

PNNL-36704

Cold Spray Cobalt Magnetostriuctive Electromagnetic Acoustic Transducers for High Temperature Structure Monitoring Update

September 2025

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for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Abstract

The Department of Energy's Advanced Sensors and Instrumentation program seeks to develop and qualify advanced sensors for the nuclear industry. Reliable high temperature and high radiation sensors for detection, characterization, and monitoring of structural flaws in pipes, vessels, and structurally critical components are a weakness for both conventional light water reactors with coolant T-hot approaching 350°C, and for advanced reactors with T-hot temperatures in the range of 500 to 800°C and potentially higher. Magnetostrictive Electromagnetic Acoustic Transducers (EMATs) using a cold spray cobalt coating have been proposed as a sensor design that can withstand these temperatures and serve as online sensors to detect flaws before cracks, pits, or erosion/corrosion damage progresses to through-wall failures. This project investigates cold spray cobalt (Co) as part of a magnetostrictive EMAT sensor for high temperature service. Co is known to have strong magnetostrictive properties; however, the effect of cold spray application is not well studied. Surprisingly, cold sprayed Co exhibited little or no magnetostrictive behavior until thermally annealed. Following annealing to 650°C however, cold spray Co did exhibit a magnetostrictive response, albeit with lower amplitude and higher acoustic noise than either Ni or FeCo. Prior work showed that Co magnetostrictive EMAT was successfully tested to 400°C with an AlNiCo permanent magnet. This report reviews the permanent magnet tests and extends the investigation to consider a Hyperco® 50 core electromagnet EMAT to >700°C. The electromagnet sensor failed at 889°C. A second electromagnet sensor was held at 700°C for 7 days in an argon environment and another 3 days in an air environment with no degradation in performance. Examinations of the sensors after heating did show some degradation and provided guidance for adjustments to improve the design but generally the feasibility for a long-term ultrasound monitoring sensor that can operate to and above 700°C is confirmed. Planned continuation of this work will include other magnetostrictive materials, and incorporation of lessons learned to guide sensor design adjustments.

Summary

Magnetostrictive EMATs have been shown to produce guided wave ultrasound that can sense flaws well away from the sensor. The EMAT sensor consists of a magnet to produce a bias field, and a coil through which a high current flows to produce a change in the magnetic field. When the changing magnetic field acts on a magnetostrictive material, a stress wave is produced. The wave mode is governed by the specific coil and magnet configuration. Normally the magnetostrictive material is the substrate under test (like steel), or an adhesively applied FeCo or Ni foil that transmits the acoustic wave into the substrate. Nuclear reactors with both high temperatures and high radiation levels are ill-suited for adhesively applied magnetostrictive foils. An alternative way to apply Ni or Co is to use cold spray. Magnetostrictive EMATs using cold spray Ni have been shown to be an effective magnetostrictive material that can sense flaws well away from the sensor. The magnetostrictive behavior of Ni however goes to zero as it approaches its Curie temperature of $\sim 320^{\circ}\text{C}$. Cobalt is known to have even stronger magnetostrictive behavior and a Curie temperature of $\sim 1115^{\circ}\text{C}$. An initial evaluation in 2024 (Glass, Good, et al. 2024) showed that indeed, a cobalt magnetostrictive EMAT with an AlNiCo permanent magnet showed a strong response to 400°C . A 100 mm x 525 mm x 12.5 mm plate was prepared with a 100 mm square coating on the plate end. The Co was applied by an automated cold spray process in a robotic cold spray booth. The cold spray coating was controlled to between 0.2-0.5 mm. The EMAT attaches magnetically to the magnetic cobalt coating, so no fixture screws are required. We did however find that a clamp pressing the coils to more closely couple to the ms material helped the response. The response was judged based on the plate end response. Surprisingly the magnetostrictive cobalt showed virtually no response until it was thermally annealed at 600°C . Thereafter the magnetostrictive EMAT showed a strong response to the maximum temperature tested. The response increased to several times the room temperature response up to $\sim 300^{\circ}\text{C}$ thereafter the response fell but the signal was still clear with good signal-to-noise behavior and an amplitude response of 46% of the room temperature signal at the maximum test temperature of 400°C .

The non-linear magnetostrictive response and the need to thermally anneal the cobalt material was micrographically evaluated with X-ray diffraction (XRD) and electron beam backscatter diffraction (EBSD). The high residual strain from the cold spray application may have placed the Cobalt coating into saturation such that the magnetostrictive response was inhibited. Once the thermal annealing and corresponding stress relief occurred, the coating could respond to the magnetic field change to produce the ultrasound stress wave. Co is a complex material that manifests in two allotropic forms; a hexagonal-close-packed form (HCP), which is stable at temperatures below about 400°C (673 K), and a face-centered cubic form (FCC) that is stable at higher temperatures up to its melting point. At atmospheric pressure, Co undergoes its phase transformation from HCP to FCC at $\sim 450\text{--}47^{\circ}\text{C}$. The magnetostrictive coefficient ranges from ~ -50 to -70 at 20°C ; to ~ 0 at 400°C ; to $\sim +50$ at 550°C . The phase transformation is suspected to cause the nonlinear magnetostrictive response.

Continuing this work as described in this paper, the permanent AlNiCo magnet was replaced with an electromagnet. The electromagnet field strength was not as strong as with the permanent magnet, but the room temperature plate end response was 24% of the permanent magnet on the test sample. The electromagnet assembly was inserted into a test oven similarly to the permanent magnet test setup with wires coming out so that the EMAT response could be monitored as the test assembly was exposed to higher temperatures. The assembly was cycled between room temperature and 600°C , 700°C , then 800°C . The EMAT system failed at 889°C and on disassembly, the electromagnet was discovered to have a broken lead as the wire entered the electromagnet coil region. Some degradation was also noted on the wafer on which the EMAT coils were wound. The lead wires of a new EMAT assembly were reinforced and then the EMAT and the Co test plate were inserted into the oven which was ramped up to 700°C for 7 days in argon and held for an additional 3 days in air. At the end of the long-term test, the room temperature sensor response was the same amplitude as before the 10 day test.

One conclusion is that a high temperature EMAT can be designed and built to withstand temperatures to at least 700°C for an extended period as may be required for online monitoring of nuclear reactor components.

Appreciating the difficulty of using Cobalt in high radiation and particularly Neutron environments that will tend to transform the material to Co-60 which is extremely hazardous to personnel working in close proximity, and appreciating the highly nonlinear Co response, continuing work will examine these or similar EMAT coils on other cold spray magnetostrictive materials like FeCo, and Galfenol.

Acknowledgment:

This work was funded by the Advanced Sensors and Instrumentation (ASI) program which is operated by the U.S. Department of Energy Office of Nuclear Energy.

Acronyms and Abbreviations

AlNiCo	iron alloy composed of aluminum, nickel, and cobalt and the rest iron
ASI	Advanced Sensors and Instrumentation (DOE program)
ASME	American Society of Mechanical Engineers
C	wave velocity
CISCC	Chloride Induced Stress Corrosion Cracking
Co	Cobalt
dB	decibels
DOE	US Department of Energy
EMAT	electromagnetic acoustic transducer
f	frequency
F	Force from changing magnetic field inducing stress wave
FBH	flat-bottom hole
FCC	face centered cubic (phase of Cobalt)
FSH	full scale height
B	Magnetic field strength
HAZ	heat-affected zone
HCP	hexagonal close packed (phase of Cobalt)
He	Helium
I	Current
J	Induced eddy currents
L	Length along coil wire
ms	magnetostriction/ magnetostrictive
msEMAT	magnetostrictive EMAT
mT	milli Tesla (unit of magnetic field strength)
NdFeB	neodymium iron boron
Ni	Nickel
N ₂	Nitrogen
SCC	stress corrosion cracking
SFC	spent fuel canister
SH	shear horizontal (wave mode)
SmCo	Samarium Cobalt
SS	stainless steel
SV	shear vertical (wave mode)
T-hot	maximum coolant operating temperature (of a nuclear plant)
TW	through wall
XRD	X-ray diffraction microscopy
θ	Angle as in steered angle relative to surface normal
λ	wavelength or magnetostrictive coefficient

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1.0 Introduction

Ultrasound is well understood as an effective way to interrogate nuclear power structural components for cracks, pits, wall thinning, and other anomalies indicative of structural damage. Piezoelectric sensors are widely used for periodic manual or robotic inspection to identify and resolve small defects or features of interest in a wide variety of materials including metals, concrete, plastics, and for medical applications. These piezoelectric sensors, however, are difficult to apply to high temperature components that may need to be inspected. Most high sensitivity piezoelectric materials degrade their performance or cease to work above $\sim 350^{\circ}\text{C}$ and long-term high temperature coupling between piezoelectric material and component is challenging even at lower temperatures.

Electromagnetic Acoustic Transducers (EMATs) can also generate and sense ultrasonic waves in structural components plus they provide some advantages over piezoelectric technologies. In particular, EMAT sensors can couple to the structural component electromagnetically with no need for either fluid or adhesive coupling between the sensor and the substrate. Also, EMAT sensors may be made of materials that can survive to much higher temperatures than most piezoelectric materials or piezoelectric couplings.

1.1 Lorentz Force EMATs

Traditional Lorentz force EMATs are governed by the Lorentz force equations (Figure 1) (Nave 2017) named after the Dutch physicist Hendrik A. Lorentz (1853-1928). The EMAT can be configured in a number of different ways to direct sound in different modes and in different directions but with a Lorentz force EMAT, the force is generated by the coil induced eddy currents generated within the substrate crossed with the magnetic field to generate the ultrasonic stress wave in the substrate material (Figure 2)(Zhang et al. 2021) (Wenze et al. 2021).

