3D Printed Stress Sensors for Non-Destructive Evaluation of Space Structures

Perla Latorre-Suarez[1], Nya Segura-Watson[2], Rohan Madathil[3], Felix Morales[4], Vanessa D'Esposito[5], and Seetha Raghavan[6]
University of Central Florida, Orlando, Florida, USA

Self-sufficient and non-contact sensors play multiple roles in lunar, planetary exploration, and Earth structures. These sensors allow engineers to accurately examine structural integrity and defects on mechanical components for optimal operations. Structural integrity allows the industry to ensure the safety and capacity of key structures. Materials like α-alumina can be employed as sensors due to the photoluminescent properties that they possess. Piezospectroscopy is a non-destructive evaluation (NDE) method capable of capturing in-situ stress using α-alumina due to the chromium ion impurities that it contains. The chromium ion impurities carry spectral characteristics, that when excited with an Nd: YAG laser (532 nm), demonstrate capabilities for structural integrity monitoring. In this work, a 3D printing method is developed to autonomously create sensors that are compatible with use in space environments. The 3D printing method intends to provide the industry flexible and adaptive solutions for structural integrity monitoring. This method includes a modified Fused Deposition Method printer by exchanging its original nozzle with a syringe base nozzle. The printing parameters such as printing speed, printing bed temperature, coating thickness, and syringe volume are determined during the testing process. Challenges include achieving uniform integration and nanoparticle dispersion as well as adhesion between the matrix and the substrates. The parameters to encounter these challenges will depend on the materials used. Experiments with three different volume fractions (VF) of α-alumina within an epoxy were performed to address the printing challenges. The sensors were applied to nine specimens, three of each VF but with varying deposition rates after the mixture process. These experiments considered the mixing and deposition method while testing the dispersion within the α-alumina and the epoxy matrix. The substrates, on which the epoxy matrix was deposited, underwent a surface treatment to ensure adhesion between the substrate and the sensor matrix. During this experiment, the epoxy matrix was deposited with a syringe onto a substrate and cured at room temperature. The specimens were tested with a tensile load using an electromechanical MTS. While the samples are tensile loaded, the sensors were

[1] Undergraduate Student, Mechanical and Aerospace Engineering, University of Central Florida, AIAA Student Member
[2] Undergraduate Student, Mechanical and Aerospace Engineering, University of Central Florida, AIAA Student Member
[3] Undergraduate Student, Mechanical and Aerospace Engineering, University of Central Florida, AIAA Student Member
[4] Undergraduate Student, Mechanical and Aerospace Engineering, University of Central Florida, AIAA Student Member
[5] Undergraduate Student, Mechanical and Aerospace Engineering, University of Central Florida, AIAA Student Member
[6] Professor, Mechanical and Aerospace Engineering (Joint appointments CREOL and MSE, Affiliated with CATER, NSTC),
University of Central Florida, AIAA Associate Fellow, seetha.raghavan@ucf.edu

characterized via photoluminescent piezo spectroscopy to determine which VF demonstrates the best stress sensing capabilities, along with the adhesion between the matrix and the substrate. The data collected allows the optimal VF to be established for future applications.

I. Nomenclature

NDE	=	Nondestructive Evaluation
DIC	=	Digital Image Correlation
PS	=	Piezospectroscopic
FDM	=	Fused Deposition Method
SLA	=	Stereolithography

II. Introduction

The importance of developing non-intrusive sensors for structural integrity monitoring in the aerospace industry cannot be overstated. The current capability of nondestructive evaluation (NDE) methods such as Digital Image Correlation (DIC) and strain gauges are effective in many applications, although they face some limitations when evaluating strains near boundaries, crack surfaces, or near stress concentration regions deformed nonuniformly [1]. This creates a necessary niche to investigate stress sensory techniques for non-invasive and autonomous forms of stress sensing measures. Photoluminescent alumina nanoparticles within a polymer matrix, for example, can be used to evaluate stress and detect regions of damage in structural parts. A methodology of using a laser to measure piezospectroscopic (PS) behavior to determine stress can be an asset for autonomous sensing in planetary exploration and structural development in space. The PS method has the ability to assess the structure on which the sensor is placed [2]. The method allows for a more diverse portfolio of potential usage ranging from on-base to in-orbit and even on other planetary bodies. The application of this concept can be used on base to provide analysis for material testing and development. For example, load-bearing elements and reusable rockets to highlight potential fatigue issues can be tested with high-resolution sensing in a simplified way. These same elements can be expanded upon and taken to the aerospace and orbital structures, such as space stations and planetary bases and rovers [3]. A system can be designed to allow for 3D printing of sensors to be applied on the structures making it feasible to normalize in space integrity monitoring. Developing a 3D printing method that can 3D print the PS stress sensing coating will provide an NDE method that can be used in multiple roles in lunar and planetary exploration [4]. In this experiment, different volume fractions are tested to investigate the effectiveness of the application method that simulates a 3D printed sensor application. Future experiments will include testing the printing method in microgravity environments and determining the right polymer matrix to be used in different environmental conditions.

