Permanent magnets for energy efficient design : from design to reality, how, when and why things get done

Dr James Mckenzie– Chief Executive Officer
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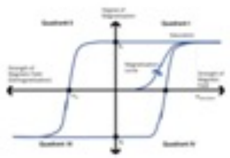
HIRST Magnetic Instruments Ltd.

A little bit about me

- 1988 -Joint Hons Physics / Computing
- 1993 – PhD Optical Control Systems – sponsors by BP
- 1994 – Research Fellow Brunel University
- 30 years bringing products to markets – with roles in Engineering, Marketing, Sales and Business Development
- Fellow of the Institute of Physics
- Joined Hirst as CEO in 2022

Hirst Magnetic Instruments Ltd

Characterise	Measure	Magnetise
		
 		
PFMs Pulsed Field Magnetometers	Gaussmeters / Fluxmeters	Magnetisers / Demagnetisers / Calibrators

- Focus on Permanent Magnets
- Award winning technology

Business Awards
2020
IOP Institute of Physics

Member of the UK Magnetic Society

History of Hirst Magnetic Instruments Ltd.

- 1938 - The Hirst Companies were originally founded as a family business by Mr. Sidney Hirst.
- 1960 - set up a division specifically involved with magnetics. By the 1970s many of the company's machines and instruments had become industry standards.
- 1970 - the 1970's saw the commercial introduction of rare earth magnets such as Samarium Cobalt and in early 1980s the introduction of Neodymium Iron Boron Permanent Magnets.
- 1990- The company moved to its present location in May 1996, where the factory was formally opened by the Olympic Athlete and local MP Sebastian Coe.
- 1998 Hirst was a leading member of a 3 million ECU research project into Pulsed Field Magnetometry (PFM) and launched its first Industrial PFM product in 1998
- 2019 Factory expansion and new building opened.
- Hirst has an unrivalled knowledge of the PFM technique which they continue to develop for industrial applications.

- Hirst Magnetiser / Demagnetiser production equipment is used across the world in
  - Aerospace – lots of sensors and actuators use magnets
  - Turbines and Generators
  - Consumer products - razor blades, needles
  - Medical equipment production
  - Audio equipment such as speakers
  - Electric Vehicle production
  - Recycling and Waste management

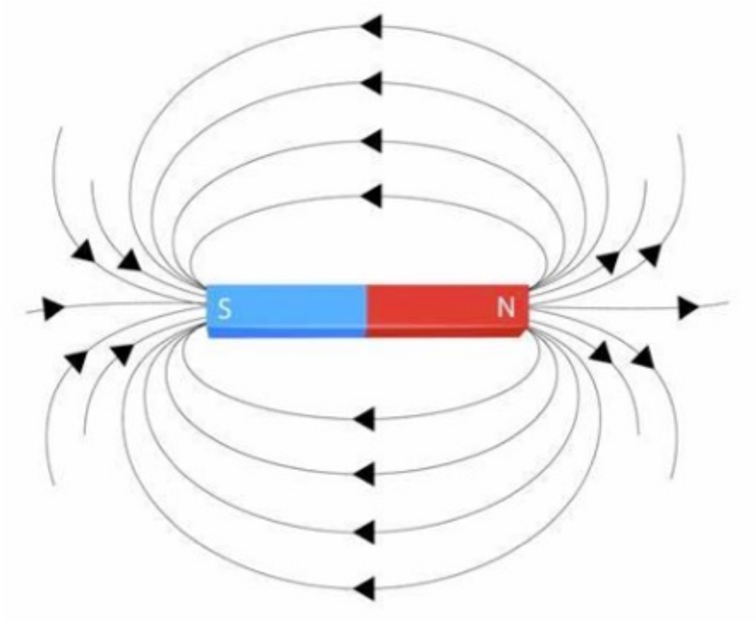
What I am going to talk about today

- Career session - overarching themes I will focus on
  - Technology, Timing, Applications
  - Economics, Markets
  - Solving problems for customers

- Business is about solving problems that matter for customers with a need – for a profit

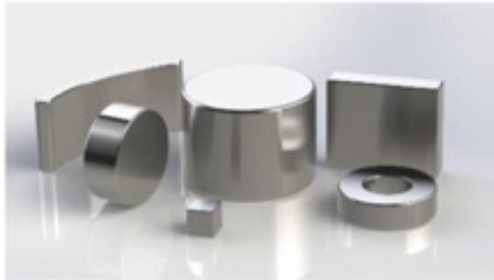
- But to do any of this I need to start with permanent magnets

Permanent Magnets



Key Magnetic Parameters

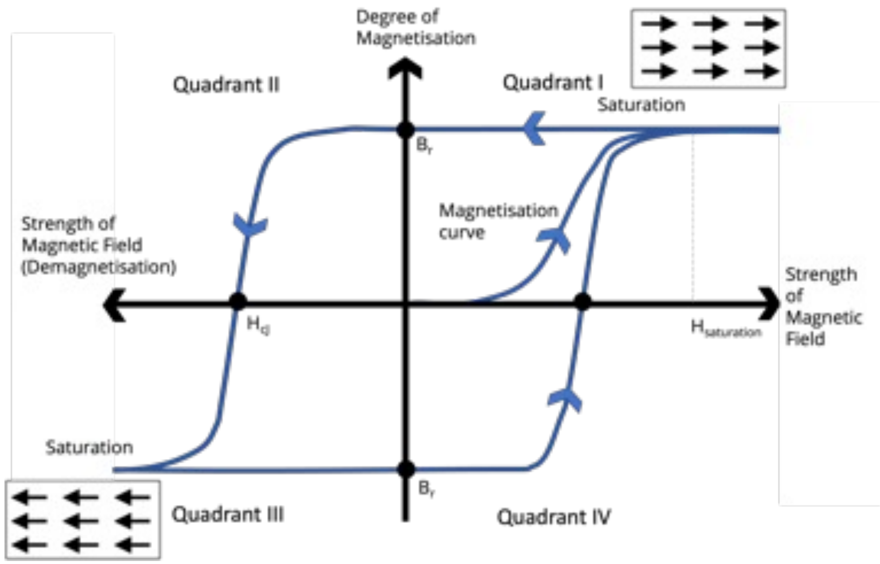
- **B_r -** Remanence (kG or **T**) – strength of the magnet
- **H_{cJ} -** Intrinsic Coercivity (kOe or **kA/m**) – the magnet's resistance to de-magnetisation
- **BH_{max} -** Maximum Energy Product (MGOe or **kJ/m³**) – how much energy is available for motors and generators
- **H_k / H_{Knee}, H_k/H_{cJ}, H_{d2}, H_{d5}, H_{d10}** describe the shape of the curve in quadrant 2 (demagnetisation curves), squareness, knee shape etc
- **Reversible Temperature Coefficients** (α for B_r and β for H_{cJ}) –indicate how these magnetic characteristics change with temperature



- **Curie point** – the temperature at which a magnet loses its permanent magnetic properties
  - For NdFeB magnets : 310 to 400 ^{o}C
  - For SmCo magnets :720-800 ^{o}C

