Magnet Thrust of the Critical Materials Institute Workshop
Providence, RI, May 6th, 2015

Bonded Magnets - Products, Processes and Markets

John Ormerod
Senior Technology Advisor
Magnet Applications Inc.

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- Introduction
- Magnet Applications Inc.
- Important characteristics of commercially important PM's
- Bonded magnet overview
- Market and production estimates
- What does the market want from a bonded magnet?

Introduction

- John Ormerod – recently returned back to Magnetics after a 12 year LOA.
- BSc, MSC and PhD in Metallurgy from the University of Manchester (1972 – 1978).
  - Post Doc 1979 in Nuclear Engineering Department
- Magnetics career began for Philips (UK and Holland) – 1979 - 1990
  - Developed and commercialized SmCo5 and 2:17
  - Developed and commercialized NdFeB
  - Founding partner in EU CEAM in 1985
  - Philips partnered with several academic institutions e.g. University of Birmingham
- Joined Arnold Engineering (US) responsible for soft and hard magnetic materials development and GM for permanent magnets (1990 – 2002).
- Since 2002 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 the Model S and future Model X
  - Retired end of 2014 and relocated to Knoxville, TN.
- 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 and Senior Technology Advisor for MAI.
- Founded business and technology consultancy for magnetics and metals related industries in 2015 – JOC LLC

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Magnet Applications Inc.

- http://www.magnetapplications.com/
- Largest North American manufacturer of injection molded ferrite and compression bonded and injection molded NdFeB magnets.
- Located in DuBois, PA – Originally established in UK over 50 years ago – sister company located in Berkhamsted, UK (30 miles NW of London)
- Primary applications are as follows: fractional HP brushless DC motors, automotive steering and brake sensors, medical devices e.g. sleep apnea machines, impeller for heart-lung machines

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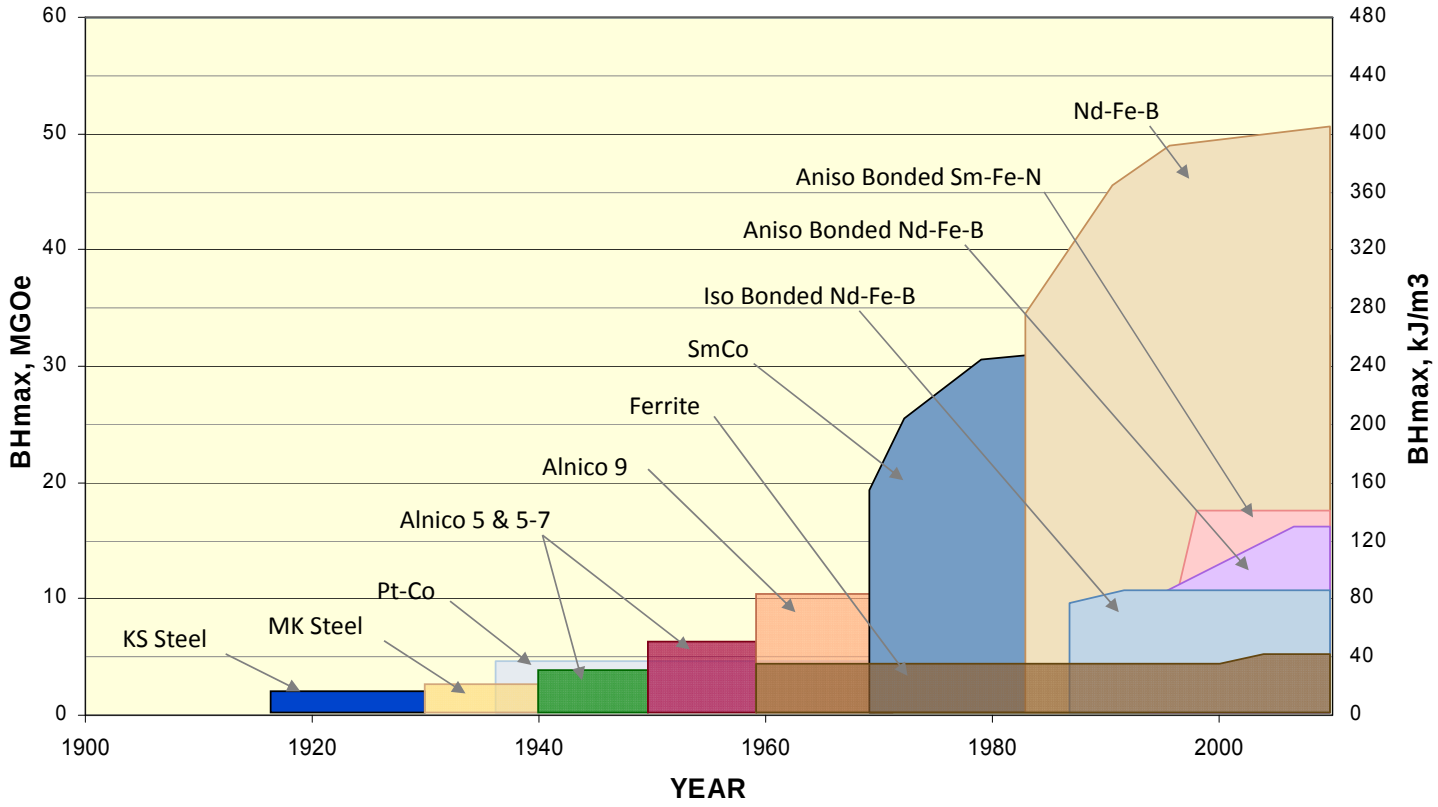
Historical Development of PM Materials