III. Stress-Sensing Theory

Photoluminescent alumina within a polymer matrix can be used to evaluate stress and detect regions of damage on structural parts. Alpha phase alumina contains chromium impurities that make the particles photoluminescent when excited with a laser. These impurities cause a piezospectroscopic (PS) behavior which is the emission spectra with stress [5,6]. The PS effect correlates the particle's stress to an observed shift in characteristic spectra lines known as R-lines, shown in Figure 1. The alpha-alumina nanoparticles within a polymer matrix undergo stress along with the underlying substrate. As shown in Figure 1, a shift in the characteristic R-lines of alpha-alumina results when a load is applied to the composite matrix. This shift takes place when the crystal field, encompassing the chromium ions within the alumina, distorts due to applied stress causing a change. Alpha alumina nanoparticles contain properties that include strength at high temperatures. The nanoparticles have shown to have the potential to adapt to conditions of a space environment [2]. Previous studies have demonstrated that the addition of particles within an epoxy matrix increases the fracture of toughness [5,6]. However, factors like particle size, particle shape, dispersion, and volume fraction need to be considered when evaluating the matrix's performance. The stress on the particles in the composite matrix also depends on the factors mentioned.

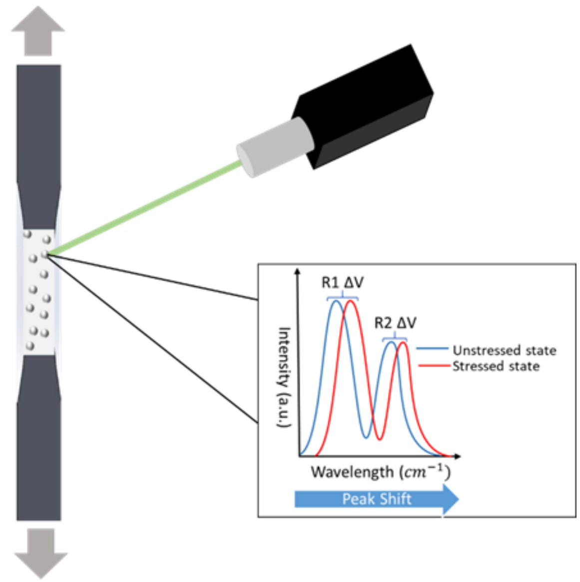


Fig. 1 Schematic of a photoluminescent coating for stress sensing with the stress characterized R-lines.

Previous research has implemented alpha-alumina nanoparticles into epoxy to create a sensor coating that would demonstrate the capability of sensing subsurface damage on underlying structural parts early on before failure [2]. The ability to sense stress on alumina embedded in epoxy has also been demonstrated. Increasing the particle volume fraction within the epoxy matrix allows for increasing the sensitivity of the sensor coating [5,6]. Based on previous studies, it was established that the minimum volume fraction of alpha-alumina with an average size of 150 nm within an epoxy that demonstrates positive sensing of mechanical properties is a 5% volume fraction. On the other hand, the maximum amount of alumina that can be added to an epoxy without the sensor demonstrating ceramic-like brittle behavior is a 43% volume fraction [5,6]. Volume fractions out of this range might affect the epoxy's mechanical properties and sensing property of the coating. Previous research has also demonstrated that as the volume fraction of the alumina nanoparticles within the epoxy matrix increase, the magnitude of emission intensity increases [2]. Additive manufacturing in space is advancing at a rapid pace at the space station and methods for in-space manufacturing of satellites, telescopes and habitable structures on a lunar base are being investigated. However, an NDE method to test these structures has not yet been determined. Developing a 3D printing method to address this need for a testing method is the focal point of this experiment. However, while the 3D printing design is being established, challenges such as adhesion, particle dispersion, and nanoparticle volume fraction need to be investigated.