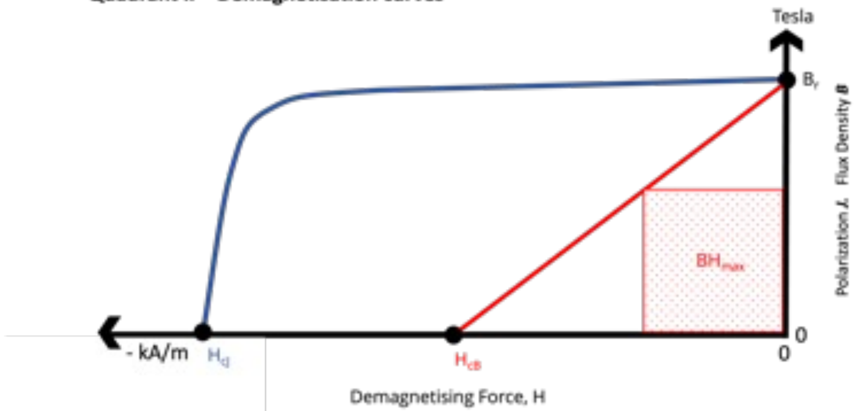
SI Units in bold

Magnetic characterisation of permanent magnets

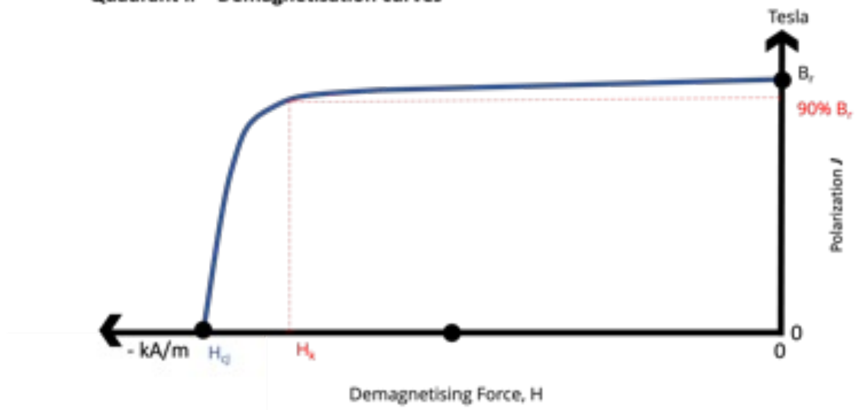


Magnetic hysteresis loop

Quadrant II – Demagnetisation curves



Quadrant II – Demagnetisation curves



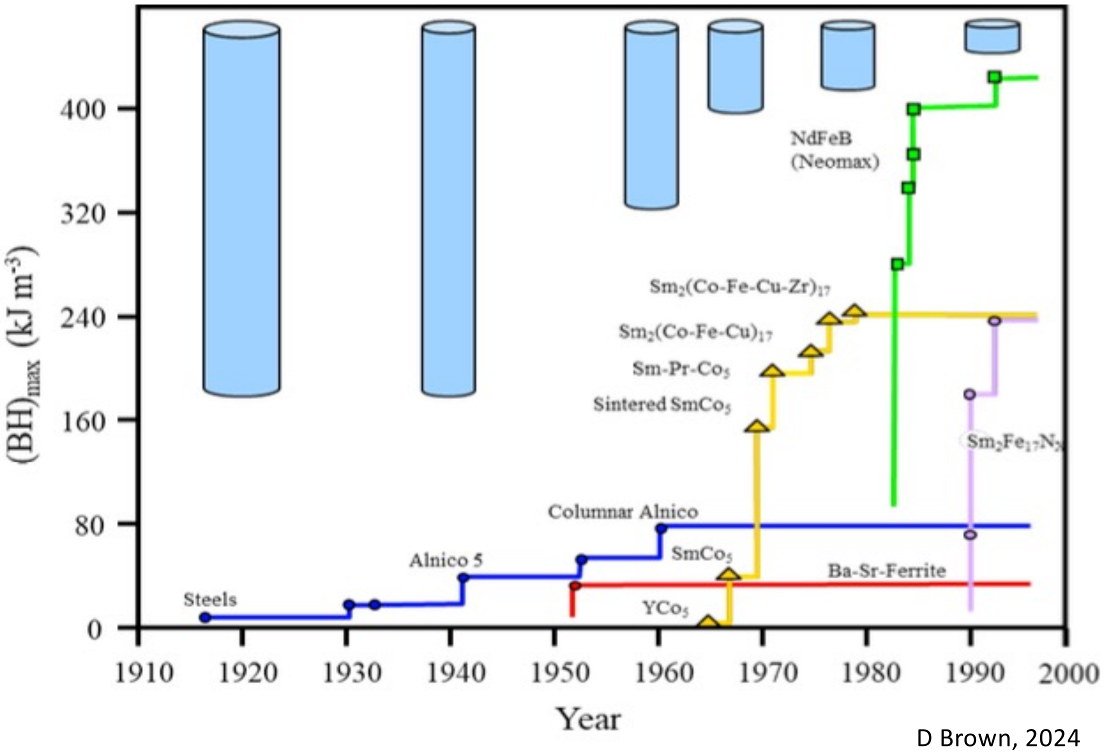
Remanence: $B_{r,}$
Coercivity: $H_{cJ,}$
Energy product: BH_{Max}
Squareness Coefficients: H_k, H_k/H_{cJ},H_d (H_{d2}, H_{d5}, H_{d10}), S_a and others
Saturation values: H_{sat}, J_{sat}

Permanent Magnet Materials

Energy product, **$(BH)_{max}$** improved exponentially between 1950 and 1990, doubling roughly every 12 years.

However, there has not been a significant improvement within the last 30 years.

However, there has been a seismic growth in applications and manufacturing innovations.



