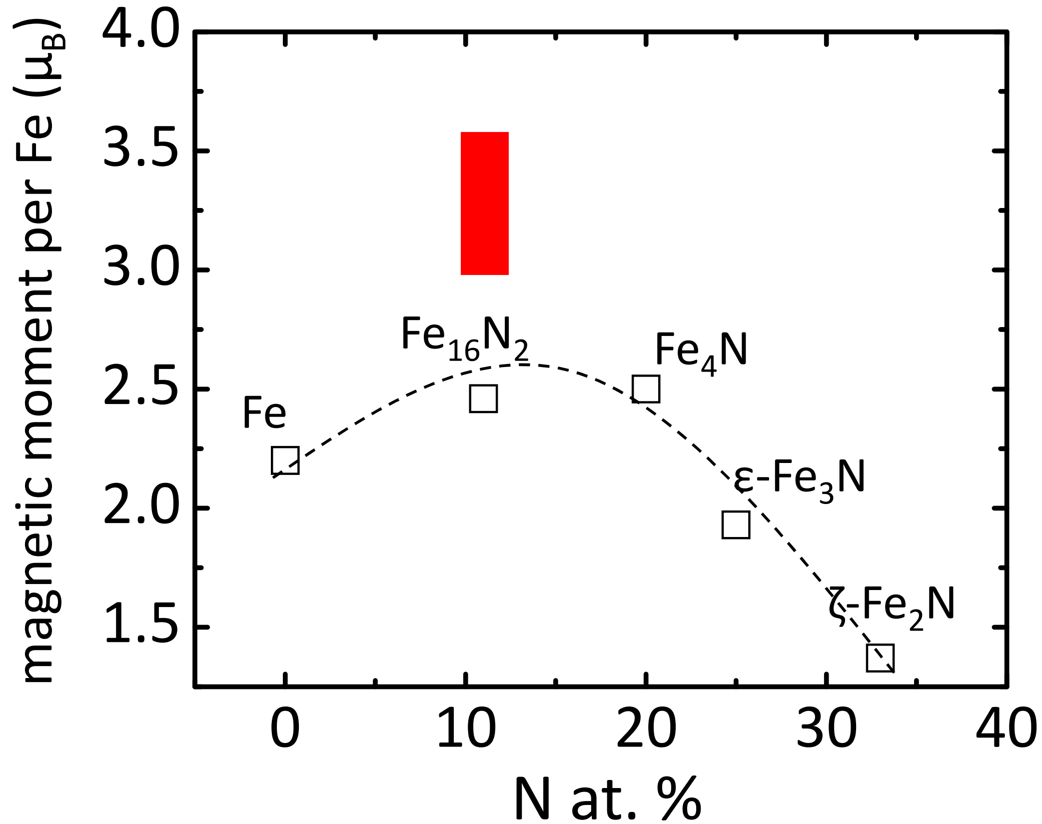
Some History of Fe16N2



Strange departure from the regular SP curve was claimed back in 1970 that $Fe_{16}N_2$ possesses a giant M_s, corresponding to an average magnetic moment of 2.9~3.5 μ_B/Fe according to different reports.

40 Years Later No $Fe_{16}N_2$ Magnet – Why?

- Difficult to synthesize pure $Fe_{16}N_2$ by conventional methods e.g. solubility of N in liquid Fe very low (0.045 versus 5.5 wt % for C).
- Alloy cannot be formed by conventional processing methods e.g. melting and casting.
- Contradictory results over the years probably due to inconsistent sample preparation and measurement techniques.
- $Fe_{16}N_2$ decomposes above 300 C.
- Cannot be formed by powder metallurgical processing.
- Lots of magnetization available but need coercivity for a useful PM compound; theoretical magnetocrystalline anisotropy H is 16 kOe but will need help from other mechanisms e.g. shape, strain.

