Bonded Magnets: Material and Process Update

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mcma Motion Control & Motor Association | TECHNICAL CONFERENCE

Presentation Outline

- Introduction
- Permanent Magnet Basics
- Bonded Magnet Overview
- New Materials and Processes
- Markets and Applications

John Ormerod

- BSc, MSC and PhD in Metallurgy from the University of Manchester (1972 – 1978).
- Magnetics career began for Philips (UK and Holland) – 1979 - 1990
  - Developed and commercialized SmCo5, 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

John Ormerod

- 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)

Magnet Applications, Inc.

- http://www.magnetapplications.com/
- A Bunting Magnetics Company https://buntingmagnetics.com/
- Largest North American manufacturer of injection molded ferrite and compression bonded and injection molded 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, automotive steering and brake sensors, medical devices.

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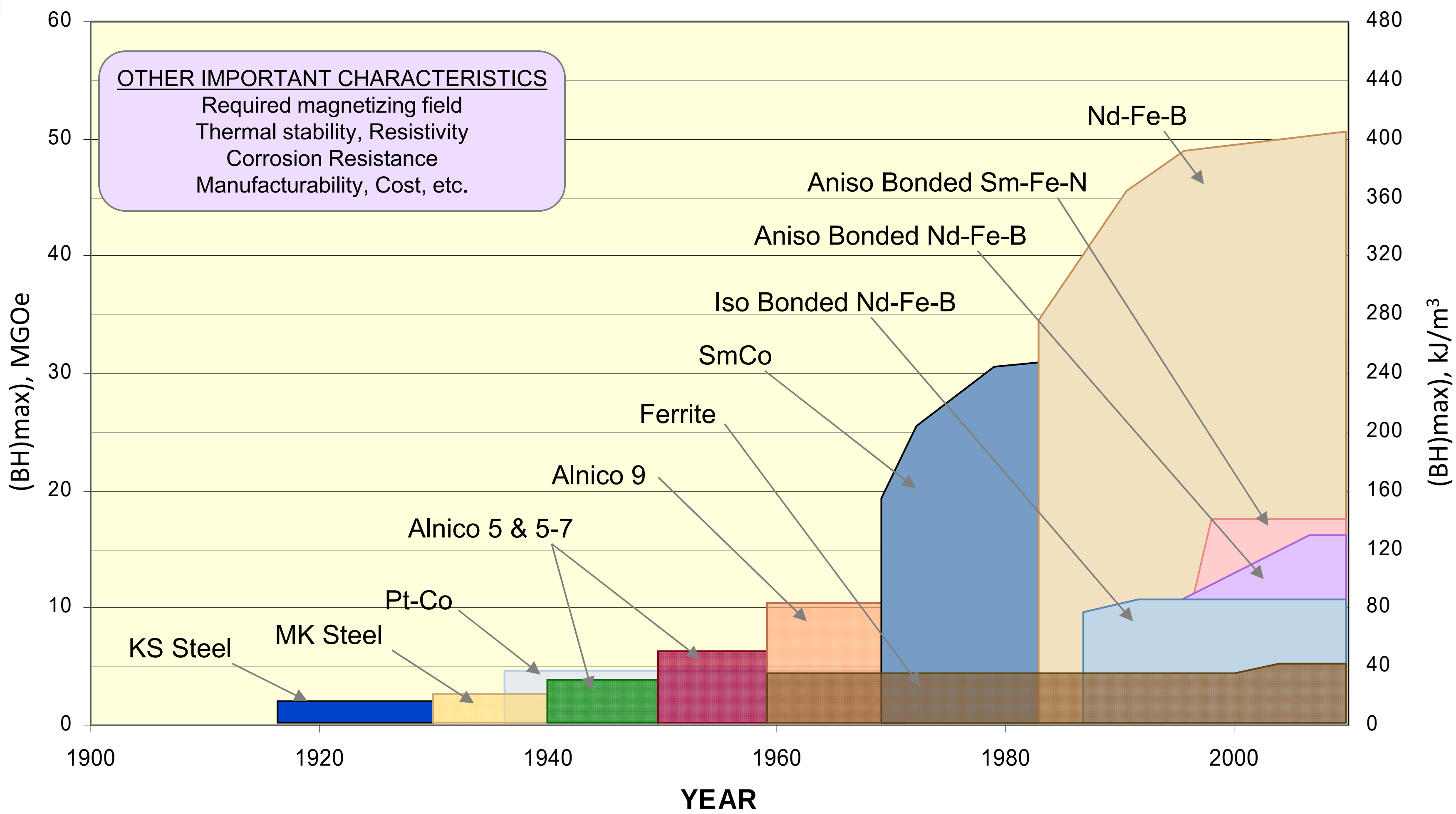
Improvement in Magnet Strength



Source: Arnold Magnetic Technologies

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Permanent Magnet Key Characteristics