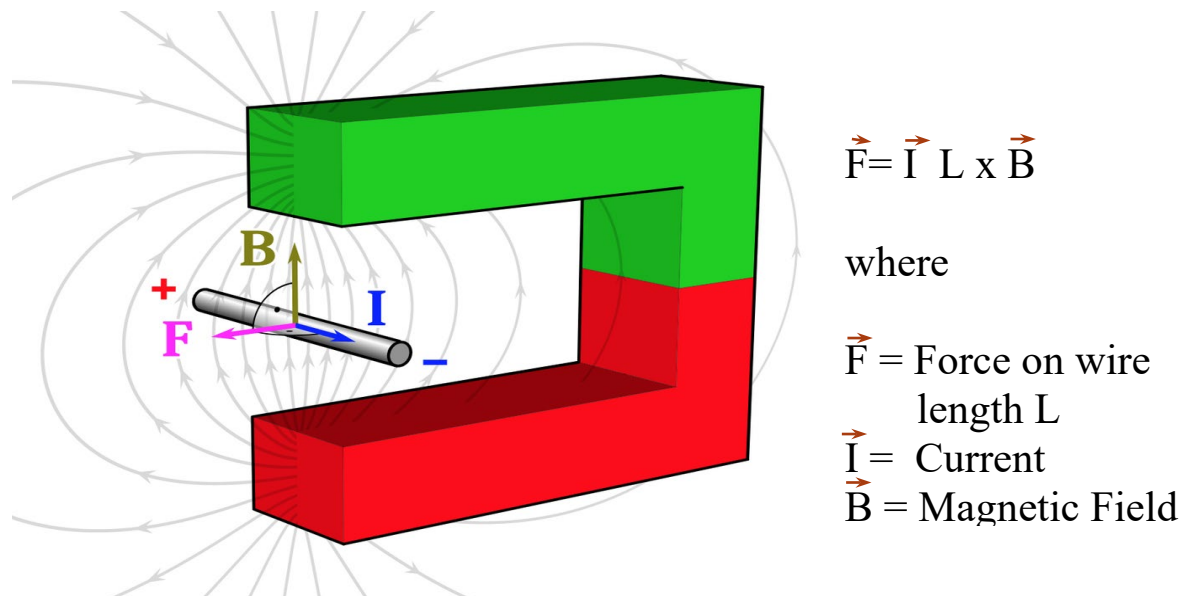


Figure 1 Lorentz force relationship among current, magnetic field, and wire length.

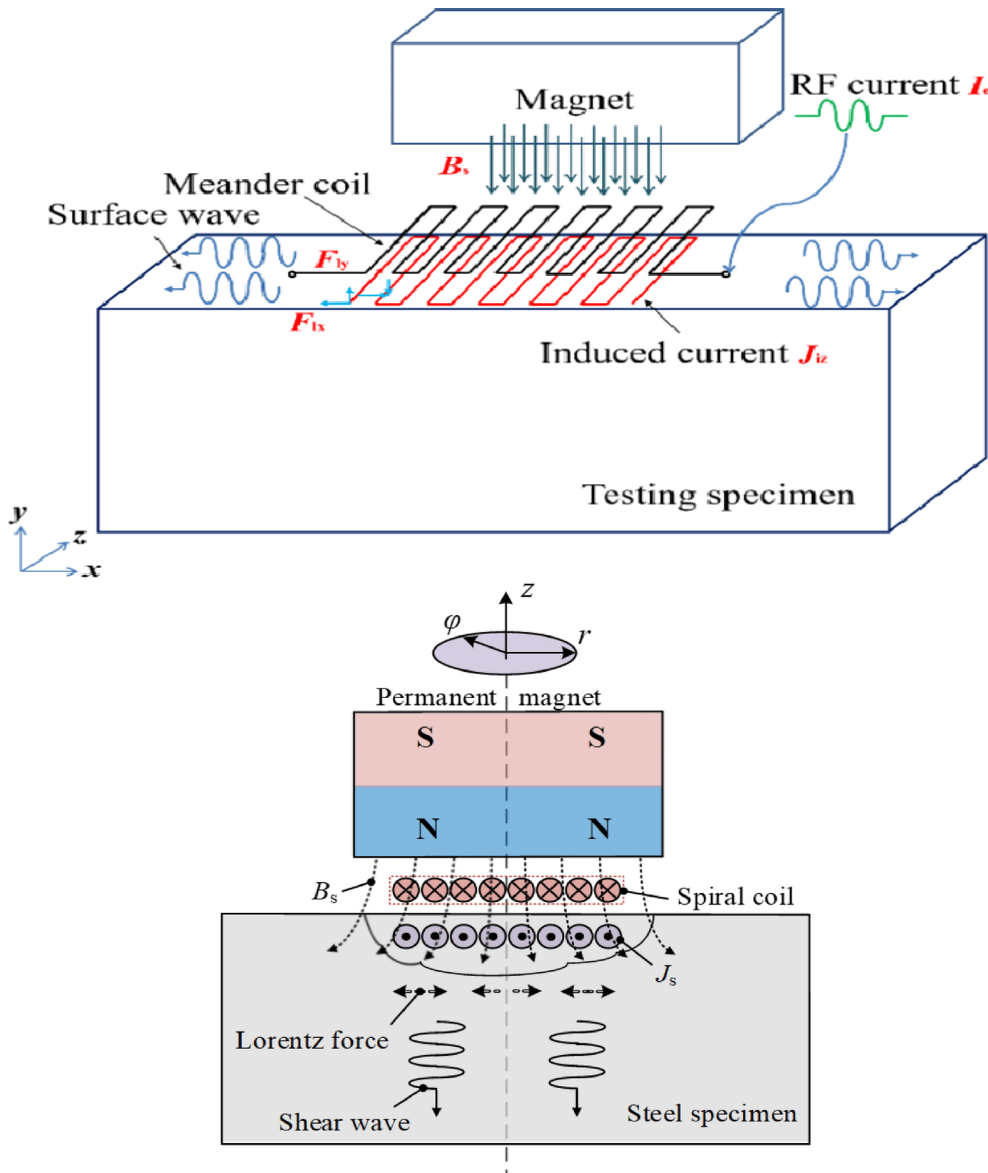


Figure 2 Examples of Lorentz force EMAT configurations. (Top) Serpentine meander coil generating surface wave and (bottom) spiral coil generating shear-wave normal to substrate surface (Wenze et al. 2021).

1.2 Magnetostrictive EMATs

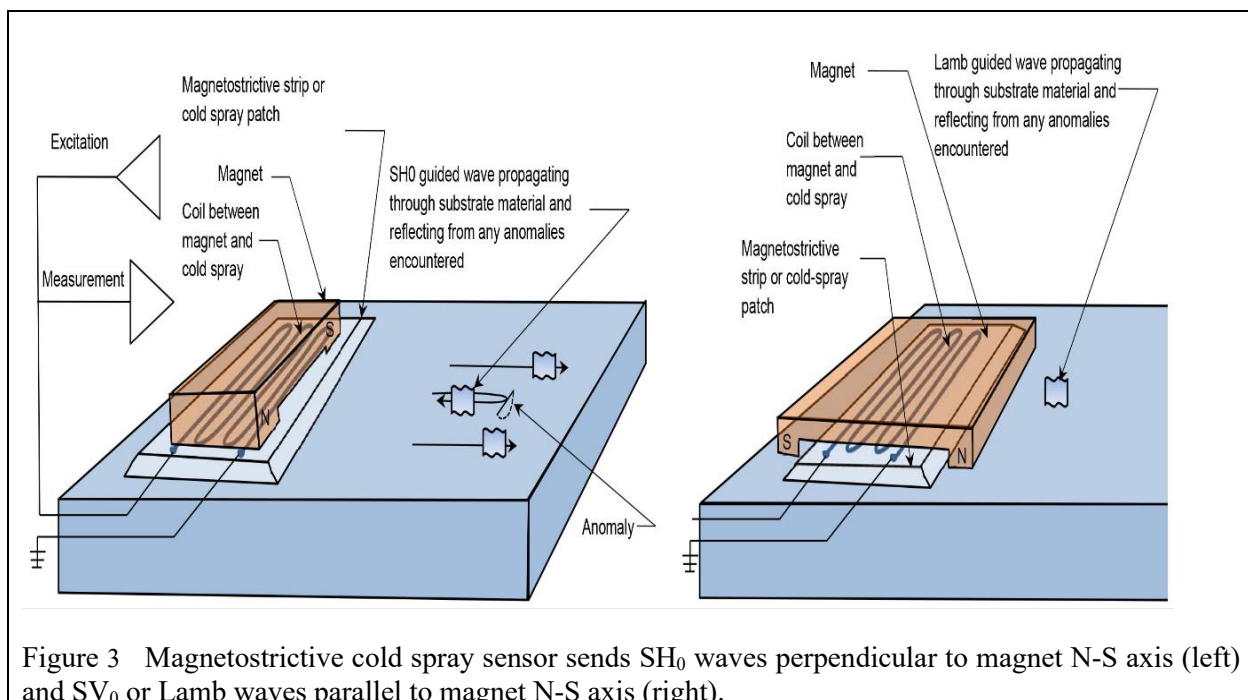
Magnetostrictive EMATs (msEMAT) do not rely on these Lorentz forces discussed above. Rather, they rely on the magnetostrictive behavior of either the substrate material or a thin magnetostrictive coating layer between the EMAT coil and the substrate material under test. A magnetostrictive material changes shape in response to an imposition or change of the magnetic field (Joule 1842). As magnetic domains within the material reorient themselves to align with the magnetic field, this reorientation causes a strain in the atomic lattice, which leads to a measurable change in its physical dimensions. The material property that governs

magnetostriction is called the magnetostrictive coefficient (normally shown as λ) and is defined as change in length / nominal length ($\Delta l/l$) in response to imposition of the magnetic field. The configuration of the EMAT magnet and coil governs how the change in magnetic field induces the magnetostrictive stress that leads to propagation of the stress wave in the material. The coil current can be oscillated at the ultrasonic frequency of interest leading to the desired ultrasonic strain wave of interest.

An effective ultrasonic sensor must also sense any reflected wave or in the case of a transmit/receive pair, it must sense changes in the transmitted ultrasonic wave. This is possible due to the reciprocal magnetostrictive behavior of msEMAT sensors also referred to as the Villari effect (Villari 1865). When mechanical stress is applied to the magnetostrictive material, it alters the alignment of magnetic domains within the material which may be sensed as an impedance change of the EMAT coil.

Generally the amplitude response of a msEMAT where it may be applied is stronger and more sensitive for NDE detection of flaws than Lorentz approaches. (Rose 2014) asserted that magnetostrictive materials have a higher magneto-mechanical coupling coefficient, which results in more efficient energy conversion and stronger ultrasonic signals compared to those generated by Lorentz force mechanisms. (Ribichini, Nagy, and Ogi 2012) found that magnetostrictive EMATs deliver higher signal amplitudes and better sensitivity especially at lower frequencies, where Lorentz force EMATs are typically less effective. These references collectively support the assertion that Magnetostrictive EMATs exhibit higher sensitivity compared to Lorentz EMATs, making them more suitable for certain applications in non-destructive testing and evaluation.

