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ENVIROMENT TESTING 3D ELECTRONICS RESEARCH PROGRAM

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Final Report

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14. ABSTRACT
Research grant was designed to investigate additive manufacturing processes using new materials to determine advantages and disadvantages to using specific types of materialsand printing processes for space applications. Results show that although great advances have been made, printing of entire satellites is still probably not possible at thistime.

15. SUBJECT TERMS
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1. Summary

This was a three year activity for a total dollar amount of approximately $450,000. The focus of this work was to investigate new research areas related to three dimensional (3D) printing for space applications. A big portion of this work was related to printing a wide variety of different materials and then testing them in space conditions to determine changes in mass and other factors to help to determine which parts have the greatest possibility for future flight survivability.

2. Introduction

The COSMIAC Research Center at the University of New Mexico (UNM) proposes to perform research related to printing and testing electronics that have been embedded into 3D fabricated systems. The future of space electronics is often related to things presented in the Star Trek television show. In particular, the development of the Enterprise's replicator – creating something from just a description. Great advances have occurred in the past year related to 3D printing, otherwise known as additive manufacturing (AM). In AM, a solid device is created by adding very thin layers of material over time until a complete (and often complex) structure is created. This is a very common practice and the proposing team does this type of work daily. The next step was to delay the printing process long enough to be able to embed wiring and electronics. An example of this type of experiment could be a soldier's helmet where the electronics that monitor health and location are embedded into the material from which the helmet is created. The designer could reduce or eliminate much of the traditional spider web of wiring. In traditional satellite design, if any of the wires are crimped or broken, the satellite is rendered inoperative. There is no redundancy in flight. A much more reliable solution would be a satellite where all the wiring is embedded into the structural walls where it cannot be accessed or damaged. It should be possible to plug in the modules to an embedded backplane.

We used the provided funds to complete three major research goals:

1. Design and print simple prototypes with hybrid materials, embedded chips and wiring.
2. Test the designed circuits using COSMIAC's in-house testing capabilities.
3. Publish the results for dissemination.

3. Methods, Assumptions and Procedures

The team has made excellent progress to date. AM continues to be a dynamic and growing research rich field. The team has experimented with (and tested) a wide variety of different AM processes. A significant amount of effort has been extended in the area of embedding chips and wiring into structures and testing them. Assumptions have to be that all work that could be done should be done with what was considered state of the art materials and processes at the time of the project and that all testing would be accomplished utilizing available equipment and standard analysis techniques.

3.1 Goal 1: Design and print simple prototypes with embedded chips and wiring. Much of this work was done in conjunction with the University of Texas (El Paso) Keck Center and with the team from the University of Southern California. The first sets of boards have been designed. One example is the RadSat panel shown in Figure 1. This board has an accelerometer, Bluetooth module and an MSP-430 processing module. The system was printed using a Fused Deposition Modeling (FDM) hybrid system. There are two independent processes that were combined to create this system.

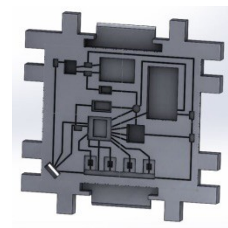

Figure 1: RadSat Image

The first is a printed circuit board (PCB) design process using a package called Eagle. Eagle is used to create two different files. The first is a schematic. This shows what electronic parts were included in the PCB design and how they were connected together. The second file is a combination of board files that are used by a PCB design and fabrication facility to actually create the plastic circuit boards. The board files are Gerber files. The Gerber format is an open two dimension (2D) binary vector image file format. It is the de facto standard used by PCB industry software to describe the printed circuit board images: copper layers, solder mask, legend, etc. The standard file extension is .GBR or .gbr though other extensions are also used. In RadSat, the gerber files were the final output.