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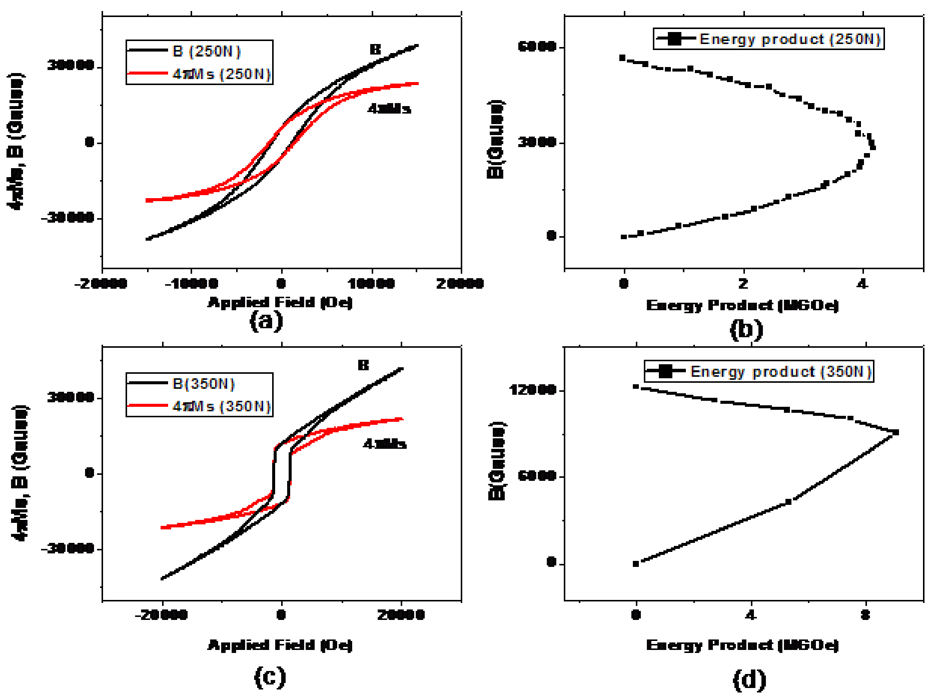
Bulk $Fe_{16}N_2$ Magnet Reported by UMN Team and Niron Magnetics Formed

- Strained wire method used to enhance magnetic property; strain-assisted annealing.



US 20140299810A1

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2014/0299810 A1**
Wang et al. (43) **Pub. Date: Oct. 9, 2014**

(54) **IRON NITRIDE PERMANENT MAGNET AND TECHNIQUE FOR FORMING IRON NITRIDE PERMANENT MAGNET**

(75) Inventors: **Jian-Ping Wang**, Shoreview, MN (US); **Shihai He**, Fremont, CA (US); **Yanfeng Jiang**, Minneapolis, MN (US)

(73) Assignee: **REGENTS OF THE UNIVERSITY OF MINNESOTA**, St. Paul, MN (US)

(21) Appl. No.: **14/238,835**

(22) PCT Filed: **Aug. 17, 2012**

(86) PCT No.: **PCT/US2012/051382**

§ 371 (c)(1), (2), (4) Date: **Jun. 9, 2014**

Related U.S. Application Data

(60) Provisional application No. 61/524,423, filed on Aug. 17, 2011.

Publication Classification

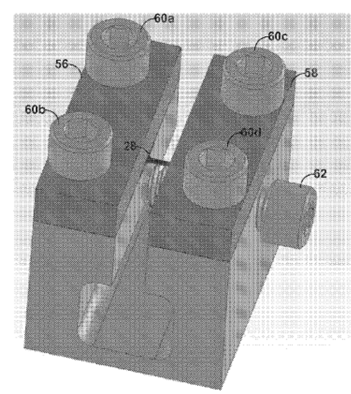
(51) **Int. Cl.**
H01F 1/01 (2006.01)
H01F 41/02 (2006.01)
H01F 7/02 (2006.01)

(52) **U.S. Cl.**
CPC ***H01F 1/01*** (2013.01); ***H01F 7/021*** (2013.01); ***H01F 41/0253*** (2013.01)
USPC ... **252/62.55**; 335/302; 423/409; 252/62.51R; 148/226; 148/101; 148/103; 118/33

(57) **ABSTRACT**

A permanent magnet may include a $Fe_{16}N_2$ phase constitution. In some examples, the permanent magnet may be formed by a technique that includes straining an iron wire or sheet comprising at least one iron crystal in a direction substantially parallel to a <001> crystal axis of the iron crystal; nitridizing the iron wire or sheet to form a nitridized iron wire or sheet; annealing the nitridized iron wire or sheet to form a $Fe_{16}N_2$ phase constitution in at least a portion of the nitridized iron wire or sheet; and pressing the nitridized iron wires and sheets to form bulk permanent magnet

54



Source: Niron Magnetics

Niron Magnetics – Good News/Bad News

Good News

- The company is producing bulk iron nitride magnets today for further research and development.
- First principles calculations demonstrate a theoretical BHmax of 135 MGOe and Hc of 16 KOe.
- Raw materials are cheap and abundant.
- Isotropic bonded magnet BHmax > 30 MGOe feasible.

Bad News

- Iron nitride by itself is inherently heat sensitive.
- It decomposes before it sinters – iron nitride magnets will all be bonded in some fashion.
- Coercivity needs to be improved.
- They will need the same corrosion protection as raw iron.
- Niron hasn’t announced a commercial product yet

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What's New in Bonded Magnets?