The concept of magnetostrictive ultrasound in general and magnetostrictive guided-wave ultrasound in particular is well understood by practitioners of the art and has been addressed by numerous researchers in the literature (Ali, Lopez, and Weinmeister 2017, Burrows, Fan, and Dixon 2014). One principal configuration of patch magnetostrictive sensing is shown in Figure 3. The sensor system consists of an electrically conductive meander shape, referred to as the coil, placed over the magnetostrictive layer (either a FeCo adhesive strip or a magnetostrictive cold-spray patch for the purpose of this publication). A perturbation in the magnetic field acting on the magnetostrictive material with its magnetic domains directionally aligned gives rise to a shear-horizontal stress wave. The acoustic wave is generated in the



magnetostrictive layer by inducing a high-current pulse or sinusoidal burst of one to several wavelengths at the desired inspection frequency that induces a transient magnetic field change. The acoustic wave transmits equally in both directions. Frequency selection is a trade-off between propagation distance, temporal/spatial resolution, and natural modes that may be enhanced or attenuated depending on material thickness, speed of sound, attenuation, etc. The amplitude of the acoustic wave is a function of the magnetostrictive coefficient of the magnetostrictive layer, the biasing field strength, the coil pulse current, lift-off between the coil and the magnetostrictive layer, and a number of other factors that are beyond the scope of this paper.

Magnetostrictive EMATs have been used for many applications. One early example (Thompson 1979), an electromagnetic transducer configuration is described for generating horizontally polarized shear (SH) waves in ferromagnetic magnetostrictive materials. The EMAT configuration is shown in Figure 4(a) with the magnetic field aligned at 90 degrees from the primary meander coil vector for lamb waves and the magnetic field for 4(b) aligned for shear horizontal waves (Thompson 1979). It was observed that peak ultrasound generation efficiencies occur at different bias levels for the two magnetic bias orientations.

(Kim and Kwon 2015) reviewed several magnetostrictive patch sensor setups. In one example, the setup was a 1 MHz, torsional-wave-based pitch–catch NDT experiment performed in a cracked aluminum pipe with a 25 mm mean diameter and 2 mm thickness. The configuration of the transducer used for this experiment is shown in Figure 5(a) and the representative signal response is shown in Figure 5(b). The transducer consists of a strip-type magnetostrictive patch that was wound around the circumference of the test pipe, two permanent magnets located in the opposite circumferential direction on the surface of the pipe, and meander coils with a distance of 1.55 mm between each finger. The distance is tuned to excite the lowest torsional wave mode in the pipe. The patch of a 19 mm width and 0.15 mm thickness is made of iron–cobalt alloy (Hiperco 50HS, Carpenter Technology Corp., Wyomissing, PA).

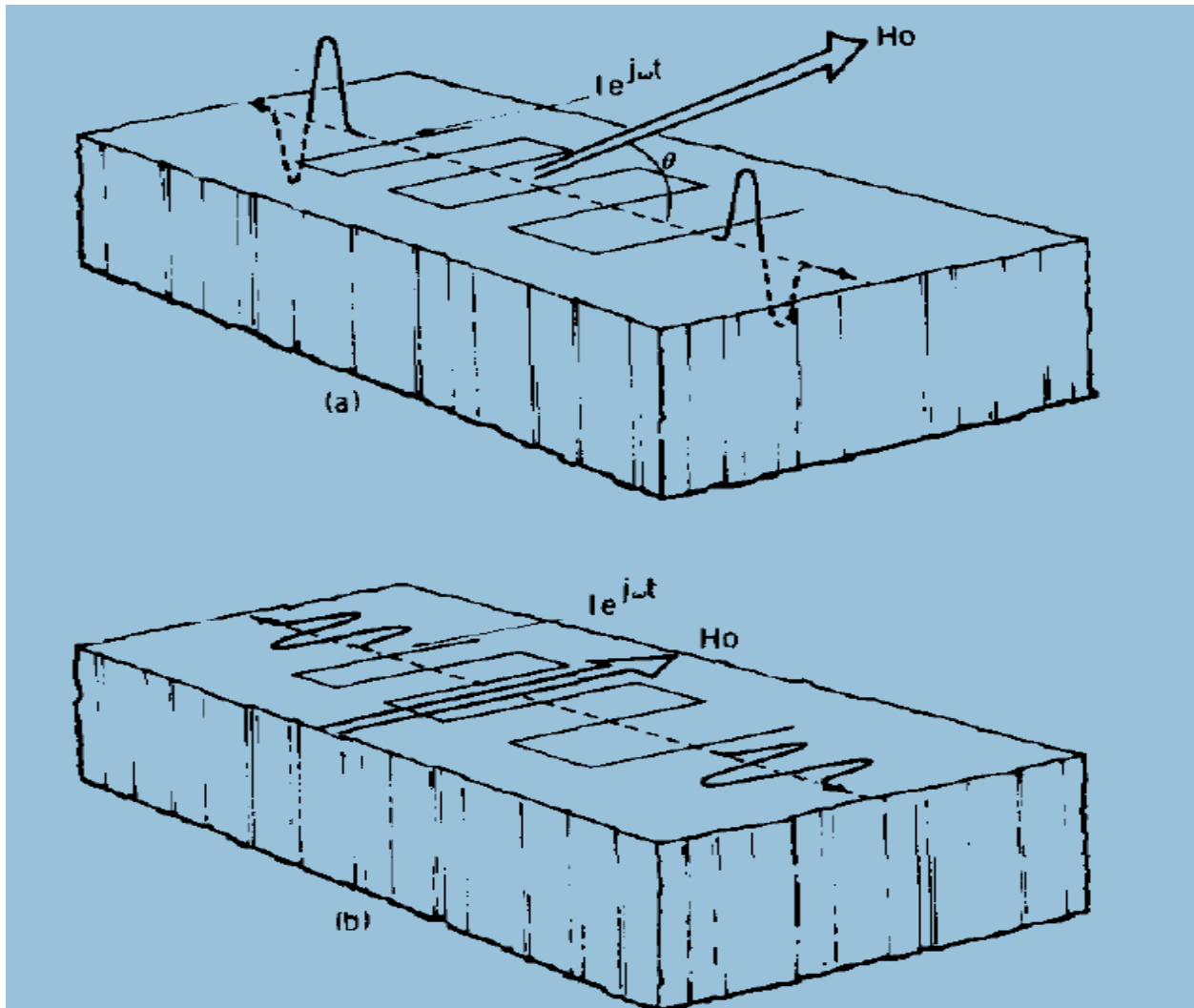


Figure 4 Meander-coil EMAT's with various bias field directions. (a) Configuration for generating Rayleigh, Lamb, or angle SV beams. Magnetic field is in the sagittal plane. (b) Configuration for generating horizontally polarized shear waves. Magnetic field is parallel to coil elements.

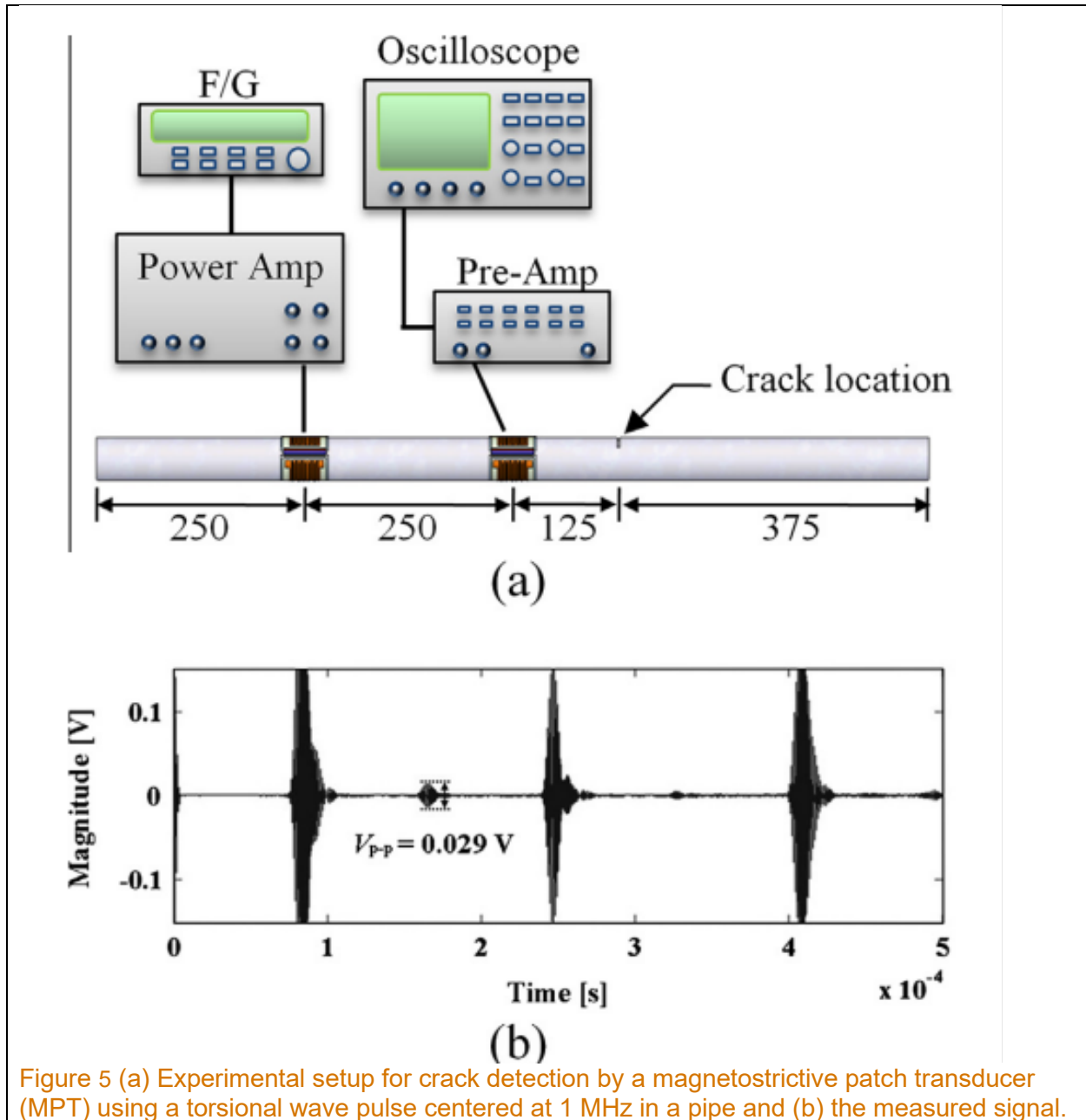
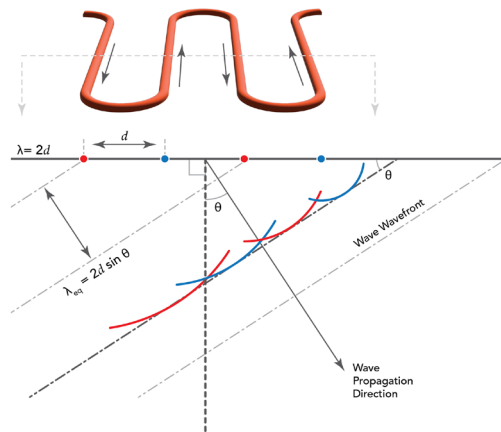


Figure 5 (a) Experimental setup for crack detection by a magnetostrictive patch transducer (MPT) using a torsional wave pulse centered at 1 MHz in a pipe and (b) the measured signal.

