Extending the limits of the Sm2Co17 System

35 MGOe and Beyond

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Global Supply Chain—from Mine to Motor

Mining & Processing (Joint Venture)

- Ganzhou, China (JV with rare earth producer)
- United States
- Multiple sources of supply

Magnet Production & Fabrication

- Samarium Cobalt RECOMA®
- Alnico
- Injection molded
- Flexible rubber

Permanent Magnets & Assemblies

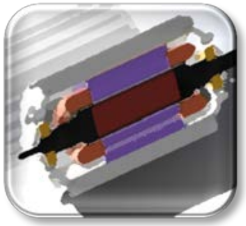
- Rotor build
- Rotor machining
- Rotor sleeving inc. carbon fiber
- Rotor balancing
- Rotor/motor design
- Magnetic modeling
- System integration

Precision Thin Metals

- Specialty alloys from 1.75 µm
- Sheets, strips, & coils
- Milling, annealing, coating, slitting
- ARNON® motor lamination material
- Light-weighting

High Performance Motors

- Smaller, faster, hotter motors
- Power dense package
- High RPM magnet containment
- >200°C operation



Engineering	Consulting	Testing	Stabilization & Calibration	Distribution	Fully Integrated Supply Chain	Mine to Motor

ARNOLD® MAGNETIC TECHNOLOGIES

Soft Magnetics – Precision Thin Metals

- **Silicon Steels for High Frequency Applications**
  - **Arnon – Non Oriented (0.18 mm & 0.13 mm)**
  - Grain Oriented (0.03 mm - 0.15 mm)
- **Popular Materials Available**
  - Titanium & Its Alloys
  - Arnokrome (FeCrCo)
  - Nickel & Its Alloys
  - Nickel Irons & Soft Magnetics
- **Exceptionally thin strip and coil**

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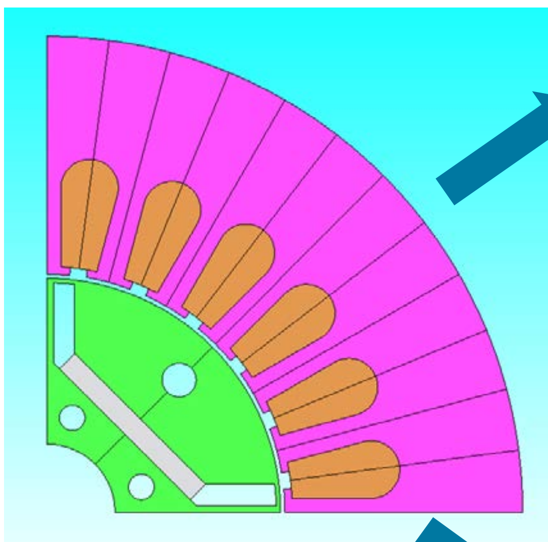
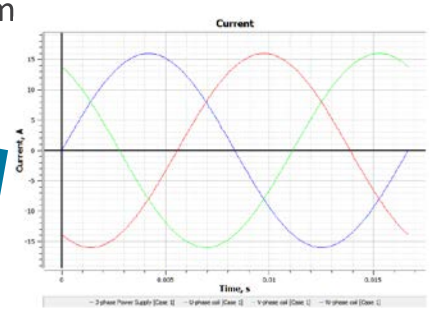
Why is thinness important?

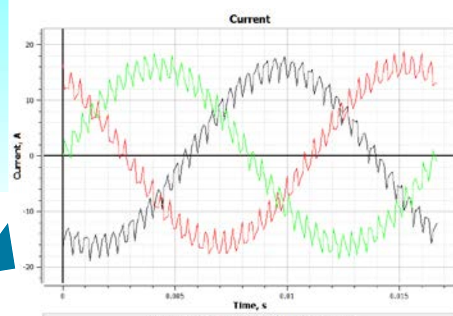
- Let's look at an example of a rotating machine
- We can compare the losses with a pure sine wave to the losses with harmonic content
- Using stator steel materials:
  - M19, 0.35mm (29 AWG)
  - Arnon 7 NGO Si Steel, 0.18mm