Permanent Magnet Key Characteristics

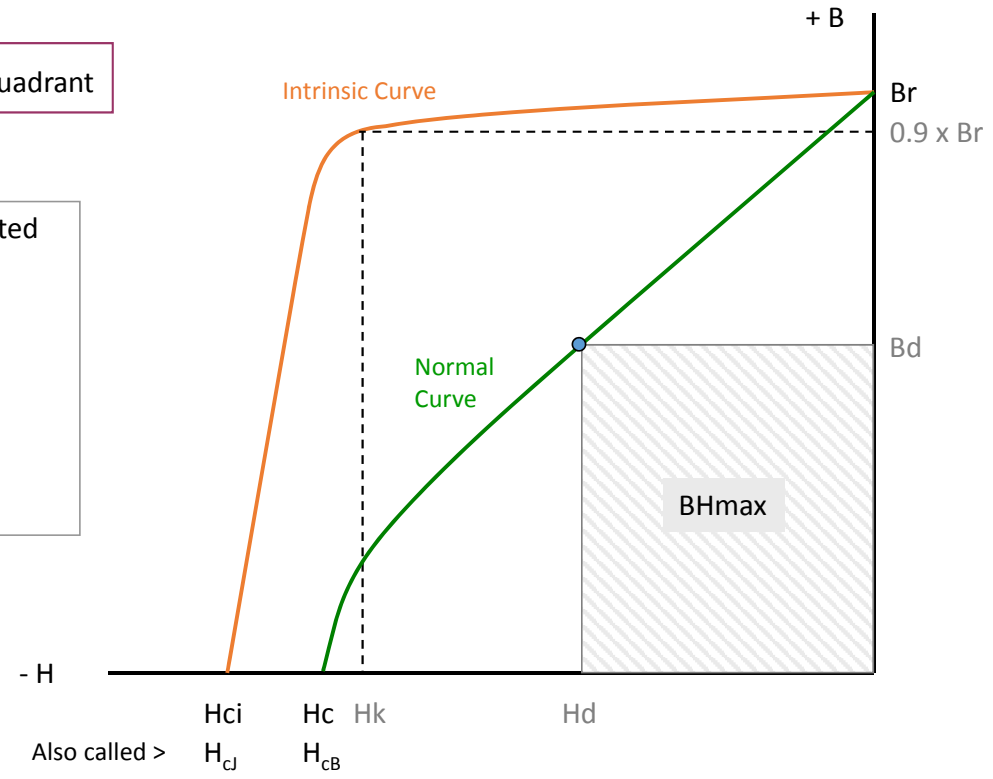
2nd Quadrant

Energy product is related to Br

BHmax ~ $Br^2 / (4 \bullet \mu_r)$

μ_r ~ 1.05

When Normal curve from Br to Operating Point is Linear



What makes a magnet a commercial success?

