Alliance LLC
Industrial Permanent Magnets

Finding Alternatives to Rare Earth Magnets for Electric Vehicles

by

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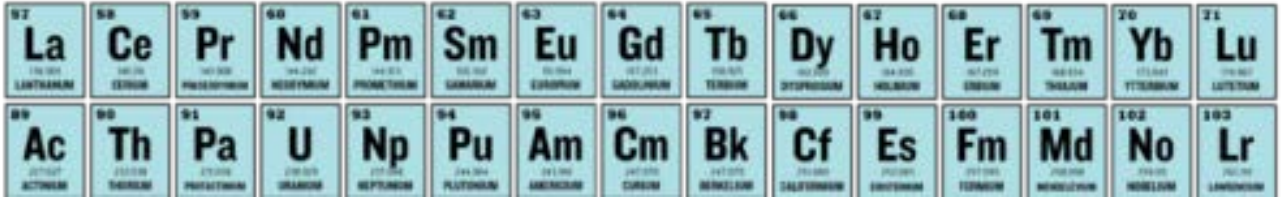
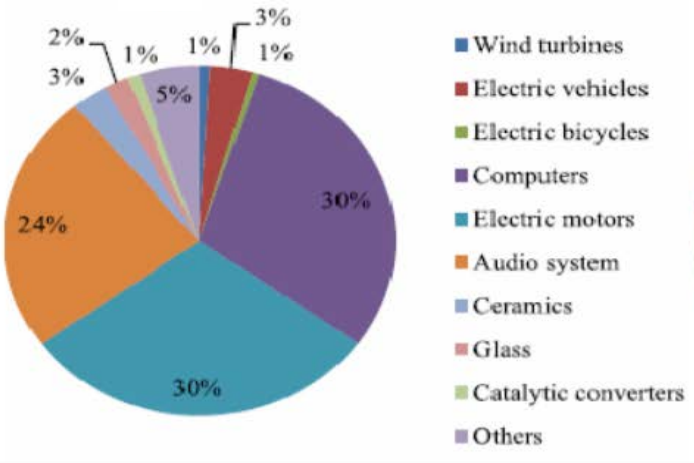
Main RE Elements Used for Production of Magnets

Lanthanum, cerium, **praseodymium**, **neodymium**, promethium, **samarium**, europium, **gadolinium**, **terbium**, **dysprosium**, holmium, erbium, thulium, ytterbium, lutetium, scandium, yttrium

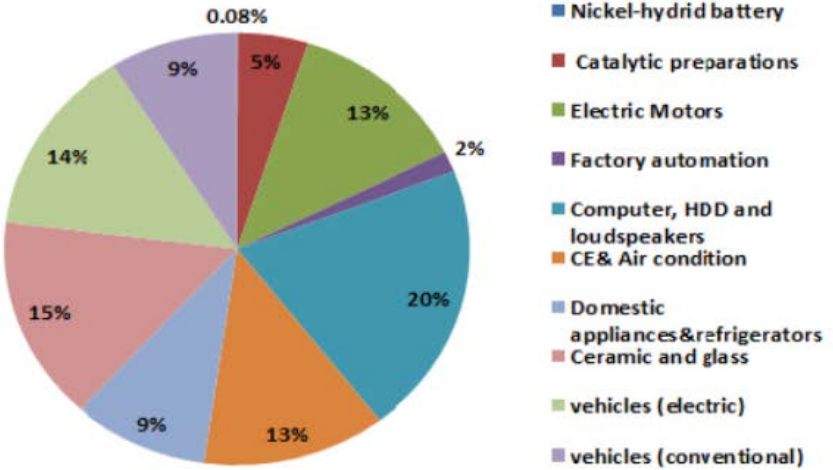


Share of End Use Applications for Nd Element

Global



Europe

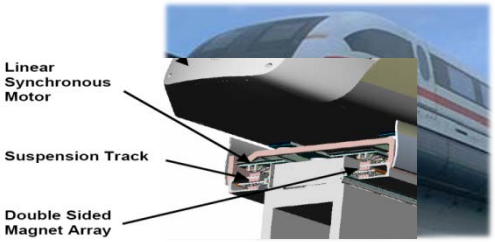


% of RE Materials Used for Manufacturing:

(in 2015)