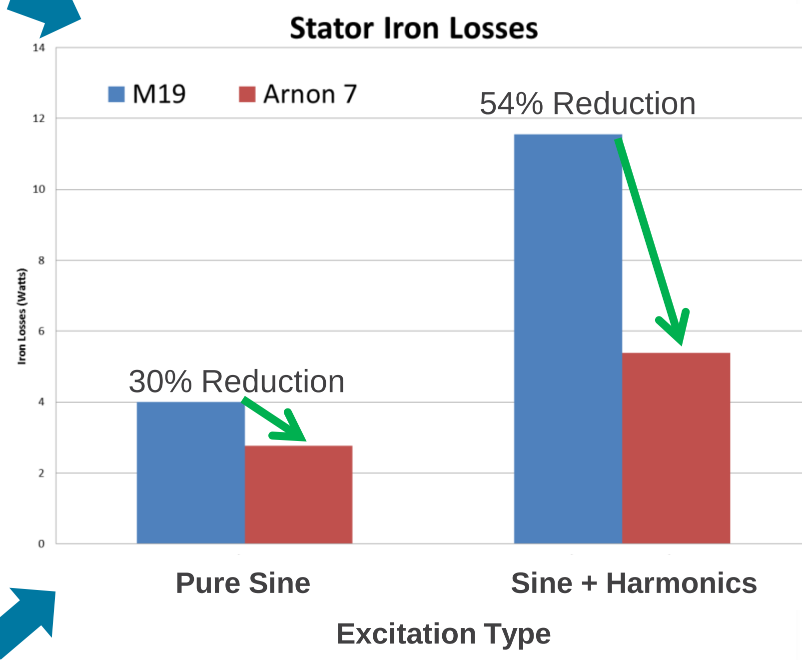
IPM Motor:
1800 rpm, 60Hz
112mm Outside Diameter
16Apk Rated Current



Pure Sine Wave Excitation



High Harmonic Excitation
(Switching Power Supply)



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Arnold in Europe

- Founded by Brown-Boveri Cie (today ABB) in 1972, making SmCo. Today:
  - Recoma HT
  - Recoma STAB
  - Recoma 33E
  - Recoma 35E
  - Did I mention Recoma?

Turning It Up To 11

33E

When we introduced 33E, we wanted to call it 32E, but that name was already taken by the 31 grade material!

32E
(31 grade)