(Glass et al. 2019) showed that Ni cold spray could be used as the magnetostrictive component of an msEMAT sensor. Cold spray metallurgically bonds the magnetostrictive material (Ni in this case) without requiring the magnetostrictive coating to be adhesively applied to the test substrate. This work was extended to (Glass et al. 2023) examine Ni cold spray magnetostrictive sensors for nuclear spent fuel canisters. The Ni cold spray formed 0.25-0.5-in thick 100mm square patch that separated the EMAT from the stainless steel substrate. Flaws of interest were 25% through-wall 6mm diameter flat-bottom holes that were shown to be detectable as far as 2-m away. This study also exploited the EMAT's ability to direct shear-horizontal waves at different angles relative to the surface normal by simply changing the excitation chirp frequency (Figure 6).



$$frequency = \frac{Velocity_{shear}}{\lambda \sin \theta}$$

Where θ = steering angle from surface normal; 45°, 60°, & 90°

λ = wavelength

Figure 6 Multiple angle beams generated by changing excitation frequency of EMAT coil.

Flaw response amplitude varies as a function of the excitation angle and flaw distance from the EMAT. Higher angles (relative to the surface-normal) have fewer bounces and propagate longer distances along the plate surface, while lower angles have more reflections and must propagate longer distances within the plate for a similar surface propagation. Although the amplitude response generally falls off with distance, due to wave bouncing between the top and bottom surface, this trend may not be monotonic and may depend on flaws initiating from the top or bottom surface. The wave-angle, frequency (f) dependence feature was exploited to produce multiple measurements with the same coil by simply changing the instrument excitation frequency. The multiple measurements serve to either corroborate or dismiss apparent indications, thereby improving the probability of a correct detection and reducing the probability of a false detection.

The SH_0 fundamental shear wave travels at constant velocity, C, and satisfies following bulk wave relationship for $\theta=90$ deg.

$$f = C/(\lambda \sin \theta)$$

The fundamental wave excited at 90 degrees still travels within the plate by bouncing within the top and bottom surfaces due to its associated beam spread. If frequency is changed causing a change in the angle of excitation for the SH_0 wave, the wave bouncing between the walls of the plate produces higher and lower energy concentrations due to half and full wave skips bouncing from the far wall to the near wall. Significantly higher frequencies can generate a dispersive higher order SH wave mode. The preference is always to generate the fundamental mode rather than higher order modes for the simplicity of interpretation and analysis of the results.

Any mode in the SH family can be considered as the superposition of up- and down-reflecting bulk shear waves polarized along the horizontal (y-plane) direction, with wave vectors lying along the vertical (z-plane) and axial (x-plane) directions and inclined at such an angle that the system of waves satisfies traction free boundary conditions on the surface of the layer (Rose 2014). The SH_0 mode can be excited at multiple angles as long as the EMAT wavelength is greater than or on the order of thickness of the plate. However, in case the wavelength of the EMAT coil is less than the thickness of the plate, the higher order SH wave modes will be excited with its dispersive behavior limiting the range of propagation. The magnetic field orientation to generate both fundamental (SH_0) and higher order shear horizontal waves must be parallel to the EMAT meander wires as explained in Figure 3.

Considering inspection from a fixed location that these energy concentration spots will change location due to beam angle and beam spread. This characteristic of the SH_0 wave mode was exploited to provide multiple wave-mode opportunities for flaw interaction by only changing the excitation frequency of a fixed-position sensor (Table 1).

Table 1 EMAT Coils Frequencies for different Beam Angles

Coil Wavelength (mm)	Angel (degrees)	Frequency (kHz)
13	90	247
	60	285
	45	349
6	90	495
	60	572
	45	700

2.0 Magnetic Field Effect on Magnetostrictive Behavior of Magnetic Materials

The magnetostrictive behavior of magnetic materials is maximized by having the magnetic bias field below the material's saturation point. The degree of magnetostriction is directly proportional to the applied magnetic field strength up to the saturation point. Beyond this point, the material's response plateaus and further increases in the magnetic field do not result in additional strain. This behavior is crucial for designing devices that rely on magnetostrictive materials, as it defines the operational limits and efficiency of these devices. In this project we found that our first selection of SmCo magnets were saturating the Cobalt cold spray coatings and so found that the magnetostrictive response was maximized by increasing the distance between the magnet and the coating by as much as 25mm.

2.1 Magnetostrictive Materials

One of the essential components of a magnetostrictive EMAT sensor is the magnetostrictive material. This can either be the substrate material under test situated directly below the EMAT coil, or it can be a thin layer of magnetostrictive material that can couple ultrasonic waves into the substrate material under test. The temperature response of these materials is critical because their magnetostrictive properties can vary significantly with temperature. Generally speaking, the magnetostrictive response is reduced with increasing temperature and radiation. The room temperature magnetostrictive coefficient and Curie temperatures for candidate magnetostrictive sensor materials are shown in (Table 2) and are discussed in the following sections.

Table 2 Magnetostrictive coefficient and curie temperature for candidate magnetostrictive materials to be used in magnetostrictive EMAT sensors

Material	Magnetostrictive Coefficient (ppm)	Curie Temperature °C	Reference
Nickel (Ni)	-34	354-360	(Legendre and Sghaier 2011)
Cobalt (Co) HCP@20°C	~-50 to -62	1121	(Kim and Yang 2018) (Britanica 2016) (Betteridge 1980)
Cobalt (Co) FCC @ 547°C	+50	1121	(Betteridge 1980)
Ferrous Cobalt (FeCo)	70-90	977-1227	(MacLaren et al. 1999); (Nolte, Severin, and Hoffmann 2000)
Galfenol	250	700	(Britanica 2016)
Iron	20-30	770	(Britanica 2016)
Steel	2-10	750-770	(Britanica 2016)

2.1.1 Nickel

Ni exhibits moderate magnetostrictive behavior (Nolte, Severin, and Hoffmann 2000). Its magnetostrictive response decreases as the temperature approaches Ni's curie temperature (~354°C), above which it loses all ferromagnetic properties. This Curie temperature is quite close to typical T-hot temperatures for conventional light water reactors and therefore is unlikely to be suitable for primary circuit Ni Magnetostrictive monitoring. The room temperature magnetostrictive coefficient is -34ppm. Ni exhibits several other traits that may be considered when evaluating suitability as a sensor material including:

- Corrosion resistance – particularly it is shown to resist chloride assisted stress corrosion cracking.
- High conductivity/low resistivity
- Easily cold sprayable but can be applied by electroplating as well.
- Demonstrated to be a suitable coating for msEMAT sensor
- Relatively unaffected by high radiation fields.

2.1.2 Cobalt

Co is a complex material that manifests in two allotropic forms; a hexagonal-close-packed form (HCP), which is stable at temperatures below about 400°C (673 K), and a face-centered cubic form (FCC) that is stable at higher temperatures up to its melting point. At atmospheric pressure, Co undergoes its phase transformation from HCP to FCC at ~ 450-470°C. The magnetostrictive coefficient ranges from ~ -50 to -70 at 20°C; to ~ 0 at 400°C; to ~+50 at 550°C (Betteridge 1980)(Figure 7). Although the specific magnetostrictive response is strongly temperature dependent, Co has the highest absolute magnetostrictive response of all natural elements (Kim and Yang 2018). For the EMAT sensor response, the sign of the magnetostrictive response is unimportant; it is only the absolute value of the magnetostrictive coefficient that is important for the EMAT response. Above ~ 600°C, Co's magnetostrictive coefficient decreases with increasing temperature back to zero at its Curie temperature of ~1121°C.

Co is normally not manufactured as a foil or tape to be adhesively adhered to a substrate for a magnetostrictive sensor, but it is possible to cold spray cobalt powder (10-100 microns) onto various substrates including aluminum and stainless steel. The cold spray powder configuration introduces additional complications for producing a magnetostrictive response. Our experience is that the magnetostrictive reaction was very weak until the cold spray coating was thermally annealed. This may have relieved some of the cold-work strain within the cobalt layer and fused grain boundary separations to facilitate the ms response, but it may also relate to the allotropic phase modes. It is noted that thermal annealing was not required in Ni, so there may be other factors influencing the magnetostrictive behavior of Co.

In high energy neutron and gamma radiation fields, there is also a concern for the normal isotope of Co (Co-59) to transform to Co-60 which constitutes a significant radiation hazard to personnel in close proximity.

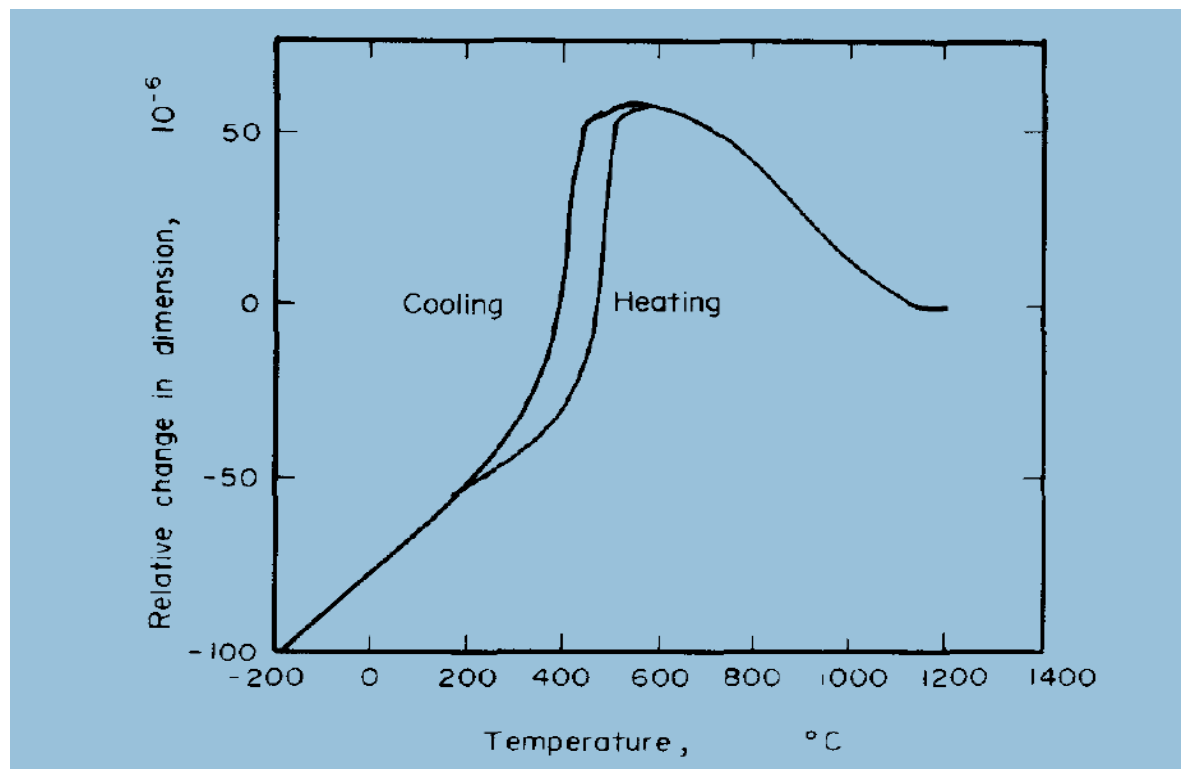


Figure 7 Saturation magnetostrictive coefficient of cobalt as a function of temperature. Note that below $\sim 470^{\circ}\text{C}$, cobalt is predominately in an HCP mode. Above 470°C , the dominant mode is FCC.