- Magnets – 47%
- Batteries – Lithium ion & NiMH
- Catalysts for – 12%
    a) petroleum refining
    b) automotive catalytic converters
- Paints & pigments – 11%
- Super alloys – 14%
- Lighting
- Other – 16%

RE Magnet Markets

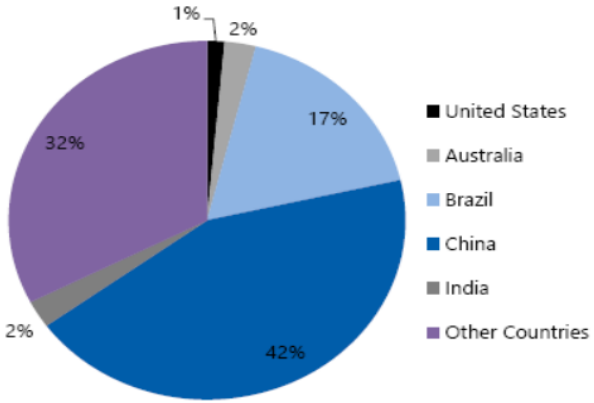


From Largest to
<u>Smallest Usage:</u>

Automotive
Consumer Electronics
Appliances
Office Automation
Military / Aerospace
Medical

Global Reserves of RE Oxide:

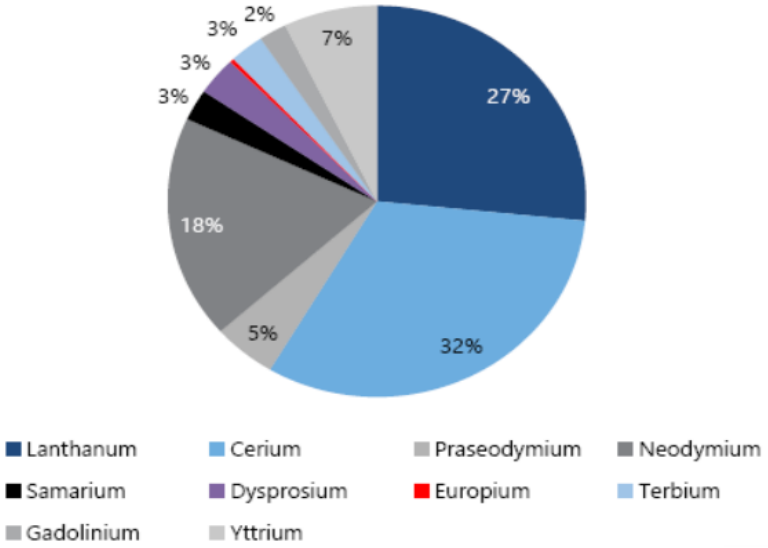
- China dominates reserves of rare earths – over 40pc of the global total
- Brazil the next largest single country with less than 20pc
- Australia, India and US account for 1-2pc of global reserves
- Relative abundance of rare earths in the earths crust, but mineable concentrations less common



Information and chart from: argus

Production of RE by Element in 2016:

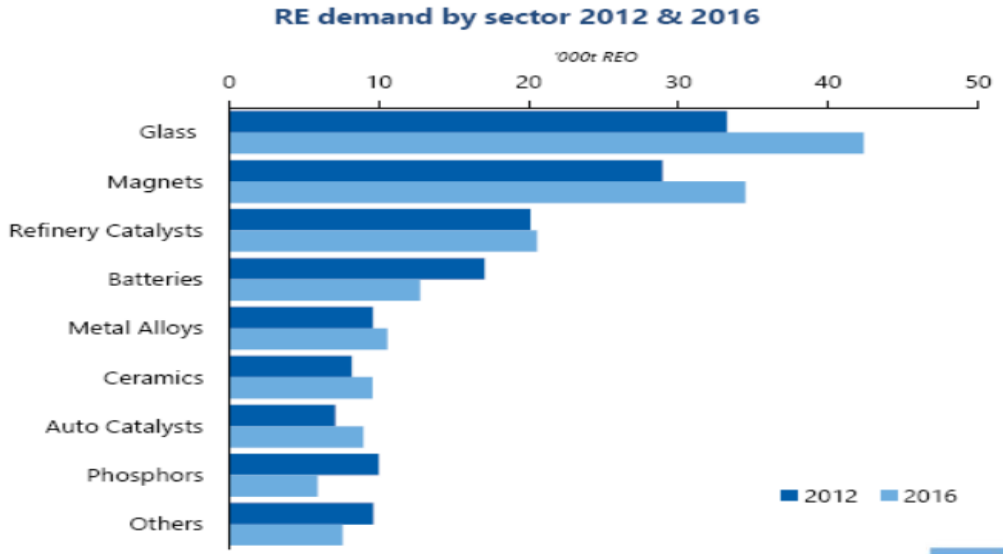
- LREEs dominate rare earths production – 85pc+
  - Cerium = 32pc
  - Lanthanum = 27pc
  - Neodymium = 18pc
  - Praseodymium = 5pc
  - Samarium = 3pc
- HREEs much less prominent in volume terms ≈ 15pc:
  - Yttrium = 7pc
  - Dysprosium = 3pc
  - Terbium = 3pc