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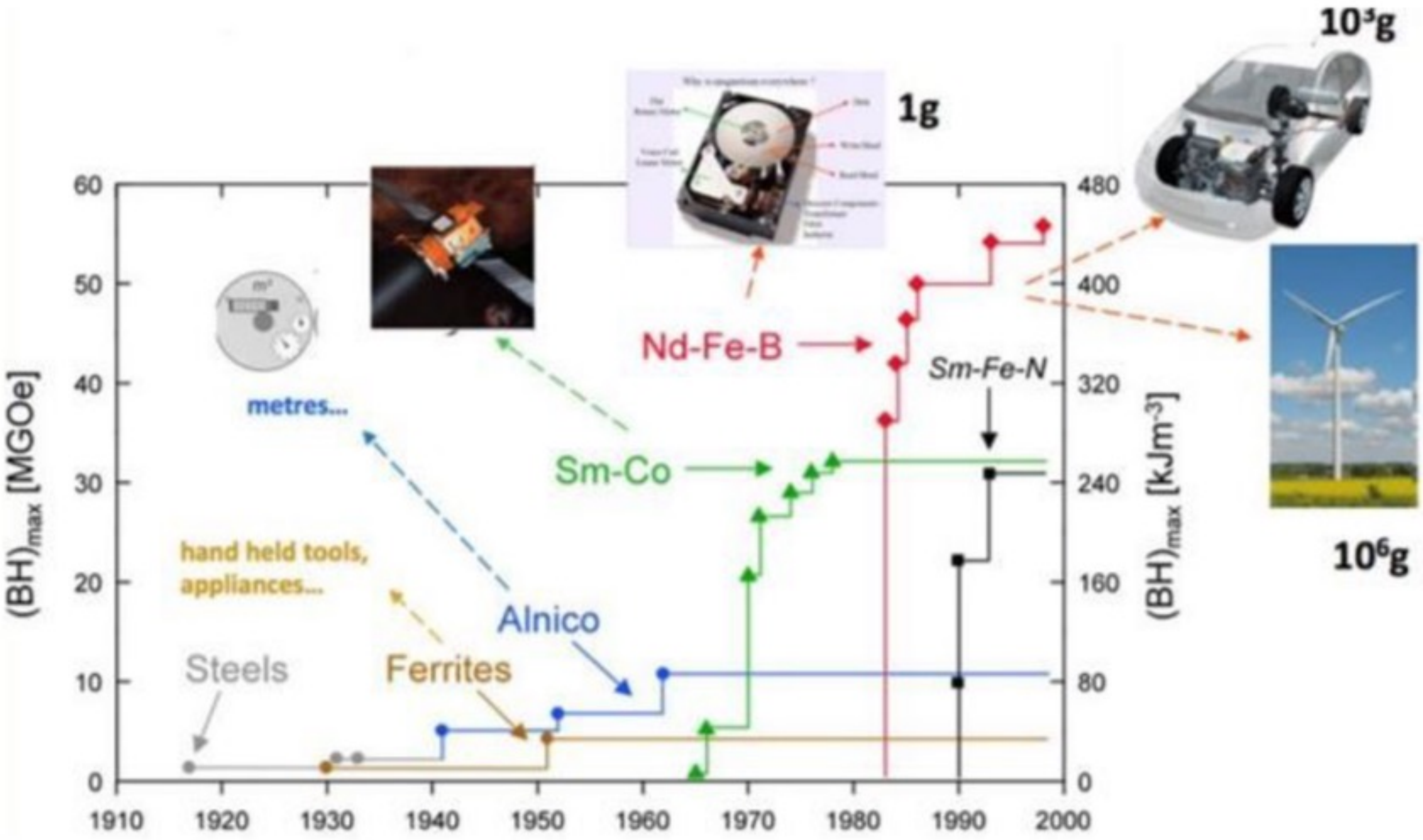
New materials enable new applications



https://www.tcd.ie/physics/research/groups/magnetism/research/permanent/

Permanent Magnets - A huge business, set to grow

MMG | University of Birmingham

Permanent Magnet Applications

Applications	Current Size (tonnes/year)	Predicted size by 2040 (tonnes/year)
Electric Passenger cars	40,000	180,000
Commercial E-vehicles	10,000	50,000
E-bikes and alike	25,000	100,000
Auto Micromotors and sensors	16,000	30,000
Wind power generation	25,000	100,000
Industrial Motors, Pumps & Compressors	10,000	25,000
Other industrial (robots, elevators etc.)	10,000	25,000
Cordless Power Tools	10,000	25,000
Consumer Electronics	6,000	28,000
Automobile Speakers	6,000	25,000
Other Applications (aerospace, Health etc)	5,000	25,000

Market sources predict annual growth rates of between 5 and 9% in NdFeB demand, depending on the type of application.

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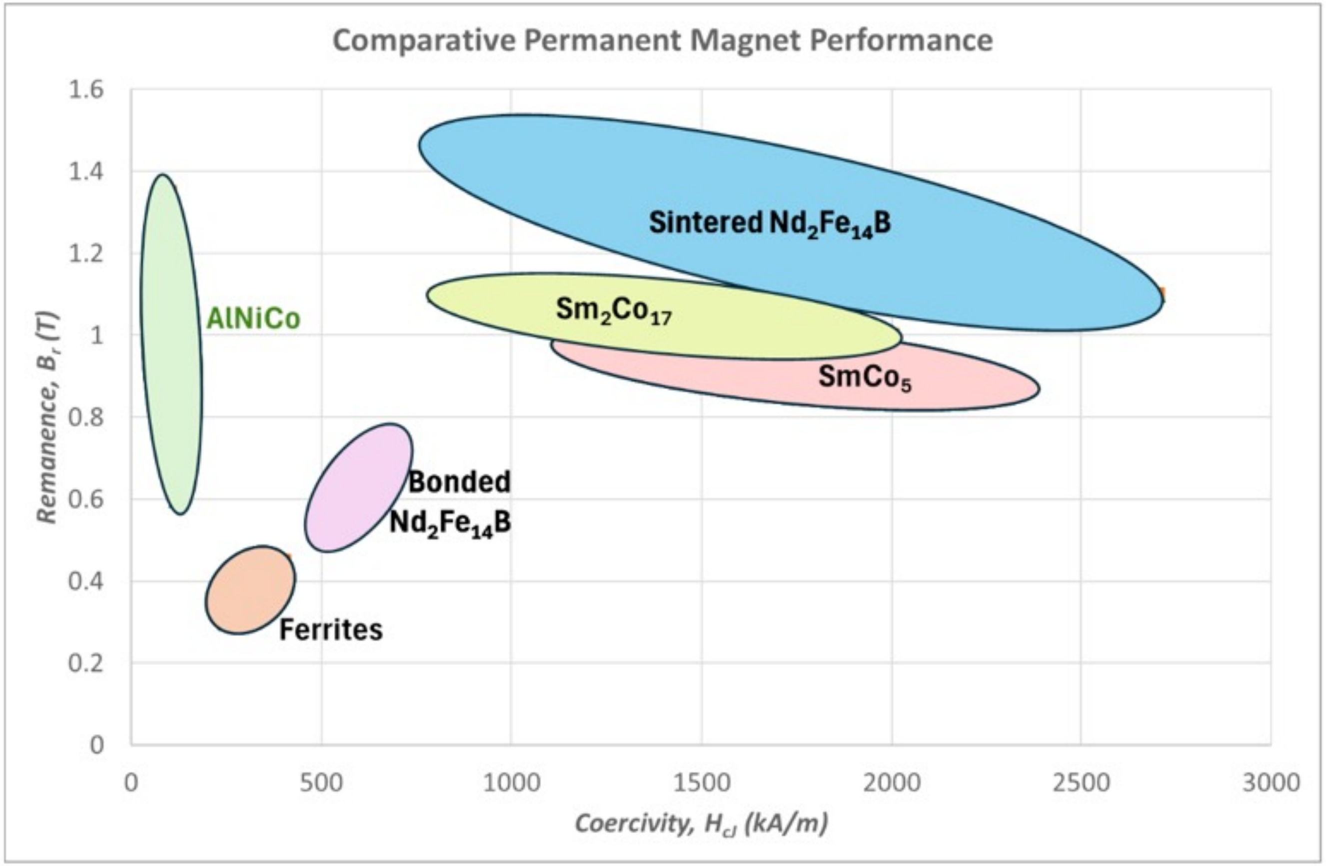
Permanent Magnet Materials