- Rare Earth-Free $Fe_{16}N_2$ based magnets.
- Application of 3D Printing/Additive Manufacturing to Bonded Magnets and Assemblies.
- Higher Energy Product Compression Bonded Isotropic NdFeB magnets.

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Additive Manufacturing – MAI and ORNL Joint R and D Project

- MAI and ORNL were recently awarded a Cooperative Research and Development award to study the application of additive manufacturing to bonded magnets and systems.

BUNTING® Magnetics Co.

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PRESS RELEASE
Date: September 30, 2015
Contact: John Ormerod
E-mail: jormerod8@gmail.com

FOR IMMEDIATE RELEASE

Magnet systems provider Magnet Applications, Inc. Signs CRADA with ORNL to enable the rapid design and manufacturing of isotropic bonded magnets by additive manufacturing technologies.

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3D Printing Project

- 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.
    - Additive manufacturing is the fabrication of geometrically complex 3D object from a computer aided design which requires little or no tooling and post-processing thus reducing the amount of waste generated.
    - Reduced time to market for new magnet/motor designers.

Types of AM/3D printing

Source:ORNL

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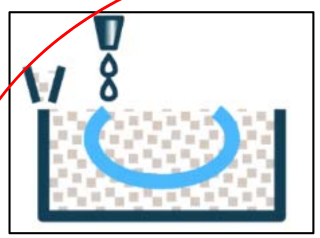
Types of Additive Manufacturing

ASTM International:

Technical Committee F42 on Additive Manufacturing

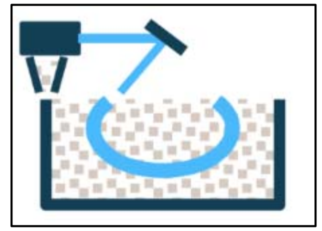
Vat Photo-polymerization

Material Jetting

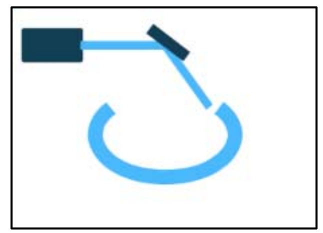


Binder Jetting

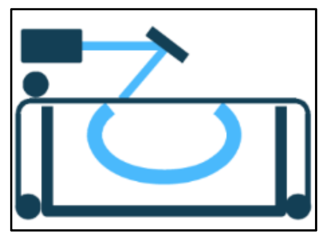
Material Extrusion



Powder Bed Fusion



Directed Energy Deposition



Sheet Lamination

Source:ORNL

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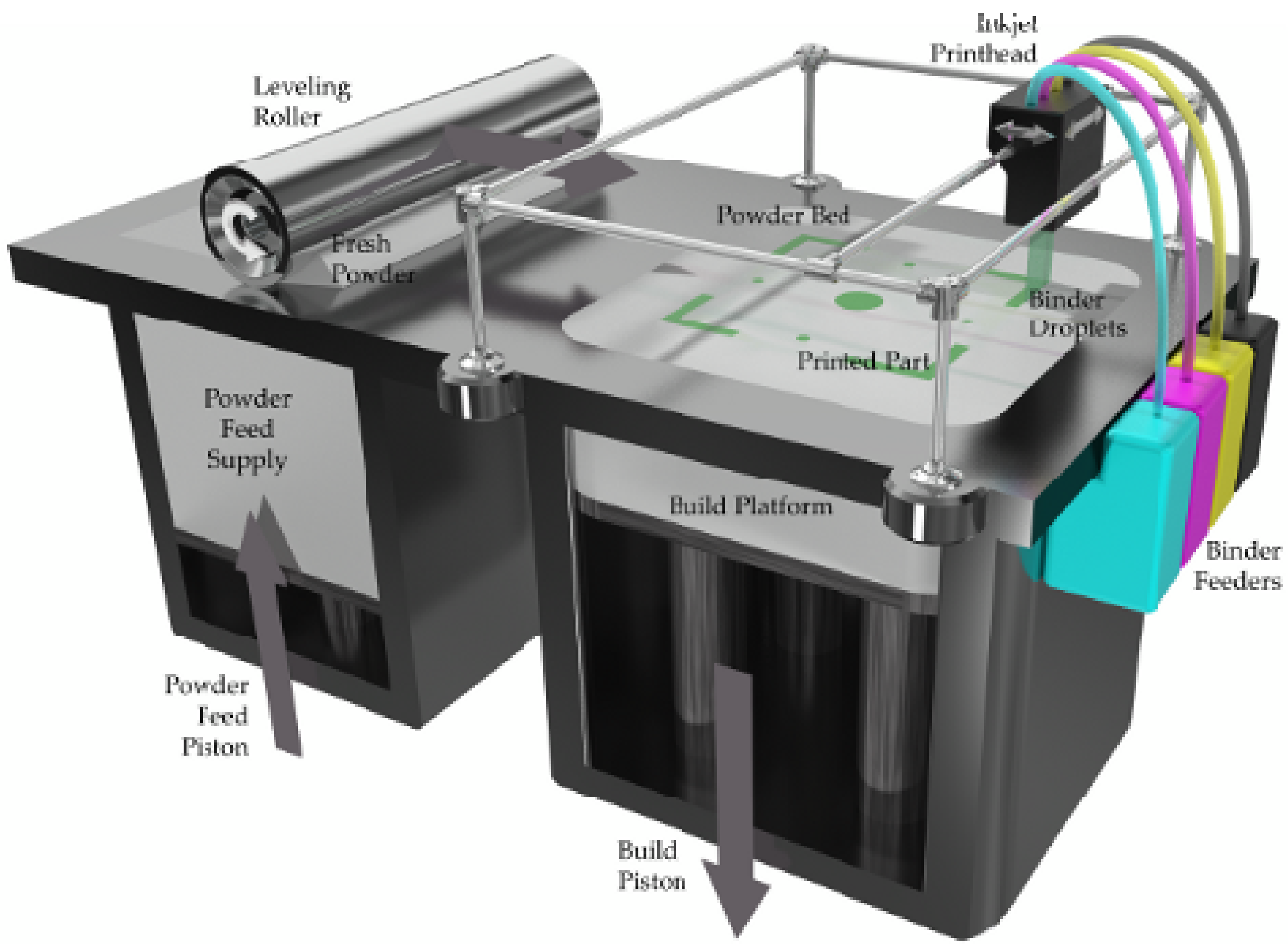
Indirect 3D Printing