The second sets of files are the 3D design files. These files are created using the Solidworks design environment. Solidworks is used to pictorially and dimensionally describe a product. In the case of RadSat, it was how thick, wide and tall the individual piece was. Stereolithography (STL) is a file format native to the computer aided design (CAD) software created by 3D systems. STL has several after-the-fact acronyms such as "Standard Triangle Language" and "Standard Tessellation Language." The STL file is what is fed into the 3D printing machine.

The next phase of the activity was the merging of the gerber files and the STL files. There is currently no automated or electronic system to accomplish this. This is a major problem that has consumed a lot of time. Currently, to create a system like the one shown in Figure 1, the printing process has to be halted and then a lot of manual labor is extended to micro machine and mill out the spots for the electronic chips as well as making the spaces for the wiring. Once the parts are placed and the wiring run, the connections are made with precise laser welds. After this part of the activity is complete, the part is returned to the printer for continued printing in the AM process. The team printed several different parts and tested for robustness. Items such as injected or liquid solder were tested but always when the boards were bent in any shape (common with vibrational testing for flight), the solder runs either broke or failed. Even when they are performing at their best, the conductivity is never as good as real wire. As of the conclusion of this project, the PI still believes this technology is still approximately ten years away from common acceptance and use even in the world of rapid nanosatellite development. The problem is in two areas. First is the printing process.

Today's printers are not of high enough quality to be able to produce space qualified and repeatable results. To print today, each item printed would need to be put through a space qualification process and the thoughts that two identical parts printed on the same machine with the same material are "the same" is unrealistic. The other major hurdle is the software to merge gerber files (such as those produced by Eagle) and mechanical files (such as those produced by Solidworks) just doesn't exist today.

In addition, COSMIAC has also teamed with the University of Southern California to perform additional design and testing along these areas.

3.1.1 Experimental Studies

An apparatus for the free-space characterization of dielectric materials was developed to study the interactions of low power W-band (75-110GHz) millimeter-waves with various materials including polymers and ceramic samples. Measurements of the complex dielectric constant, loss tangent, and scattering parameters will be used to study the effects of millimeter-wave absorption and related electromagnetic interactions applicable to 3D printed materials, power beaming, and heat exchangers. In addition, dielectric and absorption measurements will be applied to higher temperature (up to 2000C) and higher power (up to 100kW) experimental setups to identify materials of interest for scaled beamed energy heat exchangers and provide inputs for future experiments in millimeter-wave dielectric heating for high temperature aerospace and industrial beamed energy processes. These experiments examined high temperature millimeter-wave interactions in materials and will be important to current research in the effects of directed energy on radomes and aerospace materials, materials processing, and beamed energy applications using millimeter-wave sources such as a 100kW-class, 94GHz gyrotron adapted from other technology.

3.1.2 Item 1: Free Space Gaussian Beam Experiment

The interaction of high power millimeter-waves with high temperature heat exchanger materials requires the complex values of the dielectric constant throughout the temperature and wavelength ranges of the heating experiment. However, the dielectric constant and loss tangent behavior of bulk ceramics and materials as a function of temperature are largely unknown for millimeter- wave frequencies, but is an important characteristic for power absorption in a device undergoing electromagnetic heating. The free space experiment configuration developed here measures intrinsic electromagnetic properties, including the temperature-dependent permittivity and dielectric loss factor as part of a study of dielectric heating effects of beamed energy millimeter- waves incident on industrial materials as well as high temperature refractory materials. In addition, a range of dielectric ceramics with different compositions and properties will be fabricated, and the thermal, mechanical, and microstructural properties were characterized to relate millimeter-wave power absorption to basic material properties.

3.1.3 Item 2: S-Parameter Conversion Techniques

The S-parameters for each test material were measured in a two-port and calibrated free-space electromagnetic beam setup, and numerically converted to the real and imaginary parts of permittivity. Constructive interference occurs where there are an integer number of half-wavelengths within the thickness of the sample and maximum transmission occurs at the half-wavelength resonant frequency. Complex permittivity and permeability is calculated from S11 and S21 parameters using least squares fitting to the transmission line equations. The minimized error between the fitted S21 magnitude parameter and the S21 measurement is calculated to provide an estimation of complex permittivity, and the phase as a second measurement for point by point fitting. Another common numerical technique for calculating complex permittivity from the transmission and reflection coefficients is the Nicholson-Ross-Weir model, which is typically used in waveguide permittivity measurements but can be applied to the free-space measurement setup. However, half-wavelength discontinuities in the S21 phase commonly occur in thicker test samples and can be difficult to account for in the numerical solution.

