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# Investigation of the Magneto-Acoustic Villari Effect for Measuring the Internal Stress in Composites

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# Outline

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- The innovation
- Technical approach
- Impact of the innovation if it is eventually implemented
- Results of the Seedling effort to date
- Distribution/Dissemination—getting the word out
- Next steps



# The Innovation

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- A novel concept to exploit a property of magnetostrictive materials to measure the internal stress rates within a material.
  - The Villari Effect states that the application of stress in a magnetostrictive material will cause a change in the magnetic permeability of the material.
  - In some magneto-elastic materials, this effect could manifest itself by the production of high frequency acoustic noise.
- The process could be used directly to determine the stress rate inside a magnetostrictive material.
- It is also theoretically possible to integrate magnetostrictive materials within a composite material to measure the internal stress within a composite
  - Such a system could produce a “smart” material that provides information about the internal state of the stress of a composite.



# Technical approach

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- Investigate the recently developed magneto-elastic material, Galfenol, that has a reported excellent combination of good magnetostriction and mechanical robustness.
- Investigate the modern magneto-elastic material, Terfenol-D, that has many excellent properties for advanced sensors. (Developed by the Navy for higher power sonar and is now used in many new sensor concepts.)
- Demonstrate/study the magneto-elastic stress generation of high frequency acoustic noise.
- Study how to integrate the material into a composite.



# Galfenol vs Terfenol-D

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- Galfenol is an alloy of Iron and Gallium.
- Very high permeability-magnetic flux saturates  $\sim 15000$  Gauss.
- Easy machinability by conventional techniques.
- Tensile Strength = 350 MPa
- Young's Modulus = 40-75 GPa

- Terfenol-D is an alloy of Iron, Terbium, and Dysprosium.
- Produces a “giant” magnetostriction strain, greater than any other commercially available “smart” material (2mm/m).
- High permeability-magnetic flux saturates  $\sim 9000$  Gauss.
- Not easily machined by conventional techniques.
- Tensile Strength = 28 MPa
- Compressive Strength = 700 MPa
- Young's Modulus = 25-35 GPa



# Technical Approach (Cont.)

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- Small amounts of each material were acquired for testing.
  - Terfenol-D samples included various small samples of bars, rod, and plates
  - Galfenol samples were small plates.
  - In addition, Terfenol-D is sold in powder form and some small quantities of that material were obtained for development of composites embedded with Terfenol-D.
- Compression testing
  - Terfenol-D has such poor tensile strength, it needed to be tested in compression.
  - As a first approach to comparing the different materials, Terfenol and Galfenol were both tested in compression.
  - Initial testing of Galfenol: Performed with a four-point bending jig, sample mounted on surface of a thick aluminum bar so magnetostrictive material would be in compression
  - Small solid bars of Terfenol-D samples were also tested in simple compression.
  - In addition to load conditions, the effects of externally applied magnetic fields were also observed.

Once the various materials were characterized for their ability to generate signals related to the strain rate of the materials, parameters for manufacturing a “smart” composite would be studied and manufacturing of such samples would be undertaken.



# Impact of the innovation if it is eventually implemented

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- Addresses the Aviation Safety R&D challenge “Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems” by enabling an embedded vehicle health management system to determine structural and material degradation.
- For new aeronautic designs, the increased performance/efficiency goals of the “Mobility challenge for commercial supersonic aircraft and the National Security and Homeland Defense challenge for military aircraft” are being realized by increased use of composite airframes and this system could be incorporated into that new direction.
- Commercial use of composite airframes is also expected to increase in the future. Composites have more complex stress states, failure behavior, and different types of acoustic emission than metals. With current technology, this requires real-time evaluation as opposed to routine inspections.
- With real-time damage detection, airframe design can be less conservative, resulting in lower weight structures without a sacrifice in safety.