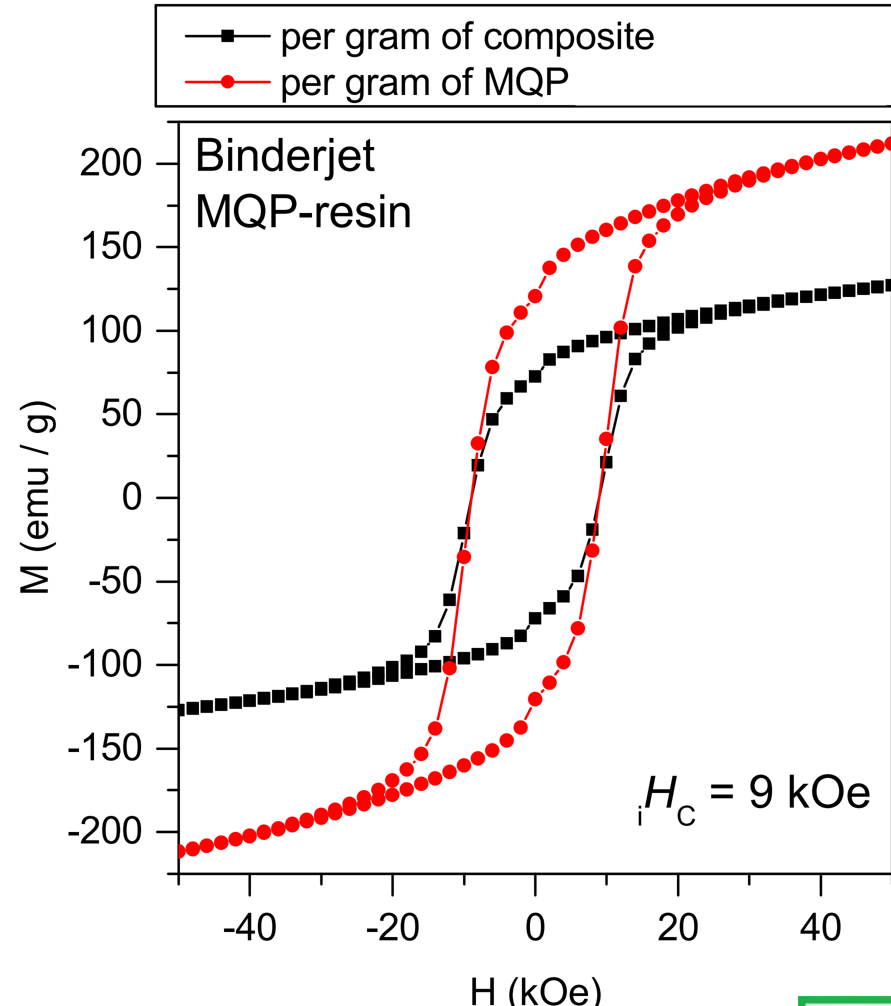


Source: ORNL

ExOne Binder Jet Process

- ExOne builds functional 3D objects from the bottom up, one layer at a time with durable, industrial-strength materials.
- ExOne 3D printing systems selectively bind thin, cross-sectional layers of fine powder.
- As the print head passes over the powder bed, binder is deposited into the powder.
- The powder bed lowers and is coated with another layer of the print powder.
- With each successive pass of the print head, more of the object is bound until a near-net shape object is completed.

Initial MQP Magnets Produced by Binder Jetting



Source: ORNL

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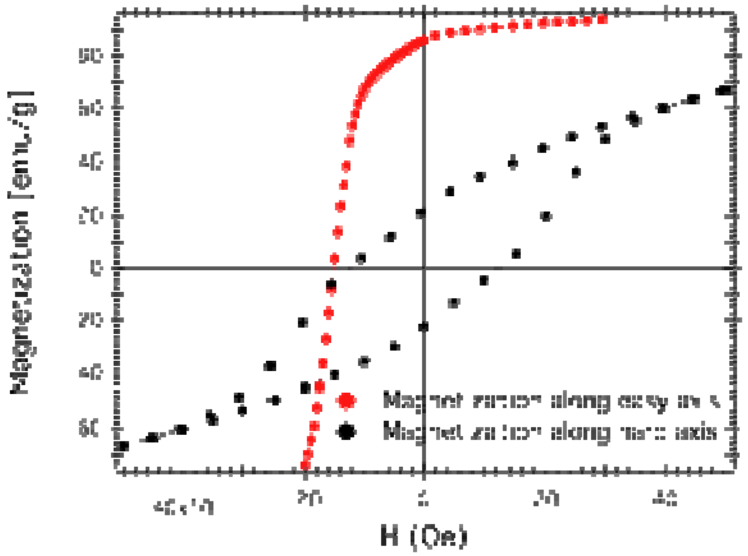
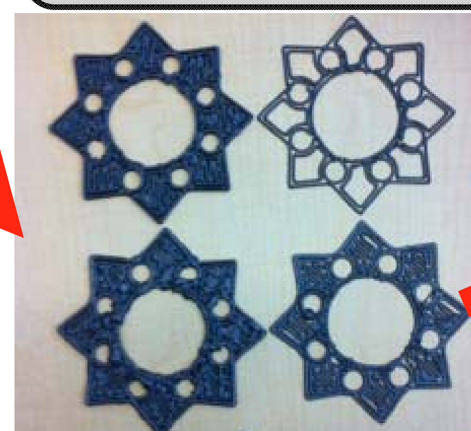
Large Scale Polymer Deposition of Bonded Magnets

The process:

BAAM system at ORNL

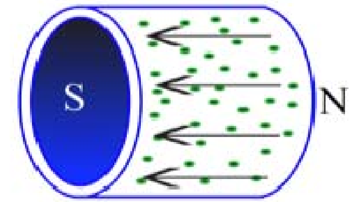


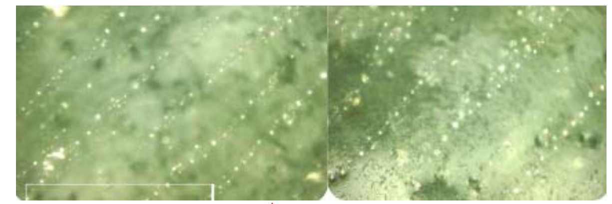
Magnetization behavior of the bonded magnet



Fabricated rotors

Post Magnetic field alignment (9 Tesla)