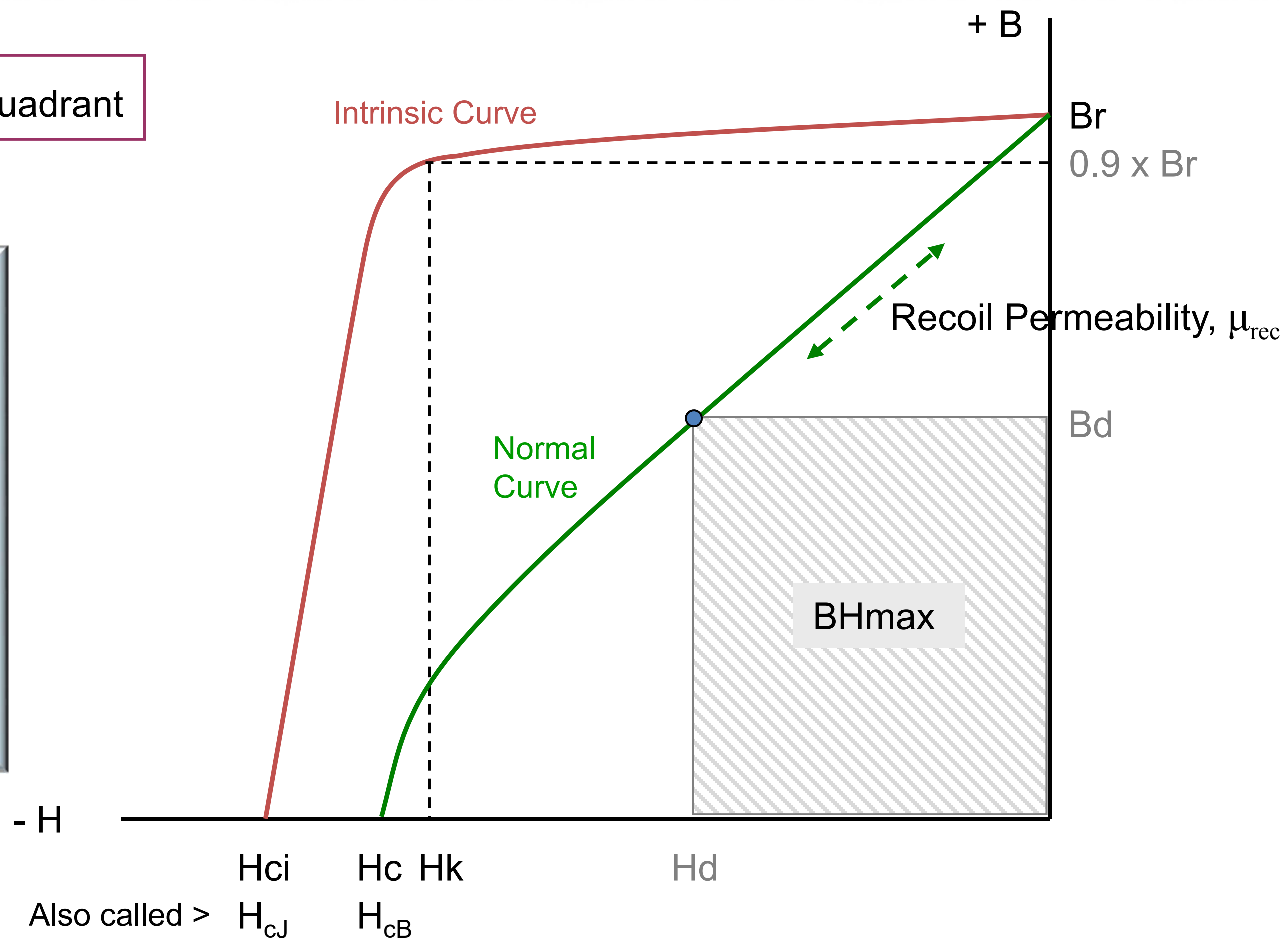
2nd Quadrant

Energy product is related to Br

$BHmax \sim Br^2 / (4 \cdot \mu_{rec})$
$\mu_{rec} \sim 1.05$

When Normal curve from Br to Operating Point is Linear

Br expressed in kG
BHmax is in MGOe



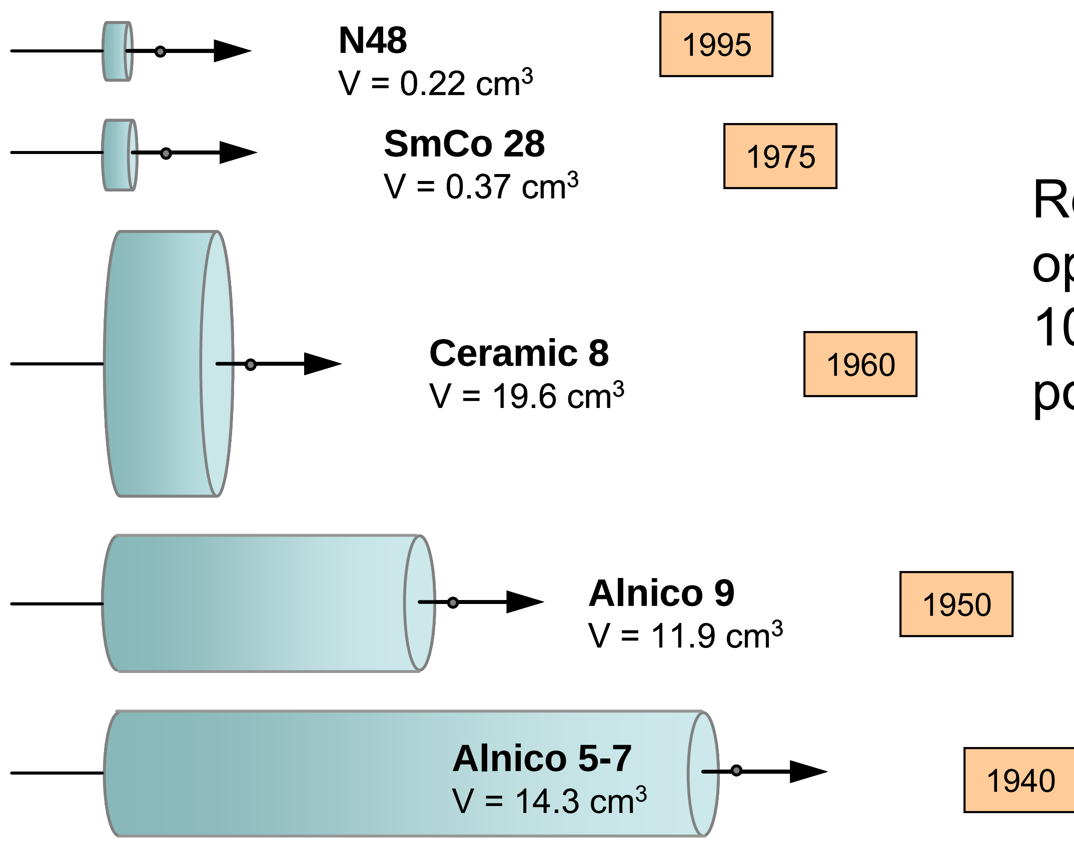
Source: Arnold Magnetic Technologies

What is BHmax?

- The energy stored in the field in an air gap is directly proportional to the product of B and H on a point on the normal curve – BH known as energy product
- The volume of a magnet required to produce a given field in a given gap is minimum when the product of BH is maximum - BHmax
- In other words the higher the BHmax the smaller the magnet volume to generate a given flux density
- However, if device volume or weight are not critical lower BHmax materials can be used with same performance

Source: Cullity and Graham, 2nd Ed.

Relative Magnet Sizes



Relative magnet size and optimal shape to generate 1000 gauss at 5 mm from the pole face of the magnet.

Source: Arnold Magnetic Technologies

What makes a magnet a commercial success?

- Energy Product (BHmax)
- Flux density (B_r)
- Resistance to demagnetization (H_{cJ})
- Usable temperature range
- Magnetizing field requirement
- Magnetization change with temperature (RTC)
- Demagnetization (2nd quadrant) curve shape
- Recoil permeability (minimal - close to one)
- Corrosion resistance
- Physical strength
- Electrical resistivity
- Available sizes, shapes, and manufacturability
- Raw material cost and availability
- Net shape processing

Isotropic Magnets

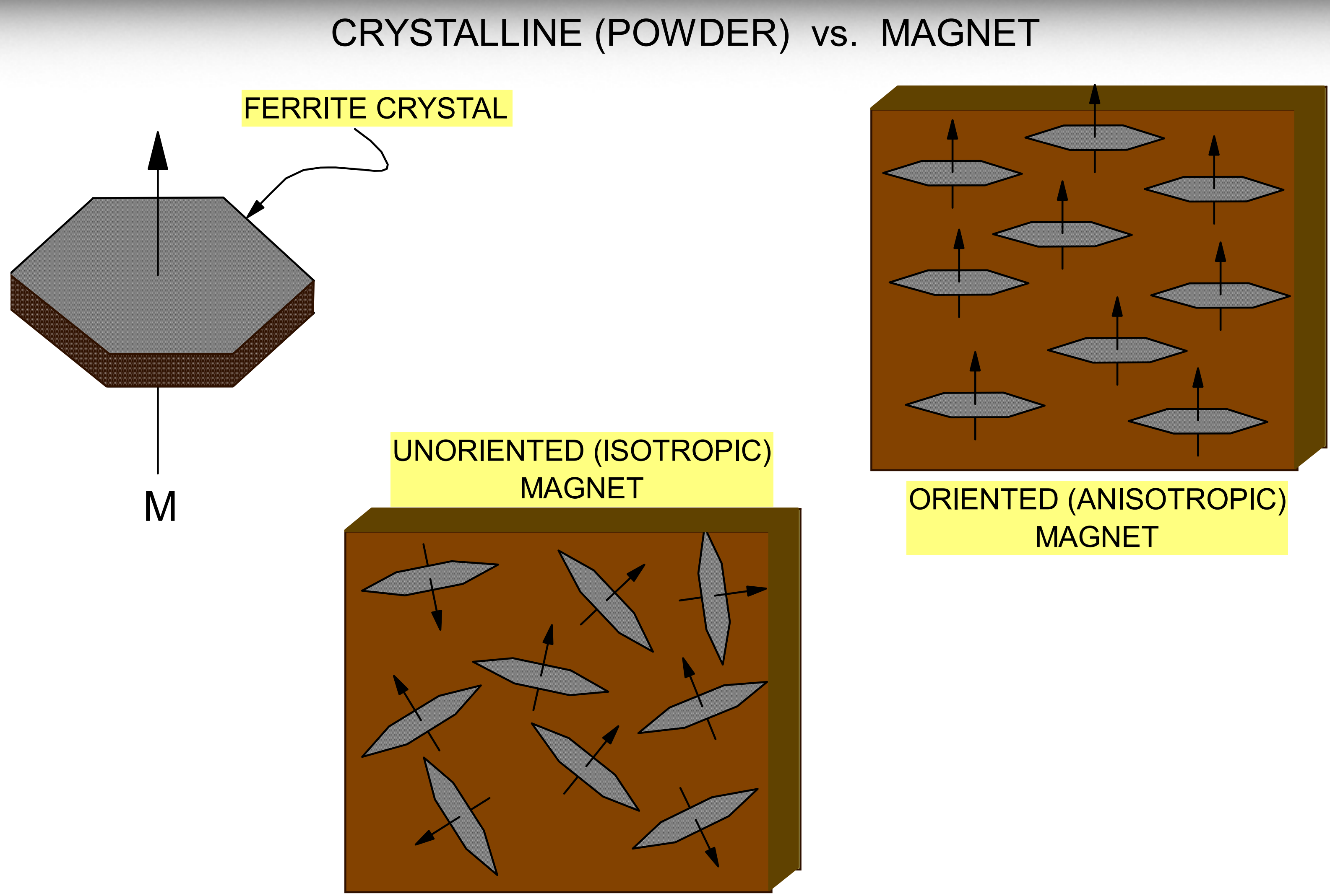
- Some magnets are made without no preferred direction of magnetization
  - These are referred to as isotropic (or “not oriented”) magnets.
- Vast majority of bonded NdFeB magnets are isotropic
  - Individual powder particles consist of numerous randomly oriented crystal grains.
- May be magnetized in 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.
  - Have developed multipole rings with 102 poles at 0.8 mm pole pitch.