Information and chart from: argus

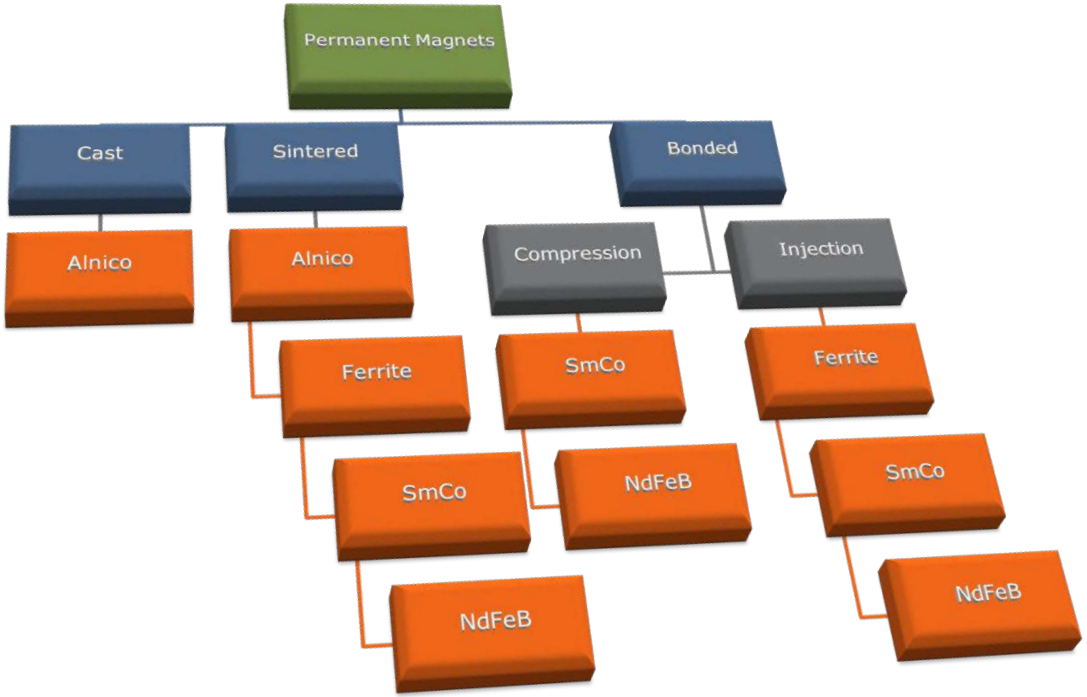
RE Demand by Sector in 2012/2016:

- Glass industry main consumer of rare earths (Ce):
  - ≈ 33,000t in 2012
    ≈ 42,500t in 2016
- Magnets (NdFeB):
  - ≈ 29,000t (2012)
    ≈ 34,500t (2016)
- Catalysts (growth in auto cats):
  - ≈ 28,000t (2012)
    ≈ 30,000t (2016)
- Batteries (NiMH):
  - ≈ 17,000t (2012)
    ≈ 13,000t (2016)
- Phosphors:
  - ≈ 10,000t (2012)
    ≈ 6,000t (2016)



Information and chart from: argus

The Magnet Family



Rare Earth Elements Used in Gas Vehicles

(total approx. 450 gr of which 350 gr are NdFeB magnets)