Source: ORNL

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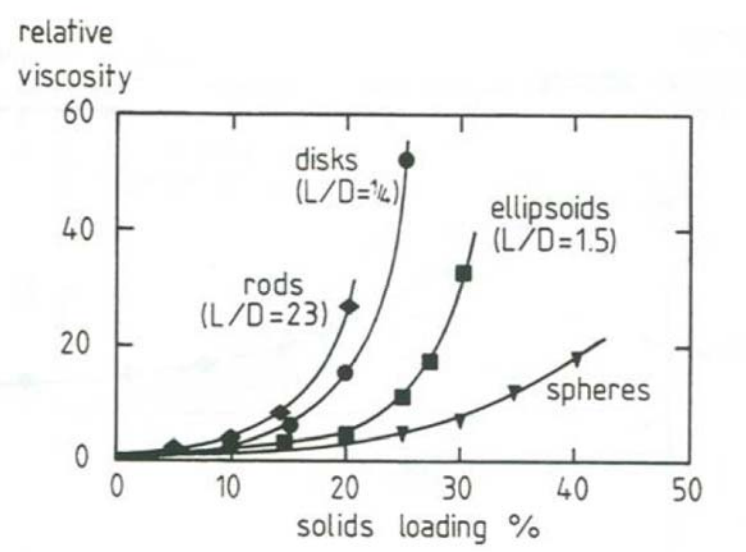
Challenges for Direct Write Inks

- Ink must flow through nozzle without jamming
- Ink filaments must form high integrity interfaces
- Ink must solidify rapidly (via gelation, coagulation, evaporation…)
- However, require high loading (> 60 volume %) of magnetic powder
- Loading limited to 40 volume % with standard jet cast powders



Current focus of research is:

- Investigating optimum particle shape and distribution
- Correlation of binder rheological properties and powder magnetic properties

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Large Scale Additive Manufacturing

3D printed all electric Shelby Cobra car

What's next?

Permanent magnet based motors!!!

Source: ORNL

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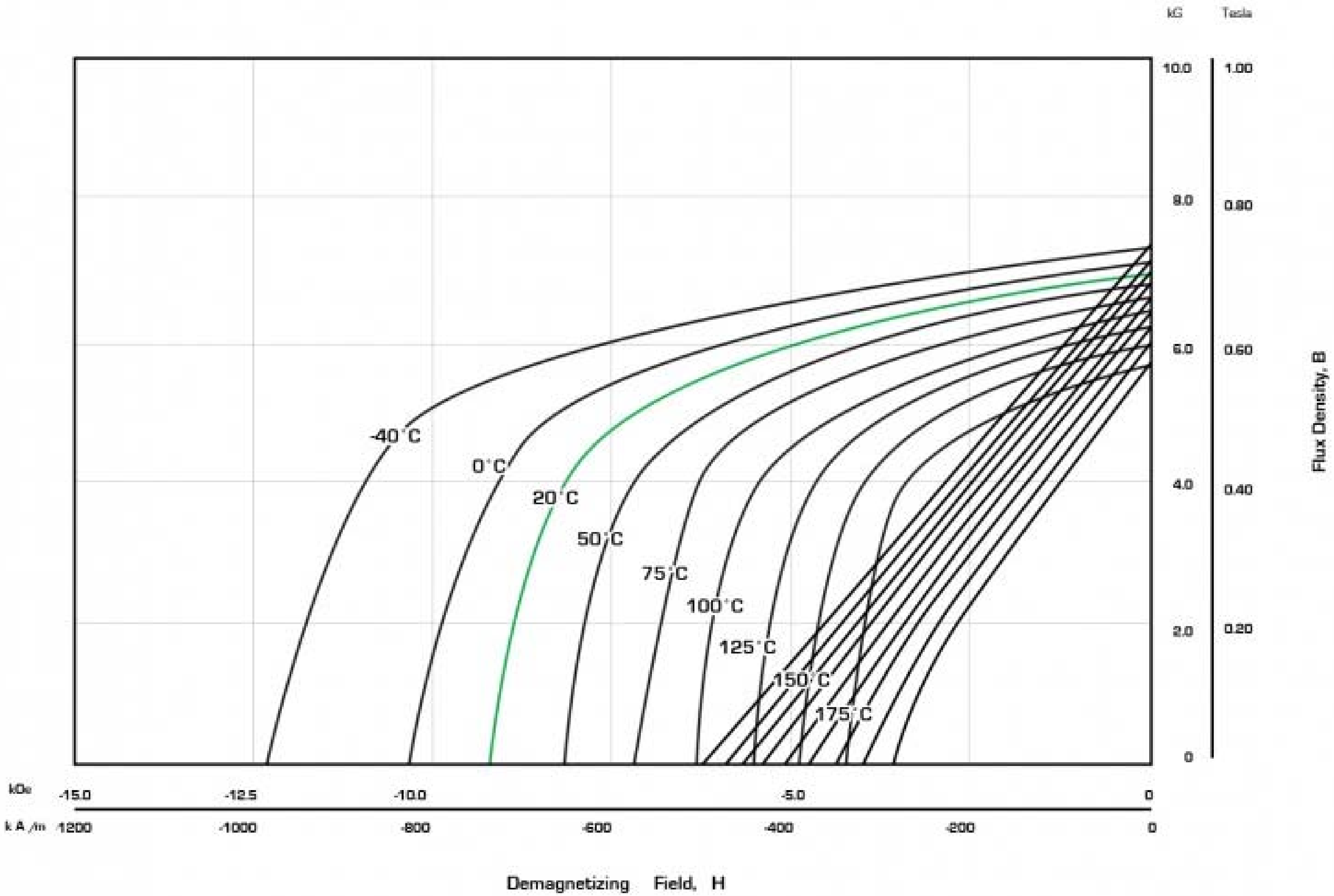
Typical Compression Bonded Magnetic Properties