Anisotropic Magnets

- Magnets have a preferred direction of magnetization
  - Referred to as an anisotropic (“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.

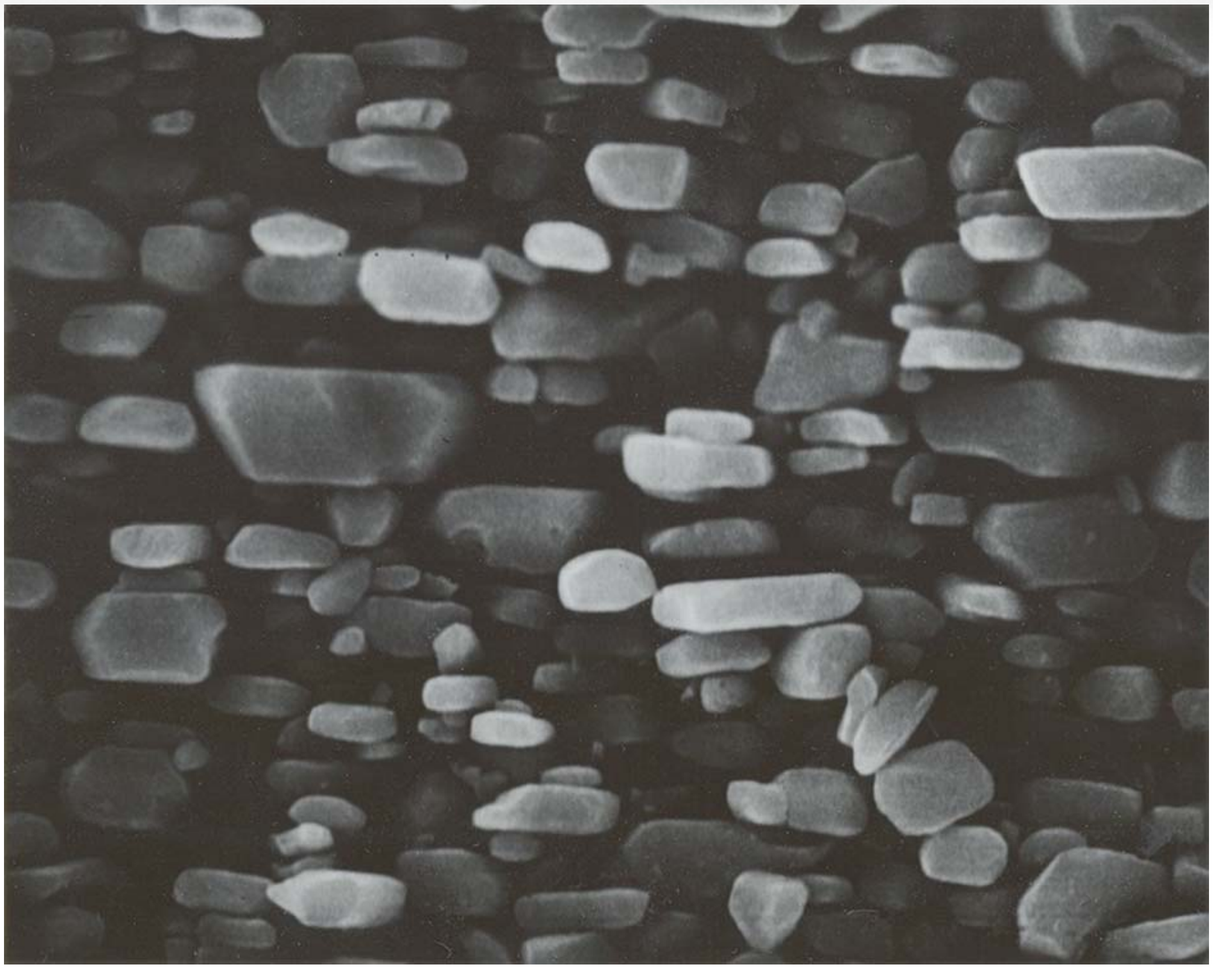
- Vast majority of sintered NdFeB magnets are anisotropic.

Isotropic vs. Anisotropic Magnets



Source: Arnold Magnetic Technologies

Oriented Ferrite Single Crystal Particles



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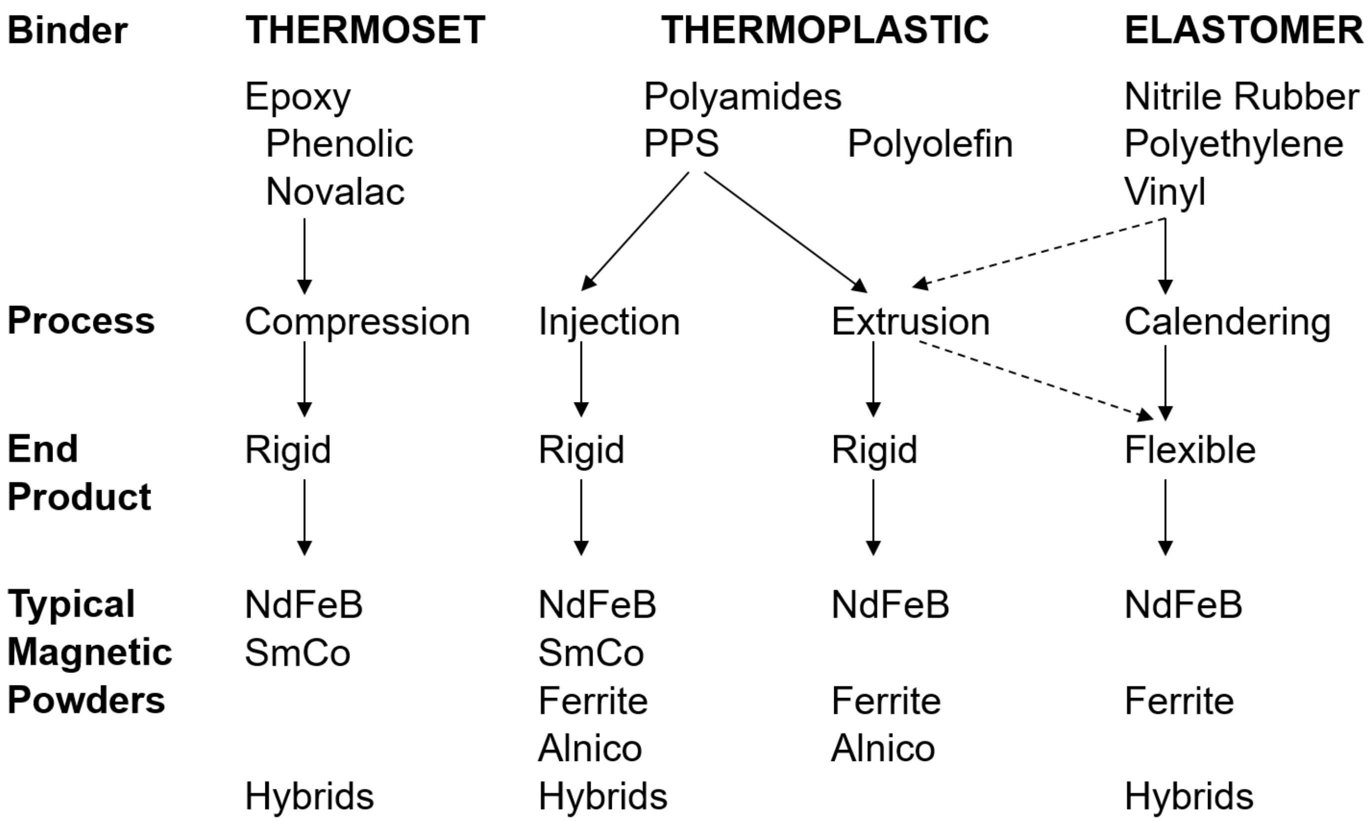
What are Bonded Magnets?

