ETREMA

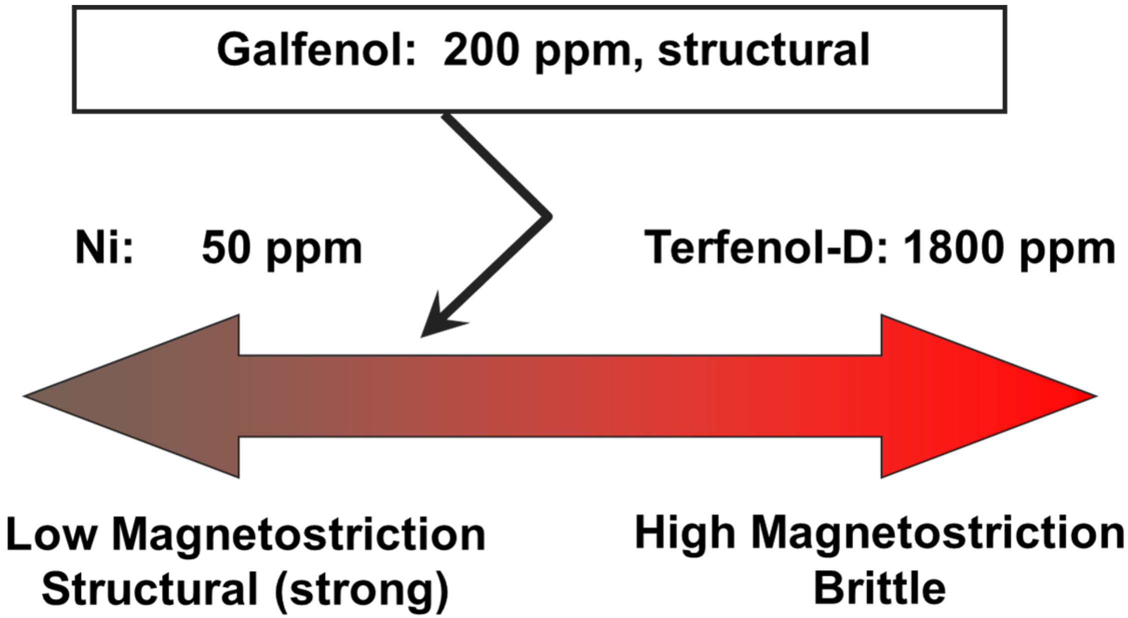
Galfenol – A New Class of Magnetostrictive Materials

GALFENOL PUBLIC RELEASE v.7

Prepared by Eric Summers, Vice President & Chief Scientist

Motivation

- Magnetostrictive alloys must exist that exhibit the optimum combination of good magnetostriction and mechanical robustness



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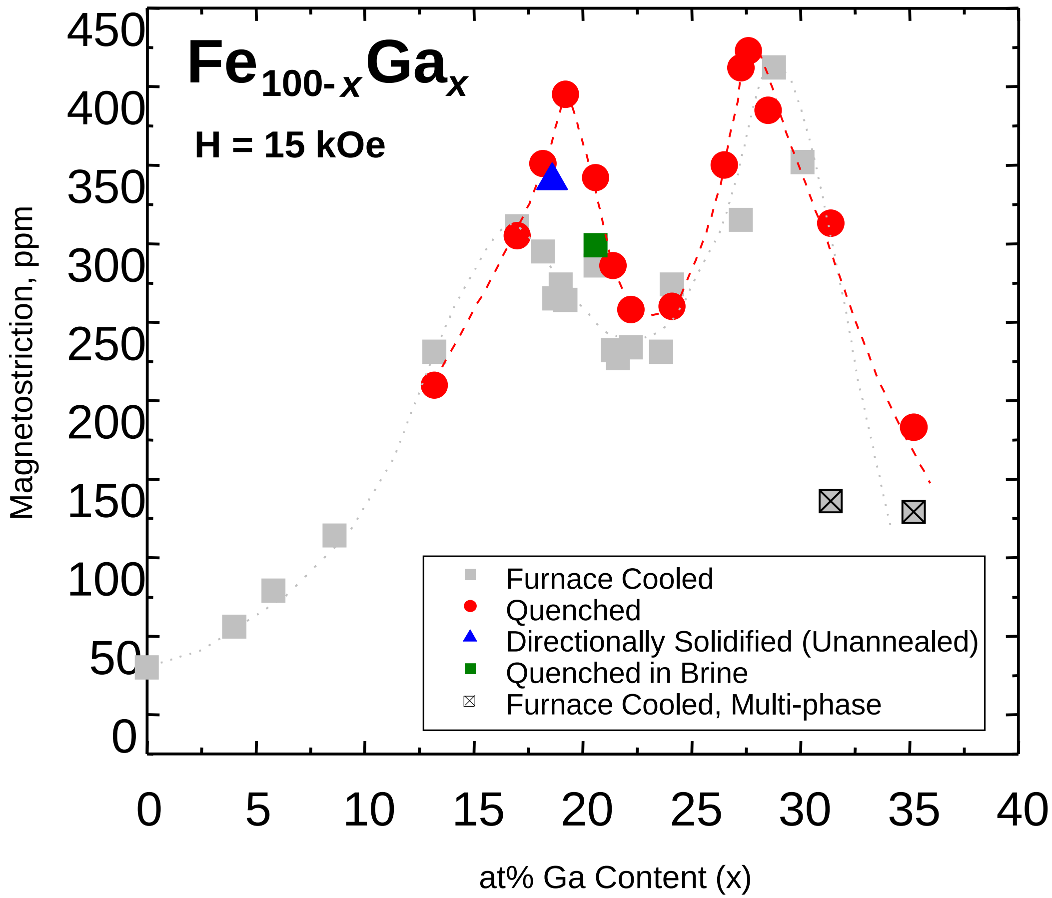
Magnetostriction vs. Composition (single crystals)