- Many suppliers publish specifications for a nominal 10 MGOe magnets with a minimum limit of 9 MGOe.
- Similar for a nominal 11 MGOe magnet; minimum limit is 10 MGOe.
- Have to design to lower limit of BHmax

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BHmax Improvement in Compression Bonded Magnets

The BHmax of a compression bonded isotropic NdFeB magnet is influenced by the following two factors:

1. Volume fraction of magnetic phase in the magnet – typically measured by the density of the magnet.
   - We are investigating increasing the pressing pressure which requires special press construction, lubricants and tooling materials – current production pressing pressures are 7tonnes/cm2 for 5.9 g/cm3 and 10MGOe; estimated that > 20 tonnes/cm2 required for 6.3 g/cm3 and > 11 MGOe.
   - Optimize the particle encapsulation chemistry and process.
   - Tailored multimodal PSD's for maximum packing density.
   - Particle shape control.
2. Magnetic powder Br/BHmax
   - Increase isotropic Br of powders while maintaining sufficient Hci to have "linear" B-H demagnetization characteristic at the application temperature.

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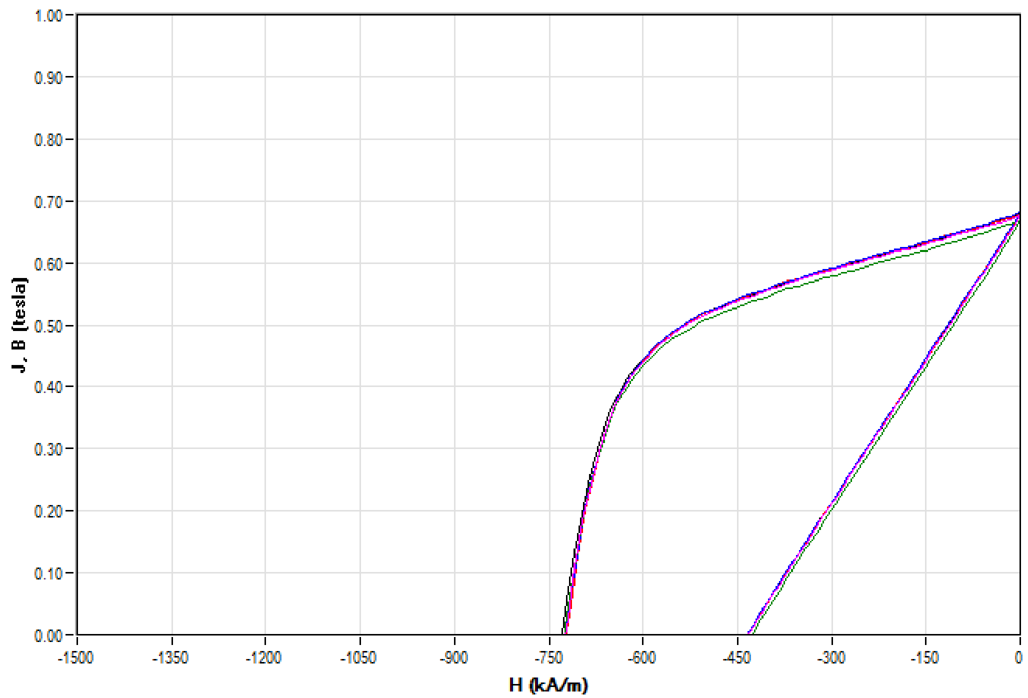
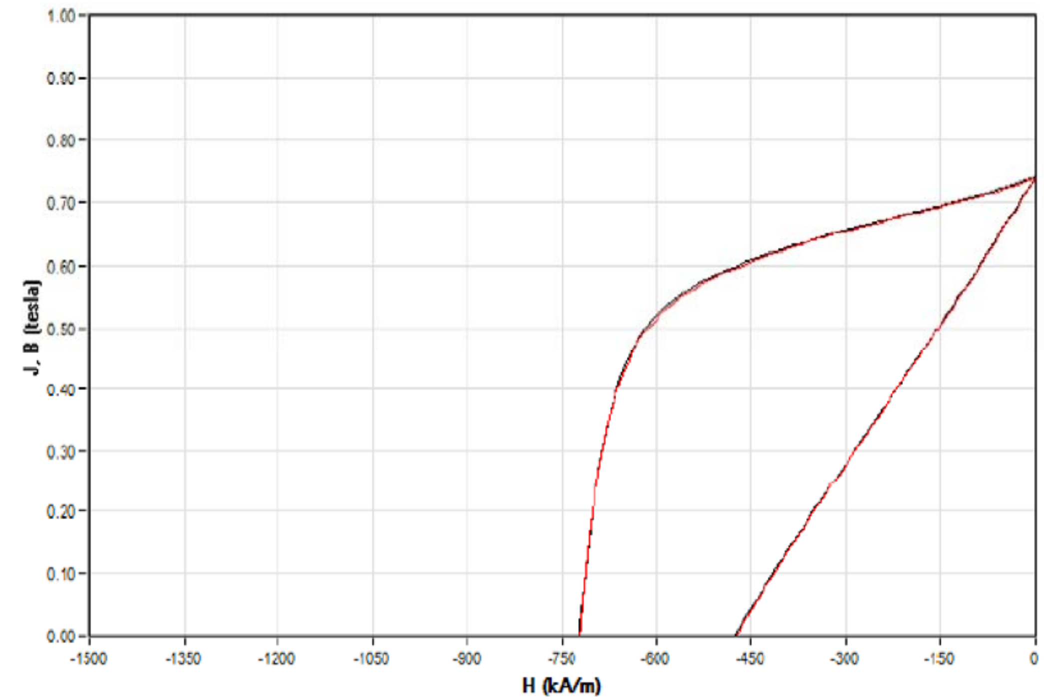
20% BHmax Improvement - True 11 MGOe