IV. Experimental Design

To address the challenges experienced in the development of an in-space NDE method, a 3D printing technique is developed during this experiment. The study here is focused on the manufacturing parameters of the sensor coating. The choice of various matrix materials for space applications is still being investigated. Three different volume fractions of alpha-alumina embedded into an epoxy matrix were tested in this work. During this experiment, it is verified whether the alpha-alumina nanoparticles would disperse effectively during the syringe deposition. The nanocomposite matrix was applied to the substrate with a syringe manually at controlled rates, simulating printer motion as shown in Figure 2. Throughout this process, the bonding behavior between the nanoparticles and the epoxy matrix can be examined. These tests were performed with the purpose of determining the volume fraction that will adhere best to the substrate and have a successful emission intensity. The samples were prepared using 150 nm alpha phase alumina, epoxy EPON 828, and curing agent EPIKURE 3055. These epoxy material components have been used in previous experimentation and demonstrated positive results.

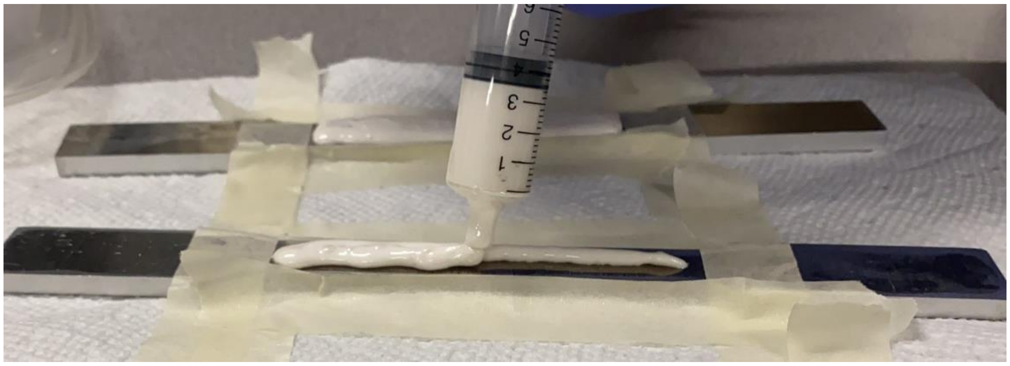


Fig. 2 Coating application with a syringe by hand

A. Printer

The ability to 3D print nanocomposite sensors will address the manufacturing challenge that is currently encountered. Different 3D printing methods were evaluated in order to determine the suitable technique to 3D print stress sensing sensors with alpha-alumina nanoparticles within an epoxy matrix. These 3D printing methods included the Fused Deposition Method (FDM), Powder bed fusion, Inkjet printing, Stereolithography (SLA), and Selective Laser Sintering [7]. However, currently, the most common printing techniques are FDM and SLA. The FDM printing technique makes use of a thermoplastic material delivered as a filament extruded through a heated nozzle and cured at room temperature. On the other hand, the SLA printing method uses a resin material, and the process is based on vat photopolymerization [7]. Therefore, it is a more complicated process compared to FDM. In order to address the manufacturing challenges encountered, and Ender 3 FDM 3D printer is modified by exchanging its actual nozzle with a syringe nozzle base. The FDM printer will still be able to print thermoplastic materials since the syringe base nozzle can be exchanged for the original nozzle anytime that is needed. Furthermore, most of the components needed for the syringe base application will be 3D printed using polylactic acid and acrylonitrile butadiene styrene filaments. While some of these components are printed with the Ender 3 printer, some others will be printed using a Matter Hacker Pulse 3D printer. This modification will allow printing viscous and customized materials. The 3D printing technique provides an application for an extensive range of materials.

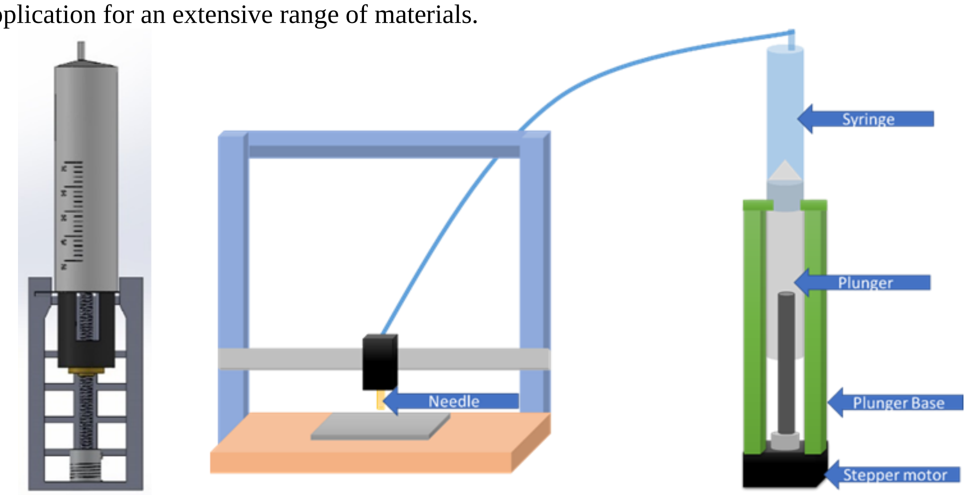


Fig. 3 Schematic of 3D Printing Methods for the stress sensors.