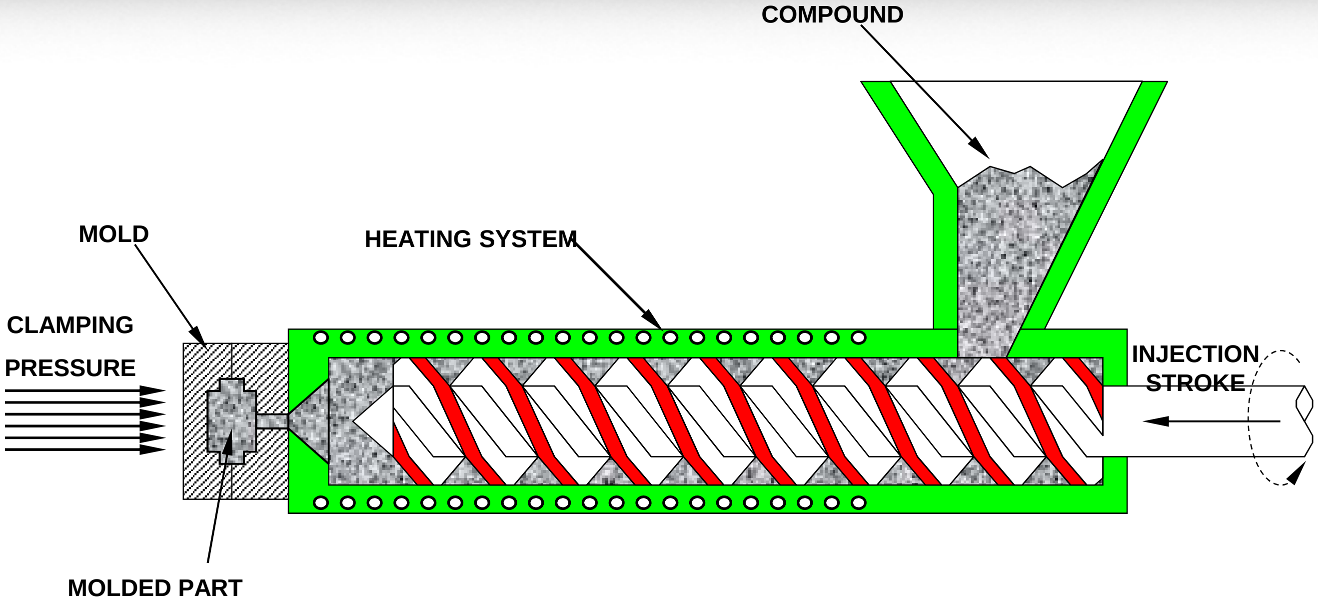
- Combination of magnetic powder in a non-magnetic binder by combining the two components using polymer/rubber processing.
- Common processing techniques are extrusion, injection molding, compression bonding, and calendering.
- Effective for very small (1/16 inch) to medium (4-5 inch) sizes.
- Good mechanical properties: strong, flexible, tough, etc.
- End product has good finish and dimensional tolerances with no finishing.
- One step assembly and added value possible.