2.1.3 Iron Cobalt (FeCo) Alloy

FeCo alloys are used for computer hard drives, electric motors and transformers, and electromagnetic sensors leveraging their useful magnetostrictive and magnetic properties. Depending on the specific formulation, the material may have a magnetostrictive coefficient of 70-90ppm (Nolte, Severin, and Hoffmann 2000) and Curie temperature from 977 to 1227°C (MacLaren et al. 1999) depending on the specific material distribution. The material may be produced as a tape or foil layer that may be suitable for magnetostrictive EMAT sensors to adhesively attach the foil to a substrate. This approach is actively used by EMAT sensor vendors for sensor applications where adhesives may be used. One problem however is that adhesives do not work well for long term high temperature or high radiation applications.

3.1.4 Galfenol Alloy

Galfenol is known for its excellent magnetostrictive properties and temperature stability. It has a lower temperature dependence compared to many other magnetostrictive materials and a Curie temperature around 700°C . Galfenol is an Iron-Gallium alloy with a typical ratio of 85-90% Fe and 10-15% Ga. The addition of Ga however increases the magnetostrictive response relative to pure iron by up to 10 times.

2.2 Magnets

The magnetostriction response benefits from the application of a bias magnetic field. When a magnetic material undergoes magnetostriction, its shape or dimensions change in response to the application of a magnetic field. The application of a bias magnetic field can help align the magnetic domains in the material, leading to a more pronounced and consistent magnetostrictive effect so long as the field strength does not push the material into saturation. Magnets are chosen based on the target field strength, target temperature, and to a lesser degree – radiation tolerance. Material choices are limited primarily to Neodymium Iron Boron (NdFeB), Samarium Cobalt (SmCo), and Aluminum Nickel, Cobalt (AlNiCo) permanent magnets and electromagnets. Relative merits of magnet choices are discussed below.

2.2.1 Neodymium Iron Boron

NdFeB permanent magnets have the strongest field strength, but the strength fades quickly as temperatures increase above 200°C. They are also more susceptible to radiation damage than SmCo or AlNiCo (Brown and Cost 1990). After high temperature exposure, limited recovery in magnetic properties may be seen if subjected to temperatures above maximum operating temperature but below the Curie temperature of 310 – 410°C. Above the Curie temperature, demagnetization is permanent and magnetic properties will not return. NdFeB materials are difficult to machine, fragile, and susceptible to impact, handling damage, and corrosion.

2.2.2 Samarium Cobalt

SmCo permanent magnets have a relatively strong field strength and can operate to temperatures of 300 – 350°C. They are less susceptible to radiation damage, corrosion, and degradation than NdFeB materials and may be a strong choice for msEMAT sensors. One caution is that SmCo materials are difficult to machine or shape, fragile, and susceptible to impact and handling damage.

2.2.3 Aluminum Nickel Cobalt

AlNiCo permanent magnets have the weakest field strength of the three materials considered. They can operate to higher temperatures with a limited reduction in performance to 500°C. They also are less susceptible to radiation damage than either SmCo or NdFeB. AlNiCo can be machined with conventional machining tools, and the finished pieces are tougher and can be more easily handled without fear of cracking or fracture. The field strength of AlNiCo magnets may be too weak to firmly attach an EMAT sensor to a magnetostrictive coating. The AlNiCo magnets can be supplemented by adjacent peripheral SmCo magnets to attach to the magnetostrictive layer or by mechanical straps over the AlNiCo sensor. An AlNiCo magnet was used for practically all of the tests for this project.

2.2.4 Electromagnets

Electromagnets are manufactured by winding a wire coil around a core with a high magnetic permeability then passing a current through the wire to generate the magnetic field. The strongest electromagnet cores are typically made from an alloy of Iron, Cobalt, and Vanadium. The field is proportional to the core magnetic permeability, the number of wire turns, and the current. Electromagnet designs can produce higher fields than permanent magnets within a similar space volume but the logistics of managing the wire and connection to a current supply make the EMAT more complex to manage. The electromagnet does offer an advantage for a scanning or moving sensor in that the magnet may be turned off while moving then energized when it is desired to attach the magnet to the magnetostrictive substrate and make a measurement. If the wire has a polymer or shellac insulation, then the wire insulation becomes the temperature limiting

component. In this application however, we have used a ceramic insulation nickel magnet wire that can function to 800°C or higher. The magnetic field strength will diminish as the temperature is elevated due to decrease in the core permeability, increase in the wire resistivity, and corresponding reduction in coil current but these variables can be managed, and the electromagnet should still have significant field strength at temperatures up to 800°C.

3.0 Design of High Temperature EMAT and test configuration

The high temperature magnetostrictive EMAT is substantially modeled after the Ni cold spray msEMATs of (Glass et al. 2023) which used a thin (0.25-0.5mm) Ni cold spray layer on a 12.5 mm thick 304 Stainless steel plate. The EMAT serpentine coils were 100mm long with a wavelength of 6 and 13mm. This EMAT however used laboratory-grade flexible Kapton printed circuit technology which encapsulated the copper coils (Figure 8). The magnets were a relatively strong simple bar SmCo permanent magnet placed over the coil with steel stand-off blocks to complete the magnetic circuit. A more industrial version of this EMAT was fabricated for use on nuclear waste spent fuel canisters (Glass, Ali, et al. 2024) (Figure 9). These materials are shown to be suitable for up to 250°C due to limitations of the Kapton and the well understood reduction in magnetostriction response of the Ni.

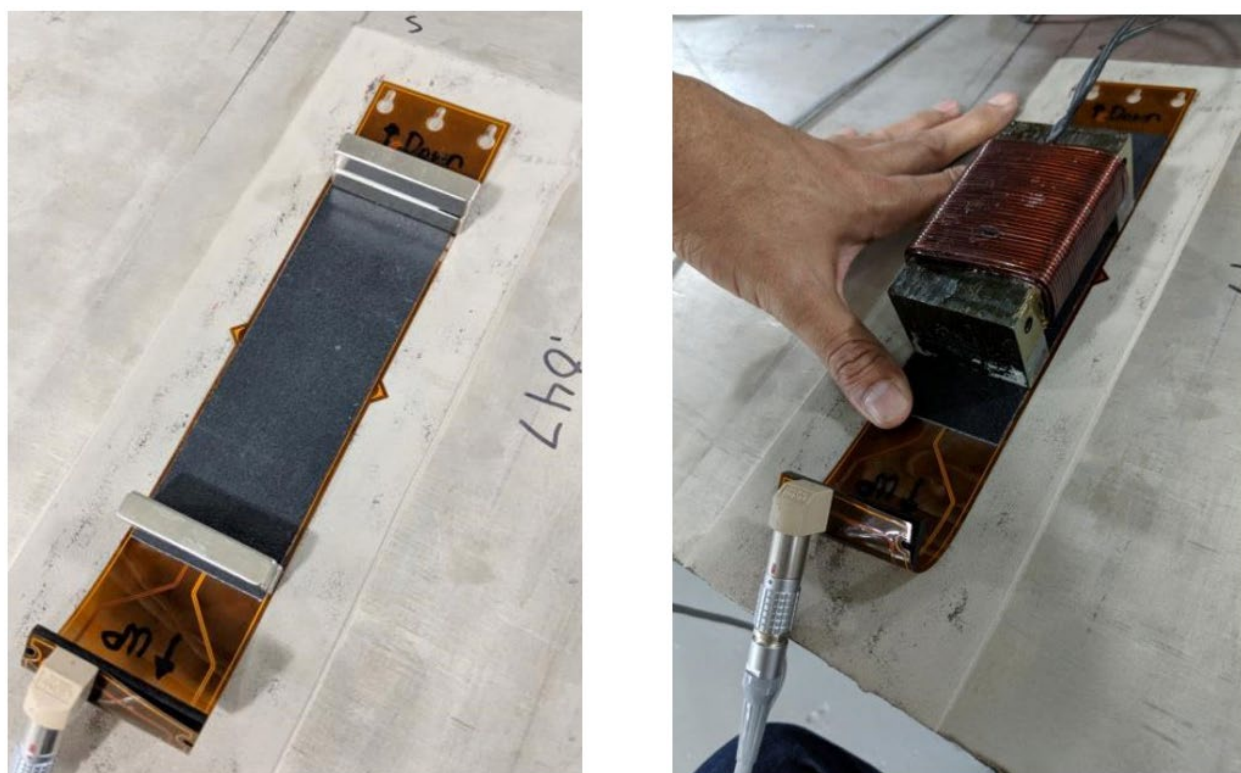


Figure 8 (left) Permanent magnets biasing the cold-spray patch beneath the coil. (right) Electromagnet biasing the magnetostrictive patch over the same coil.