# Impact of the innovation if it is eventually implemented (Cont.)

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- Directly, this method might be able to provide a new method for measuring stress concentration factors in ferrous materials and in composite samples that contain an appropriate level of ferrous inclusions. This might be possible in nonstandard testing configurations.
- In the appropriate applications, remote detection of high strain rate events can find or predict pending damage in unexpected locations at unexpected times to allow better structural management to further increasing the margin of safety.
- This method could be applied to the application of composite repair patches on aircraft. In military aircraft, the certification of composite patches is problematic and incorporation of this concept into the repair patches will allow monitoring the integrity of the patch in a cost effective manner.



# Results of the Seedling effort to date

## Background

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In the field of Acoustic Emission (AE) applied to the testing of structural steels (bridges, pressure vessels, nuclear power plants, etc.) sometimes, practitioners have noted that ferrous alloys were “noisy” when looking for indications of crack growth.

- Most testing is designed to trigger on a crack generated signal, not background noise—Usually, the trigger threshold is set high enough to eliminate the noise effects, but sometimes at the cost of missed crack growth events.
- In cases where the noise triggers a measurement, filters are applied to delete that data.
- The presence of this noise appears to violate the Kaiser Effect in AE (suggests that the noise source is not from an irreversible process).



# Results of the Seedling effort to date

## Background (Cont.)

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From a general time behavioral model for magnetostrictive materials:

$$\frac{\partial M(H, \sigma)}{\partial t} = \left( \frac{\partial M}{\partial H} \right) \frac{\partial H}{\partial t} + \left( \frac{\partial M}{\partial \sigma} \right) \frac{\partial \sigma}{\partial t}$$

For the case where H is constant,

$$\left( \frac{\partial M}{\partial H} \right) \frac{\partial H}{\partial t} = 0$$

which implies that

$$\frac{\partial M}{\partial t}(t) = \left( \frac{\partial M}{\partial \sigma} \right) \frac{\partial \sigma}{\partial t}$$

For Barkhausen noise and Magnetic Acoustic Emission,

H is a time varying function so  $\left( \frac{\partial M}{\partial H} \right) \frac{\partial H}{\partial t} \neq 0$ , while  $\left( \frac{\partial M}{\partial \sigma} \right) \frac{\partial \sigma}{\partial t} = 0$

- M can depend on many effects, such as hysteresis magnetization as well as reversible and irreversible magnetic components.
- Hysteresis is often modeled as depending on the pinning of magnetic domain walls.

As the stress is changed, it may be energetically beneficial for the magnetic domain walls to jump. This causes a momentary stress discontinuity that can show up as a stress wave. Multiple jumps would look like acoustic noise.



# Results of the Seedling effort to date

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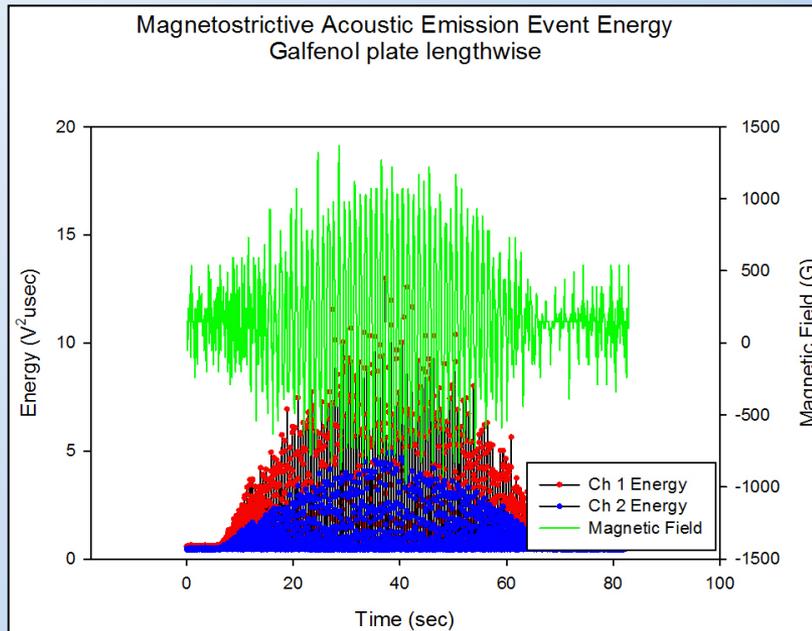
- Initial testing with our Galfenol samples in the four point bending jig at modest load levels were not producing a detectable signal.
- Decided to set up an MAE system and check our samples for their “Barkhausen” type response in that configuration under the assumption that the domain pinning that causes Barkhausen response has theoretical similarity to the underlying model of the Magneto-Acoustic Valeri Effect.
- Based on the MAE response of the materials, focused on Terfenol-D material.
- Initial testing of a small bar of Terfanol-D at modest loads under compression generated signals that correlated with our hypothesis.