$Fe_{1-x}Ga_{(0.15 \leq x \leq 0.20)}$

- Single crystal data from: Magnetic Materials Group – Carderock Division, Naval Surface Warfare Center (NSWC)
- ETREMA's efforts have focused on the first magnetostrictive peak between 15 at% Ga and 20 at% Ga
- Nominal Ga content in ETREMA produced Galfenol is 18.4 at%
- ETREMA produces coarse-grained polycrystalline samples

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Galfenol Production Method

Advanced Bridgman Process

- Directional solidification process
- Primary composition centers on 18.4 at% Ga, nominal
  - Other compositions available upon request
- Standard diameter produced = 24 mm
  - 30 mm in development
- Typical length produced = 250 mm
- This is followed by machining of requested component geometry

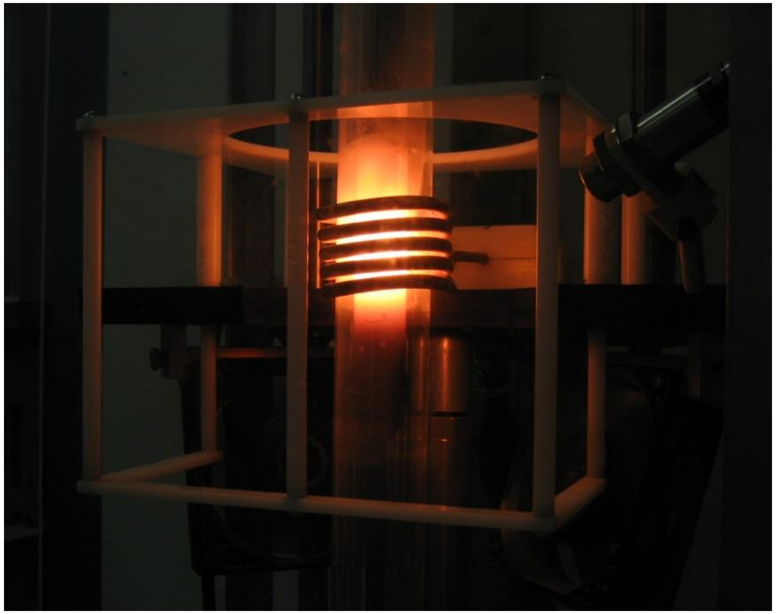

Photo of Galfenol being produced via Bridgman Process

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Typical Properties

- Typical properties of polycrystalline Galfenol ($Fe_{81.6}Ga_{18.4}$)
- As-grown material via Bridgman Process

Saturation Strain	200 – 250 ppm at 48 MPa applied compressive load
Piezomagnetic Constant, d_{33}	15 – 30 nm/A, lower values at larger stresses
Saturating Magnetic Field	100 – 250 Oe, value depends upon stress applied with larger stresses requiring high magnetic fields to reach saturation
Saturation Magnetic Flux Density	1.5 Tesla
Magnetic Permeability, μ_r	75 – 100, lower values at larger stresses
Coercivity, H_c	10 Oe
Hysteresis (major loop)	1000 J/m^3
Curie Temp.	≈ 950 K
Density	7800 kg/m^3
Hard Young's Modulus	75 GPa
Soft Young's Modulus	≈ 40 GPa, achieved during magnetic moment rotation
Tensile Strength	≈ 350 MPa
Elongation	≈ 1%