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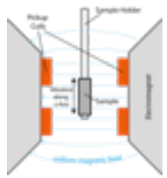
Three main test methods used

Permeameter / BH Loop tracer
- **Closed loop method**
- Slow loop tracing
- **Pole piece saturation limits Coercivity measurement higher magnet grades**
- Standard IEC 60404-5



Vibrating Sample Magnetometer (VSM)
- Open circuit method
- **Slow loop tracing**
- **Small sample size only**
- **No sample Coercivity limit (superconducting versions)**
- Standard IEC 60404-7

Pulsed Field Magnetometer (PFM)
- Open circuit method
- **Fastest measurements – 10ms**
- **Any size and sample shape**
- **No sample Coercivity limit**
- IEC technical report TR 62331, shows compliance with IEC 60404-5

Magnet Material Types

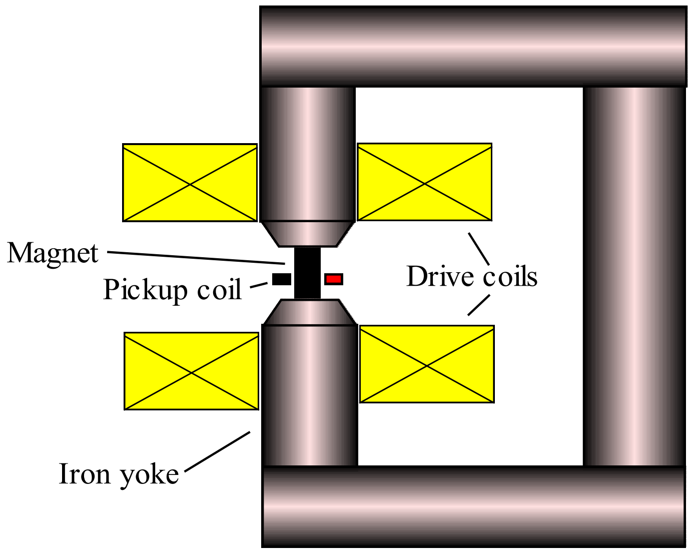
Material	Mag Field
Alnico	< 0.6 T
Ferrite	1.1 T

< Hsat Fe

> Hsat Fe

NdFeB	2.5 T - 3.5T
Sm1 Co5	~ 2.5 T

The need for PFM - The permeameter (BH Loop tracer, Hysterysis graph)



Permeameter

Considered an industry standard but :-

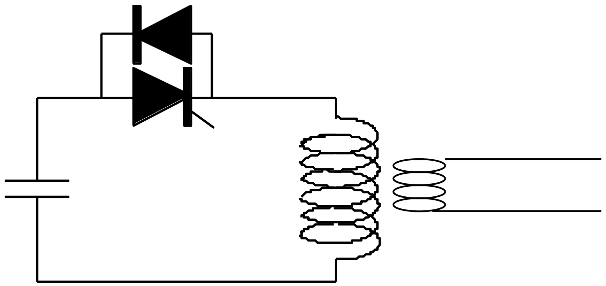
- Slow
- Limited applied field (cannot measure many HcJ of many NdFeB)
- Requires machined samples with parallel ends
- Limited shapes and sizes

Use of Cobalt Steel pole pieces allows measurements at higher fields than Iron with saturation up to 3.2T

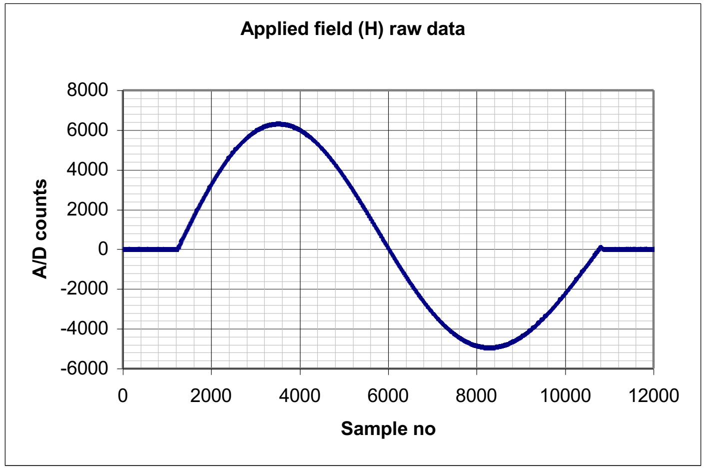
What is Pulsed Field Magnetometry?

- A High speed full loop characterisation system
- Very fast capable of 4 second cycle time
- Suitable for large volumes of magnets for 100% testing
- Open circuit measurement, no limiting iron involved
- No long measurements with associated integrator drift
- Can accept a wide range of sample sizes and shapes
- No limit on applied field and therefore HcJ capability

Field generation



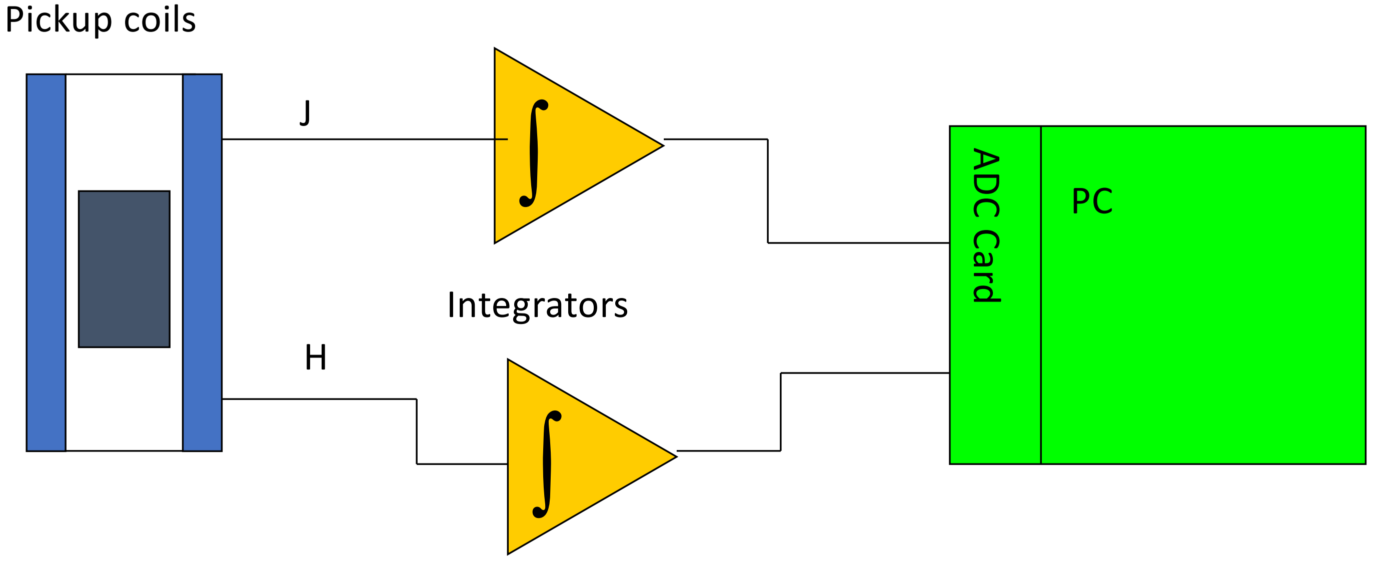
Capacitor bank is discharged into pulsed magnet producing damped sinusoidal waveform. Thyristor is used to only allow one cycle of oscillation (0 – 360 degrees)