Requirements depend upon the application

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

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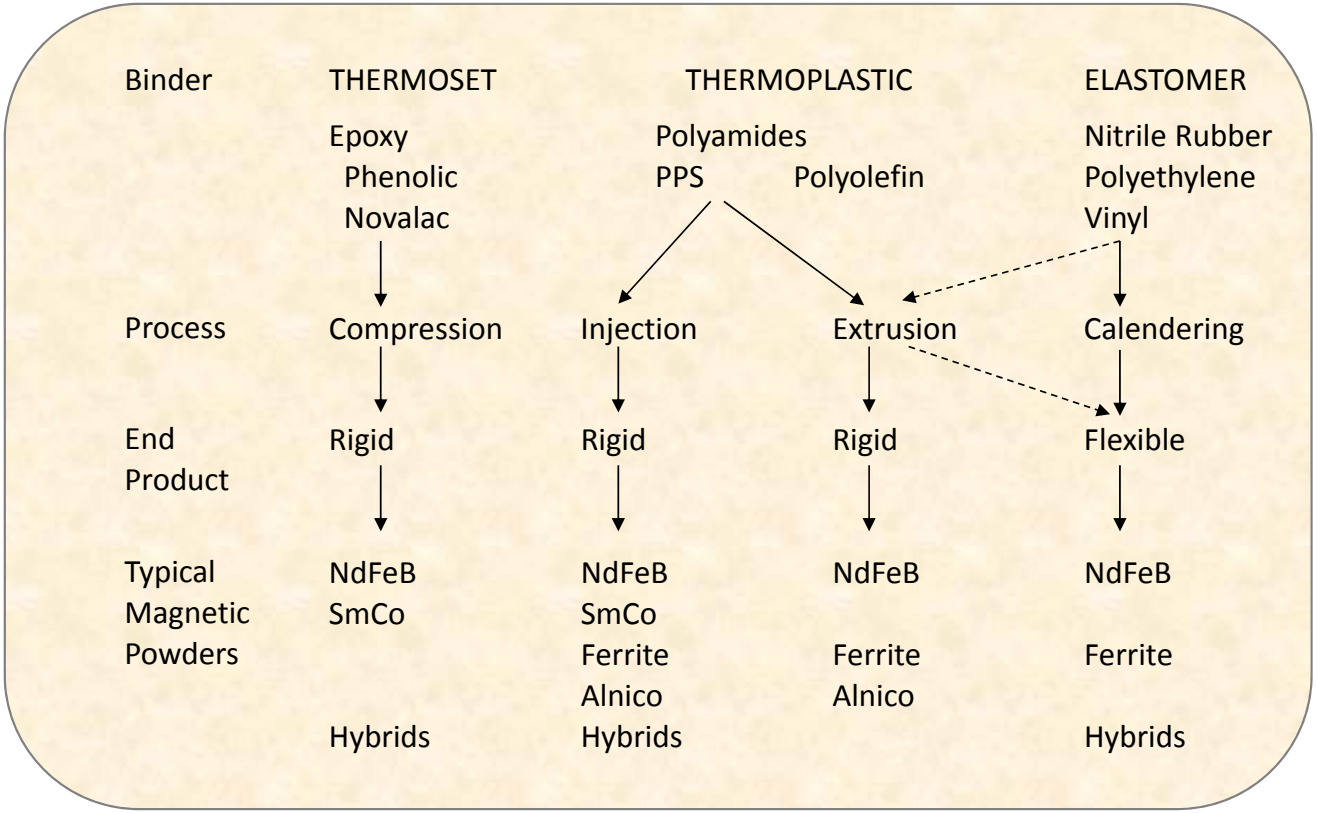
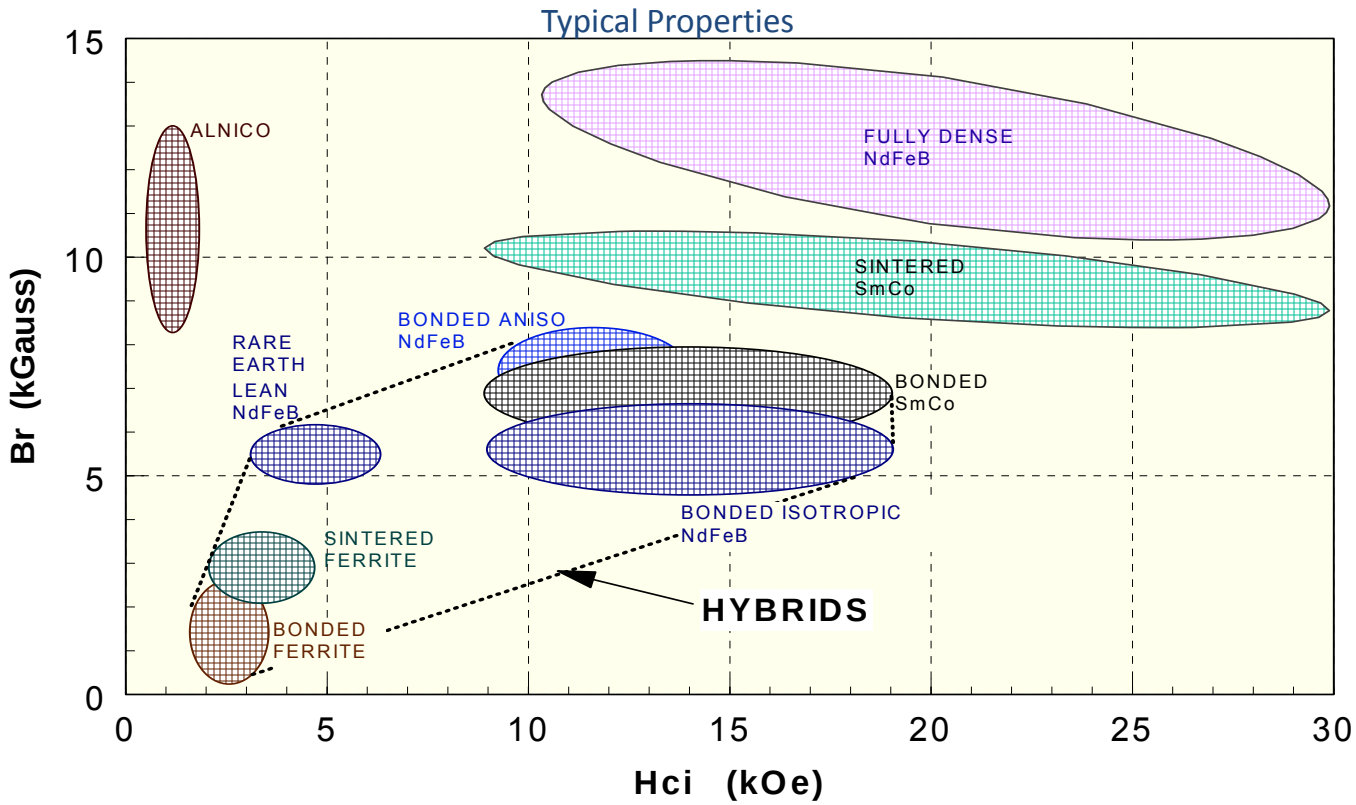
What are Bonded Magnets?