HVAC Systems:
45-50 gr, mostly magnets w/Nd&Dy

Door & Window Systems:
67-85 gr, mostly NdFeB

Entertainment (speakers,radio,DVD)
40-55 gr, mostly NdFeB magnets

Steering, Transmission Braking Systems:
160-200 gr, mostly NdFeB magnets

Engine Compartment
20-45 gr, mostly NdFeB

Fuel and Exhaust Systems:
75-90 gr, mostly Ce

Various Other Items (Instrumentation, Security, Seats, Haptics, Cameras, etc.) 20-30 gr, mostly NdFeB magnets

Economy cars with few options use approximately 60% less RE

Rare Earth Elements Used in Hybrid & EV

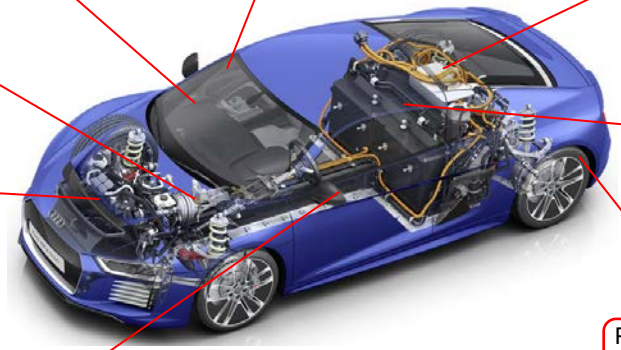
(total approx. 9200 gr of which 8900 gr is Nd)

HVAC Systems:
45-50 gr, mostly Nd&Dy magnets

Door & Window Systems:
67-85 gr, mostly NdFeB

Entertainment (speakers,radio,DVD)
40-55 gr, mostly NdFeB magnets

Steering, Transmission, Braking Systems:
160-200 gr, mostly NdFeB magnets



EV Batteries:
3800-4200 gr, Nd

Hybrid Engine or Electric Motor Compartment
800-5000 gr, mostly Nd, Dy

Fuel and Exhaust Systems for Hybrids:
70-80 gr, mostly Ce

Various Other Items (Instrumentation, Security, Seats, Haptics, Cameras, etc.) 20-30 gr, mostly Nd

RE Use Related to Vehicle Production

Total Worldwide Light Vehicles:

Production in 2016: 72,105,435

Total Amount of RE used: 12,616 MT

Estimated Worldwide Vehicle Production in 2025: 173 million

Estimated Amount of RE for vehicles used in 2025: 128,668 MT

(considers estimate that 25% of all vehicles will be electric)

China, the world's largest market:

2017 sales of EV's is estimated to be 1,200,000 and in 2020 around 5 million. Hybrids use 1-3 kg/unit while EV's use 5-10 kg/unit of Nd. The NdFeB magnet demand is estimated at 30,000 MT in 2020, a growth rate of 60% per year.

Recycling RE magnets into elements

Benefits:

- A proven technique used by many magnet manufacturers
- The properties of an element do not wear out
- A material once owned by someone can be controlled by whomever reclaims it
- The environmental impact of recycling is considerably less than that of mining & refining the raw material

Problems associated with recycling:

- Volume of rare earth used in final application is often small
- Technical difficulties associated with extraction and separation
- Energy, chemical, labor and equipment intensive
- Consumer perception of products containing recycled material is not often positive

Extracting RE From Coal

Approximately 1B Tons of Coal Burned in U.S. Annually

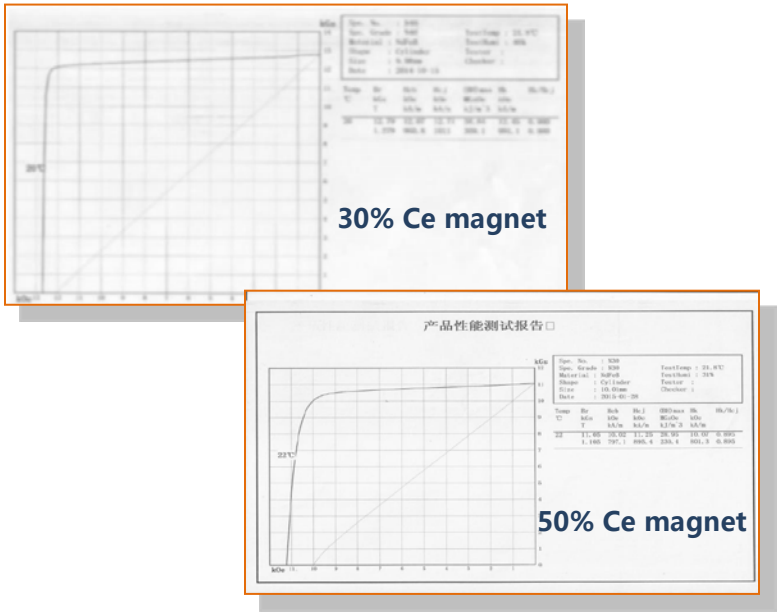
- ~100M tons of coal ash generated
  - Average concentration of ~470 ppm REE+Y, yields ~47,000 tons (~42,638 tonnes) of REE+Y annually
- If completely extracted, potential for generation of REEs from coal exceeds U.S demand

