Applied Machine Learning for Detection of Gallium Infiltration Attacks on Aluminum Alloys Common to Military Structures

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Abstract—**The proposed research is to create a real-time sensor for detecting aluminum degradation due to gallium infiltration attacks, specifically in military vehicles and structures. Gallium acts as a poison to aluminum, leading to catastrophic failures of structural integrity. The proliferation of educational material on this subject raises security concerns for the United States Military, where nearly all structures utilize aluminum due to its high-strength, light-weight profile. Utilizing fiber Bragg grating (FBG) sensors and machine learning techniques, this research aims to develop a real-time sensor to detect these attacks.**

Index Terms—**Gallium Attack, Aluminum Alloy, Structural Integrity, Cantilever Beam, fiber Bragg grating, Machine Learning**

I. INTRODUCTION

GALLIUM is pure poison to aluminum. It penetrates the protective aluminum oxide layers, disrupting the interfaces between the metal microcrystals resulting in catastrophic mechanical failures of defensive military armors. Due to the nature of our military, this interaction between gallium and aluminum poses an impending threat. Aluminum alloys are common to nearly all military structures and given that gallium can be machined into frangible bullets utilizing cheap and readily available supplies, the danger is obvious. Coupling this with the widespread evidence of the effects gallium has upon aluminum, the threat becomes immanent. To oppose this issue, optical fibers utilizing fiber Bragg gratings are proposed in order to monitor the structural health of aluminum alloys common to military structures and vehicles.

A. Aluminum Use in the Military

From the early 1900s until the present day, aluminum has been the primary material used in a wide variety of military vehicles and structures. Most recently, military combat vehicles and structures have deployed 5xxx series strain-hardenable alloys that offer similar ballistic merit to steel at a reduced weight. Military applications that require improved ballistic protection employ 7xxx series heat-treatable alloys, which offer enhanced ballistic merits compared to their steel counterparts. While strength is a large deciding factor on the materials used in military applications, several other criteria are also used to determine the optimal choice for a material selection. Strength must be maintained through the various stresses that the vehicle or structure will encounter, whether from extensive use or corrosive environments. The material must also be resistant to extreme conditions such as harsh temperatures and humidity for extended periods after being assembled. During storage, the material must retain all properties to prevent mechanical failure or corrosion. Other advantages of aluminum over other materials include its increased rigidity over steel and its lack of low-temperature embrittlement. As for the main applications of aluminum in the present-day Army, it is often used in military vehicles and structures due to its increased mobility, transportability, ease of maintenance, and the ability to deploy the vehicle or structure in aquatic situations. Support vehicles, primarily used in the transportation of materials, equipment, and personnel, are commonly built out of aluminum 5xxx series alloy sheet metal with extrusions commonly machined from aluminum alloys 6061-T6 and 6063-T5. While vehicles that will remain on the ground are typically made of aluminum sheet metal and extrusions, any vehicle that will serve as either aquatic or partially-aquatic are made of welded aluminum 5xxx series alloy. Other uses of aluminum alloys within the Army include structures such as the Army mobile floating assault bridge, the armored vehicle-launched bridge, footbridges, and common ordnance. The Army mobile floating assault bridge, which serves as a floating bridge or ferry for military vehicles, is composed of 5456-H343 aluminum sheet metal as the hull and deck and 6061-T6, 2014-T6, or I5456 alloys for the framework. The armored vehicle-launched bridge uses 6061-T6 or 2014-T6 alloys for extrusions of its structure, allowing the bridge to be lightweight enough to be mobile while still retaining the necessary strength for the structure. Any of the various footbridges in commission all use 2014-T6 extrusions that are welded to the main framework to maintain adequate strength. Overall, aluminum is seen in a wide variety of military applications due to its comparable strength and reduced weight to other metal alloys. This improved weight-to-strength ratio is extremely important for the mobility, floatability, and transportability of these vehicles and structures. While the types of aluminum alloys used in each application may vary depending on military specifications, the threat of gallium-based attacks remains constant for all cases and must be addressed proactively [2].