- Combination of magnetic particulate (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.

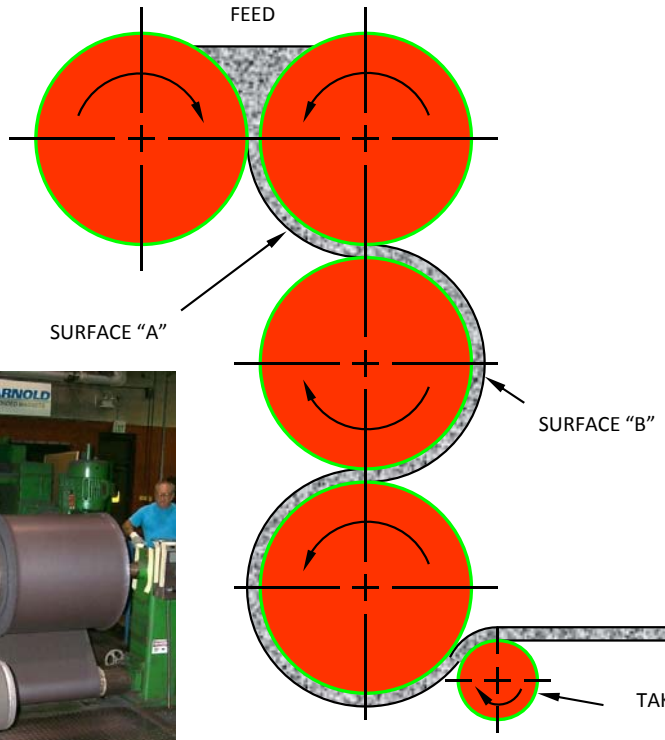
MATERIAL AND PROCESS OPTIONS



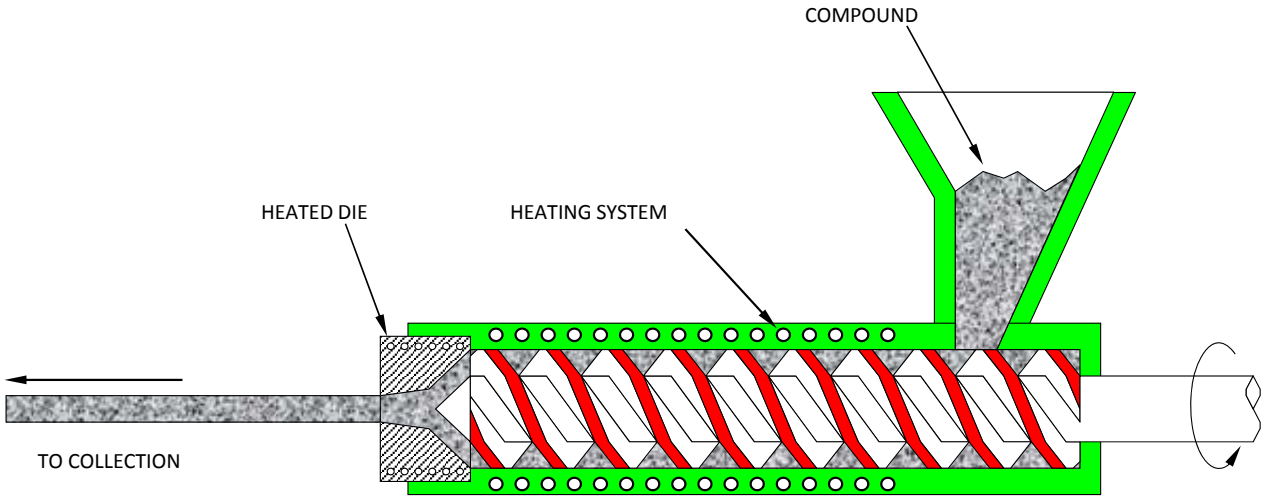
Common Permanent Magnet Materials



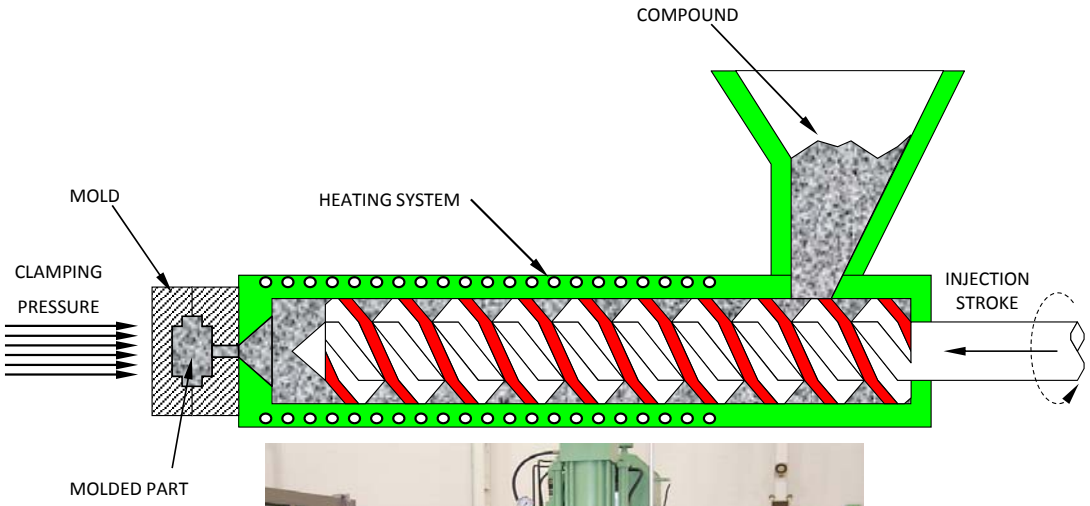
Calendering Process



Extrusion Process

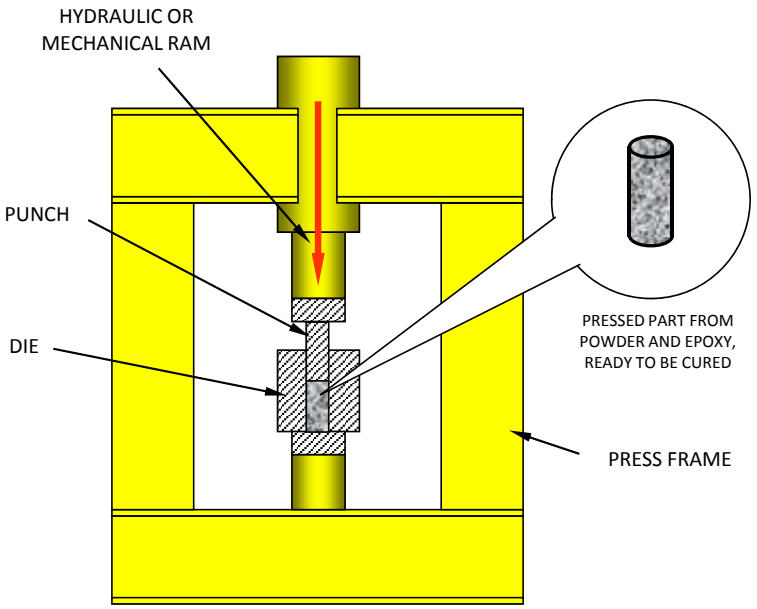


Injection Molding

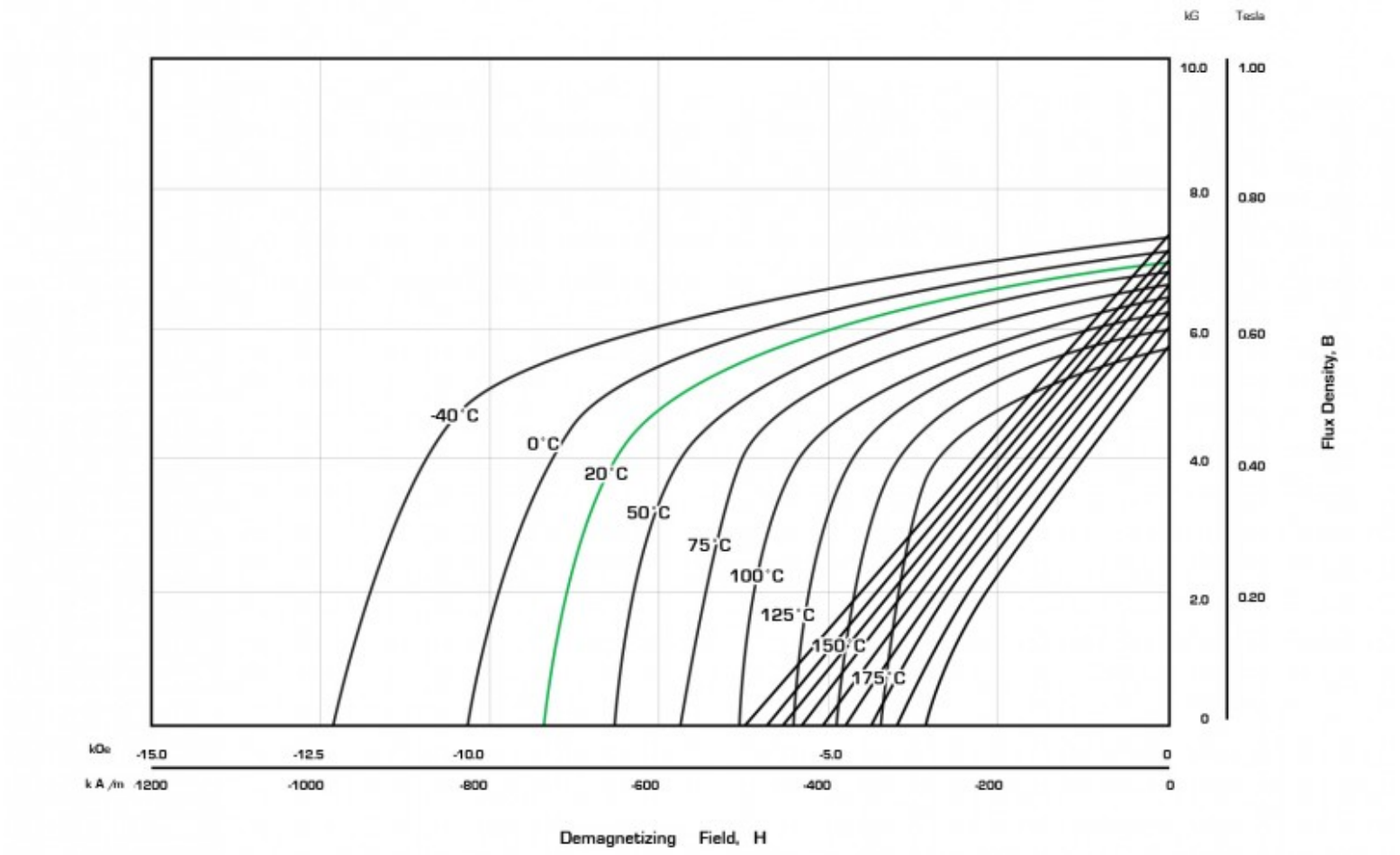


Compression Bonding

- Room temperature pressing of magnetic powder encapsulated with an epoxy resin.
- Heat cured after pressing.
- Simple shapes may be pressed (rectangles, cylinders, arcs, etc.).
- Highest density bonded magnets.
- Highest performance achieved by liquid encapsulating particle with polymer and lubricant.
- Typically isotropic properties.



Bonded Neodymium B10



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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%**	**-**

From POLYMER BONDED MAGNETS 2000 presentation

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)

Slide 21

JO1 John Ormerod, 4/22/2015

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 -seat motors, EPS sensors, HEV, EV appications
    - 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.

How to improve BHmax of a compression bonded magnet

The BHmax in a compression bonded isotropic NdFeB magnet is only influenced by two variables:

1. Volume fraction of magnetic phase in the magnet – typically measured by the density of the magnet.
    - Today's approach is brute force i.e. increasing the pressing pressure which requires special press construction and tooling materials – can we produce powders that are more compressible? Current production pressing pressures are 7tonnes/cm2 for 5.7 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.
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.

What does the market want in an new bonded magnet?