Material and Process Options

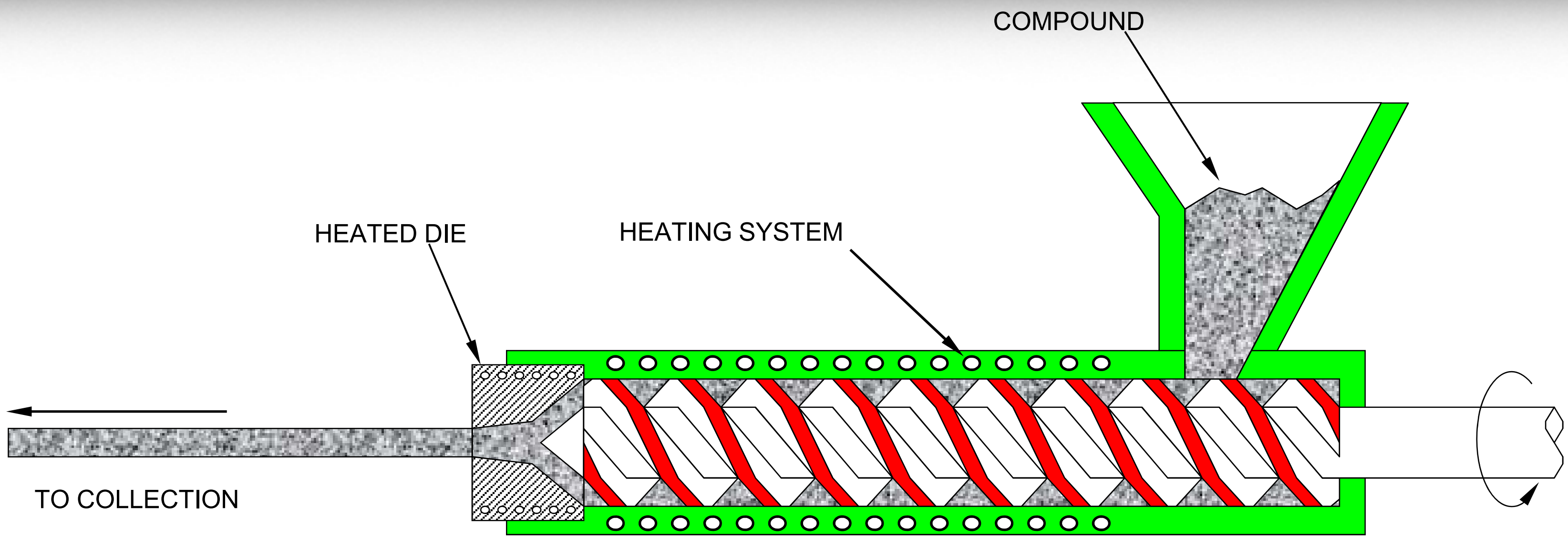


Source: Arnold Magnetic Technologies

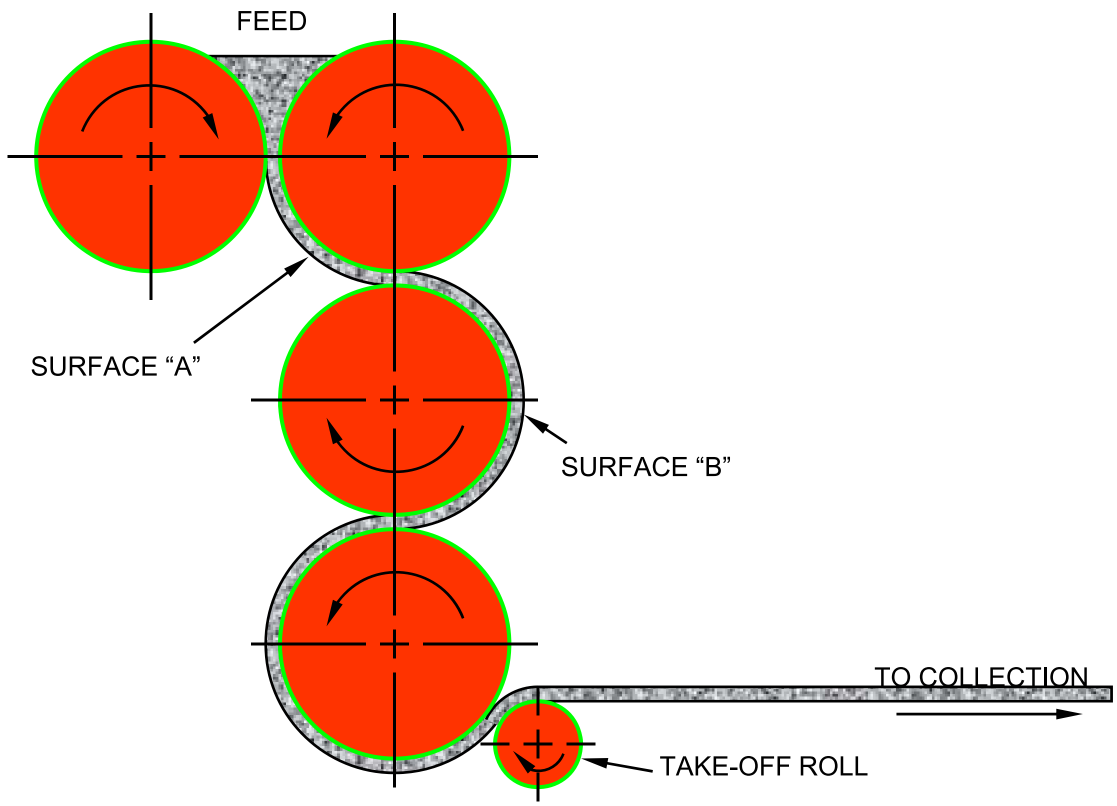
Injection Molding



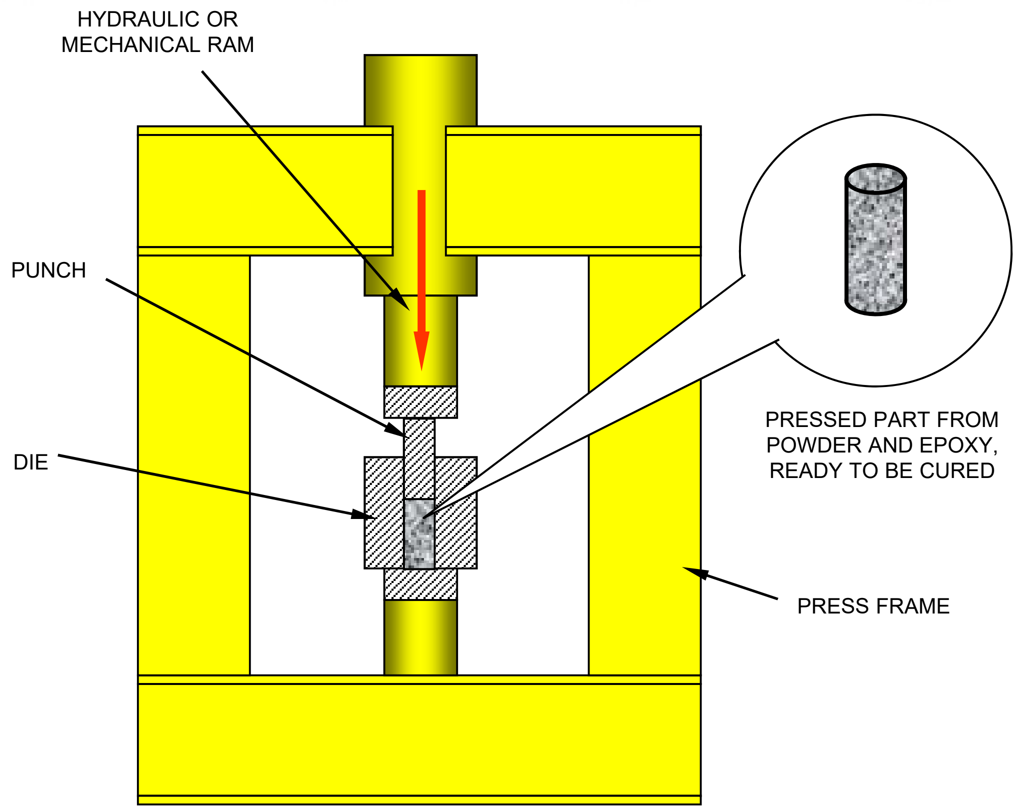
Extrusion



Calendering



Compression Bonding



Hybrid Bonded Magnets

A BONDED MAGNET

↓

WITH TWO OR MORE

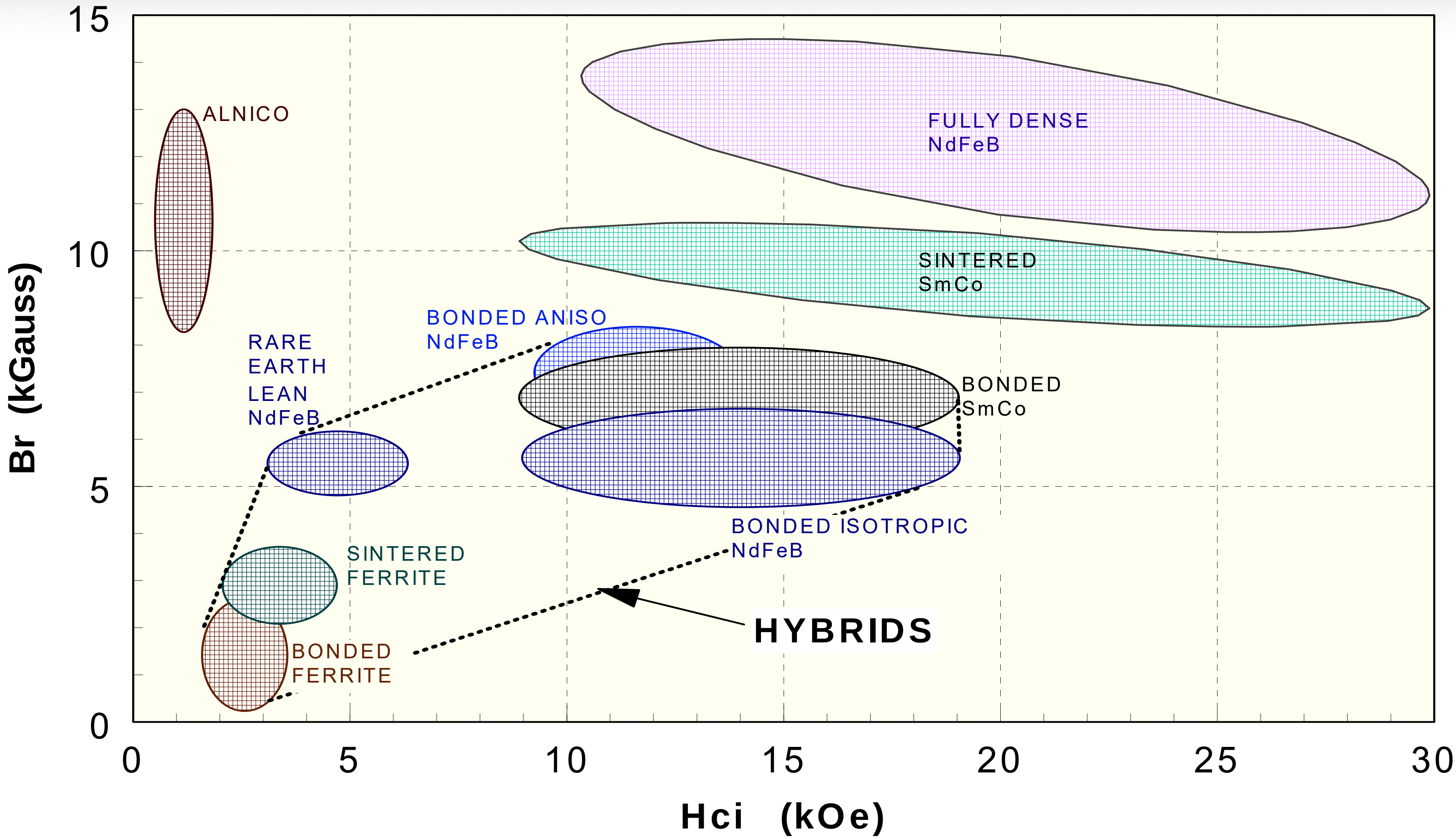
DISTINCTLY DIFFERENT MAGNETIC MATERIALS

↓

EMBEDDED IN A NON-MAGNETIC MATRIX

Source: Arnold Magnetic Technologies

Hybrid Bonded Magnets



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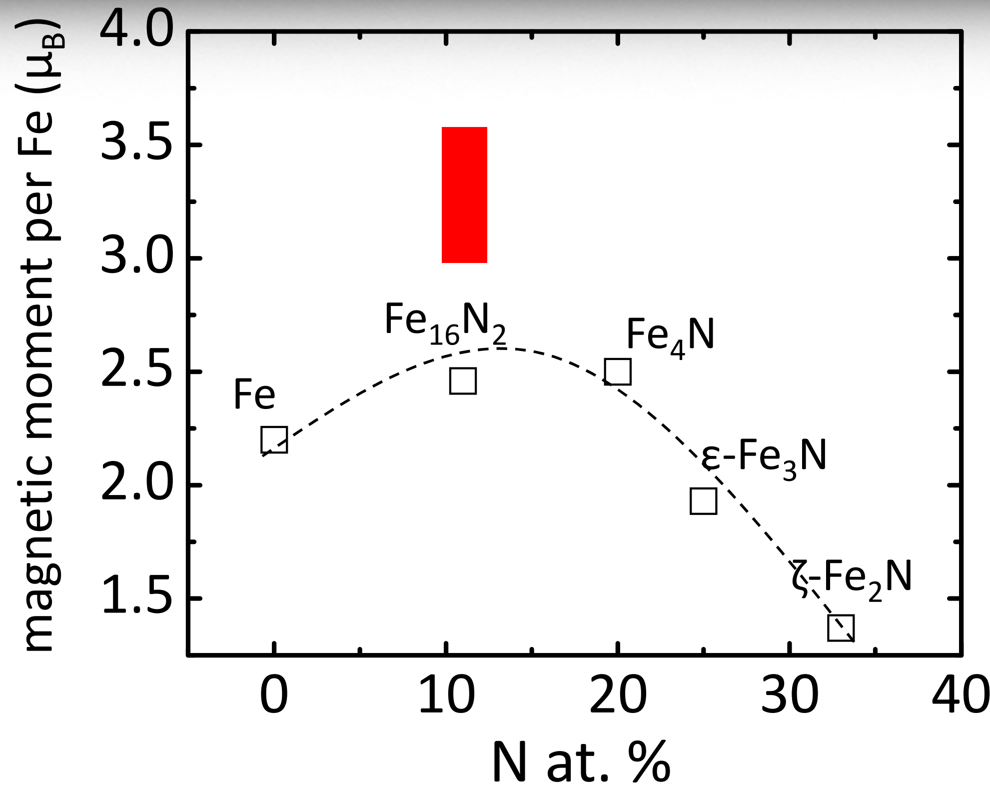
New Materials and Processes

- Rare Earth-Free Fe16N2 based magnets.
- Application of 3D Printing/Additive Manufacturing to Bonded Magnets and Assemblies.
- Higher Energy Product Compression Bonded Isotropic NdFeB magnets

Historical viewpoint on Fe16N2



Strange departure from the expected curve was claimed back in 1970 that $Fe_{16}N_2$ possesses a giant M_s.

Fe16N2 – 40 Years of Debate

First report of giant $4\pi M_s$~2.83T

port

New Magnetic Material Having Ultrahigh Magnetic Moment

T.K. Kim and M. Takahashi
Department of Applied Physics, Tohoku University, Sendai, Japan
(Received 28 December 1971)

The change of the saturation magnetization of Fe films with the pressure of nitrogen during deposition ranging from 2×10^{-5} to 7×10^{-3} Torr has been investigated systematically. We found a new magnetic material which has the highest saturation magnetization at room temperature, 2050 G, among those of all the magnetic materials. This was attributed to $Fe_{16}N_2$, which has a bct structure, and the magnetic moment associated with Fe atoms of $Fe_{16}N_2$ was deduced to be 3.0 μ_B.

Appl. Phys. Lett., Vol. 20, No. 12, 15 June 1972 492

Pure phase sample
confirms giant $4\pi M_s$~3.0T

Magnetic moment of α''-$Fe_{16}N_2$ films (invited)

Migaku Takahashi, H. Shoji, H. Takahashi, H. Nashi, and T. Wakiyama
Department of Electronics Engineering, Tohoku University, Sendai 980-77, Japan
M. Doi and M. Matsui
Department of Materials Science, Nagoya University, Nagoya 464-01, Japan

6642 J. Appl. Phys. 76 (10), 15 November 1994

But