B. *Fiber Bragg Grating*

The proposed technology relies on two fiber Bragg grating sensors (FBG) that will be mounted orthogonal to one another. An FBG is a specialized type of Bragg reflector that has been etched into an optical fiber, allowing for the monitoring of strain and temperature changes to the mounted surface. Depending on the magnitude of the strain or temperature change, the sensor will reflect varying wavelengths of transmitted light which can then be analyzed through machine learning techniques in order to determine the location, size, and magnitude of the applied strain. Mathematically, the Bragg formula describes the wavelength shift of the reflected light:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\epsilon + (\alpha_\Lambda + \alpha_n)\Delta T \qquad (1)$$

, where λ_B is the Bragg wavelength, $\Delta\lambda_B$ is the change in the Bragg wavelength, ρ_e is strain optic coefficient, ϵ is the applied strain, α_Λ is the thermal expansion coefficient of the optical fiber, α_n is the thermo-optic coefficient, and ΔT is the change in temperature.

While there are conventional strain sensors employed by the military, the proposed technology offers significant advantages over any electrical system. First, this technology can be specifically designed and tailored to assess the progress of gallium-induced metal cracks versus those from wear-and-tear or mechanical fatigue. Next, the proposed optical fiber system is a miniature, embeddable, noninvasive, reliable, and user-friendly technology that can be mass-produced at low costs. The power consumption of this technology is minute compared to conventional systems. Additionally, the system also will allow for real-time interpretation of the test results, even when the structure or vehicle is in use. The use of fiber optics allows for transmission of sensed information over long distances in difficult environments (e.g. through small holes, underground, ect.). Lastly, since the system is based on optical fibers rather than electric wires, the system is immune to electromagnetic interference and poses no ignition threat when mounted near flammable materials or in explosive environments.

II. SUPPORTING RESEARCH AND RESULTS

The sensing technologies utilized in this project are in no way new. Bragg reflectors have been used in countless sensing technologies to gather data on strain and temperature change. The noteworthy research being conducted in this project, therefore, is the application of machine learning algorithms to the FBG sensors that enable specified detection of gallium attacks. Coupling these two established technologies allows for more robust, trustworthy results that are necessary for the strength of the US Military. However, since previous work has been conducted that explores the use of fiber Bragg gratings in structural health monitoring, this project has been built off of these findings.

A. *Structural Health Monitoring using FBGs*

Fiber Bragg grating was first demonstrated by Hill et al. in 1978 through the use of intense Argon-ion laser radiation into a germania-doped optical fiber. The researchers observed a reflection of the transmitted light that increased significantly over time, amounting to nearly all of the transmitted light within several minutes [8]. The etching in the core of the fiber, which can be thought of as a crystal lattice, acts as a stop-band filter. Thus, a narrow band of light spectrum is reflected by successive scattering from the variations in the fiber core's index [7].

Since Hill et al.'s breakthrough in 1987, one particular sector that has reaped the benefits of this technology is structural health monitoring (SHM). Numerous publications cite the use of FBG sensors as their main methodology of strain sensing and, when analyzed with algorithms, have been able to localize the damage to a structure.

Carvajal-Castrillon et al. in 2017 found implemented fiber Bragg gratings and non-supervised classification networks in order to recognize different operational conditions of the wing of an unmanned aerial vehicle. The experiment resulted in five classifications of healthy operational conditions which, according to the researchers, could eventually be developed to perform effective damage detection in the vehicle through remote monitoring [1].

Moslehi, Black, and Faridian performed a similar experiment in 2011 in an attempt to create a real-time sensor to perform non-destructive evaluation on composite wings of military aircrafts. The research found that FBG sensors outperform typical strain sensors due to its better signal to noise ratio and electromagnetic interference insensitivity [3].