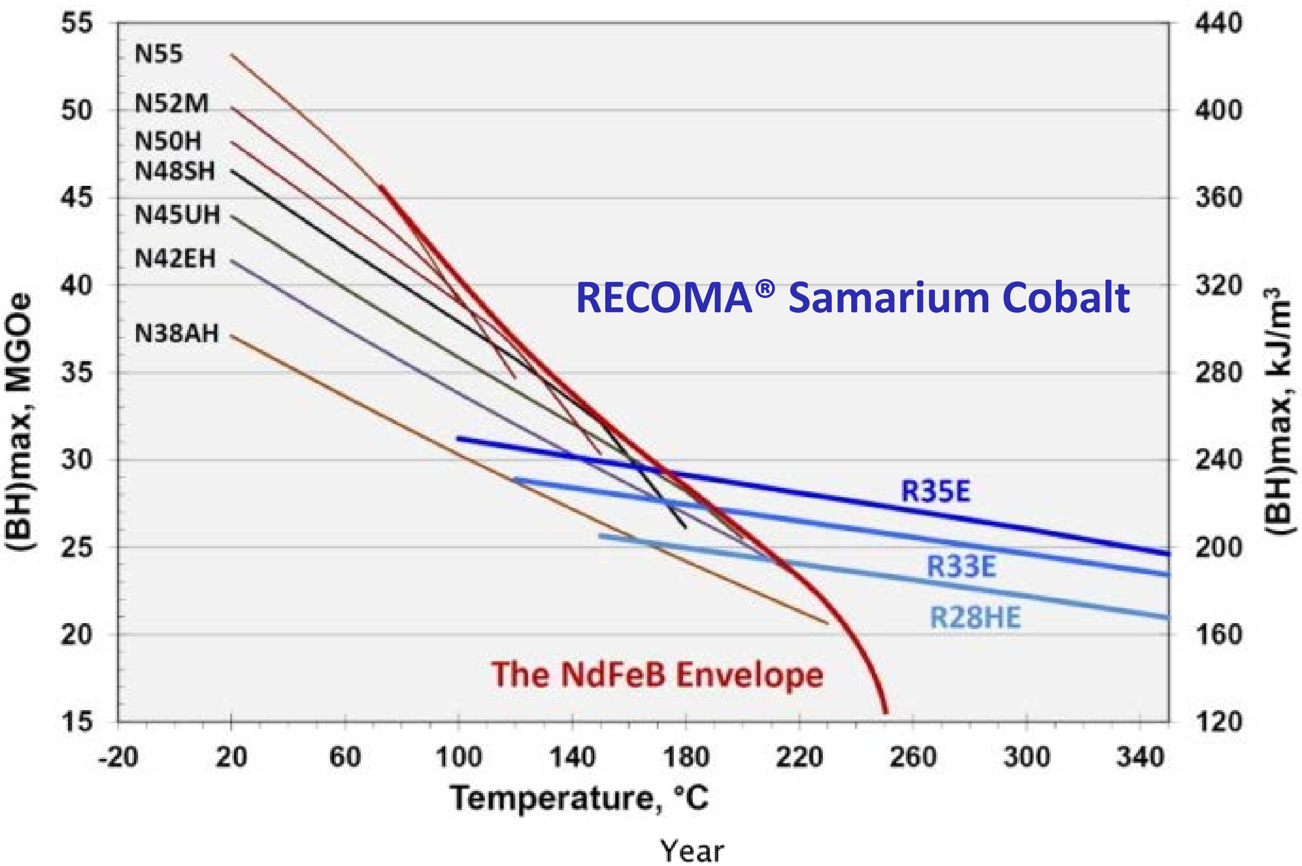
33.3
MGOe

Typical energy product

Today we are in the Spinal Tap Zone, where 35E is “two better” than 33E

35E

SmCo Untapped Potential



When compared to Neo, SmCo does bring some unique capabilities to the table, and these capabilities are greatly enhanced by higher energy density.