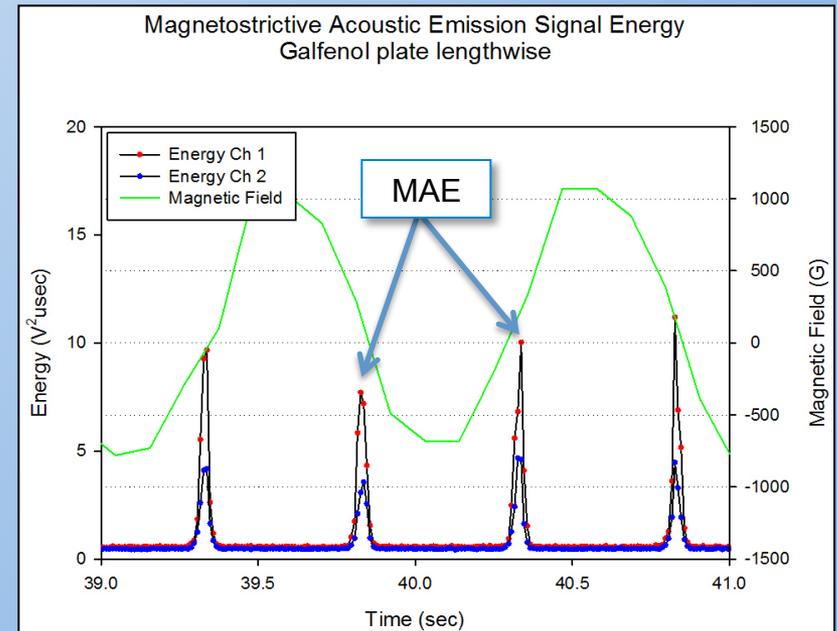
# Results of the Seedling effort to date

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- Galfenol plate
- Results:
  - MAE peaks are approximately 10x that of steel
  - MAE occurs twice per magnetic field cycle near the zero field points.