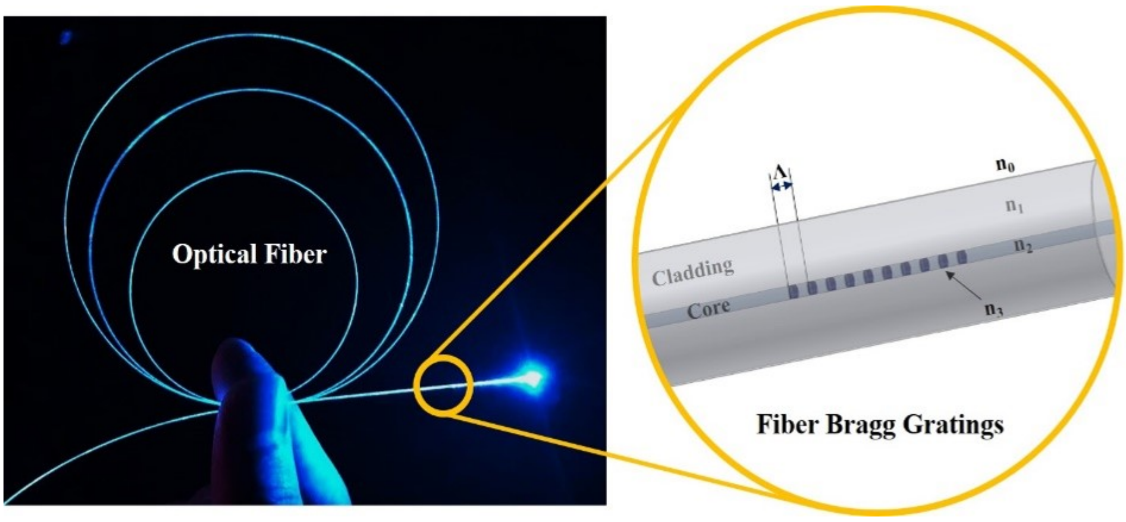

Fig. 1: Bragg reflectors are etched into the fiber core.

Kahandawa, Epaarachchi, Wang, and Lau in 2012 aimed to determine the reliability of FBG sensors within aerospace structures. Through experimentation, it was found that issues with embedding the sensor during the manufacturing process and internal damage to the fiber limit this technology to a laboratory setting, extinguishing hopes of utilizing generic FBG technology in military applications [6]. With a goal of widespread integration into military structures, reliability and durable packaging of the fiber system is crucial. One solution to the problem discussed by Kahandawa et al. is to ensure the consistent strength of the fiber itself. Davis et al. in 2012 investigated the durability of FBG sensors through various fabrication techniques. The findings of this research indicate that fibers which have the reflectors inscribed during the fiber fabrication process (referred to as Draw Tower Gratings by the authors) greatly outperform fibers that are cleaved, inscribed, and then spliced back together [4]. This finding renews the case for FBG sensors in military structures.

Each of these previous experiments displays valuable information to be used in this aim of creating a real-time sensor to detect gallium infiltration attacks. It is through these building blocks that the foundation for the gallium infiltration experiment is developed.

B. *Cantilever Beam Theory*

In order to efficiently simulate a gallium infiltration attack on a military structure, the experiment requires the aluminum alloys to experience transient vibrations so that meaningful data can be collected by the sensor. To best simulate a military structure under stress, several aluminum alloy plates will be mounted at one end to an optics table with the sensors attached on the fixed end. The opposite end will be free, essentially making the plate a cantilever beam with uniform mass. The vibrations will be induced on the free end. The exact details of this process will be discussed more thoroughly in a later section. To justify the simulation as a cantilever beam, it is easy to argue that the wing of an airplane follows the general design of a long surface with a fixed end. Thus, the experimentation and training of the machine learning algorithm will be done using a cantilever beam apparatus, although the transfer learning of the network will allow for other shapes and apparatuses to detect gallium attacks with the same ease.

To better understand the physics of a cantilever beam, this project once again relies on previous experimentation. The governing equations of a cantilever beam with uniformly distributed mass are as follows:

$$\frac{d^4Y(x)}{dx^4} - \beta^4 Y(x) = 0 \qquad (2)$$

$$\beta = \frac{\omega^2 m}{EI}, \qquad (3)$$

where $Y(x)$ is the displacement of the beam in the y direction at a distance x from the fixed end, ω is the circular natural frequency, m is the mass of the beam per unit length, E is the Young's modulus of the material, and I is the moment of inertia. The closed circular natural frequency in closed form, ω_{nf}, can be found as

$$\omega_{nf} = \alpha_n^2 \sqrt{\frac{EI}{mL^4}}, \qquad (4)$$

where L is the length of the beam, $\alpha_1 = 1.875$, $\alpha_2 = 4.694$, and $\alpha_n \approx \frac{(2n-1)pi}{2}$ $for\ n \geq 3$.