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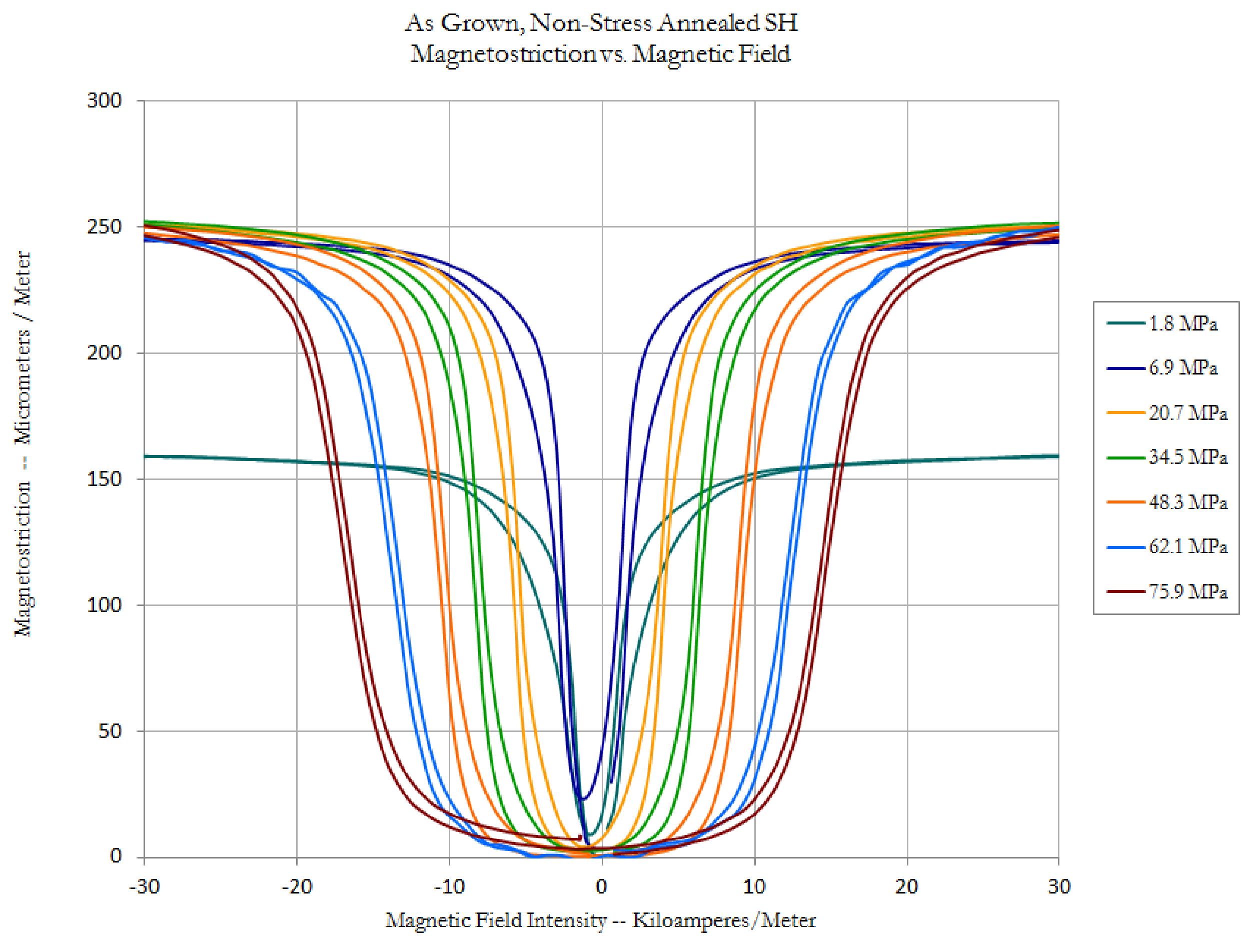
Typical as-grown Strain-H Curves (under various compressive loads)