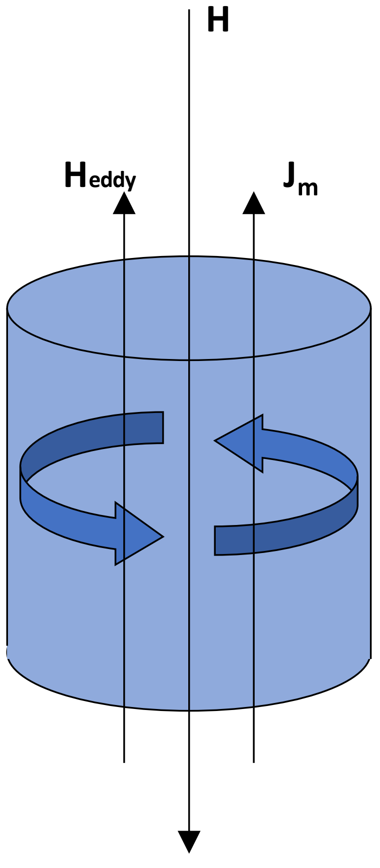
$$i(t) = \frac{V_0}{\omega L}.e^{-\beta t}\sin\omega t$$

$$\beta = \frac{R}{2L} \qquad \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

Data capture



Eddy currents



- Sintered magnets are electrically conductive
- Dynamic magnetic pulse introduces unwanted eddy currents

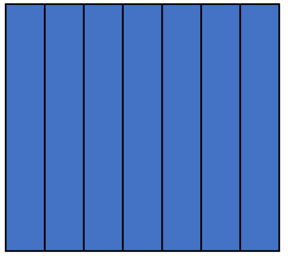
$$\nabla \times \mathbf{J}_C = -\sigma \left(\frac{d\mathbf{H}}{dt} + \frac{d\mathbf{J}_m}{dt} - \frac{d\mathbf{E}}{dt} \right)$$

Hirst F/2F* Eddy current removal

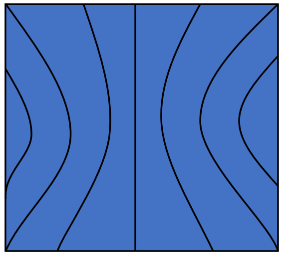
- 2 Pulses of different rates change of applied field are applied to magnet
- Both results are analysed for eddy current contribution
- Original “static” eddy current free waveform is obtained

* F2F is a Hirst Magnetic Instruments Ltd Patented Process

Self demagnetisation



M in Closed Magnetic Circuit



M in Open Magnetic Circuit

Open circuit measurement

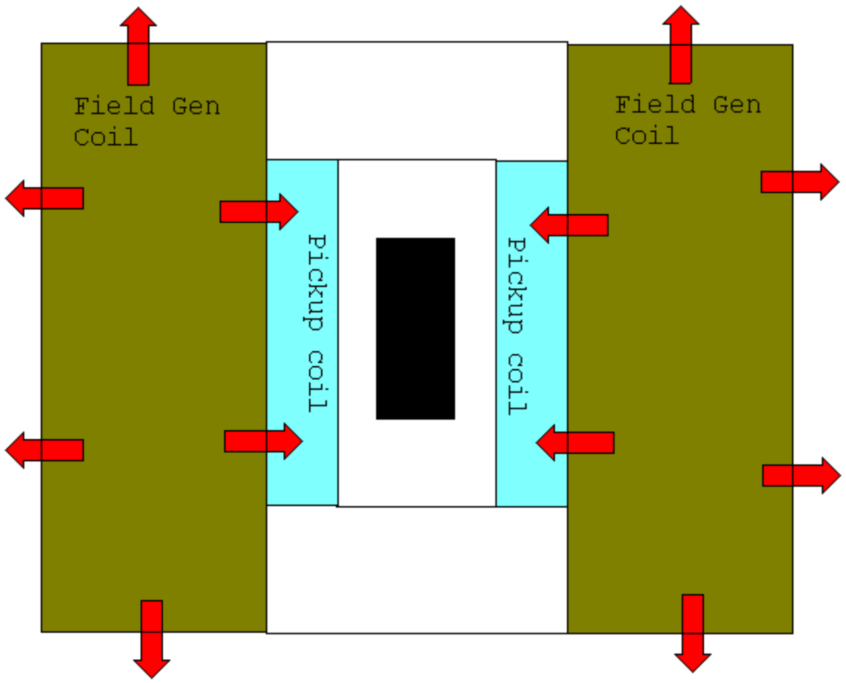
A proportion of the magnets magnetisation backs off the internal applied field H_{int}

Correction :-

$$\boldsymbol{H}_{int} = \boldsymbol{H} + N\frac{\boldsymbol{J}}{\mu_0}$$

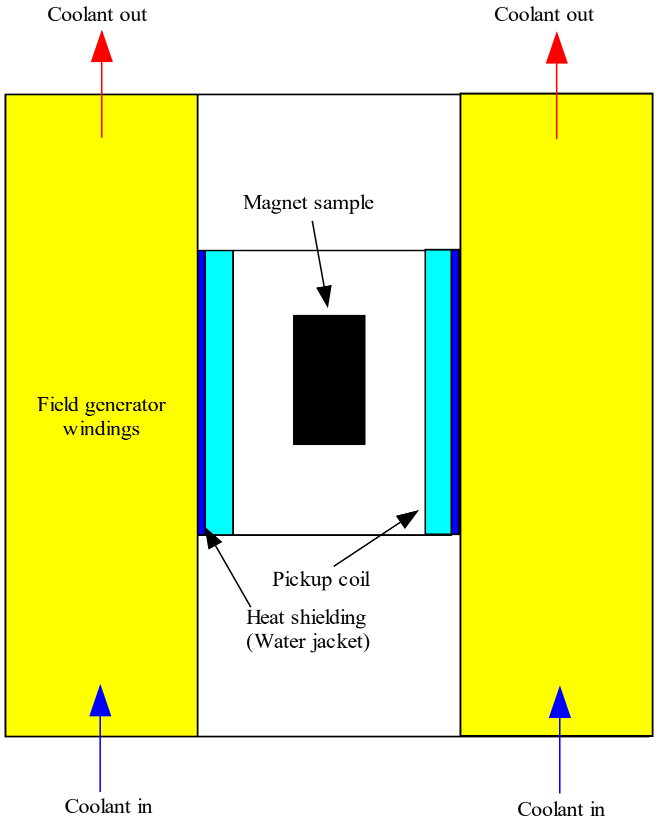
Where N is determined by Chen's tables or by FE calculations for more complex shapes