The damped frequency of the system is described as

$$\omega_d = \omega_n \sqrt{1 - \zeta^2}, \qquad (5)$$

where ζ is the damping factor, which represents the ratio of the actual damping coefficient and the critical damping coefficient.

$$\zeta = \frac{c}{c_c} = \frac{actual\ damping}{critical\ damping} \qquad (6)$$

The critical damping coefficient is simple to

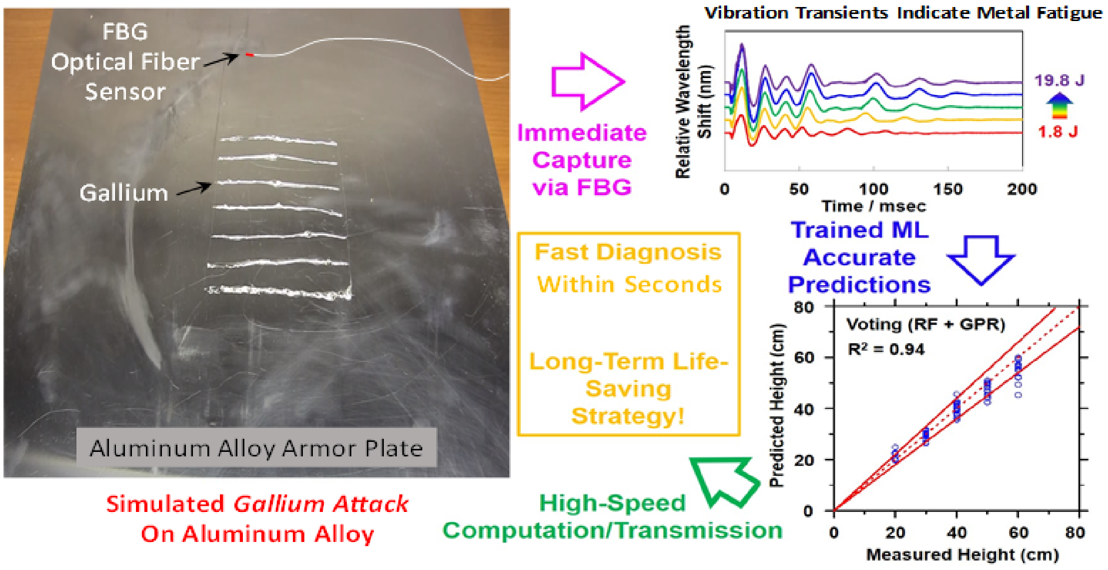

Fig. 2: Gallium-induced degradation of the alloy will be detected by the FBG, analyzed with machine learning techniques, and localized with the developed network.

determine, using

$$c_c = 2\sqrt{km} = 2\sqrt{(\frac{3EI}{L^3})m}. \tag{7}$$

In relation to gallium infiltration attacks, there is an obvious relationship between the damping factor, ζ, and gallium-induced degradation. As the aluminum plate is degraded, the actual damping of the system is expected to decrease, thus decreasing the damping factor and increasing the damped frequency, allowing it to approach the natural frequency over time. As the gallium continually corrupts the aluminum structure, the system is less damped, leading to a less stable system since it takes longer for the transient vibrations to settle. This is the clear relationship between gallium-induced degradation and the cantilever beam and illustrates why this simplified model of a gallium attack is so fruitful.

C. *Transfer Learning*

The governing principle of this research project is that of transfer learning. Transfer learning is a machine learning technique where an algorithm that is developed using one data set can be applied as a starting point or guide to another, similar data set. This allows for significantly reduced training time and increased accuracy. Research conducted by Zhang and Wang in 2020 showcase the advantages of utilizing transfer learning. In this study, a long-gauge FBG and accelerometers were used to train a convolutional neural network (CNN) to identify damage within a steel I-beam. From here, transfer learning was then implemented by holding all but the final layer in the network's weights constant and then retraining the final layer to identify damage on a similar system, namely a T-shaped concrete beam. Results showed greater than 90% accuracy in damage identification of the concrete beam, exceeding expectations of the researchers [9].