Challenges & Opportunities
Material Reserves
Environmental & Economic Impact

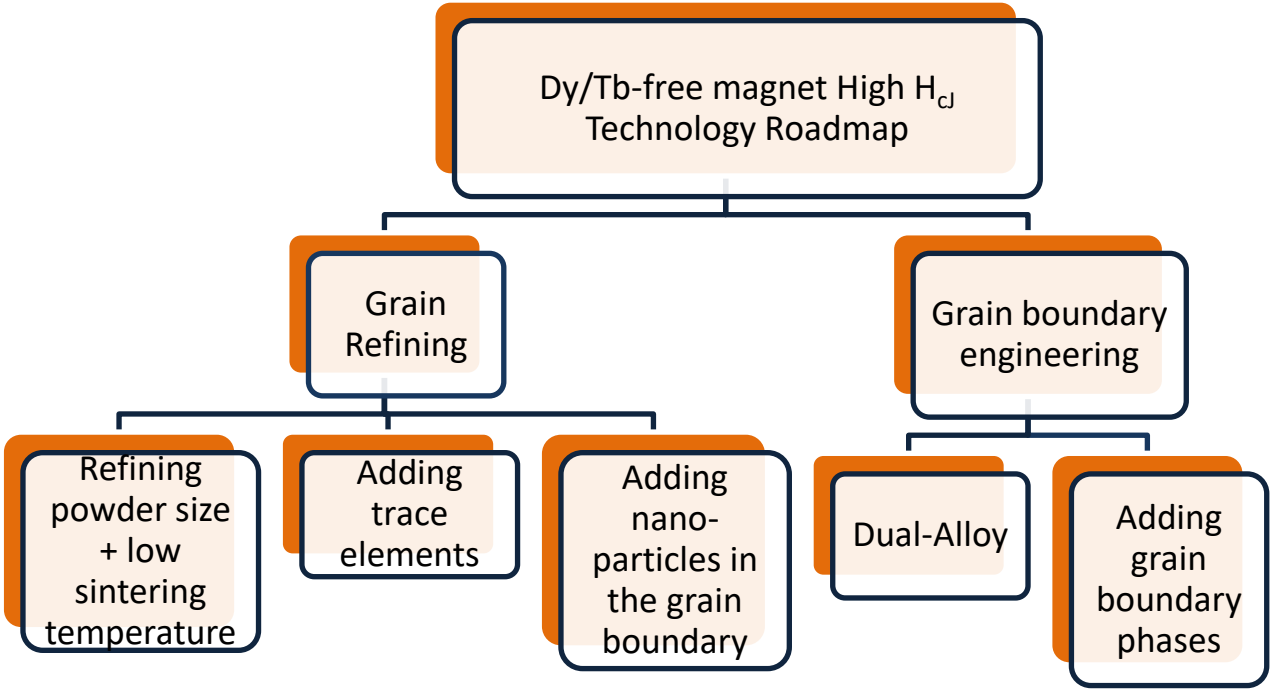
Changing the Composition of Magnets

Lower prices and greater availability can be achieved by utilizing more abundant RE elements like Cerium and eliminating rarer elements like Dy and Tb.