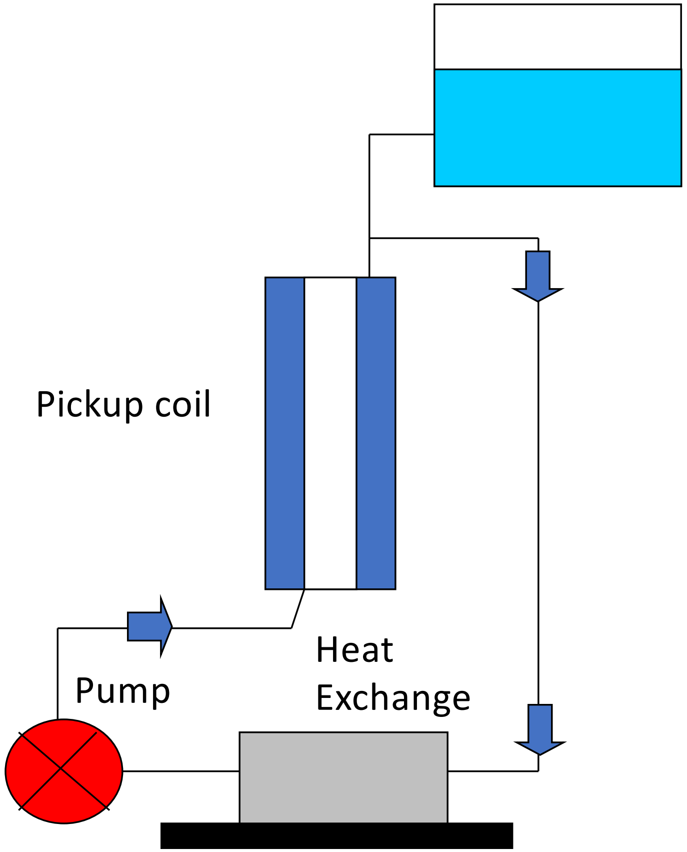
Sources of heat



- From field generation coil
- Changes in ambient
- Hysteresis loss within the magnet under test

Thermal control temperature control of measurement coils





No temperature control – results are of limited use to customer

Time	Br	Hci	Hc	BHMax
	T	kA/m	kA/m	kJ/m^3
10:47:11	1.225	2254	966.4	301.4
10:56:51	1.225	2246	964.0	300.5
11:08:57	1.228	2255	946.2	288.7
11:14:35	1.220	2172	940.1	285.0
11:25:20	1.225	2234	943.6	287.5
11:34:44	1.226	2236	944.5	288.9
11:37:41	1.223	2219	944.7	287.7
12:06:23	1.227	2238	946.3	289.1
12:26:15	1.225	2218	944.3	287.8
Max	1.228	2255	966.4	301.4
Min	1.220	2172	940.1	285
Spread	0.008	83	26.3	16.4
Mean	1.224	2230	948.9	290.7
%Err +/-	0.326%	1.860%	1.386%	2.820%

A single ND153 magnet was repeatability measured.

No temperature control was provided so the magnet was susceptible to changes in ambient and local heating

Article in recent UK MagSoc magazine

Pulsed Field Magnetometers – closing the loop on material characterisation

Dr James Mckenzie, CEO & Dr Robin Cornelius, CTO, Hirst Magnetic Instruments Ltd

Introduction

The Pulsed-Field Magnetometer (PFM) is internationally recognised for the complete characterisation of modern magnetic materials. It is a method for generating a hysteresis graph similar to that of a permeameter.

Historically demagnetisation curves were measured using a permeameter. A permeameter uses an iron-core, closed-magnetic-circuit to deliver a uniform magnetic field to the sample. However, modern hard magnetic materials often cannot be accurately characterised using a permeameter because the high coercive fields required will saturate the iron-based cores thus corrupting the measurement and in extreme cases the measurement cannot be obtained.

PFMs have gained in popularity over the years as a measurement technique (compared to the permeameter) as they are easily scalable in sample size (from 1 mm to several tens of mm), with a significantly faster measurement time. Plus crucially can accurately characterise the high coercivity magnet samples used in today's high performance motor applications such as electric vehicles (EV). Larger sample sizes meet the requirements of magnets used in EV rotors, allowing accurate quality control for batch testing of production magnets for the key performance metrics including high temperature coercivity. If a batch does not have the correct composition for whatever reason, its high temperature performance can be compromised causing in extreme cases loss of motor power and possible warranty claims.

PFM measurements are non-destructive, which is particularly important for larger, more expensive high-performance magnets. PFMs have historically found application in production testing and quality control in magnet factories across the world for rapid standard sample block tests, as well as materials research and development requiring magnet samples tested down to -50 °C and to over 230 °C requiring the highest level of repeatably and accuracy.

Small size testing down to 1x1x1 mm and thin slices have been used over the years in grain boundary diffusion (GBD) magnets, and more recently developing selective diffusion of heavy rare earths (to toughen up edges and corners of magnets to improve performance cost effectively) in magnet research, development and production testing.

The International Electrotechnical Commission (IEC) has issued IEC TR62331, a draft to define the standard methodology for the characterisation of permanent magnetic materials using the PFM technique.

Hirst Magnetic Instruments Ltd originally manufactured permeameters (hysteresisgraphs) and vibrating sample magnetometers. Research work at Hirst into PFMs began in the 1990s, and Hirst introduced its first commercial PFM in 1998, winning an Institute of Physics award in 2020 for the technology, and launching its latest 8th generation PFMs in early 2023.

In this article we will review magnetic measurements, focussing on the PFM technique to compare it to other standard approaches, and look at Hirst's PFM08 range with its associated software.

Industry – Applied R&D

- Its all about solving problems customers have or will have at the right time.
- Very few companies do fundamental R&D
- Its mostly applied R&D in fact its mostly D / Engineering
- Increasingly software development
- Cost and timing are always factors
- The problem defines the direction….