B. Samples

The coating mixture was prepared using 150 nm alpha-alumina, epoxy EPON 828, and the curing agent EPIKURE 3055. The three volume fractions of alpha-alumina applied to the coating were 5%, 10%, and 20%. These materials were mixed using a high-shear centrifugal mixer for a total time of 5 minutes; or until uniformly mixed. It was observed that the 20% volume fraction had a denser composition; therefore, higher volume fractions were not able to be achieved for this application method. The structural specimen used as a substrate to conduct the volume fraction experimentation of the sensor coating were customized using aluminum 2024 and the ATSM E8M-21. In order to ensure adhesion between the alpha-alumina epoxy matrix and the surface of the substrate, the specimen's surface was prepared by applying a trichloroethylene degreaser. The coating was applied with a syringe by hand, shown in Figure 2. As shown in Figure 3, the coating was applied at different times; the sample series A and B were applied at about 30 minutes after coating the mixture, while the sample series C was applied after about an hour of coating mixture. During the application process, the specimen with 10% and 20% volume fraction demonstrated to have entrapped air at the surface of the coating. This issue is considered to be due to the syringe method application and the time the coating was applied after the mixture. The longer the time, the denser the coating to be deposited. However, the 20% volume fraction applied after an hour of mixture demonstrated to have less entrapped air than the coating applied after about 30 minutes of coating mixture.

Sample Parameters			Coating Area		
ID	VF (%)	Application Time (min)	Coating + specimenThickness (mm)	Coating thickness (mm)	Width (mm)
A	5	30	6.7	1.88	12.7
B	5	30	6.7	1.88	12.7
C	5	60	6.9	2.08	12.7
A	10	30	7	2.18	12.7
B	10	30	7	2.18	12.7
C	10	60	6.8	1.98	12.7
A	20	30	7.3	2.48	12.7
B	20	30	7.2	2.38	12.7
C	20	60	6.6	1.78	12.7

Fig. 4 – Sample table with specific application parameters

C. Testing Method

The specimens were to be tested under an eight-step tensile load and loaded up to 10 kN using an electromechanical MTS machine. Zero load scans were performed in order to understand the intensity of each volume fraction and determine the testing parameters. After each load, the specimens were held at each step while scanned with the PS system, as shown in Figure 5. The sensors were scanned with laser power of 15 mW for each volume fraction. However, the exposure time for the 5% and 10% volume fraction was 50 ms, while for the 20% volume fraction was 20 ms in order to avoid saturation. The resolution used for each volume fraction was 200 micrometers, and the scanned area was 14 x 14 mm. The displacement rate for each load step was 0.15 mm/min, which took about six minutes for each load step.

Fig. 5 Sample testing with MTS machine and PS system

V. Results and Discussion

Previous research demonstrated the alpha-alumina nanoparticle volume fractions effects within an epoxy matrix. However, the application method tested in this experiment was different, and the proper amount of particles is to be determined after comparing the intensity maps of the data gathered. Figure 6 shows the intensity maps for each volume fraction at three different loads. In other words, the intensity of this maps is the emission received from the chromium ions found in the alumina nanoparticles and demonstrates how well these nanoparticles are distributed within the matrix.

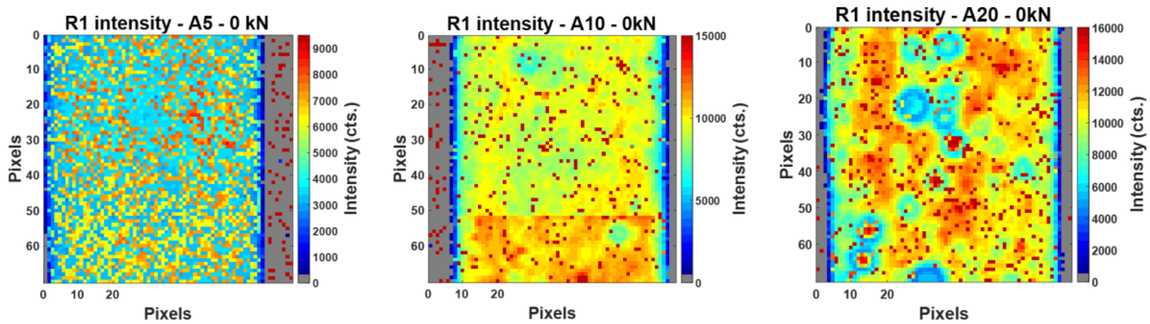
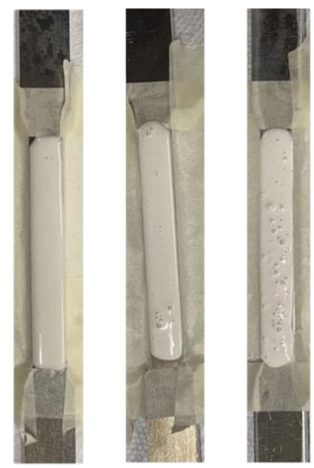