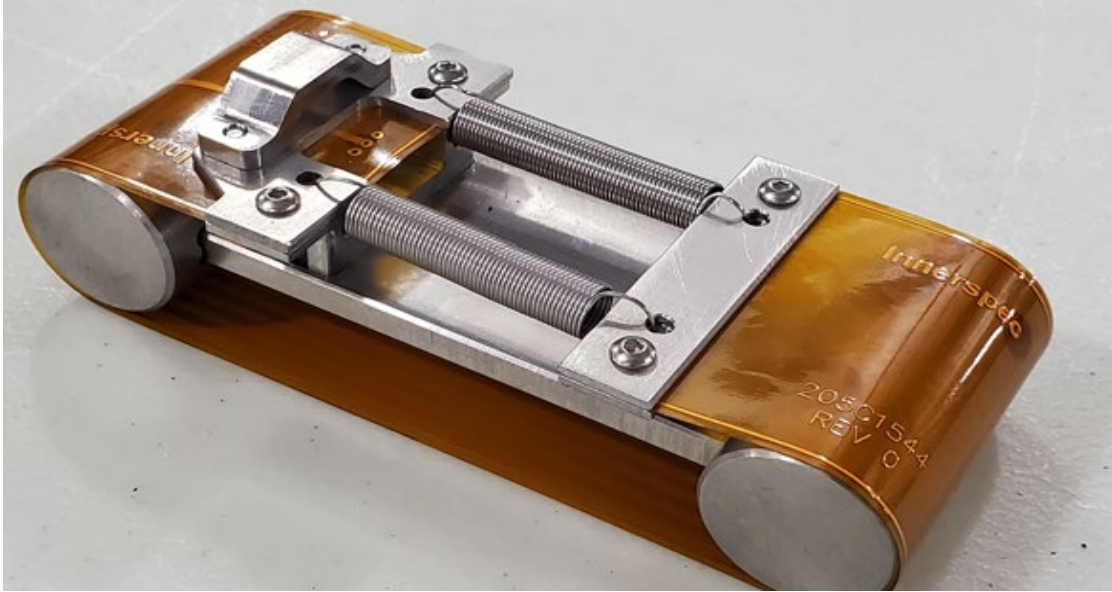


Figure 9 Industrialized and hardened magnetostrictive EMAT for nuclear spent fuel canisters.

The high temperature EMAT assembly shown in Figure 10 included custom coils with wire wound and imbedded within a high-temperature mica wafer rather than printed onto a Kapton flexible sheet. Also, since the coils were wound from high temperature insulation wire, the availability of more than one layer could be used to increase the cumulative current affecting the magnetic field and thereby increase the magnetostrictive response (Figure 11). Note that the current flows clockwise in the top/1st coil and the 3rd coil then counterclockwise in the 2nd from the top and in the bottom coil.

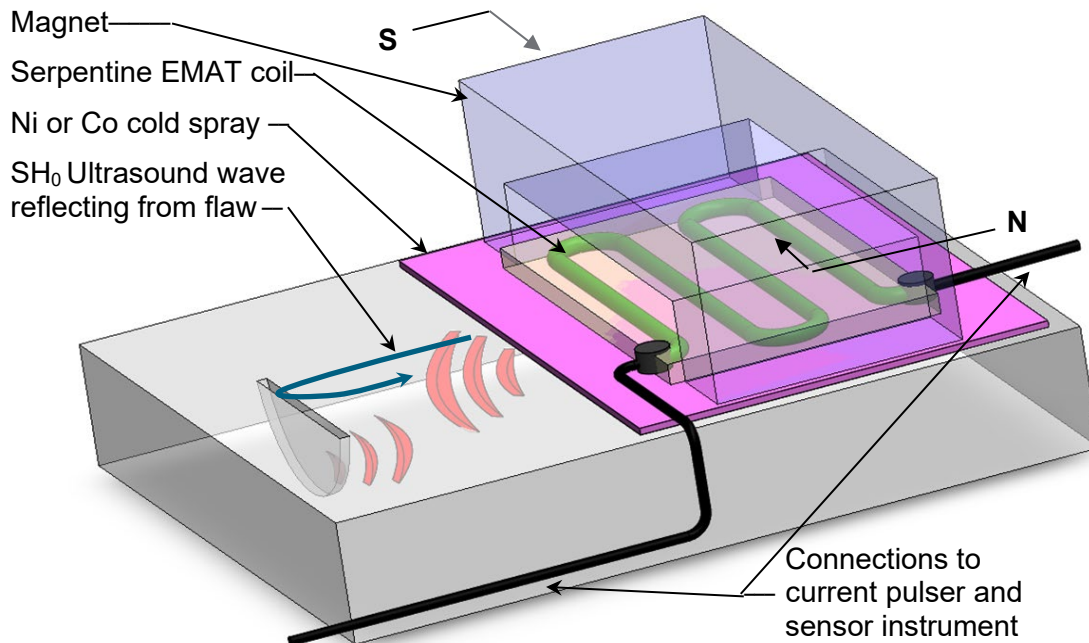


Figure 10 Magnetostrictive cold spray sensor sends SH_0 waves perpendicular to the coil, and magnet N-S axis as shown.

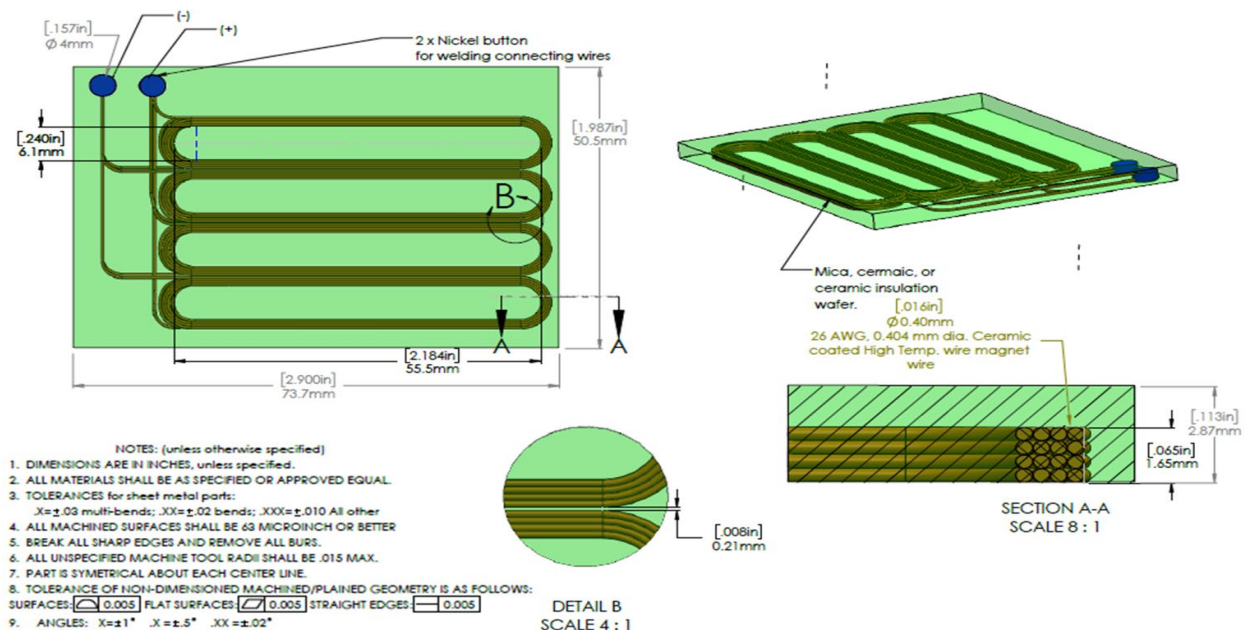


Figure 11 Details of high temperature 3-D coil design that provides 16 times the effective coil current compared to a single serpentine coil on the top and bottom coil outer edges and 32 times serpentine coil current where two coils are adjacent to each other.

The permanent magnets initially planned for the EMAT were SmCo magnets, but they were significantly stronger than the AlNiCo magnets which also have a higher operating temperature with more stable long-term performance. The SmCo magnets were separated from the magnetostrictive cobalt by 2.5 cm or more to get out of the saturated range and allow the magnetostriction to occur. The permanent magnets are known to lose strength with elevated temperature and so it was planned from the beginning to use an electromagnet for higher temperature tests.

The initial design for the high temperature cable connection inside the oven to the coil was a glass-wool insulated coaxial cable with an inconel sheath and a nickel conductor. The inconel sheath proved difficult to weld and generally showed high resistance values that may have contributed to the sensor noise. The high temperature leads were replaced with a single conductor ceramic insulated Ni wire that offered a lower resistance and seemed to produce a clearer signal.

The electromagnet core was made from an Iron, Cobalt, and Vanadium compound (trademarked Hyperco-50) material chosen for a maximum magnetic field response at elevated temperatures. The core was machined to closely cap the mica wafer coil after wrapping with the same kind of Ni conductor ceramic insulated magnet wire used for the EMAT coil as shown in Figure 10. The electromagnet design is shown in Figure 12

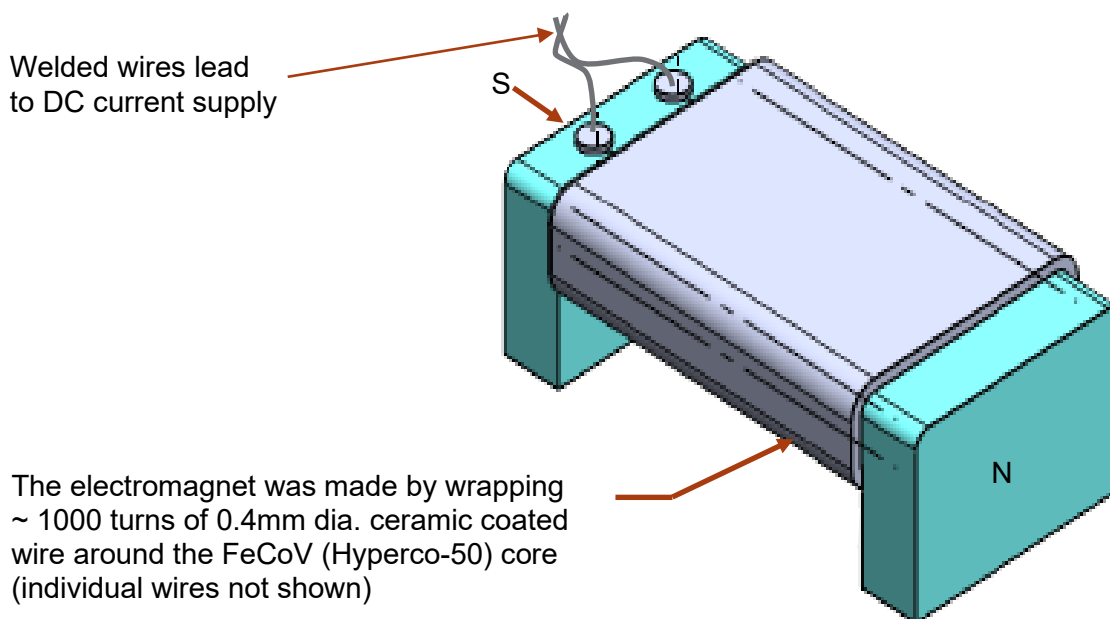


Figure 12 Electromagnet assembly shown without the EMAT coil that would normally go between the north and south magnet pole ends. The magnet strength can be adjusted by changing the DC current.