Magnet basics drive metrology needs

"The Rule of Ten" states that the measuring instrument should be at least 10 times as precise as the characteristic to be measured

- H_{cJ} between grades

Grade	Br (T) min	α % / ℃	Hcj (kA/m) min	β % / ℃	BHmax (kj/m3)	Max Operating Temp (℃)
45SH	1.33	0.115	1750	0.55	334	150
45UH	1.33	0.115	1990	0.5	334	180
45EH	1.33	0.112	2400	0.45	334	200
45AH	1.33	0.112	2800	0.45	334	240

- On H_{cJ} delta of 240 kA/m between SH and UH grades & 400 kA/m between EH and AH grades

Magnet basics drive metrology needs

45AH example – ambient measurement

Sample Temperature Control

Temperature (℃)	Δ Temperature (℃)	Br change (T)	Difference %	Hcj change (kA/m)	Difference %
± 0.2	0.4	0.001	0.04%	5.04	0.2%
± 0.5	1.0	0.001	0.11%	12.6	0.5%
± 1.0	2.0	0.003	0.22%	25.2	0.9%
± 1.5	3.0	0.004	0.34%	37.8	1.4%
± 2.0	4.0	0.006	0.45%	50.4	1.8%
± 2.5	5.0	0.007	0.56%	63	2.3%
± 5.0	10.0	0.015	1.12%	126	4.5%

Sample Reload Repeatability

Reload Repeatablity %	Δ %	Br change (kJ/m3)	Hcj change (kA/m)
± 0.2	0.4%	0.005	11.2
± 0.5	1.0%	0.013	28
± 1.0	2.0%	0.027	56
± 1.5	3.0%	0.040	84
± 2.0	4.0%	0.053	112
± 2.5	5.0%	0.067	140
± 5.0	10.0%	0.133	280

✗ If a PFM has a poor repeatability of ±2.5°C on Temperature and poor reload repeatability on H_{cJ} of ±2.5%

- H_{cJ} delta could be >200 kA/m (the difference between EH & AH grades is only 400 kA/m !)
- This is simply not precise enough for R&D or quality control (QC) purposes

✓ Hirst generation 8 machines offer repeatability of ±0.1℃ and ±0.2% for H_{cJ} on most samples

Where do customers use PFMs ?

Magnet Manufacturers

- Magnet Development
  - Inc GBD magnets
  - Selective GBD magnets
- Magnet Block testing
- Finished Magnet testing

PFMs are used in

- Magnet Block testing
- Magnet R&D
- Finished Magnet testing

Magnet Users – R & D

- National Labs
- Consumer electronics
- Wind turbines
- Motors

What's important in R&D

- Precision and repeatability
- Traceability
- Stability
- Wide Sample size range

Magnet users - Quality control

- EV and traction motors
- Some smaller applications in consumer electronics

What's important in QC

- Large sample size
- Fast test times
- High temperature measurement of coercivity

Where do customers use PFMs ?

Magnet manufacturers

- Magnet Development
  - Inc GBD magnets
  - Selective GBD magnets
- Magnet Block testing
- Finished Magnet testing

PFMs are used in

- Magnet Block testing
- Magnet R&D
- Finished Magnet testing

About the measurement

- Standard Sample sizes – 10mm (d) cylinders or 10x10mm cubes
- Ambient Test at specific temperature
- **Test time 5 minutes to 1 min**
- Reliability and Stability are key

- Production quality control
- Traceability to reference samples and permeameter tests

PFM08-10 AT

PFM 08-10 AT

- Sample size 5-10mm(d), 1-20mm (h)
- Repeatability on Br and HcJ ±0.2 %
- Ambient temperature selectable 23℃ ±5℃ with temperature control to ±0.1℃.

2024 - 25 years of commercial PFMs at Hirst

PFM02 – Gen 1 1999
20T fields, 5mm sample

EU-PFM21 2003
5s fully automatic tests !

Gen 4 PFM15 2009
50mm, 220 °C

Gen 7 PFM12 and 14 2021
Repeatability H_{cJ} ± 0.2%

PFM Gen8 2023

PFM08-10

PFM08-40 and 08-70

Gen 2 PFM12.cn 2006
10.5T, 10mm samples
Ambient testing to ± 0.1 °C

Gen 5 PFM14 2012
+200 °C tests

Gen 6 PFM06 2016
1x1x1mm

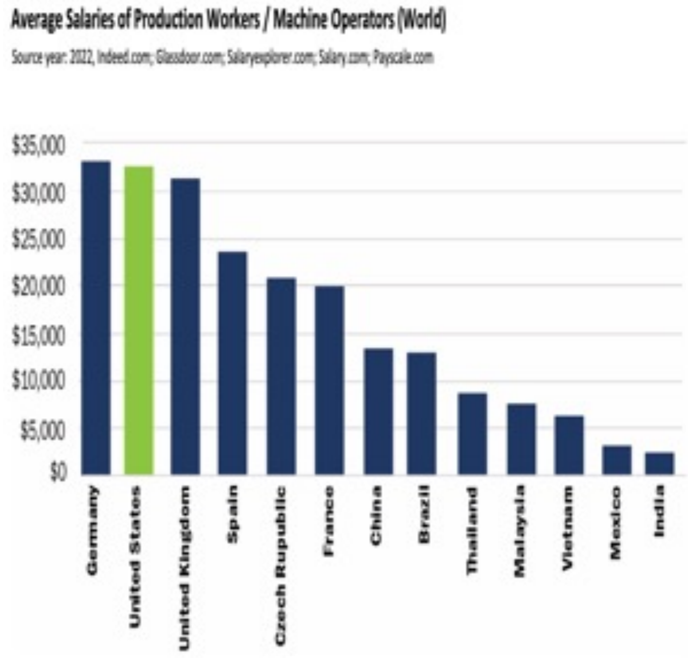
What are the future Challenges ?

- **Standards** – despite PFM measurements being well established technique in industry there is no formal standard

- Path to a standard
  - IEC technical report TR 62331, shows compliance with IEC 60404-5
  - Dr Graeme Finch (NPL) Convenor on ad hoc group 6, development of PFM standard - IEC TC-68 Working Group 5 (Permanent Magnets)
    - 4 manufacturers are represented Hirst, Metis, Toei, LE
  - Published standard expected in 2025/26

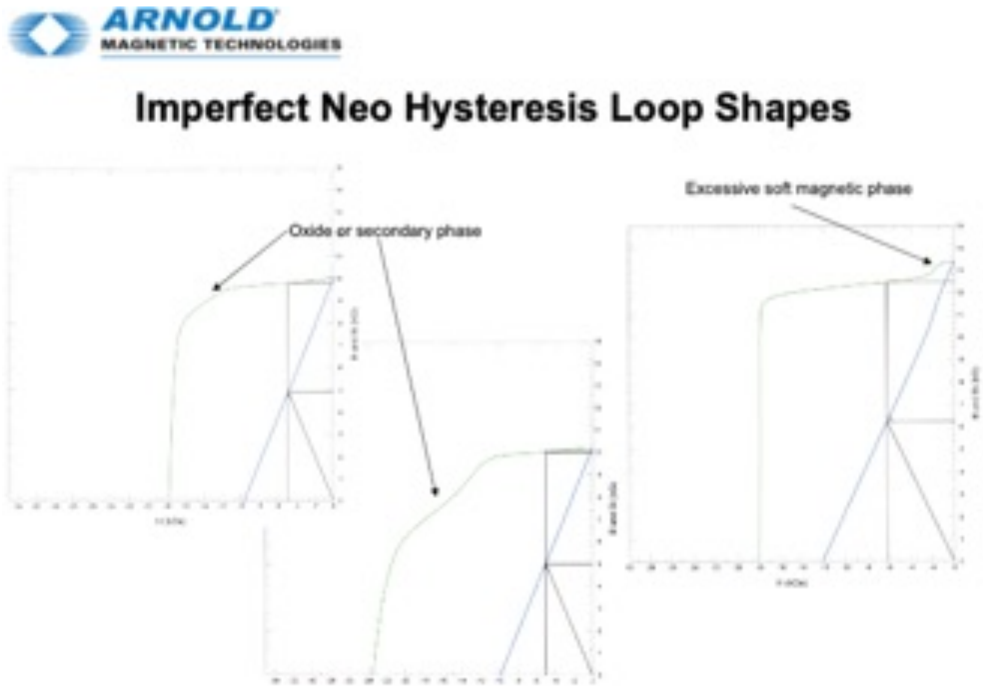
What are the Challenges ?