No giant $4\pi M_s$~2.1T

Magnetic moment of α''-$Fe_{16}N_2$ films (invited)

Migaku Takahashi, H. Shoji, H. Takahashi, H. Nashi, and T. Wakiyama
Department of Electronics Engineering, Tohoku University, Sendai 980-77, Japan
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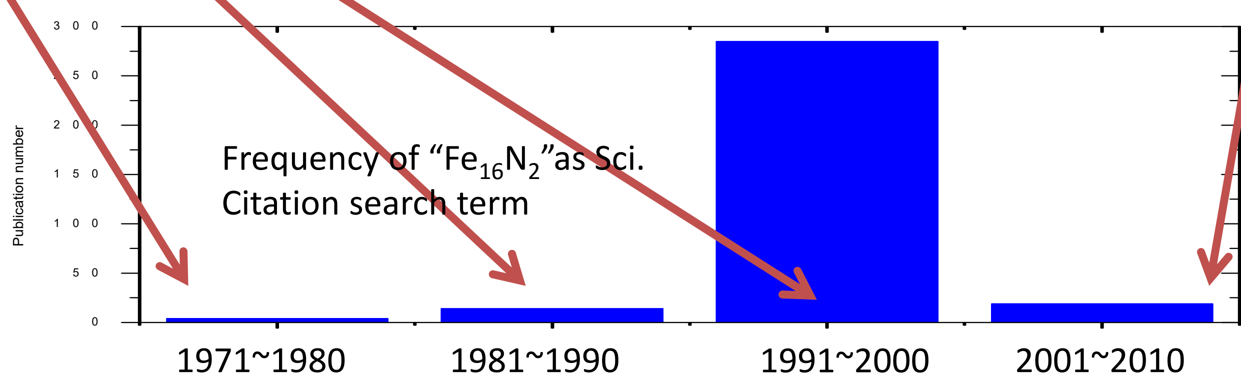
6642 J. Appl. Phys. 76 (10), 15 November 1994

Fabrication of $Fe_{16}N_2$ Films by Sputtering Process and Experimental Investigation of Origin of Giant Saturation Magnetization in $Fe_{16}N_2$

Jian-Ping Wang[1], Nian Ji[1], Xiaoqi Liu[1], Yunhao Xu[1], C. Sánchez-Hanke[2], Yiming Wu[1], F. M. F. de Groot[3], Lawrence F. Allard[4], and Edgar Lara-Curzio[4]

We present a systematic study to address a longstanding mystery in magnetic materials and magnetism, whether there is giant saturation magnetization in $Fe_{16}N_2$ and why. Experimental results based on sputtered thin film samples are presented. The magnetism of $Fe_{16}N_2$ is discussed systematically from the aspects of material processing, magnetic characterization and theoretical investigation. It is observed that thin films with $Fe_{16}N_2$ + Fe_8N mixture phases and high degree of N ordering, exhibit a saturation magnetization up to 2.68T at room temperature, which substantially exceeds the ferromagnetism limit based on the traditional band magnetism understanding. From X-ray magnetic circular Dichorism (XMCD) experiment, transport measurement and first-principle calculation based on LDA+U method, it is both experimentally and theoretically justified that the origin of giant saturation magnetization is correlated with the formation of highly localized 3d electron states in this Fe-N system. A large magnetocrystalline anisotropy for such a material is also discussed. Our proposed "cluster+atom" theory provides promising directions on designing novel magnetic materials with unique performances.

Case closed:
Giant $4\pi M_s$ is real



Source: Niron Magnetics

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Bulk Fe16N2 Magnet

Two Years Later The Wang Lab at UMN Produced The First $Fe_{16}N_2$ <u>Bulk</u> Magnet And Incorporated Niron Magnetics, Inc.