Because NdFeB was discovered so soon after SmCo, research in enhancing SmCo soon flatlined, suggesting there may be untapped potential to mine.

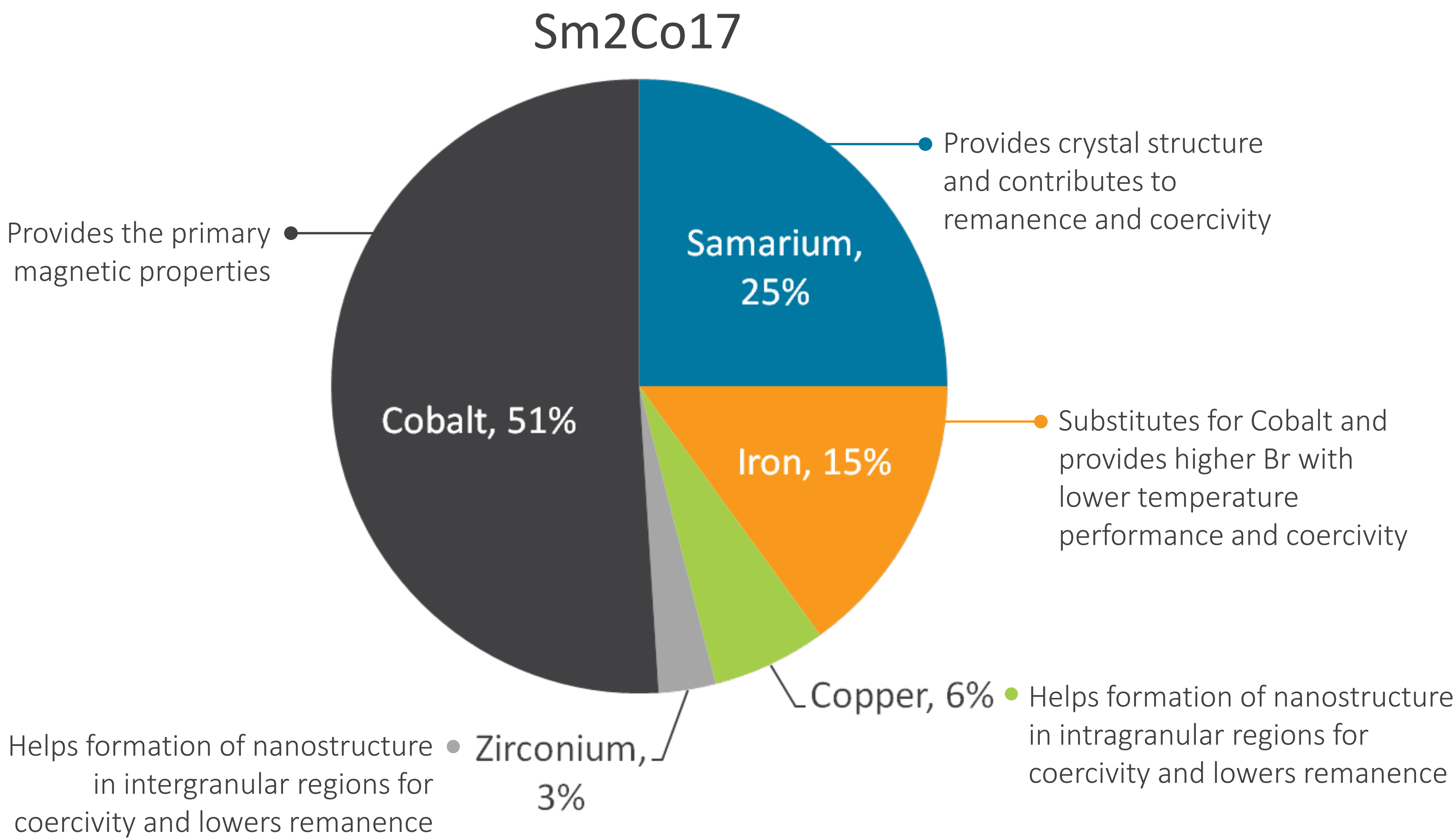
The zone where Samarium Cobalt performance overlaps NdFeB correlates to the operating points for automotive and aerospace applications.