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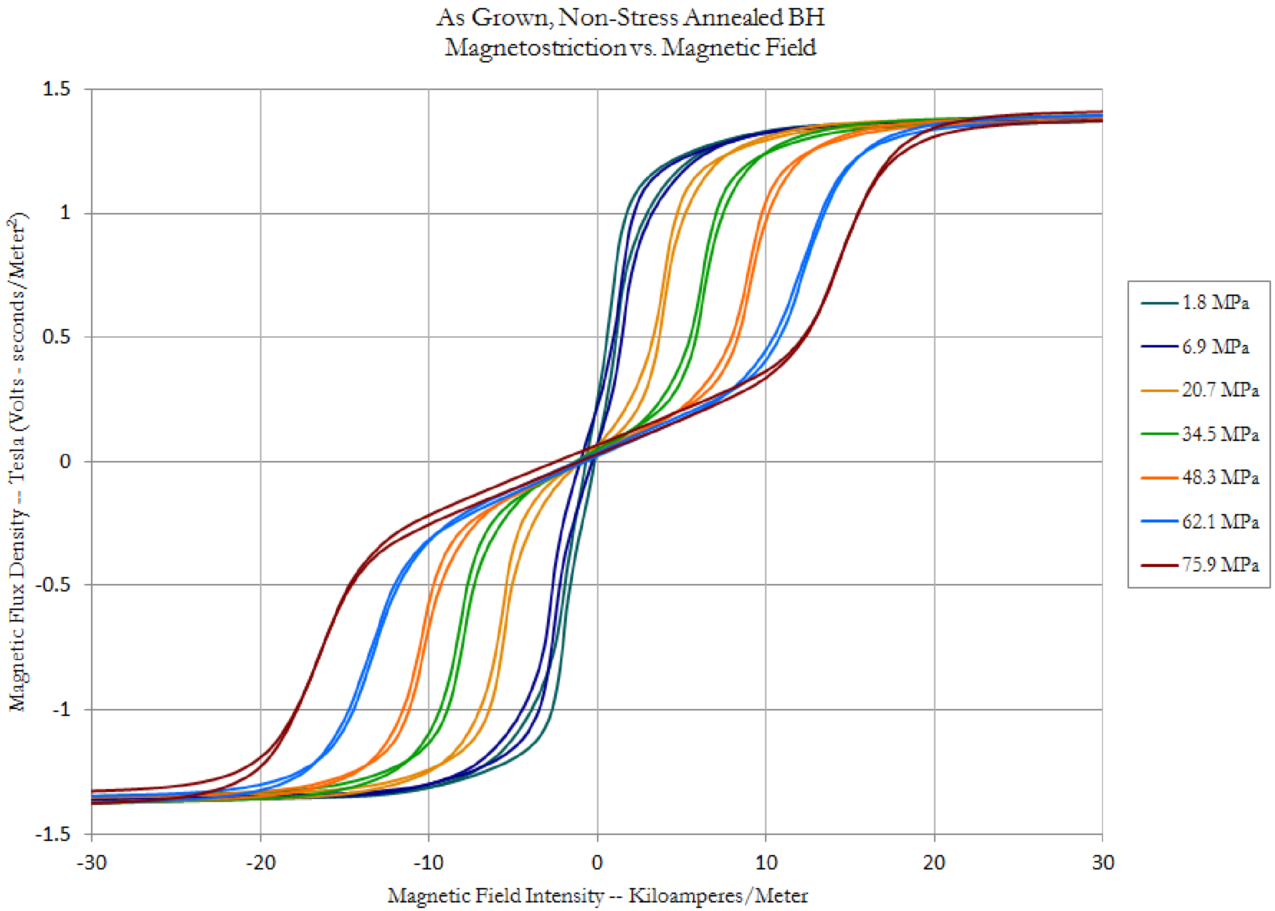
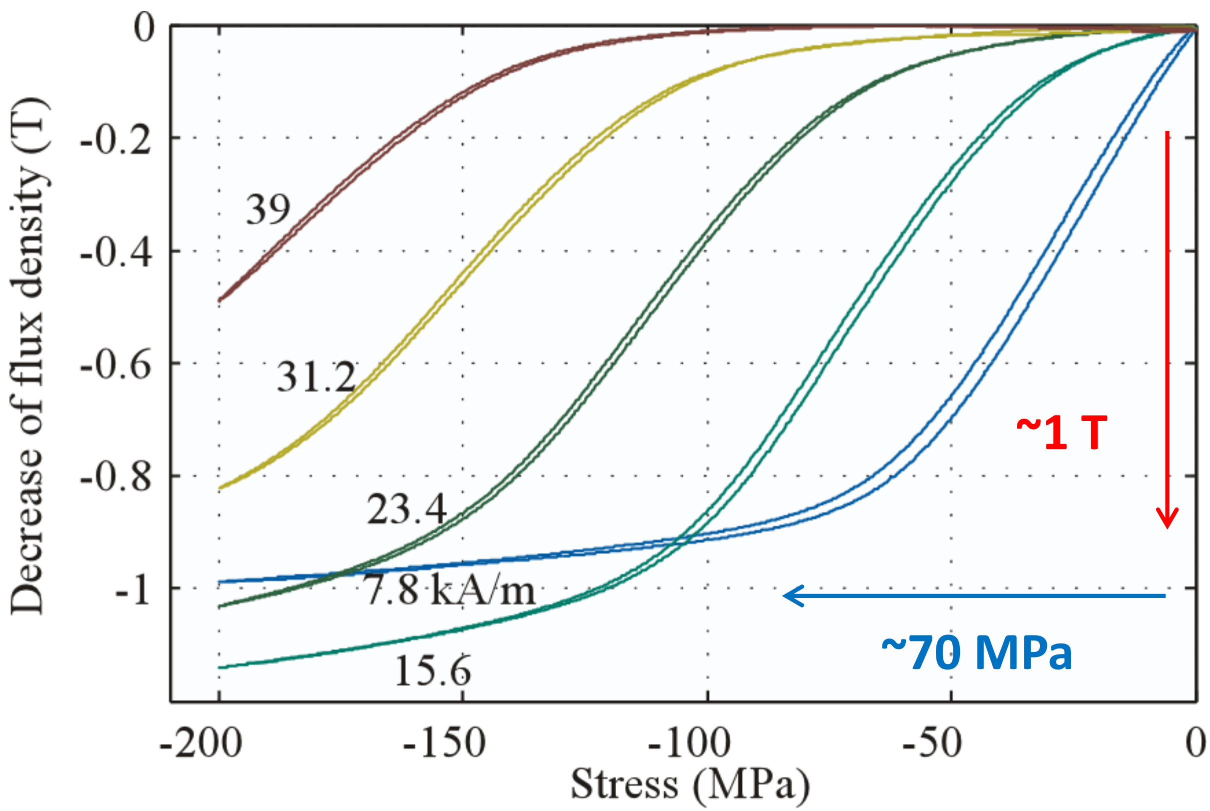
Typical as-grown B-H Curves (under various compressive loads)