D. *Previous Experimentation from the Lightwave Technology Laboratory*

The Lightwave Technology Laboratory has performed several preliminary experiments that showcase the applications of strain measurements in various situations. Previous work includes research on traumatic brain injuries for the US Army, where a single FBG sensor was used to map 3-dimensional space through a series of machine learning algorithms. Also previously performed was preliminary tests in which a single FBG was mounted to a cantilever beam in order to verify that inducing transient vibrations in the beam will allow for proper identification of degradation within the plate through analysis of the damping factor.

III. EXPERIMENTAL DESIGN

The experimental design for the creation of the proposed technology follows three simple steps:

1) Optical fiber system assembly and verification. An optical fiber system will be assembled and then it will be verified that the system is capable of acquiring transient mechanical vibrations.
2) Machine learning algorithm selection and testing. A commercially available machine learning algorithm will be selected and tested against the mechanical vibrations. Correlation plots will be used to determine the prediction accuracies of the position and magnitude of the fatigue zones in alloys subjected to varying amounts of gallium infusions.
3) Widespread system integration planning. A plan and cost estimate to deploy the proposed optical fiber monitoring

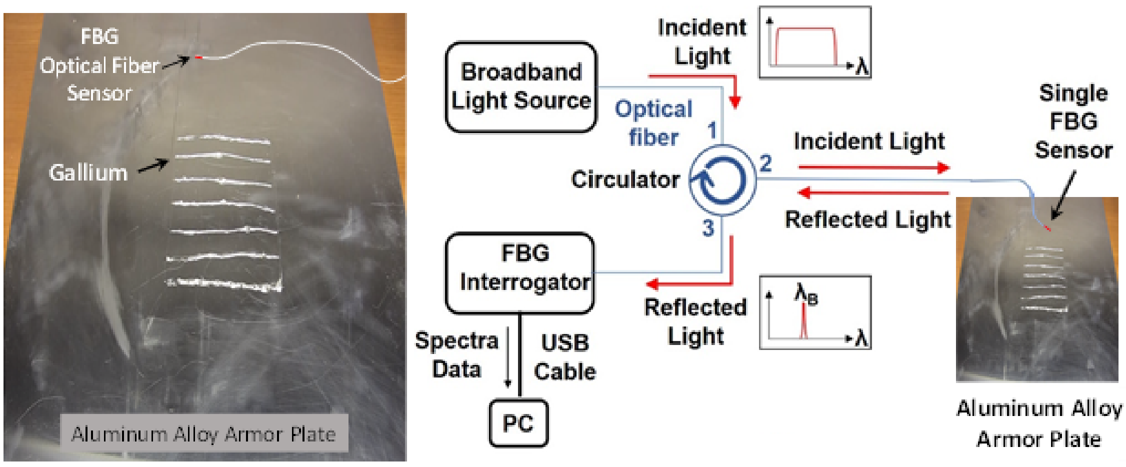

Fig. 3: A light source transmits a spectrum into the fiber's core. The Bragg wavelength is reflected back and received by the interrogator, allowing the machine learning algorithm to determine if any damage to the plate has occured.

systems in new and existing armor plates for periodic and continuous use.

Through each step, it is important to keep the end-consumer in mind. As such, the experimental design is made with the intention of using vetted systems and technologies, allowing for a more accurate collection of data and eventually a quicker large-scale implementation of this technology.

A. Optical Fiber System Assembly and Verification

The first step towards the creation of the proposed technology is to fabricate and assemble the fiber system. While the Lightwave Technology Laboratory has the capabilities to fabricate FBGs in-house, the technology will be much more consistent with military values of vetted support networks if the FBGs are produced from a reputable source that has capabilities of mass production. As such, its been decided to use prefabricated fibers with two Bragg reflectors etched into the core. With the two Bragg reflectors separated with sufficient length, the fiber can be mounted in a way that the FBG sensors intersect orthogonal, allowing for data to be captured in a 2-dimensional manner across the surface of the aluminum.