Full view



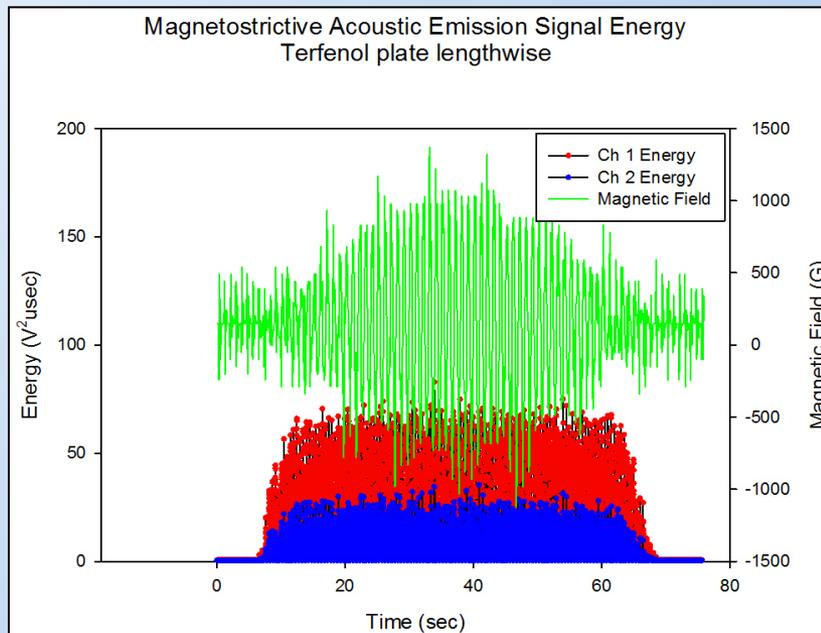
Zoomed view



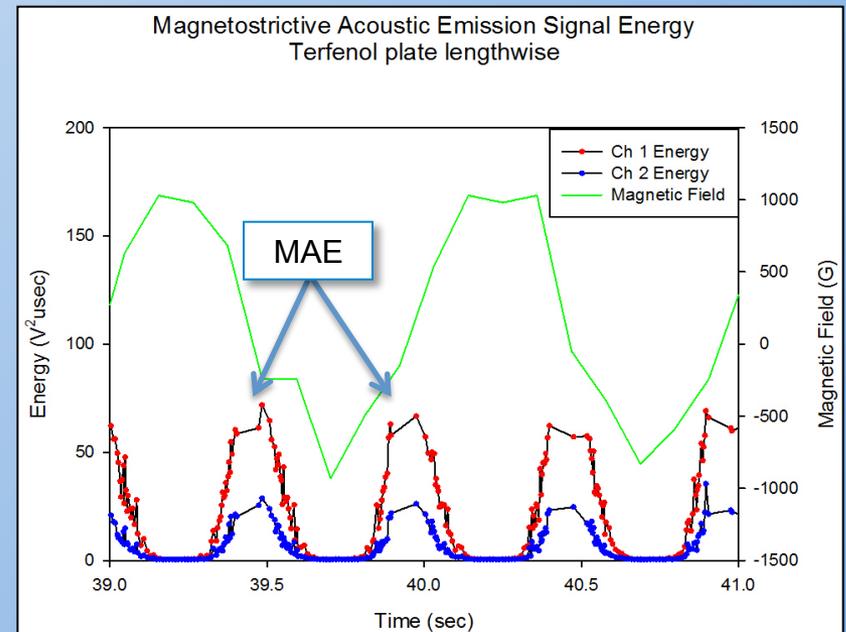
# MAE of Terfenol plate

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- Tefenol-D plate:
- Results:
  - MAE peaks are approximately 8x that of Galfenol
  - MAE occurs twice per magnetic field cycle near the zero field points
  - Wider MAE peaks indicate higher magnetic field saturation threshold than for Galfenol



Full view



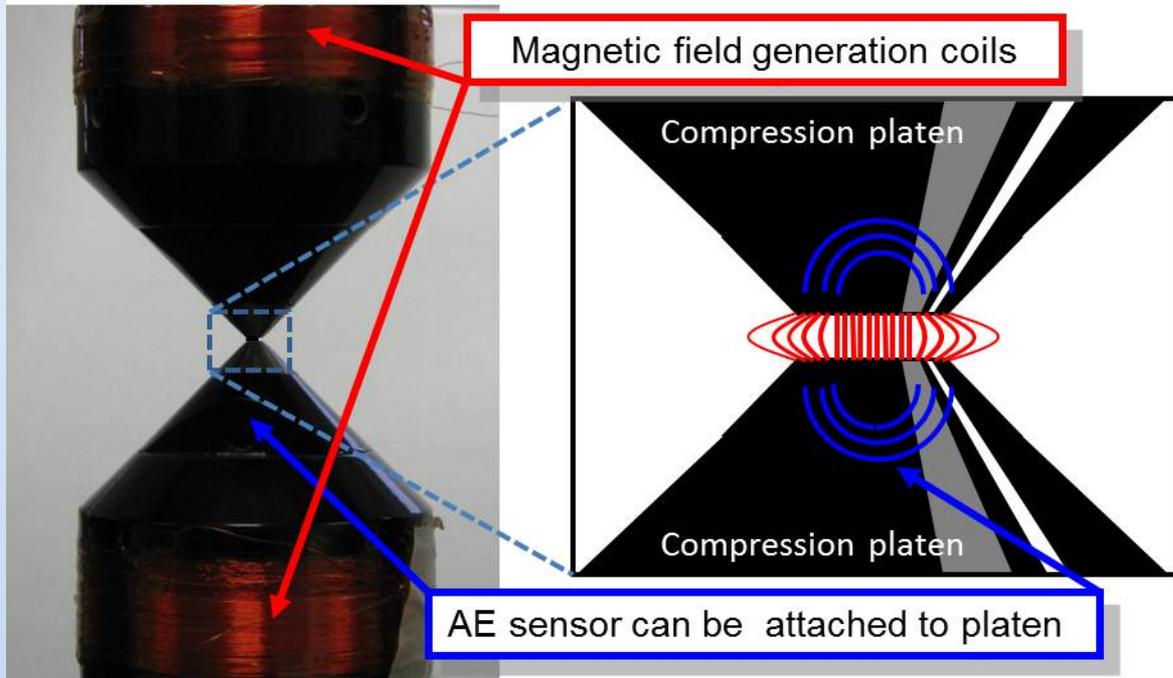
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# Results of the Seedling effort to date