Villari Effect for Galfenol Sensing/Energy Harvesting

Compressive stress vs. flux density



Graph from testing completed by Dr. Toshiyuki Ueno, Kanazawa University, Japan

Test results from a typical Galfenol sample

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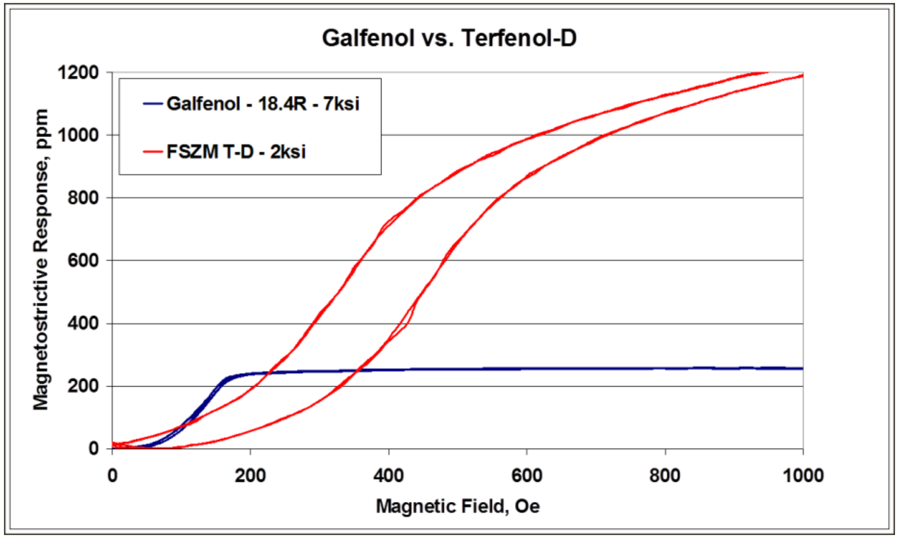
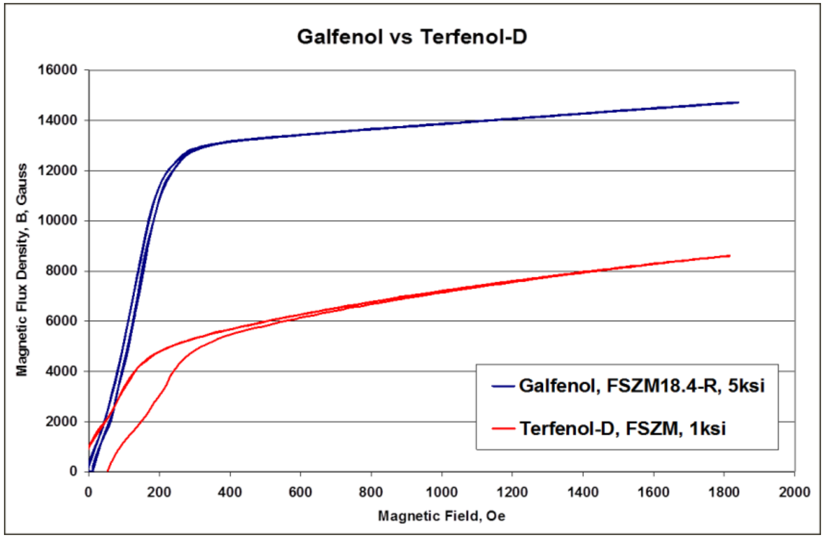
Comparison to Terfenol-D

- Less magnetic field required to reach saturation
- Larger pre-stresses maybe necessary
- Larger saturation flux density
- Higher permeability
- Less hysteresis



Strain vs. Magnetic Field



Flux Density vs. Magnetic Field

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Galfenol Characteristics

- Photos shown are of 18.4 at% Ga samples, nominal composition
- Material can be machined using conventional machining techniques; such as mills, lathes, and EDM's
- Material can be welded using TIG welding techniques