Additionally, in these ranges, SmCo varies much less with respect temperature, meaning the device needs less temperature compensation.

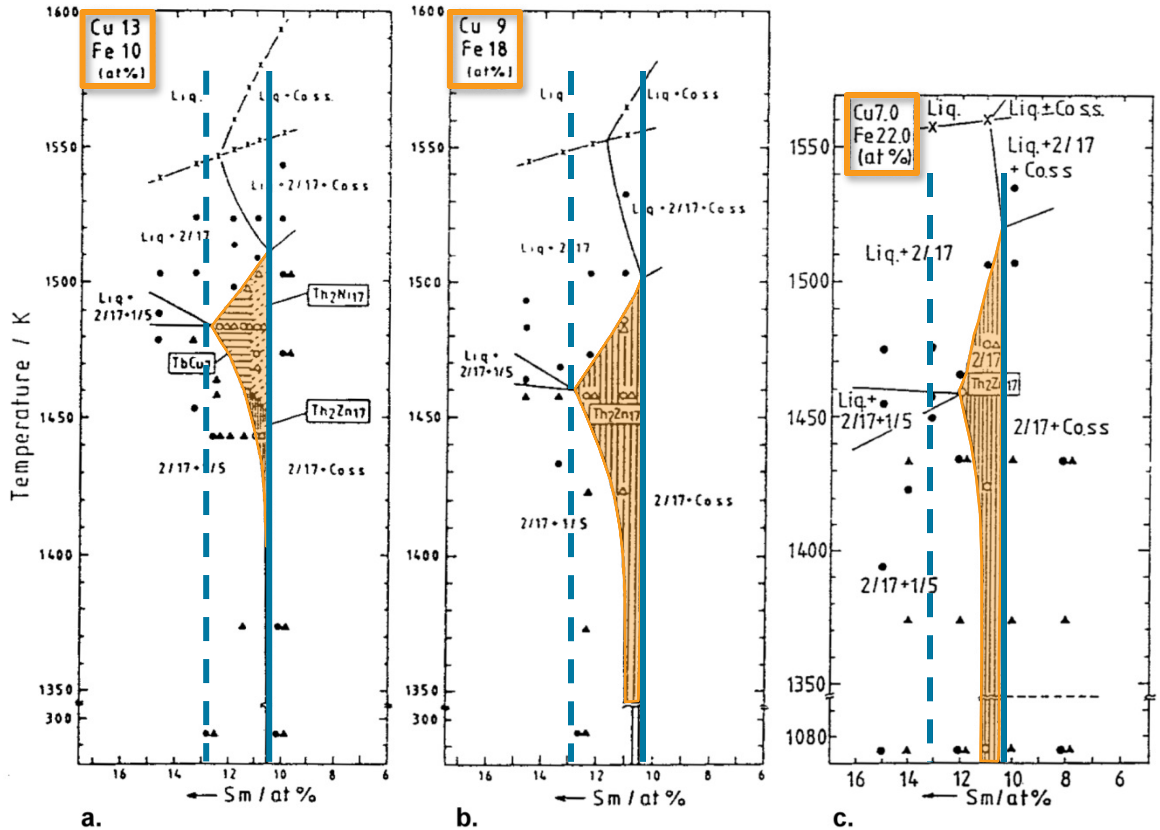
How to Improve SmCo

- Elemental substitution
- Improve starting alloy condition
- Eliminate contamination
- Improve alignment
- Thermal processing & microstructure development

Improved SmCo – Elemental Substitution



Elemental Substitution — Iron



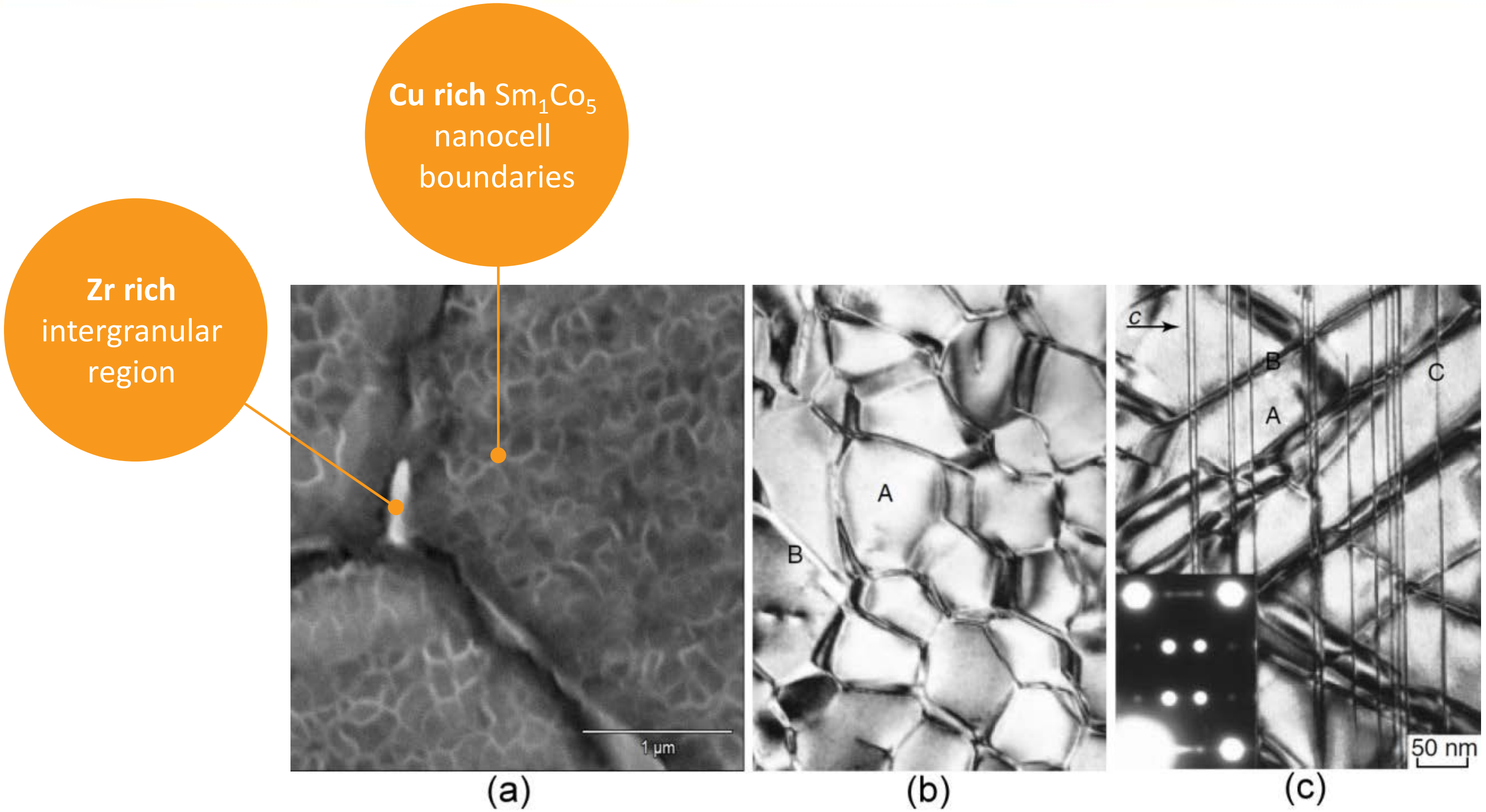
Easy solution – add iron at the expense of cobalt = more energy!