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## Conical Compression Platens w/magnetic field generation coils



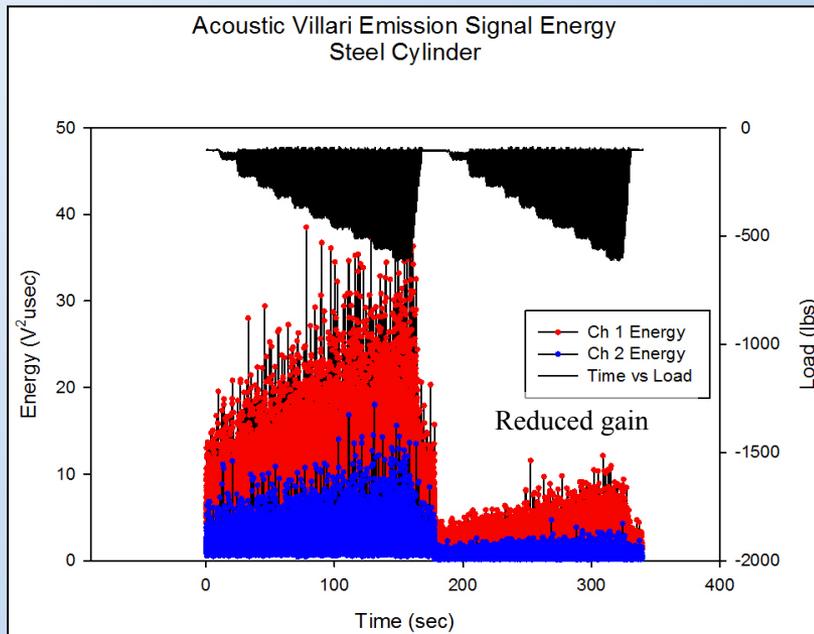
- Decided to focus on the Terfenol-D samples.
- Using compression platens that can be magnetized.
- Use some simple small bar samples and higher compression levels than before.