3.1.4 Item 3: Manufacture and Layout of Test Samples

Classes of materials for these initial millimeter-wave measurements include common polymers, ceramics with controlled composition and material properties, and materials applicable to 3D printing. Teflon, Alumina, and chlorinated polyvinyl chloride are used as comparison cases to previously measured millimeter-wave dielectric constants measured by other methods such as interferometry or waveguides present in literature. Initial samples for 3D printing include the common polyactide (PLA), polyamide, nylon, and Acrylonitrile Butadiene Styrene (ABS), and will include industrially available samples. The free space setup is also modifiable to incorporate powders in a crucible composed of two Teflon discs, and a scattering matrix can be solved to calculate the reflection and transmission coefficients of the powder sample. The millimeter-wave absorption and dielectric properties of these materials have been tested at room temperature and are currently in the process of measurement at room temperature and higher temperatures up to 1200C in a tube furnace.

3.1.5 Modeling Studies

The classical molecular dynamics (MD) simulation method has been applied to study the microwave heating of dielectric materials. The studies were mainly focused on the MD study of Al2O3 (alumina). In particular, we were interested to understand how the heating process responds to different field intensities, frequencies, directions as well as the materials purities.

The interatomic potential is the key to carry out MD simulations correctly and accurately. The interatomic potential used for Al2O3 consists of Buckingham potential and Coulombic interactions between each ion. The validation of this potential was tested by comparing our simulations with experimental data as well as other simulation results in the literature.

Effective heating of the system due to the alternating electric fields has been observed by MD simulations. It is believed that the mechanism of dielectric heating is mainly due to the response of the dipoles lagging behind the external alternating field. The direct measurement of the phase delay of the system's total dipole moments was conducted by the MD simulations. What was observed was that the phase delay increases as the temperature of the system increases. This is consistent with our observation of the increase of heating rate with the temperature. It is also observed that the absorbed energy is used to increase the shortrange (Buckingham) potential energy as well as the system's kinetic energy (temperature). The change of Coulomb energy is negligible compared with the other two.

For the effects of different frequencies, simulations show that higher frequencies can heat the system up more easily. This is because the system would experience more oscillating periods within a given time interval, and thus receive more energy deposition. We also applied the E-field along different axes (a- and c-axis) of the α-Al_2O_3 crystal. Our MD results reveal the microwave heating behavior of α-Al_2O_3 is heterogeneous.

A series of MD simulations were conducted to compute the loss tangent with different electric field frequencies and different purities of the materials. We compared our preliminary simulation results with a number of experimental data available in the literature. The comparison between our MD predicted loss tangent and Martin Hilario's measurement is satisfactory.

3.2 Goal 2: Test the designed circuits using COSMIAC's in-house testing capabilities as well as with AFRL's thermal vacuum chamber. Testing was accomplished using COSMIAC's bake oven on site and the thermal vacuum chambers in building 277 and building 595 on Kirtland Air Force Base. For printing diversity, COSMIAC now has three distinct types of printers. The first is the inexpensive Makerbots which provide an excellent ability to print prototypes. Quality and precision are not exceptional but they are good for rough part printing. The second one is from the Stratasys Corporation (model name is uPrint). Like the Makerbot, it is also a Fused Deposition Modeling (FDM) type system but since the build area is controlled and heated, the quality of the printed products is much superior. The Center also acquired a 3D Systems ProJet 3500 printer. This printer uses two materials like the UPrint but in the case of the 3D System printer, the material is laid down and then immediately cured with a UV light thus creating a much harder and more reliable printed product. Once the part is complete, it is put in the bake oven and support material is melted away. To test the various printers' capabilities, a model 6U CubeSat satellite was obtained where every component was printed (see Figure 2). This process was an excellent opportunity for the students to see how to print a satellite body and then be able to use the components for performing fit checks on the modules and their associated hole and thread