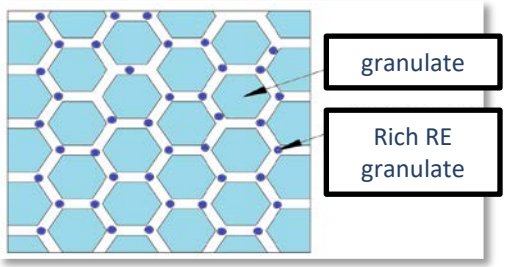
Many NdFeB manufacturers have already started production eliminating Dy and research continues into using Ce instead of Nd and Pr



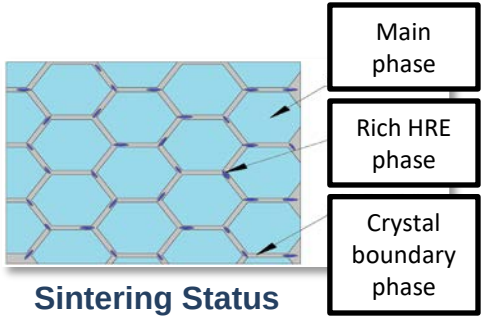
Techniques for Eliminating Heavy RE Elements in Magnets



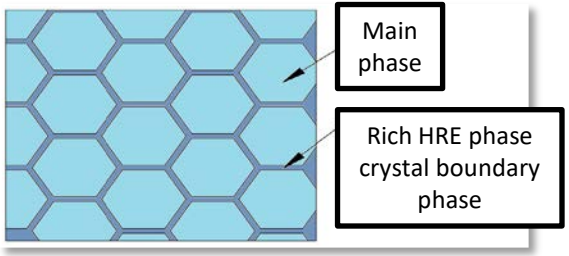
Grain Boundary Engineering to Eliminate Heavy RE Elements in Magnets



Before Sintering



Sintering Status

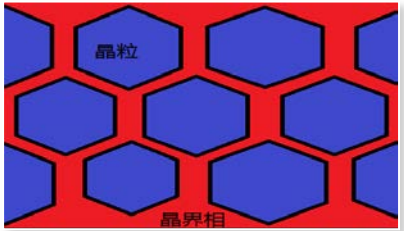


After Homogeneous Processing

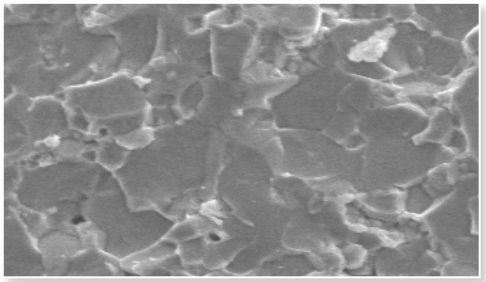
Adding Grain Boundary Phases to Eliminate Heavy RE Elements in Magnets

Melt point of main phase close to crystal boundary

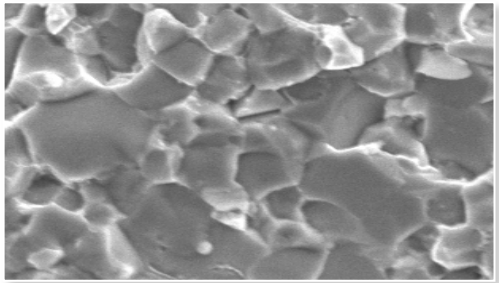
Raise the main phase melt point



Main phase melt point higher than crystal boundary phase



Improved



Grain Size Refining and Adding Trace Elements to Eliminate Heavy RE Elements in Magnets

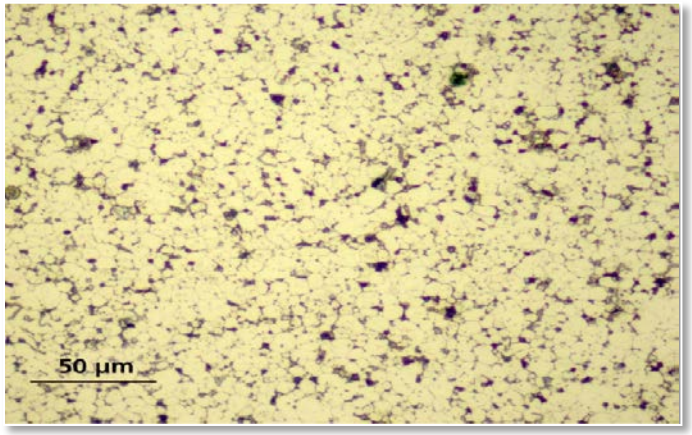
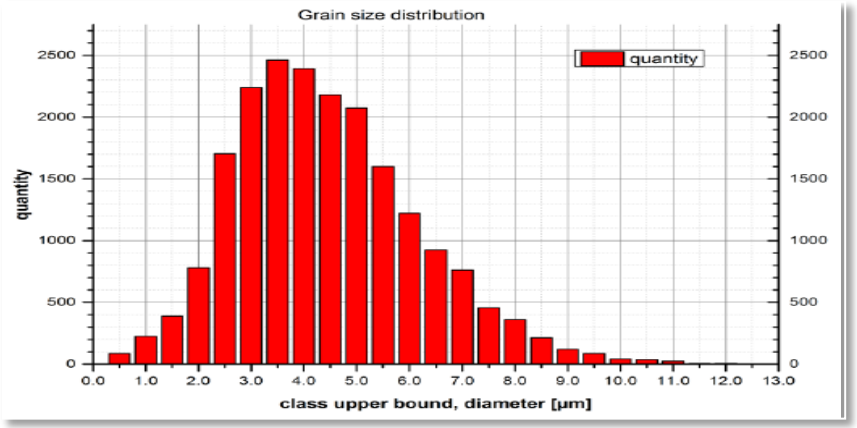