Galfenol plate TIG welded to a steel cylinder

Galfenol that has been milled and lathed

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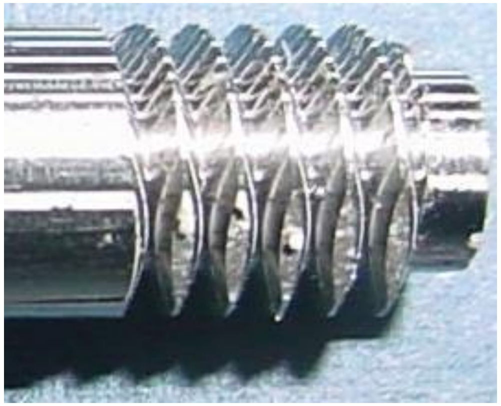
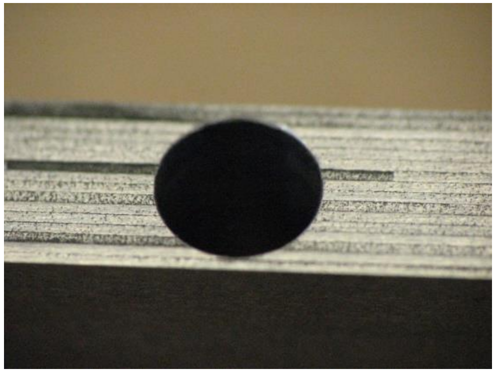
Fabricated Galfenol Part Examples

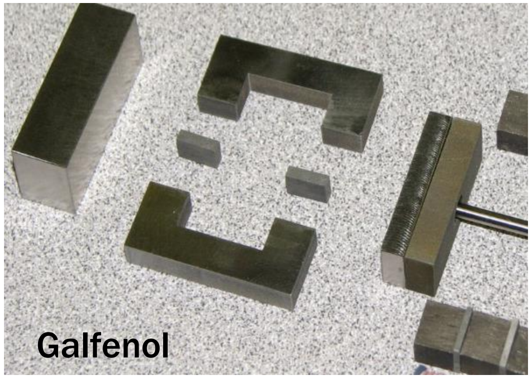


Laminated and machined threads

Forged and machined horseshoes



Laminated and milled stack



Machined and laminated “C”-cores

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Stress Annealing of Galfenol alloys

- Stress annealing process builds in a compressive stress into the Galfenol sample (referred to as an ‘uniaxial anisotropy’)
  - Result: full magnetostrictive performance without application of an external compressive stress mechanism
  - Good magnetostrictive performance under tensile loads
  - Tension limitation around 50 MPa

- ETREMA has successfully stress annealed Galfenol alloys from 15 at% to 18.4 at% Ga

- Recent processing advancements have doubled the length that can be stress annealed to 250 mm