- **Automation** to tackle rising labour costs
- PFMs have been used in production in China (this 90% of global magnet production since 2006)
  - Between 2010-2021, the index in China increased by 37.9%.
  - Strong need to automate measurements in US, EU and now China
  - PFMs are the fast measurements and easiest to automate



What are the Challenges ?

- Advanced Diagnostics – tools for quality measurement
- Simple BH Loop Metrics – loop shape and structure allows measurement soft phases of Nd or alpha Fe in the grain boundaries



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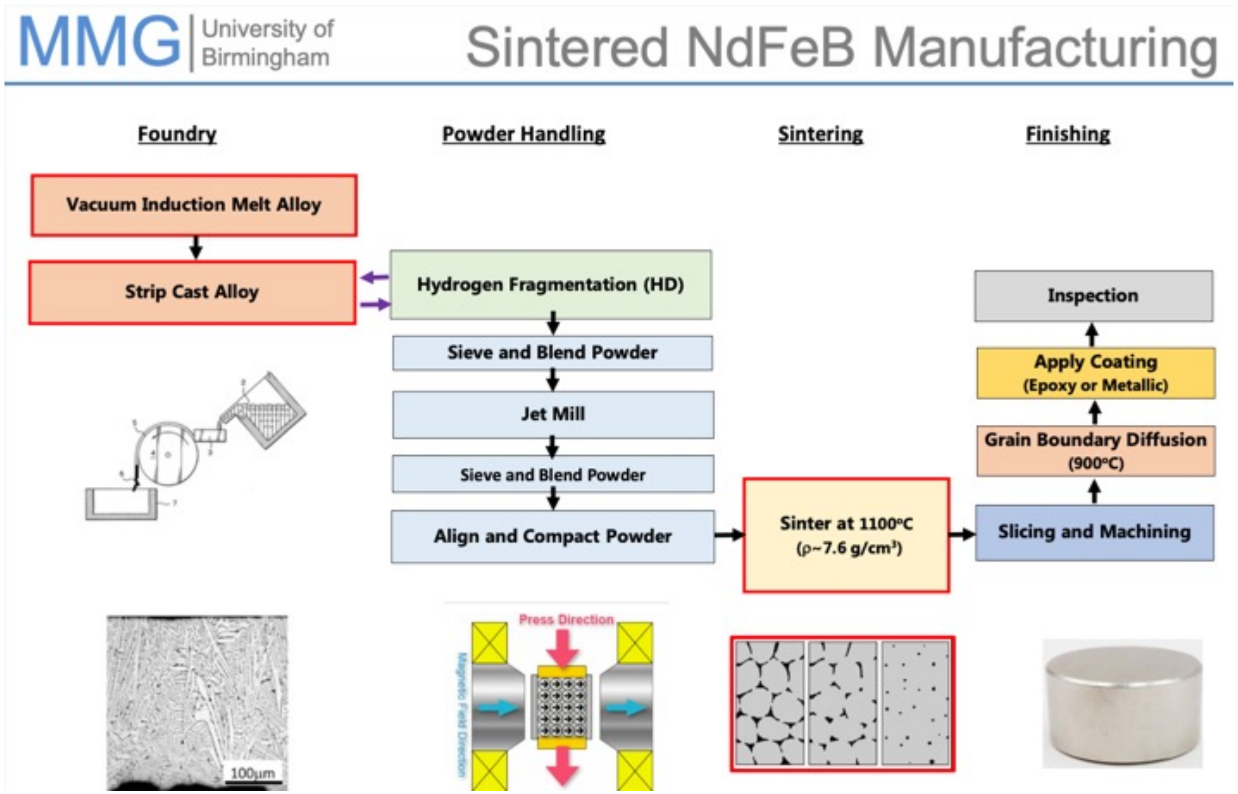
Complicated manufacture



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Dynamic Magnet Performance - Hirst iX Challenge

Developing ways to measure and use eddy current and hysteresis loss data in permanent magnets used in dynamic motor environments

COPY LINK

Hirst Magnetics carry out magnetic measurements using a pulsed field magnetometer. The development of more powerful motors in the EV industry has demonstrated that magnet and motor manufacturers do not measure or understand the losses associated with dynamic hysteresis and eddy current losses in motors. These can involve 100's of Watts (of heat generated in magnets) and are relying on static measurements to design motors which are of course are dynamic systems. As magnetic materials dislike heat, such sources must be measured and reduced where possible. Hirst Magnetics invites companies, Universities or individuals who develop magnetic models to work with them to explore how eddy current correction and hysteresis loss data can be simulated in a dynamic motor environment.

Opportunity

Challenge opens
30/11/2023

Challenge closes
24/01/2024

Benefit
Hirst Magnetics seeks to use open innovation to understand the unexplored dynamic nature of eddy current and hysteresis losses in permanent magnets in motors and generators. This will help build more efficient and cost-effective motor and generator designs. Successful projects will be awarded up to £25k over 3 months to explore their solution with the challenge holder with the possibility of further adoption upon successful trials.

Background

Hirst Magnetic Instruments have been providing solutions for 60 years in magnetics and magnetic measurement. Hirst manufactures precision hand-held Gaussmeters, Fluxmeters, bench top & workstation industrial magnetisers & demagnetisers, industrial production-line magnetisers and pulsed field magnetometers (PFMs) for developing / characterising magnetic materials. These instruments are used in multiple industries including aerospace, automotive, electronics and medical equipment to support the productions of a range of different end use products.

Currently Hirst Magnetics carry out magnetic characterisation measurements using a PFM. This collects a range of different magnetic parameters that are both static and dynamic in nature. The measurements made on a PFM are used to generate static data sheet parameters for high performance permanent magnets – the dynamic information is currently not exposed or shared outside of the PFM but it offers useful information that we can address.

Current models and simulations use static measurements and magnet parameters to predict the performance of the motors. These usually have a significant error in predicting performance and an experience factor tends to be incorporated into product design, the experience factor is not linear, and increases with magnet size and motor power.

- The aim is to develop dynamic measurements to ensure better data goes into simulation tools

Conclusions

- Science is only the start – there is so much more
  - Technology, Timing, Applications
  - Economics, Markets
  - High amount of engineering…..electronics, materials and increasing amounts of software

- Business is about solving problems that matter for customers with a need – for a profit

- R&D : Industrial R&D is focused on solving problems for customers

Over 60 years experience in providing magnetic solutions.

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