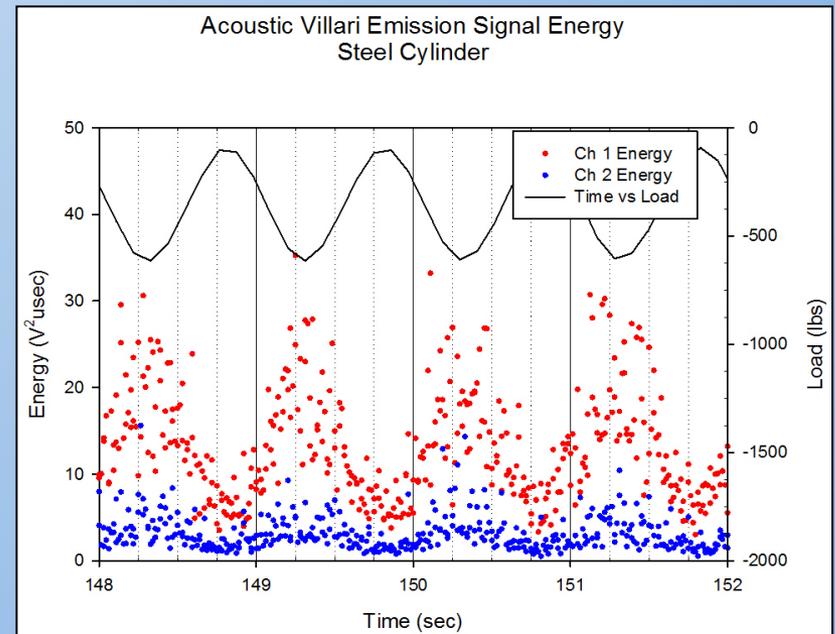
# Results of the Seedling effort to date

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- Specimen Loading on a steel cylinder: Two sets of stepped compression fatigue (~10 cycle/step) via conical compression platens
- Acoustic measurement: AE sensors on compression platen
- Zero Magnetic field applied
- Note: Data acquisition gain reduced for second set of fatigue for this one test
- Results: Acoustic response peaks occur once per cycle at maximum compression



Full view



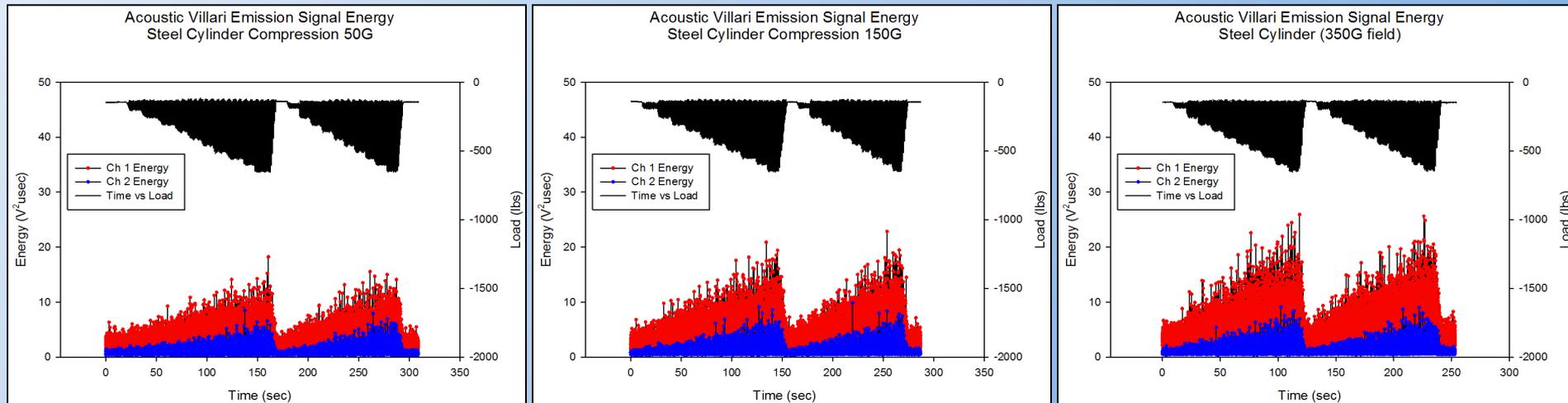
Zoomed view



# Results of the Seedling effort to date

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- Specimen Loading on a steel cylinder: Two sets of stepped compression fatigue (~10 cycle/step) via conical compression platens
- Acoustic measurement: AE sensors on compression platen
- Magnetic field: 50, 150 350 Gauss across specimen
- Results:
  - Acoustic response peaks occur once per cycle at maximum compression, therefore do not exhibit the expected Acoustic Villari behavior
  - Acoustic peaks increase with field strength