Standard production nominal magnetics at 5.9 g/cm3:
Br = 6800 G
Hci = 9.1 kOe
HcB = 5.4 kOe
BHmax = 9.2 MGOe



High density nominal magnetics at 6.3 g/cm3:
Br = 7400 G
Hci = 9.1 kOe
HcB = 6.0 kOe
BHmax = 11.1 MGOe

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Global Production Of Permanent Magnets In 2014

Magnet Type	Tons x 1,000	% by Weight	Million USD	% by Value	ASP - $/Kg
Sintered NdFeB	70	10.9%	$10,500	54.8 %	$150
Bonded NdFeB	9	1.4	750	3.9	90
Sintered /Bonded Ferrite	565	87.6	6,780	35.4	12
Samarium Cobalt	4	0.6	700	3.7	175
Alnico	6	0.9	420	2.2	70
TOTAL	**645**	**100.0%**	**$19,150**	**100.0%**	**-**

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PM Markets and Devices/Applications

Devices

- Electromechanical machines and devices e.g. motors, generators, actuators
- Acoustic transducers e.g. speakers, earphones, ringers
- Mechanical force and torque devices e.g. holding, lifting, clutches
- Microwave and ion beam control e.g. TWT's, particle accelerators
- Conversion of external stimuli to electrical signal e.g. sensors
- DC field generation e.g. MRI

Markets and Industries

- Automotive and transportation
- Industrial and commercial
- Consumer products
- Military and aerospace
- Medical

Sensors/Encoders

Hall Effect Encoder for end of shaft applications. Available as either absolute or incremental encoders they can provide digital position, analog position, and quadrature speed outputs. Capable of rotational speeds over 20k RPM. Hall IC used for this application uses a diametrically magnetized magnet.

Hall Effect through-shaft encoder. Requires use of Hall IC capable of off-axis sensing using multipole bonded magnet.

Low cost, speed or position sensors typically seen in automotive applications – Cam position, crank position, engine speed, ABS. This type of sensor can be designed for either face or lateral sensing applications and may, in addition to the Hall IC, incorporate a magnet if sensing a metal target or a pole piece if sensing an encoder multipole magnet.

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Summary

- What is the best permanent magnet material and process?
  - It depends; on the weight/space limitations, application operating conditions, operating parameters of the magnetic circuit, annual quantity, device assembly mechanization etc.
  - Despite have lower flux output bonded magnets can offer advantages over sintered magnets for many applications.
  - Despite lack of breakthrough in new materials over the last 30 years there are several promising developments in bonded magnets on the horizon.
  - Always discuss your specific application/device criteria with our Sales/Application Engineers before freezing in a material.

THANK YOU FOR YOUR ATTENTION – ANY QUESTIONS

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