With the fiber fabricated, it is then attached to an interrogation unit that can transmit a spectrum of light and record the reflected wavelength. This experiment will be using an interrogator with an included light source produced by BaySpec [5].

From this point, the experimentation can begin. In order to effectively simulate gallium-induced degradation of aluminum, grooves will be iterative machined into several aluminum alloys of consistent dimensions. With the aluminum plate mounted as a cantilever beam and the fiber mounted in the described configuration at the center of the plate on the fixed end of the beam, data can be collected in order to determine typical characteristics of aluminum degradation. The aluminum plates measure 12" by 12" with a depth of $\frac{5}{8}$". The grooves will be machined iterative, increasing the groove depth by $\frac{1}{32}$ of an inch each time, for a total of fifteen iterations.

The collected data from the iterative groove testing will be applied to machine learning algorithms. These algorithms will characterize the vibrational data from each groove depth, allowing for accurate predictions of aluminum degradation induced by machined grooves. To apply this model to gallium attacks, transfer learning will be employed.

B. Machine Learning Algorithm Selection and Testing

Machine learning allows for the real-time interpretation of the vibrational data, resulting in better structural health monitoring. The selection and training of a machine learning algorithm is the main focus of this research. Furthermore, it is once again important to consider the consumer of this technology, namely the US Military. Doing so, the importance that tested and approved algorithms are chosen is obvious.

Before discussing the varying options of machine learning algorithms, the importance of machine learning in this specific application needs to be stressed. It would be a fair criticism of many projects to argue that machine learning is unnecessary. However, due to the vast quantity of different structures and vehicles that this technology is being developed for, it is crucial that the abilities of machine learning are utilized. For example, without machine learning, a different model would have to be developed for each circumstance that this sensing technology was deployed upon. Even small variations such as those between different aircraft models could make the sensing technology applicable to one system irrelevant to the next. By utilizing machine learning and transfer learning techniques, the technology is allowed to create a generalized algorithm that can then adapt to each circumstance that arises.

In order to best utilize the capabilities of transfer learning, this project aims to use a convolutional neural network (CNN). A CNN allows for the implementation of transfer learning, which as previously discussed will allow for fewer data sets to be collected once the gallium experiment begins. Once the vibrational data is collected from the groove experiments and a corresponding CNN has been developed, all weights of the neural network can be held constant besides those of the final layer and a new system can be trained using far fewer experiments in which actual gallium is applied to the aluminum plates. From here, the verification process is repeated and the prediction accuracies will be determined.

C. Widespread System Integration Planning

The final step in the creation of this technology will be the large-scale implementation of the sensor and machine learning algorithm within military structures. This includes the mass production of FBG sensors coupled with the interrogation unit, developed algorithm, and any software and user interface created. This turn-key solution will allow for quicker implementation and acceptance throughout the military.

IV. RESULTS & DISCUSSION

Current progress on the project is delayed due to lead times. At this point, all experimentation that has been conducted has been fairly basic. However, this unexpected time has allowed for better understanding on the topics of cantilever beam theory and the relationship between the gallium-induced degradation and the damping factor of the plate. Current work aims at creating a 3-dimensional model in COMSOL Multiphsics in order to simulate the groove experiment.

NOMENCLATURE

Abbr.	FBG	Fiber Bragg Grating
	SHM	Structural Health Monitoring
	CNN	Convolutional Neural Network
Fiber Bragg Grating	λ_B	Bragg Wavelength
	$\delta\lambda_B$	Change in Bragg Wavelength
	ρ_e	Strain Optic Coefficient
	ϵ	Applied Strain
	α_Λ	Thermal Expansion Coefficient of the Optical Fiber
	α_n	Thermo-Optic Coefficient
	T	Temperature
	ΔT	Change in Temperature
Cantilever Beam Theory	$Y(x)$	Displacement of Cantilever Beam in y direction at x distance from fixed end
	ω	Circular Natural Frequency
	m	Mass of the Beam per unit length
	E	Young's Modulus
	I	Moment of Interia
	ω_{nf}	Closed Circular Natural Frequency
	L	Length of Beam
	ω_d	Damped Frequency
	ζ	Damping Factor
	c	Damping Coefficient
	c_c	Critical Damping Coefficient

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