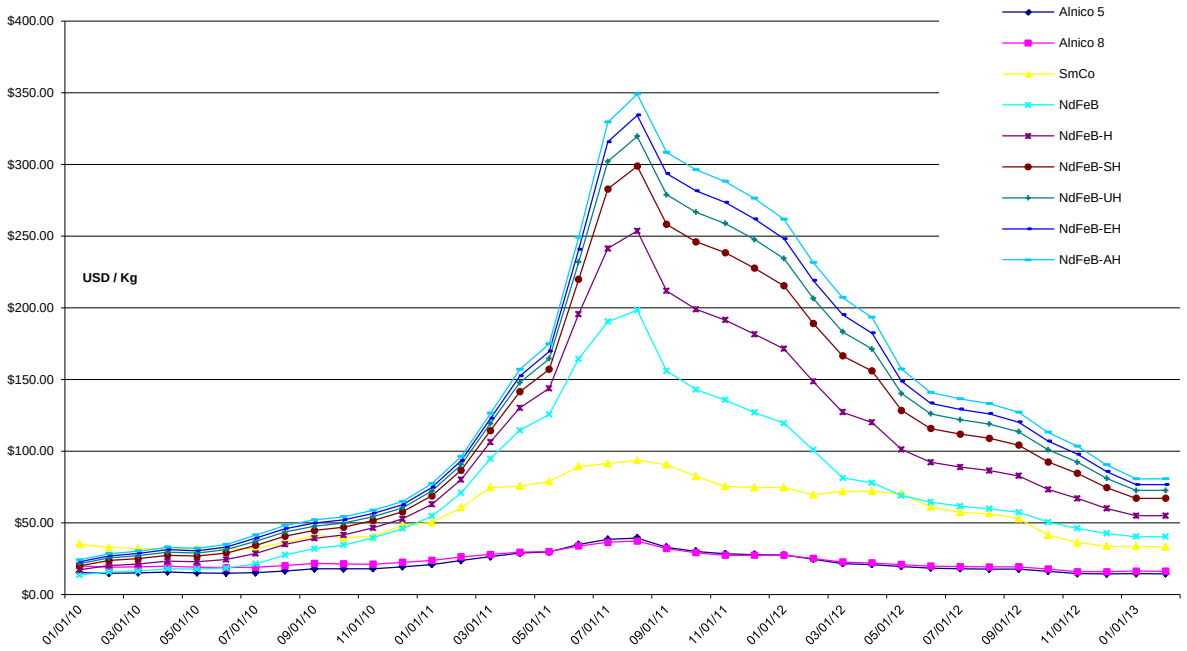
Photo of Grain Crystals Under Microscope



Crystal Distribution

Will This Prevent Another 2011 RE Crisis?

- The raw material costs for RE metal magnets increased dramatically, some over 1,500%
- Dysprosium, not shown because of scale, reached a high point of $2200/kg from an earlier $130/kg



Factors Affecting a Future Crisis

- China has a virtual monopoly at 97% supply
- NdFeB and SmCo Magnets would be affected because they contain Rare Earth elements
- Because of the RE properties, no other magnet materials can match the high performance of NdFeB
- Unknown political and stronger enforcement of environmental issues
- Demand will outpace supply for these RE elements for magnets
- There does not seem to be any short or long term term fix