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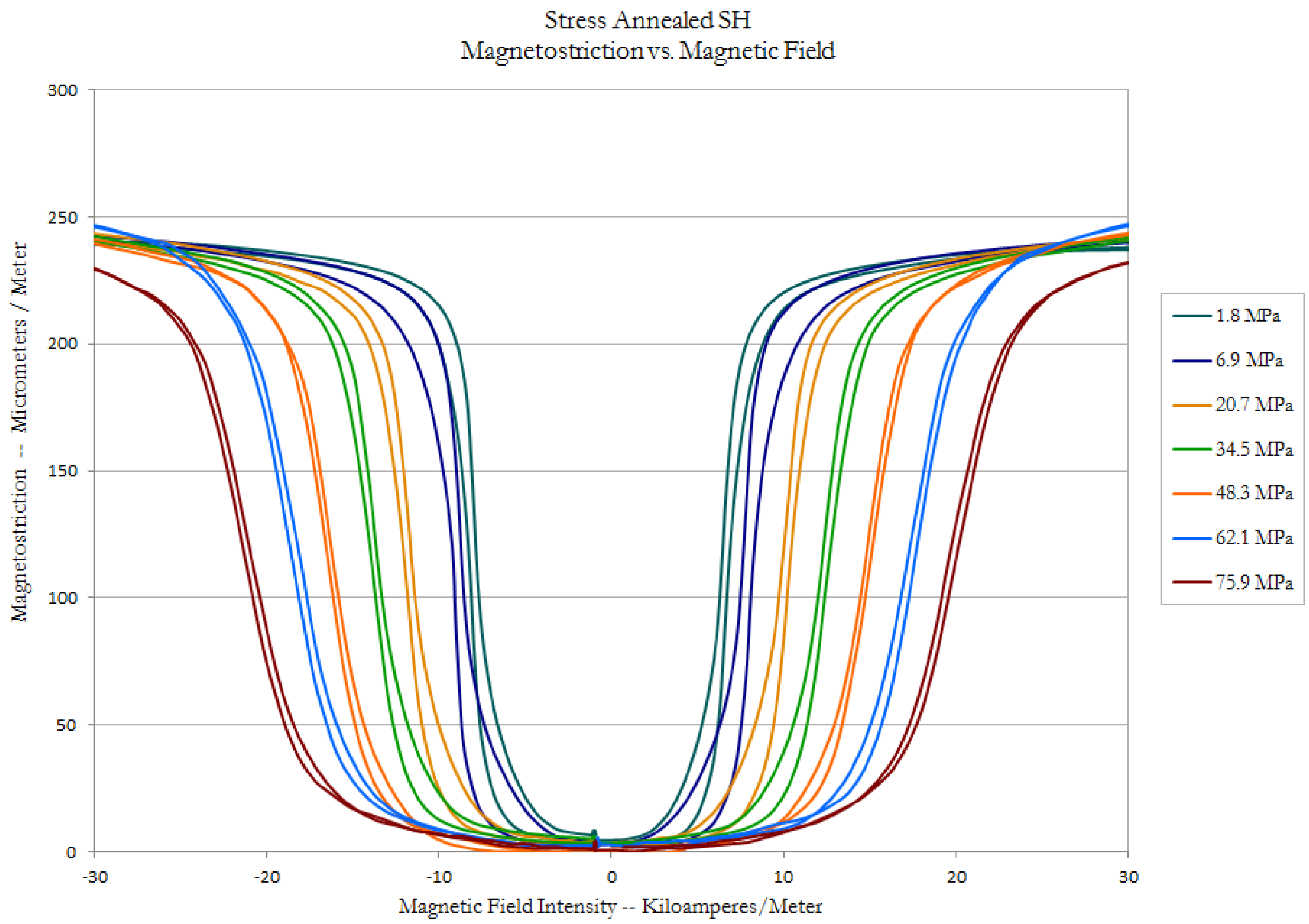
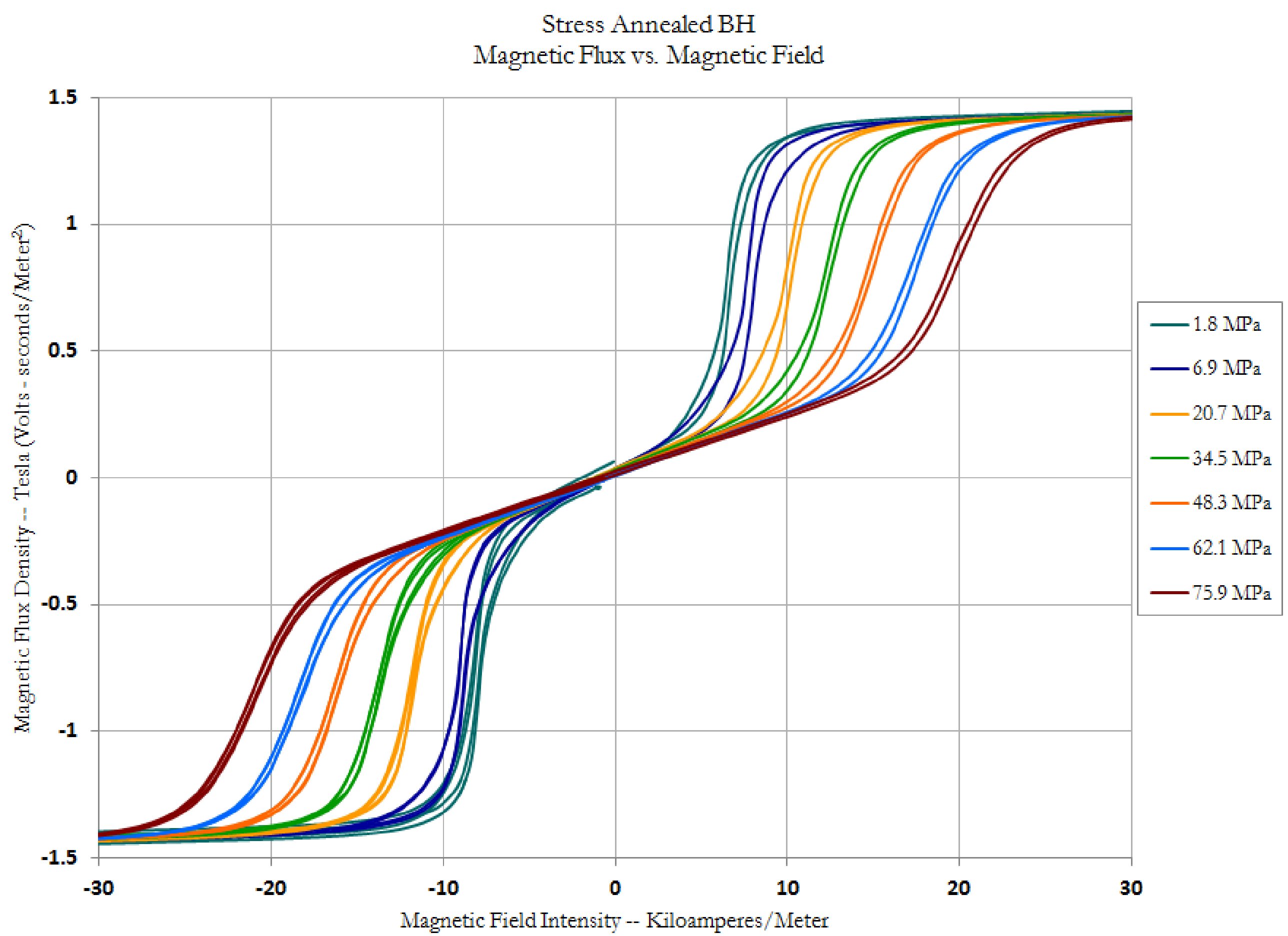
Typical stress-annealed Strain-H Curves (under various compressive loads)