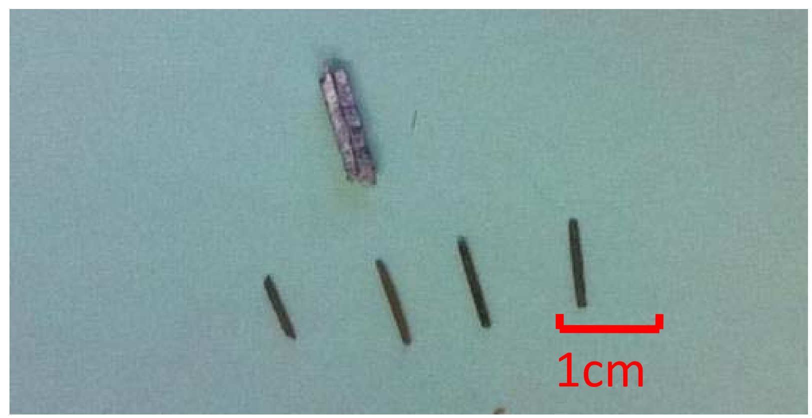
United States Patent Application	***20140299810***
Kind Code	**A1**
Wang; Jian-Ping ; et al.	**October 9, 2014**

IRON NITRIDE PERMANENT MAGNET AND TECHNIQUE FOR FORMING IRON NITRIDE PERMANENT MAGNET

Abstract

A permanent magnet may include a Fe.sub.16N.sub.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.sub.16N.sub.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

N Niron Magnetics™



Source: Niron Magnetics

Niron: Good News/Bad News

The Good

- 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.

The Bad

- 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.

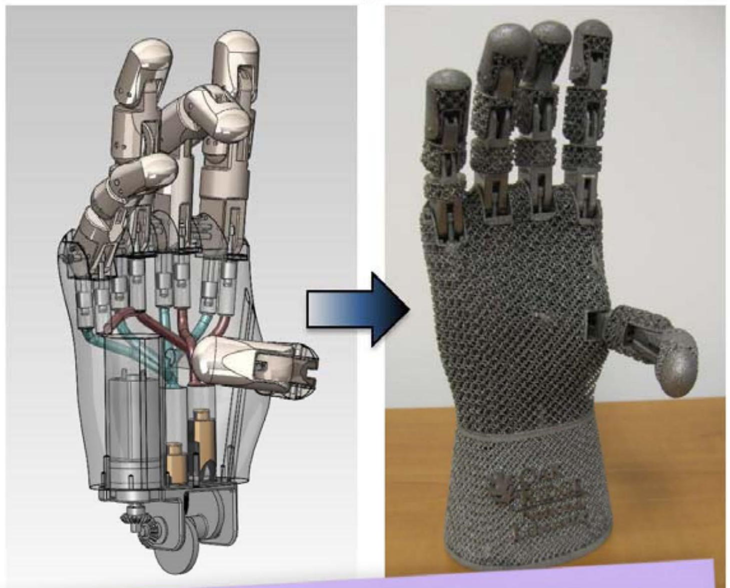
Additive Manufacturing – MAI and ORNL Joint R and D Project

- MAI and ORNL were recently awarded a Cooperative Research and Development award to study the application of additive manufacturing to bonded magnets and systems.
- The technical objective is to fabricate net shape isotropic NdFeB bonded magnets utilizing additive manufacturing technologies at ORNL MDF. The goal is to form complex shapes of both thermoplastic and thermoset bonded magnets without expensive tooling and minimal wasted material.

Additive Manufacturing/3D Printing

Additive manufacturing

CAD Model to Physical Part



"Additive Manufacturing will become the most important, most strategic, and most used manufacturing technology ever."
Wohlers 2012

- Increased Complexity
- Topology Optimization
- Less Material Scrap
- Shorter Design Cycle
- Reduced Part Count
- Polymers, Metals, Ceramics, Multi material integration
- Tailored Microstructures and properties

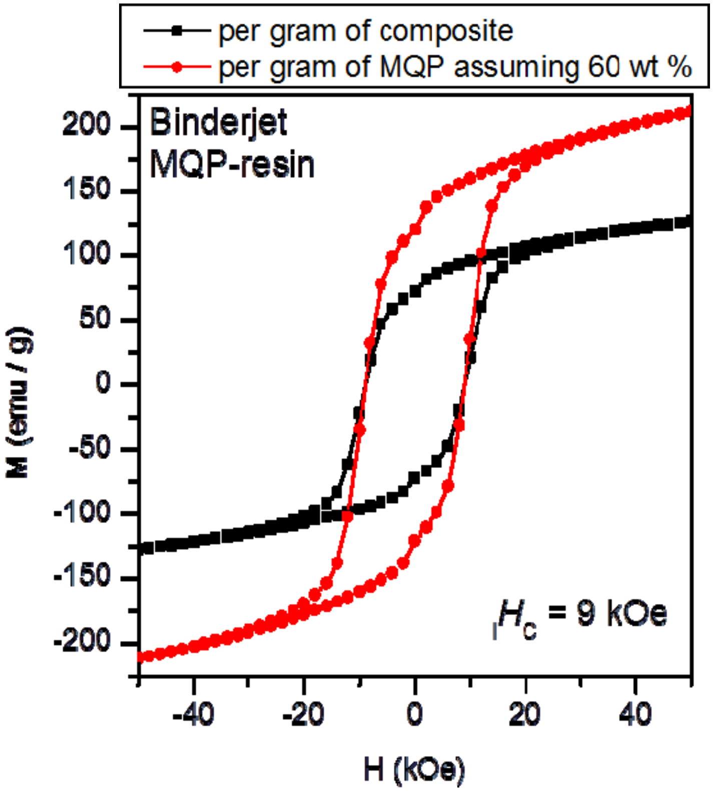
Oak Ridge National Laboratory
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

Source: Oak Ridge National Labs

Additive Manufacturing/3D Printing

Source: Oak Ridge National Labs

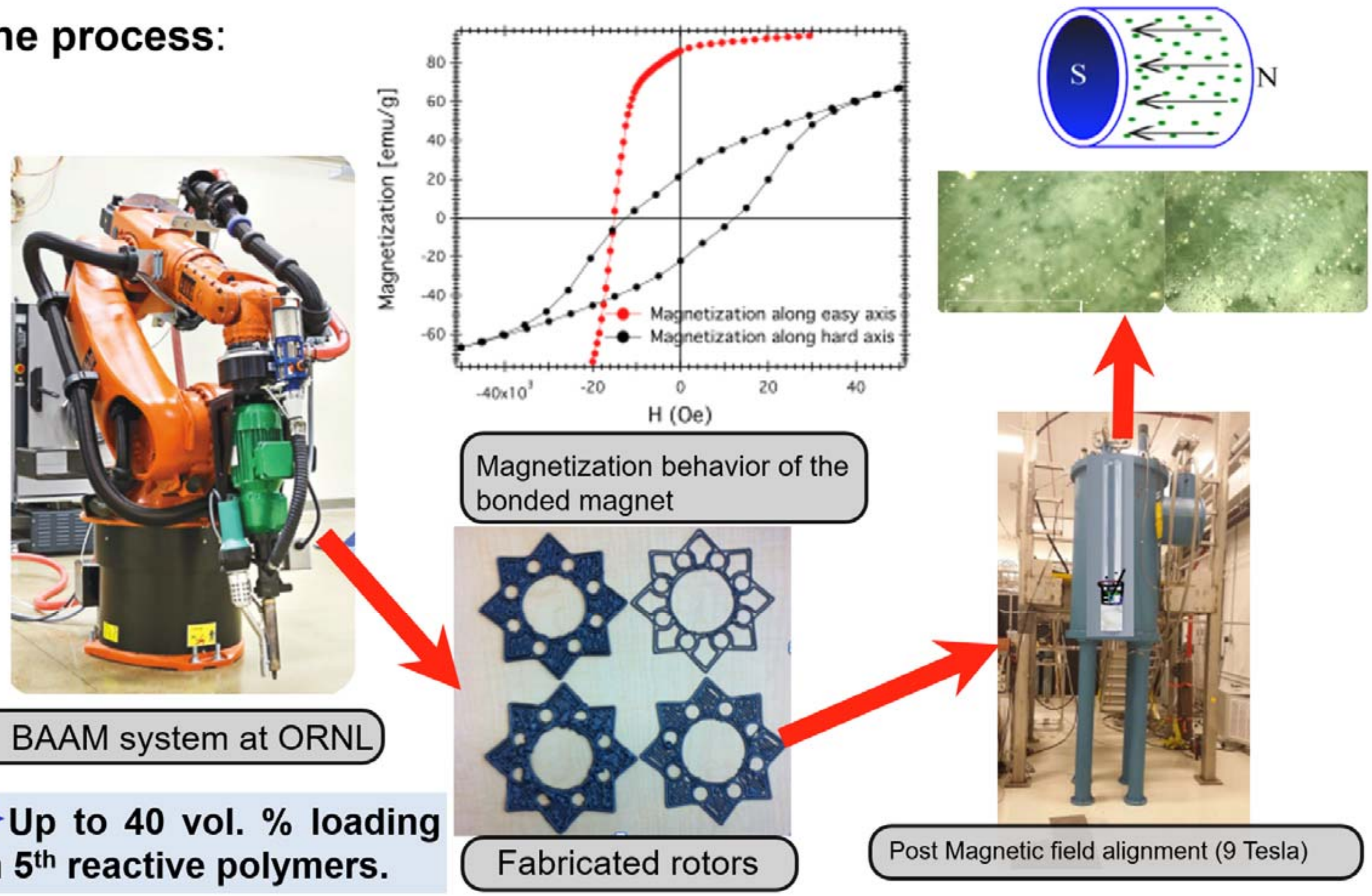
Initial Magnets From ExOne Binderjet Process