4.0 Test Plan, test setup, and result overview

The primary focus of this work was to assess the feasibility of a high temperature magnetostrictive EMAT sensor based on a cold spray cobalt magnetostrictive patch. Although extensive optimization of the sensor was not undertaken, a number of configurations were tested as noted in Table 3. Testing was expanded when we noted that the cobalt coating exhibited very little response until it was thermally annealed including micrographic XRD and EBSD analysis. All EMAT oven performance tests were implemented on a 10cm by 53cm x 1.3cm plate as shown in (Figure 13) designed to just fit into the test oven (Figure 14). The test plate had a 100mm square by 0.25-0.5 mm cold spray patch on one end and a 6mm x 50% TW flat bottom hole 75mm from the plate end. The ultrasonic response of the flat bottom hole was barely visible or not visible, but the plate end response was identifiable. Results of the complete battery of tests are summarized in the right hand (Notes and References) of Table 3

Table 3 Test Matrix

Test Description	Notes and References
20oC comparison of commercial coil to high temperature PNNL 4-loop coil.	Signal quality was substantially the same. Documented in (Glass, Good, et al. 2024)
20oC comparison of HT EMAT on 500°C annealed N2 sprayed Co versus 650°C annealed He sprayed Co	Signal quality was substantially the same. Documented in (Glass, Good, et al. 2024)
20°C comparison of High Temperature EMAT on as-sprayed Ni and 650°C annealed He sprayed Co.	1 st and 2 nd plate end responses were clearly visible in both cases, but Co response was reduced by ~ 30dB or a factor of 32. Documented in (Glass, Good, et al. 2024)
20°C comparison of N2 Sprayed Ni versus N2 sprayed Ni with Chromium/Ni bonding coat	No significant differences were noted between these two samples. (Glass, Good, et al. 2024)
Elevated Temperature AlNiCo magnet EMAT (to 400°C) on 650°C annealed He sprayed Co	Both first and second end-wall reflections were clearly visible to 400oC. Amplitude was reduced by ~ 59% @ 20oC to 29% screen height (49%) @ 400°C. (Glass, Good, et al. 2024)
1SEM, EBSD, and XRD micrographic analysis were performed to investigate need for thermal annealing and the non-linear ms response.	The combination of residual strain and the mixed FCC and HCP phases negatively impacts Co's ability to demonstrate its inherently high magnetostrictive coefficient. Annealing facilitates the release of residual strain and promotes phase transformation, contributing to the enhanced magnetostrictive behavior observed in the Co layer post-annealing. . (Glass, Good, et al. 2024)
New work: Initial Electromagnet EMAT on annealed He sprayed Co	End plate electromagnet response amplitude was 24% of the AlNiCo magnet. Suspect this is because electromagnet magnetic field strength is also lower. See section 6.0
New work: Electromagnet EMAT test several cycles to 700°C then to failure (at 889°C) under Argon environment	Good signals to the highest temperature. 889°C response was 19% of 23°C response before failure. . Autopsy revealed failure of electromagnet lead wire connection plus some degradation of mica wafer and ceramic insulation. See section 7.0.
New work: Extended time (7days) test of Electromagnet EMAT at 700°C under Argon environment and an additional 3 days under air environment.	The sensor continued to work with little signal change over 10 days. The room temperature sensor amplitude after the 10 day test was similar to the signal amplitude before the test. See section 7.0

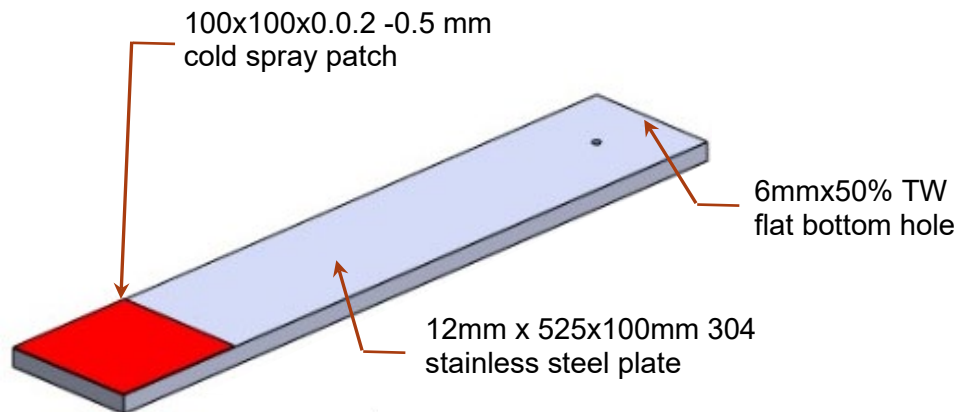


Figure 13 Test plate designed to fit into oven. Plates were made with several different types of cold spray including pure Ni, Ni with a 0.08mm Ni/Chrome bond coat, N2 sprayed Co with a 0.08mm Chrome bond coat, and He sprayed pure Co.

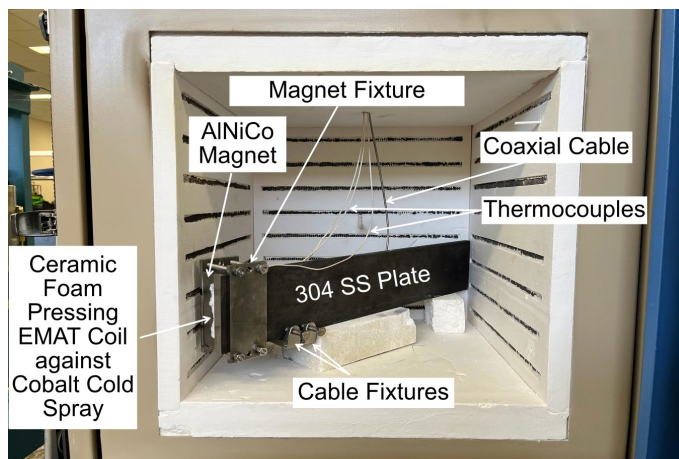


Figure 14 Photograph of test plate with the EMAT in place within the oven

Sensor performance of the Ni cold spray msEMAT at room temperature has been well established. As the substrate and sensor heat up, the sensor performance was predicted to degrade because of known material behaviors (primarily decreased magnetostriction coefficient, reduced magnet strength, and increased coil resistivity). The test plan was designed to show the potential for a high temperature cold spray Cobalt sensor to operate at significantly elevated temperatures despite these thermal degradation challenges.

5.0 Permanent Magnet msEMAT Performance to 400°C

The permanent magnet EMAT configuration was initially tested with a samarium cobalt (SmCo) permanent magnet with a very high field strength that produced quite poor results. We noted that responses improved significantly by elevating the magnet more than 10cm above the coil. This indicated that the EMAT was trying to operate in the saturated range of the BxH curve. The AlNiCo magnet (with a field strength of 71 mT) produced much better results plus it was easier to handle. The AlNiCo magnet was also less likely to impact and fracture as it attached to the magnetostrictive coating. The EMAT assembly and test plate were placed into the oven with wires routed through a port in the oven ceiling. Responses were noted at room temperature (27°C) and as the temperature was raised to 400°C. The test was stopped at 400°C as that represented the temperature limit for long-term magnet operation without degradation of the magnetic field strength. As shown in Figure 15, the 27°C 2nd end-plate response was 60% full screen and the 400°C response was 27% full screen height or 45% of the 27°C response. Note that the peak response surprisingly occurred at approximately 250°C and was almost 4x the 27°C value.

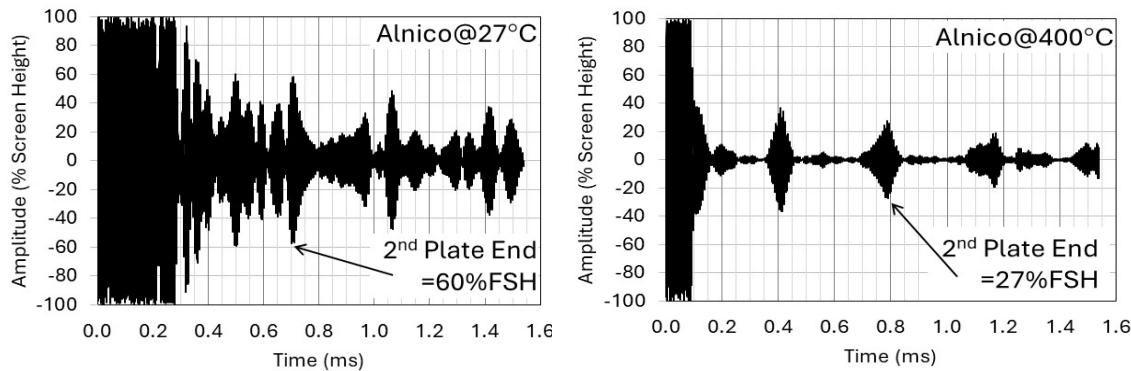


Figure 15 (Left) AlNiCo EMAT sensor A-scan responses at 25°C and (Right) 400°C. This 400°C response was $27/60 = 45\%$ of the 27°C response.

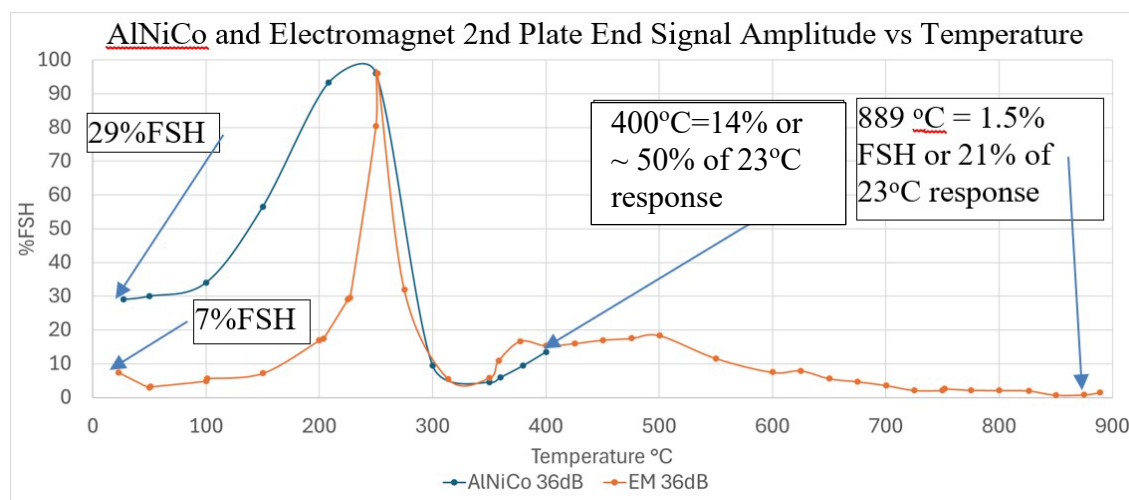


Figure 16 2nd plate end reflection of AlNiCo permanent magnet and electromagnet EMAT vs. temperature. (Amplitudes do not match Fig. 15 or 17 A-scans due to scaling.)