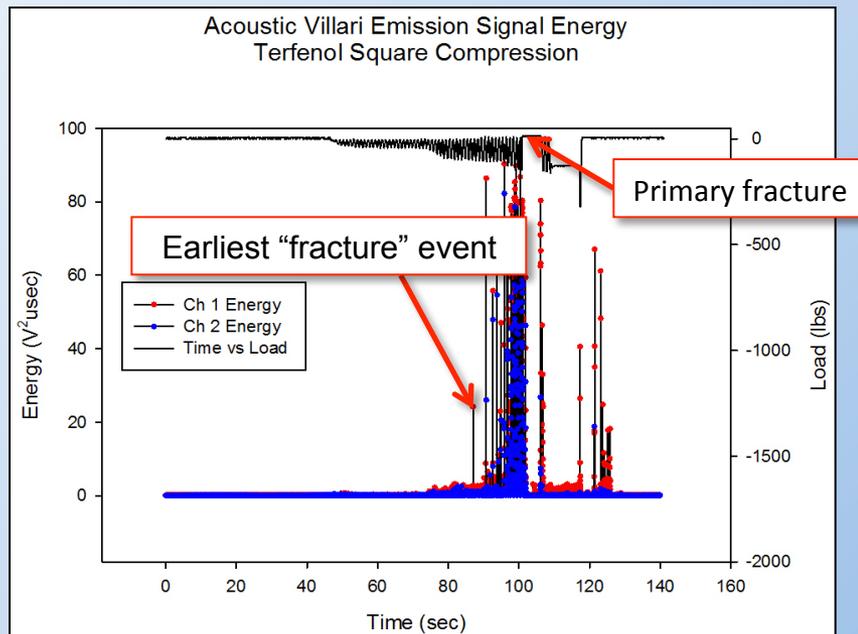




# Results of the Seedling effort to date

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- Specimen Loading on a Terfenol-D square bar: Two sets of stepped compression fatigue ( $\sim 10$  cycle/step) via conical compression platens
- Tried to run full load profile of two sets of stepped fatigue but failed early
- AE sensors on specimen (acoustic isolation compression pads to insulate specimen from frame noise)
- No applied magnetic field



Full view

- Primary fracture begins at 100 seconds
- Large signal energy events above  $5 V^2\mu\text{sec}$  contain discrete emission (as opposed to the continuous emission type of the other data).
- This large AE appears to be predominantly micro-fracture, and not Acoustic Villari effect
- What is of interest are the signals prior to fracture.