- Improved performance
- Reduced cost
- Reduced time to market for new circuit designers

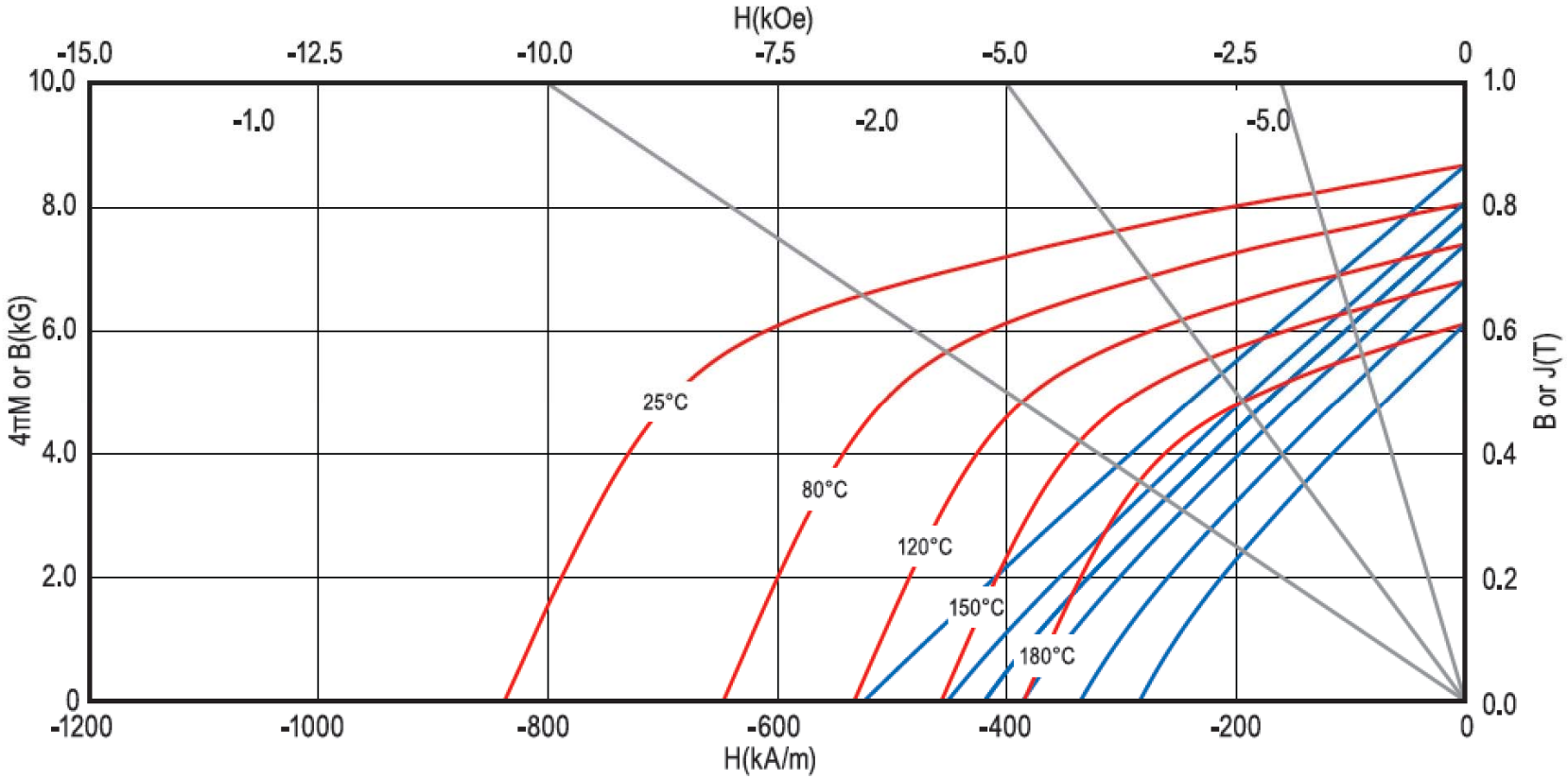
Prefer all three but any one with no negative impact on the other two is also acceptable.

Specific targets are as follows:

What does the market want in an new bonded magnet?

- 11 to 15 MGOe with a linear normal demagnetization curve
- Manufacturing cost of hard ferrite.
- RE-free e.g. Fe16N2 isotropic powders.
- Operating temperature of 180 C.
- Additive manufacturing of bonded magnets is of interest for at least reducing time to market and potentially cost reduction for low volume production (no tooling).

Target magnetics for a bonded magnet powder Based on MQI MQP-B powder



ORNL MDF Technical Collaborations Project Proposal

The technical objective of the MDF proposal 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.