Typical stress-annealed B-H Curves (under various compressive loads)



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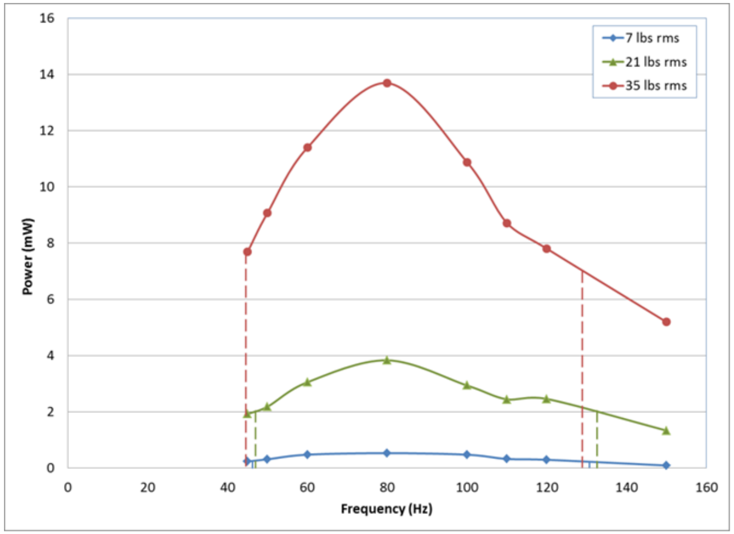
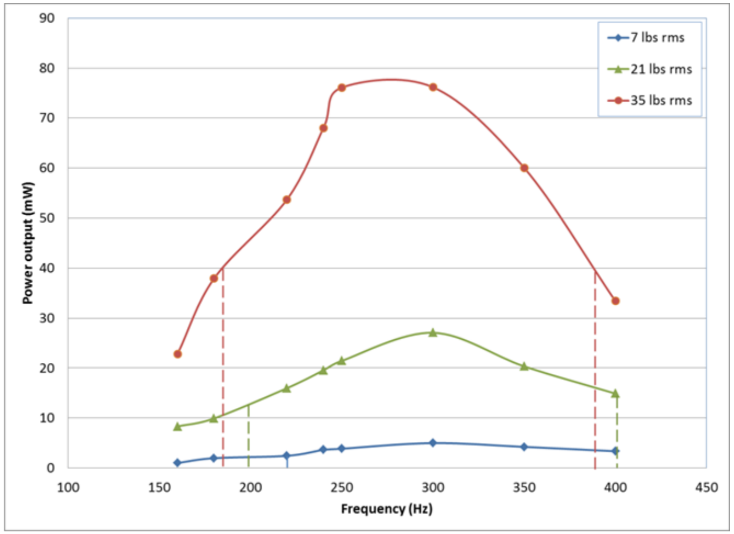
Energy Harvesting Possibilities

- Galfenol can be designed into various energy harvesting configurations
- Large half-power bandwidths exhibited when directly coupled to large forces or displacements
  - Examples shown below for a lab prototype Galfenol energy harvester



Voltage quadrupler circuitry – 90 Hz bandwidth



Voltage doubler circuitry – 180 Hz bandwidth

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Conclusions

- Galfenol currently produced using an Advanced Bridgman directional solidification method
- Can use conventional machining and welding techniques to form a variety of shapes
- Galfenol can be stress annealed to operate without an applied compressive load and achieve 100% of it's magnetostrictive performance
- Galfenol's mechanical robustness allow it to be used in a displacement (force) based energy harvester that exhibits large half-power bandwidths

ETREMA is actively searching for collaborators to help advance and integrate Galfenol technologies into next-generation products

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