Fig. 6 Intensity results for specimens of 3 different volume fractions

Figure 6 demonstrates the distribution of the alumina nanoparticles. The 5% volume fraction specimen exhibits less intensity compared to the 10% and 20% volume fraction. This means that fewer particles are found in this volume fraction as expected. Consequently, the low intensity may not be ideal for tracking the emissions for stress sensing. The 10% volume fraction is seen to have better dispersion than the 20% volume fraction. The 20% volume fraction sample demonstrated more particle agglomeration or red regions due to the high viscosity that this volume fraction the matrix exhibited as seen in Fig 6. However, the 20% volume fraction was seen to exhibit more bubbles at the surface of the sample as seen in Fig 7. The reason that the 10% volume fraction is thought to have better nanoparticle dispersion is due to the lower viscosity of the material when it was mixed. The greater the volume fraction of alumina nanoparticles, the more difficult the ability to mix it within the matrix for uniform dispersion.



5 % Volume Fraction | **10 % Volume Fraction** | **20 % Volume Fraction**

Fig. 7 Coating images

The sensors were applied after about 30 minutes of manufacturing coating mixture, allowing the mixture be less viscous and with the possibility of having less air entrapped. The data shown here for the intensity studies were taken at no load. Data from this experiment is still in the analysis process. The shifts of the emission R-lines as the samples were loaded will be analyzed next to determine the particle's behavior with the applied load.

VI. Conclusion

The study presented a method for 3D printing a sensor coating on a substrate structure. Among the 3 volume fractions of alumina investigated, although the 20% volume fraction demonstrated better intensity results, the 10% volume fraction demonstrated better dispersion and less agglomeration. During this analysis, the effects of the coating particle dispersion and the effects of the coating application time was determined and studied. Future work will include establishing a more effective way of ensuring particle dispersion through the epoxy matrix after application. Furthermore, future work also includes determining how to eliminate the entrapped air in the epoxy when added to the syringe and deposited into the substrate to avoid the formation of bubbles. Future testing will incorporate testing the 3D printing process in microgravity while investigating various material options to 3D print in space and the curing process.

Acknowledgments

This experimental work is supported by the NASA MINDS program. The work is based on studies and methods developed from projects under the National Science Foundation under Grant Nos. IIP 1701983 and CMMI 1130837.

References

[1] Yoneyama, S., & Murasawa, G. (2009). Digital image correlation. Experimental mechanics, 207.

[2] S. Raghavan and P.K. Imbrie, “The development of photo stimulated luminescence spectroscopy for 3D stress measurements in the thermally grown oxide layer of thermal barrier coatings” Proc. Mater. Sci. Technol., 2056-2067, 2007

[3] Musso, G., Lentini, G., Enrietti, L., Volpe, C., Ambrosio, E. P., Lorusso, M., ... & Valentini, G. (2016). Portable on orbit printer 3D: 1st European additive manufacturing machine on international space station. In Advances in Physical Ergonomics and Human Factors (pp. 643-655). Springer, Cham.

[4] Waller, J. M., Saulsberry, R. L., Parker, B. H., Hodges, K. L., Burke, E. R., & Taminger, K. M. (2015, March). Summary of NDE of additive manufacturing efforts in NASA. In AIP Conference Proceedings (Vol. 1650, No. 1, pp. 51-62). American Institute of Physics.

[5] A. Stevenson, A. Jones, and S. Raghavan, “Stress-sensing nanomaterial calibrated with photostimulated luminescence emission,” Nano letters 11(8), 3274–3278 (2011).

[6] Gregory Freihofer, Joshua Dustin, Hong Tat, Axel Schülzgen, Seetha Raghavan, “Stress and structural damage sensing piezospectroscopic coatings validated with digital image correlation”, AIP Advances 5 (3), 037139, 2015

[7] Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering, 143, 172-196.