Sample Dimension

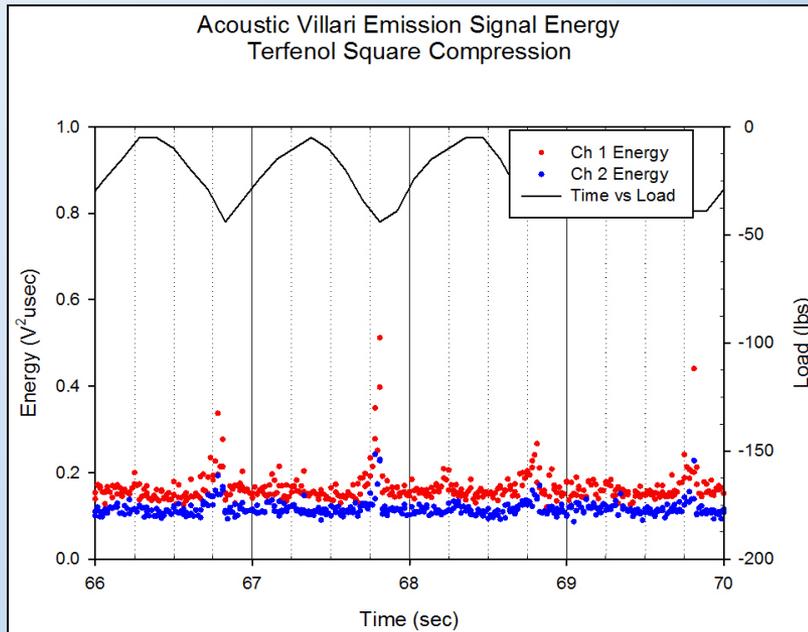


# Results of the Seedling effort to date

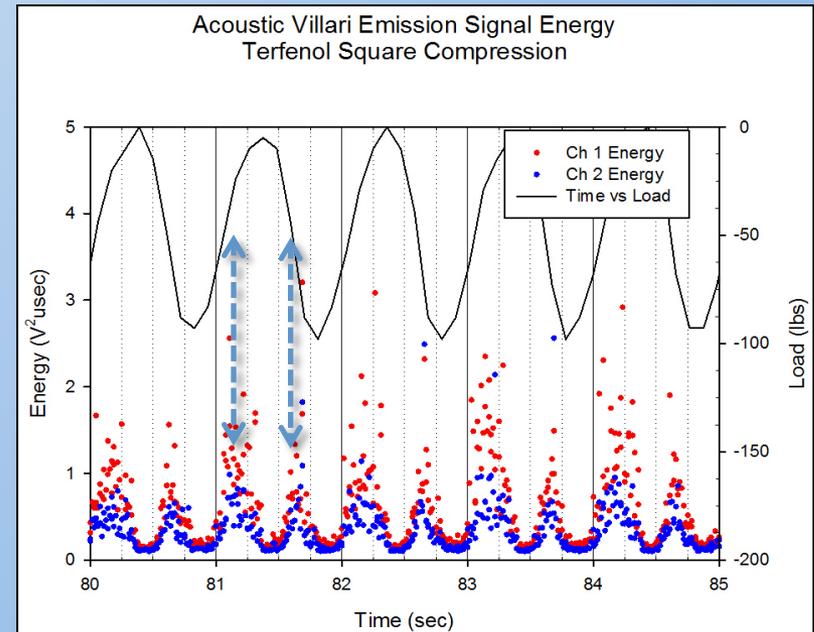
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The earliest signal peaks appear to occur primarily at compression load peaks, although some minor peak are occurring at other points in the load cycle

Later peaks occurring before the beginning of fracture do exhibit the expected behavior of Magnetic Acoustic Villari Effect by appearing twice per load cycle at the points of highest load rate.



Early closeup view



Later closeup view



# Distribution/Dissemination— getting the word out

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No dissemination has occurred yet

Would like to present these results at either the Quantitative Nondestructive Evaluation meeting or possibly at the AE Working Group Meeting.

- These groups do publish proceeding papers
- The meetings are attended by university, government, and industry personnel.

Last year the project office requested that travel be limited or eliminated for that round of seedling projects due to travel funds availability. Not aware if such funds are available for current year.

No patent disclosures have been submitted.

- At this point, only a concept.
- Specifics of an implementation have not been defined.



# Next steps: Patentable Research

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- Continue compressional testing on Terfenol-D samples, including larger sample pieces to try to improve the noise levels and compute the signal levels/gram and signal levels/load rate.
- Perform compressional testing on Terfenol-D samples under different externally applied magnetic fields improve understanding of the internal physical mechanisms of the materials.
- Once the Terfenol-D samples are characterized for their ability to generate signals related to the strain rate of the materials, parameters for manufacturing a “smart” composite would be studied and manufacturing of such samples would be undertaken.
  - Make samples of Terfenol-D embedded in matrix materials only
  - Make graphite or carbon composite samples containing Terfenol-D to characterize the ability to monitor the internal stresses within a composite sample.
- Investigate the ability of the method to be applied to measuring stress concentration factors in magnetic materials.



# Next steps: Integration into Aeronautics

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- This work is still at a very low TRL and most Aeronautics programs are not research programs: This work may not be ready for their consideration at this point in its development.
- The Aeronautics Safety Office, which has the Vehicle Safety and Systems Technology Project Office under it, has some IVHM work that they support. This work needs to be discussed with some members of that Project Office to let them know about its potential to try to encourage their investment into it.