Problem – the more iron you add, the smaller your composition window gets.

Traditional binary alloy processes make it even worse!

Source: Phase diagrams for Sm2Co17 magnets; Morita et al; MRS Int'l. Mtg. on Adv. Mats. Vol. 11, 1989

Functional Benefits of Cu and Zr



Cu and Zr aid the development of the nanostructure that delivers the magnetic properties.

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Elemental Substitution – Copper and Zirconium

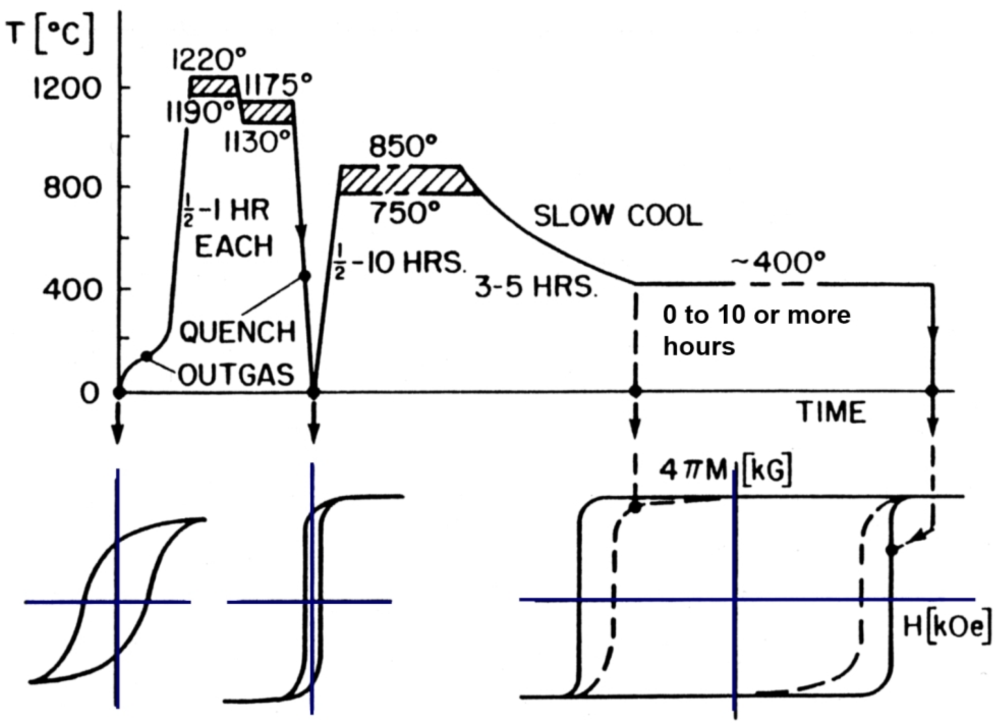


Figure 9. Sinter, solution and tempering thermal treatment as described in Strnat [95] showing development of the hysteresis loop shape.

As we continue to increase the iron content, other things have to be reduced.

Copper and Zirconium are good targets, since they don't help the remanence of the material.

But Copper and Zirconium **DO help the coercivity**. So how do we keep that effect while getting rid of the drag on remanence?

The secret is in the oven.
(More on that later.)