6.0 New Work-Electromagnet msEMAT Test to Failure

The electromagnet msEMAT was cycled several times to temperatures above 500°C and showed a clear plate-end response. The plate end response amplitude is shown in Figure 16 and sample A-scans are shown in Figure 17. As the oven hit 889°C, the sensor failed but the sensor still showed a clear end-wall response of 21% of the 23°C response (Figure 16). On inspection, the sensor's electromagnet lead wires had failed at the junction between the lead wires and the electromagnet. We speculated that the wires were fatigued from handling and routing the wires through the access port in the oven ceiling. The mica wafers holding the EMAT coils and the ceramic insulation were also showing signs of damage.

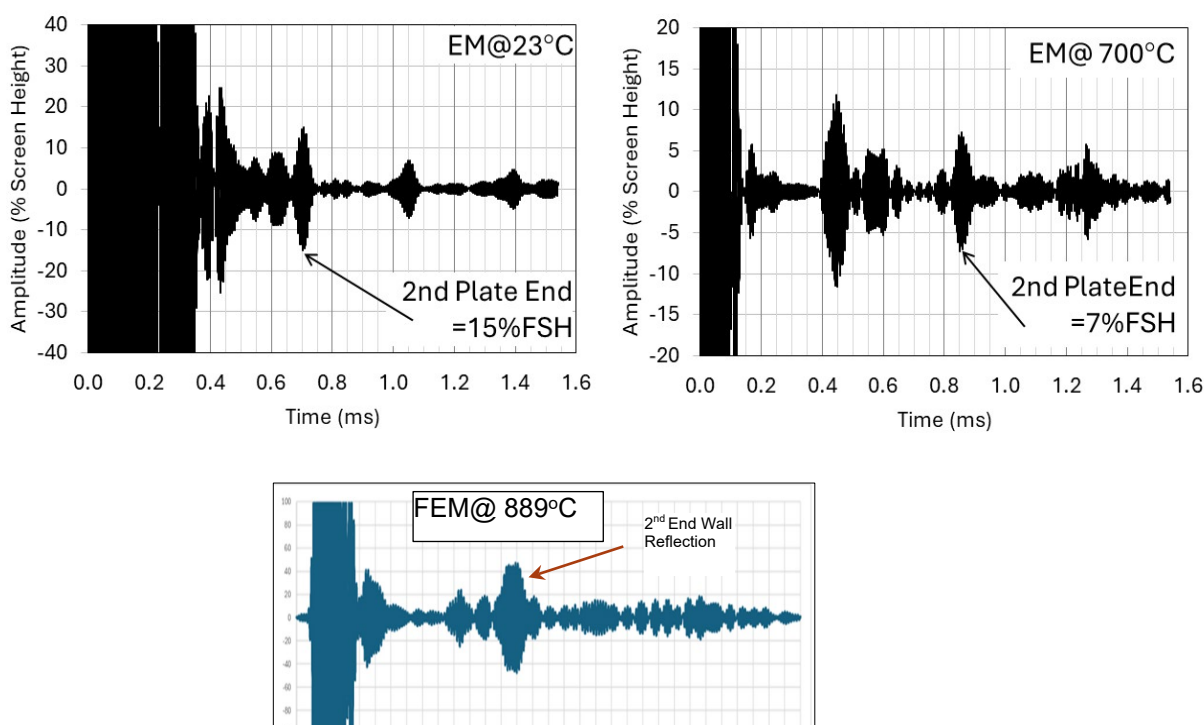


Figure 17 23°C, 700°C, and 889oC sensor response showed clear plate end reflections. Gain corrections and time scales are different and do not necessarily correspond to Figure 16's full screen height amplitude temperature responses.

7.0 New Work-Electromagnet msEMAT Long-Term test at 700°C

A new electromagnet EMAT sensor was prepared with strain-relieving support to minimize the probability of a repeat failure of the lead wires. The sensor assembly was carefully re-inserted into the oven. The oven temperature was ramped up to 700°C over 2 hours then held for 7 days under an argon blanket with no apparent change in the EMAT response. The argon purge gas was then removed transforming the sensor environment to air, and the test was continued for 3 additional days. The sensor continued to work with no significant response change over the full 10 days at 700°C(Figure 18).

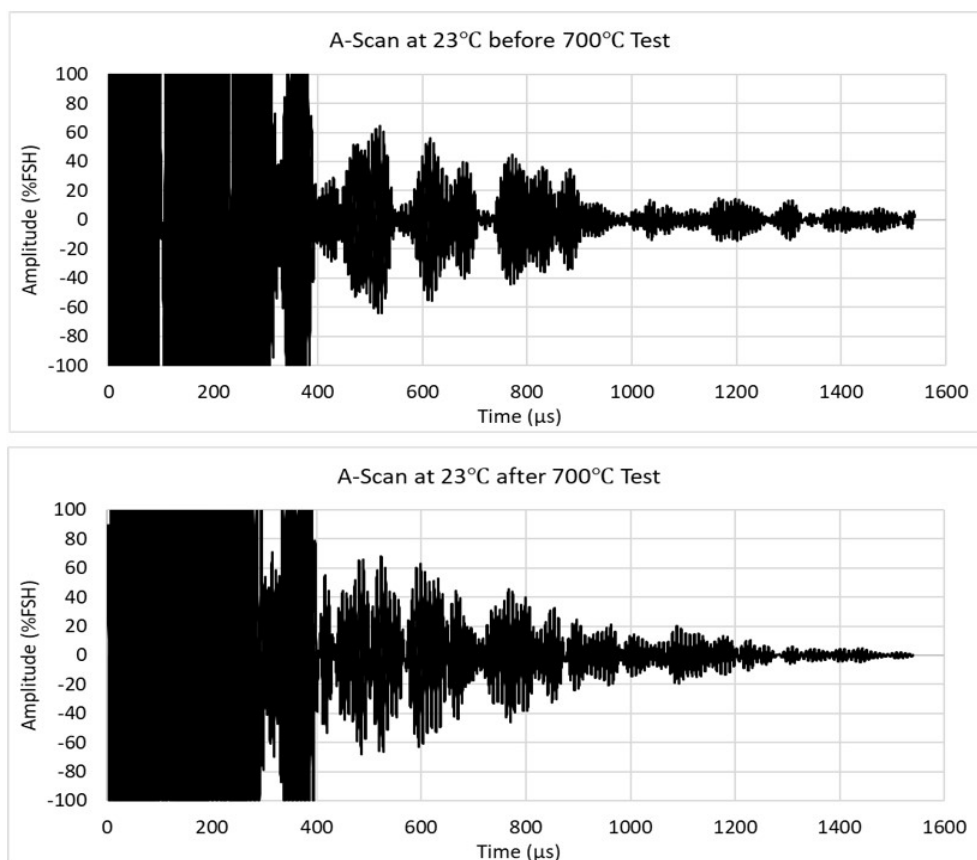


Figure 18 Long term A-scan responses at 23°C before (top) and after (bottom) long term oven test @ 700°C.

Following the long term oven test at 700°C. A visual inspection of the sensor and connecting cable was conducted. Observations were:

- Some discoloration of both the coil and magnet wire were observed – probably from surface metal oxidation.
- The ceramic wire coating insulation was cracked and significantly more brittle than prior to the high temperature test.

8.0 Plans for sensor improvements and continued research

The EMAT design and performance was reviewed by the PNNL staff and also with external experts skilled in high temperature EMAT fabrication (T-axel 2016) and with msEMAT instrumentation expertise (INNERSPEC 2020). Recommendations for improved sensor response were:

- The EMAT coil should be wound for a push/pull excitation taking advantage of the +,ground,- connection on the VOLTA EMAT instrument.
- The degraded mica wafer might be expected for exposure above 800°C. For long term operation, the wafer and coil form might be machined from Aluminum Oxide to better withstand the higher temperatures.
- The Ni wire is subject to oxidation and for extended operation (10 years or more), Ni alloys or platinum that may be a little higher in resistivity but would resist oxidation better. If the environment is argon, then oxidation will not be a problem but in air, oxidation will significantly influence wire resistance over a prolonged exposure (like 10 years or more).
- Wire insulation degradation was observed. This can be mitigated by including an alumina fiber into the insulation. This will have a drawback though of slightly increasing the wire diameter thereby limiting the number of coils that can be incorporated into the sensor.

The Cobalt magnetostrictive material did not have the expected magnetostrictive response plus the substantially nonlinear behavior as a function of temperature may complicate signal interpretation under different temperature conditions. Other magnetostrictive materials are planned to be investigated – primarily FeCo and Galfenol.

9.0 Observations and Conclusions

High Temperature Magnetostrictive EMAT does seem feasible up to 400°C with an AlNiCo permanent magnet/ Co cold sprayed sensor. The AlNiCo magnets are known to undergo irreversible reduction in magnetic strength at temperatures above 400°C and so were not tested to higher levels. The magnetic field strength at room temperature remained unchanged despite exposure from multiple data acquisition runs to 400°C.

The permanent magnet sensor response more than doubled between 25 and 250°C. Between 250 and 300°C, the response dropped but then continued to rise as the temperature approached 400°C. The sensor system at 400°C showed a persistent plate end response of 49% of the room temperature response. The 400°C temperature signal quality was also quite similar to or even slightly improved from the room temperature response. These behaviors further support feasibility of a Co msEMAT sensor up to 400°C.

Surprising differences between cold spray Ni and cold spray Co were observed. In particular, the as-sprayed Ni produced a strong magnetostrictive response but the Co (which – according to the literature should have demonstrated a stronger response) only showed a magnetostrictive response only after thermal annealing.

The two phase modes of Co (HCP and FCC) were noted by XRD in 500°C annealed, N₂ sprayed Co. Only HCP mode was observed by XRD in the 650°C, H₂ sprayed Co. XRD tests of unannealed samples were inconclusive. The magnitude of the ms. coefficient is known to vary widely between the two modes, and this may have a bearing on sensor response, but further study is required to understand phase mode influences on the sensor response.

The electromagnet sensor configuration should be able to retain a significant magnetic field well above 400°C. The electromagnet was not as strong as the permanent AlNiCo magnet but there was still a strong EMAT response up to the failure point at 889°C. Autopsy of the failed sensor showed that the lead wires to the electromagnet failed but there was also degradation of the ceramic insulation and the mica coil support wafer.

A new electromagnet sensor was re-tested for 7 days in an argon gas environment at 700°C and for an additional 3 days in air with virtually no change in the sensor response. After the long-term test at 700°C, visual inspection of the assembly showed oxidation of the Ni wire and some insulation cracking and embrittlement. Neither the mica degradation nor any lead-wire failures (after lead-wire strain-relief protection) as noted following the 889°C test-to-failure were observed. Several potential improvements to the sensor were identified but generally the tests performed confirmed the feasibility of using a cold spray Co msEMAT for long term monitoring.

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