Additive Manufacturing /3D Printing

Successful Additive Printing of NdFeB Bonded Magnets

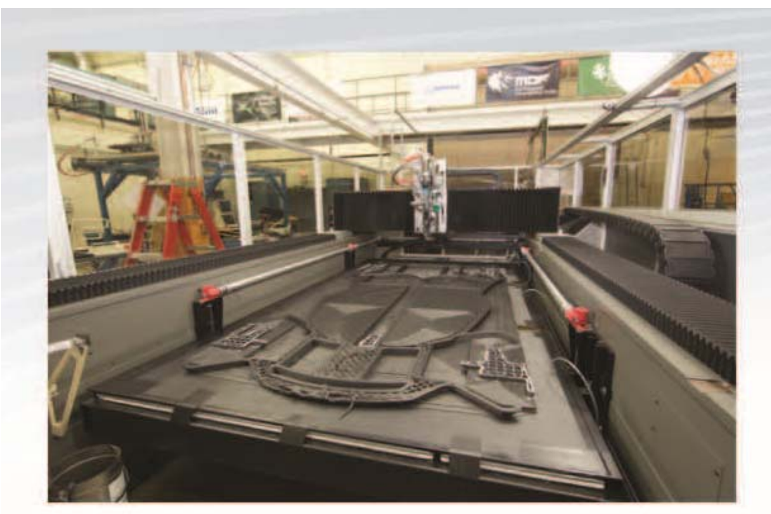
The process:



✦Up to 40 vol. % loading in 5th reactive polymers.

Source: Oak Ridge National Labs

Large Scale Additive Manufacturing



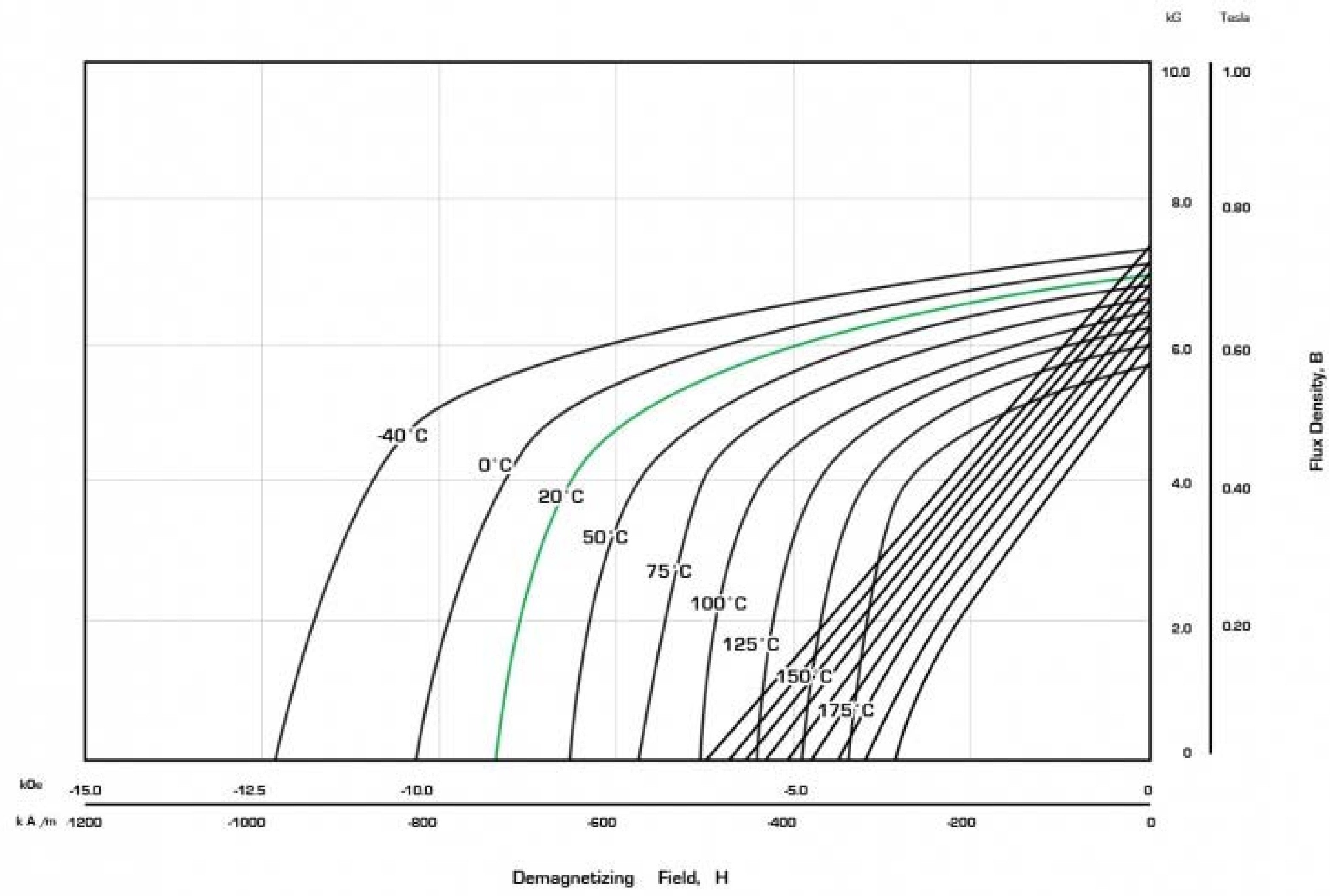
3D printed all electric Shelby Cobra car

What's next?

Permanent magnet based motors!!!

Source: Oak Ridge National Labs

B10 Magnetic Properties



BHmax Improvement

- The BHmax in a compression bonded isotropic NdFeB magnet is only influenced by two variables:
  - 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.
    - Also need to have good flowability with a particle size that easily fills small die cavities.
  - 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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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%**	**-**

Global Bonded Magnet Production (1999)

	Flexible Ferrite	Molded Ferrite	Bonded Rare Earth	Total
Japan	$50	$130	$210	$390
US	$105	$45	$40	$190
SE Asia	$15	$40	$50	$105
China	$25	$45	$20	$90
Europe	$10	$15	$15	$40
Other	$10	$30	$20	$60
Total	$215	$305	$355	$875

(All figures are USD x million)

Market Growth

- CAGR for rare earth bonded magnets from 2000 to 2014 is > 5% per year.
- Is that good growth rate?
  - According to Beverage Marketing Corp., beer saw a compound annual growth rate of 2.8% from 2000 to 2005.
  - Data gathered from all sources this year points to an industry that continues to grow at a rate of just about 1.6% - PMQ's report on the pizza industry
- Some market/application drivers are the following:
  - Automotive - sensors, interior motors, fuel pump seat motors, EPS sensors
  - Circulation pumps – primarily in Europe to meet home efficiency heating mandates
  - HDD spindle motors – PC down but cloud storage up
  - Office automation motors in printers, copiers etc.

Contact

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