Eliminate Contamination

New outgassing cycle to eliminate organics

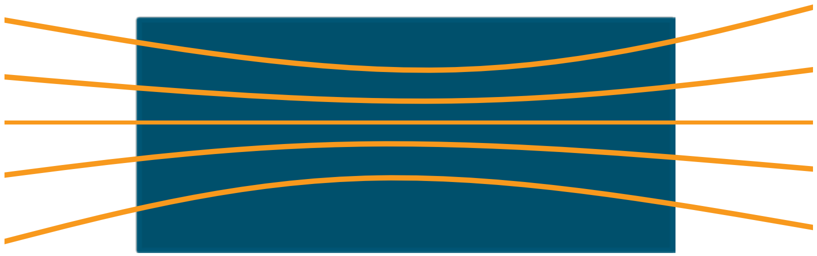
Increased used of protective atmosphere

Specialty carts for transport under gas

New Sinter Boat construction

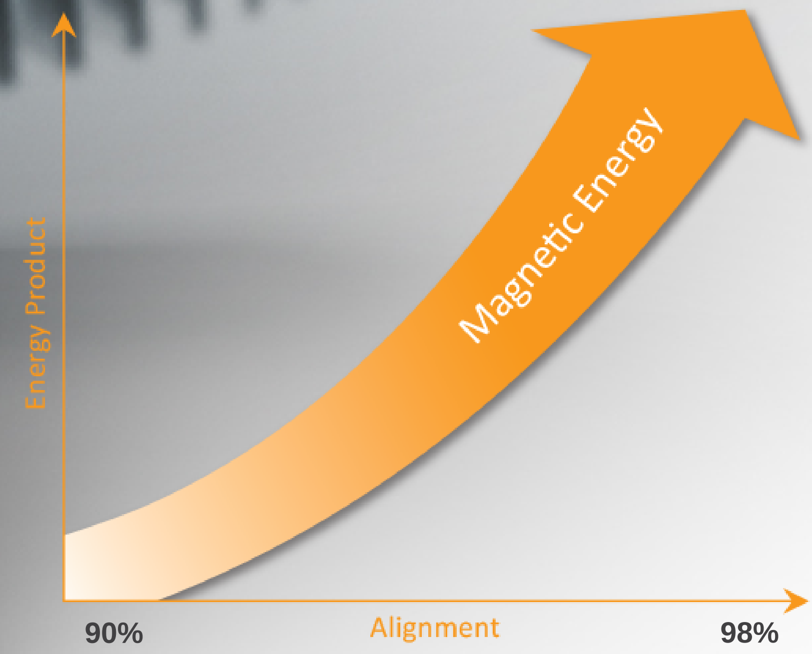
Improve Alignment

- **Co-parallel direction**
  One block of magnetic material is composed of many discrete grains. An important part of the process is orienting all of the grains in a co-parallel direction.
- **Trumpeting effect**
  One significant challenge is the trumpeting effect. This is due to the difference in permeability and saturation of the die material and magnet powder.



- **Property matching**
  Property matching our die materials yields improvements in the quality of orientation.

Improve Alignment



Every 1% improvement in alignment quality = 2% more energy in the magnet

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Thermal Processing

Sinter: As we increase iron content, lower temperature and shorter duration cycles are more successful.

Outgas: Arnold has developed a new, separate outgas cycle we perform in a common lab furnace that eliminates about 3 times more organics.

Solutionize: Magic happens.

Quench: A straight run to room temperature is not necessary. We use a variable quench strategy.

Temper: Small optimizations in temperature can enable dramatic changes in cycle time.

Cool: As with quenching, a variable program has yielded significant improvements

Age: With better control on the previous steps, this step becomes less important.

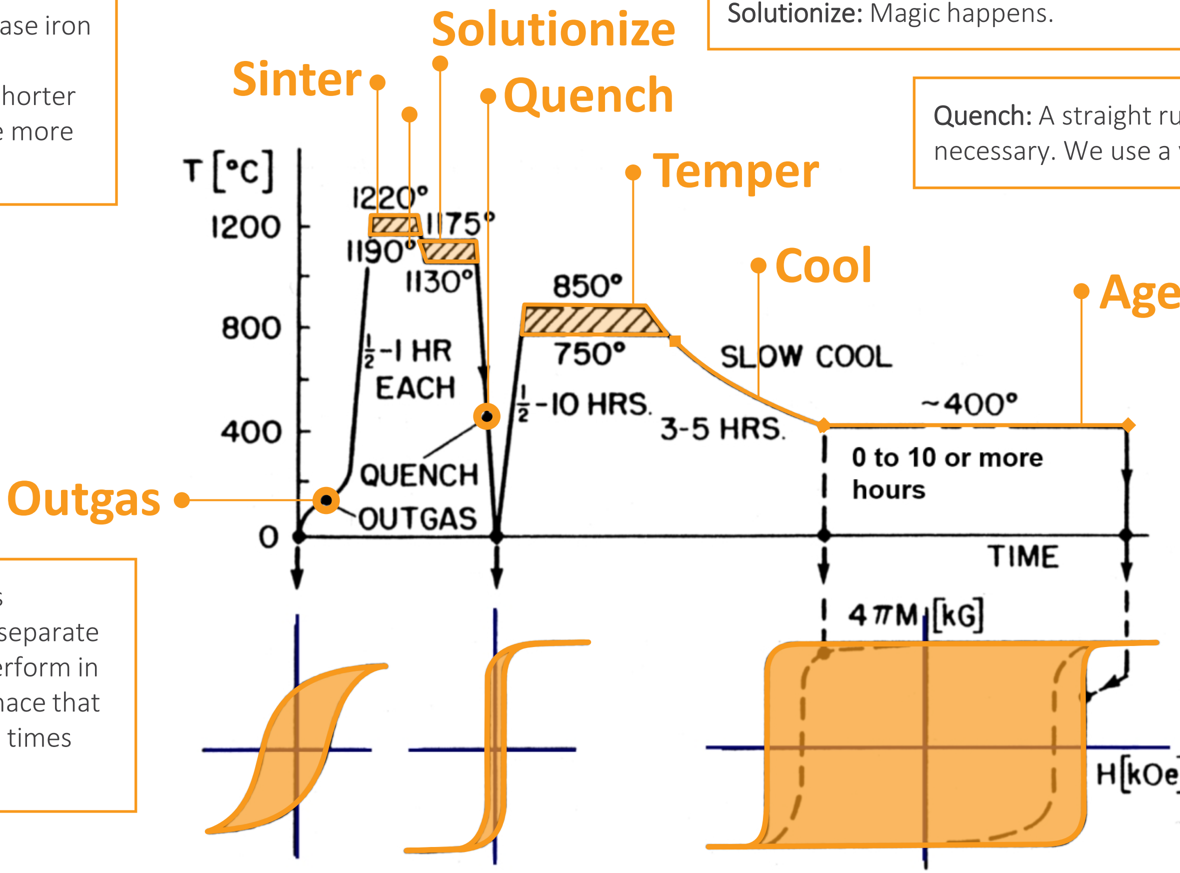


Figure 9. Sinter, solution and tempering thermal treatment as described in Strnat [95] showing development of the hysteresis loop shape.

Thermal Processing

CHALLENGE: Uniformity

Minimize/eliminate the variations in temperature in a furnace, under partial pressure

ANSWER: Design

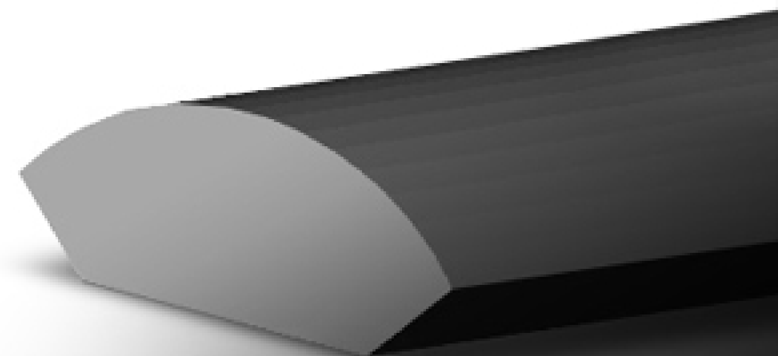
Optimize the design to select off the correct microstructure during the process and quench out when desired

RESULT: Coercivity

Develop the best coercivity while depleting the material of all of the constituents that help coercivity

Conclusion

- SmCo still has significant potential to be unlocked.
- Small increases in the energy density of samarium have dramatic effects on its usefulness.
- A top-to-bottom look at the process is necessary in order to make these improvements work.
- Process changes have synergistic effects on each other.
- Arnold continues to the lead the way in the development of samarium cobalt.



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