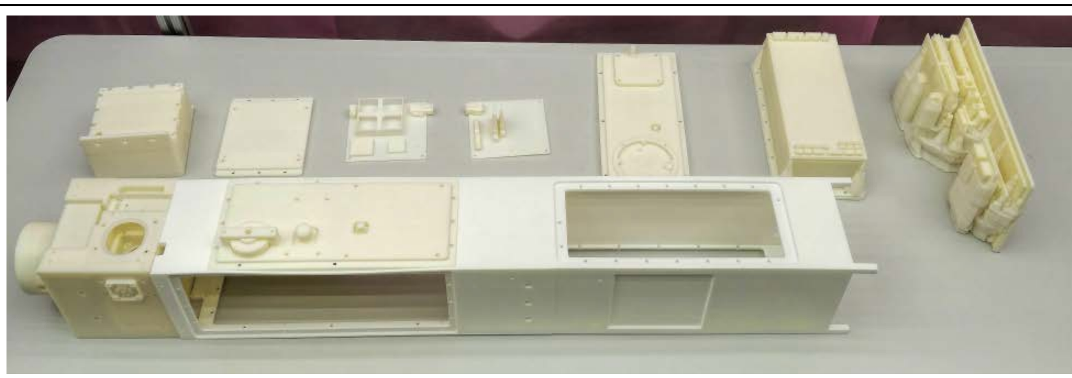

Figure 2. 3D Printed Satellite

spacing. The satellite shown was then used to make measurements for determining how long to make cables for the real satellite.

COSMIAC personnel have also taken printed circuit boards and have put them in the thermal vacuum chamber (under space level atmospheric conditions of 10^{-6} torr) at 60 degrees Celsius for six hours. The team printed six each identical objects made from 16 different materials. The test article used for printing is shown in figure 3. Three of the objects (of each material) were placed into a humidor for controlled temperature and humidity. They were kept in this humidor at 70% of relative humidity for six months. The remaining three each items from the 15 different materials were tested. There were four measurements that were done on each piece: mass, Residual Gas Analyzer, Quartz Crystal Microbalance, and Fourier Transform Infrared Spectroscopy (was only done on one of three pieces due to cost constraints). For the Spectroscopy testing, a small aluminum plate (contamination plate) was placed in a stainless steel can. This contamination plate was shipped to Texas for testing after the outgassing.

The following materials were the items that were tested as part of this activity. Assistance in this activity was provided by Dr. Eric MacDonald from the University of El Paso's Keck Center. Their expertise in the printing of these unique materials was essential to the success of the activity.

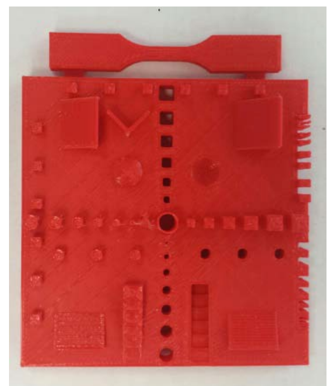

Figure 3. Test Piece

1 ABS ESD7
2 PC-ABS
3 PC-10
4 ASA
5 Nylon 12
6 Ultem 9085
7 Ultem 1010
8 Somos Next
9 Prototherm 12120
10 Nanoform 15120
11 Somos Nanotool
12 Digital ABS Green
13 Durus White (RGD450)
14 DuraForm EX
15 DuraForm PA
16 Somos WaterShed 11122

As can be seen from the charts in Figure 4 and Figure 5, some materials such as the FDM materials had a significant amount of moisture change whereas the SLA materials didn't (making them more favorable for space applications).

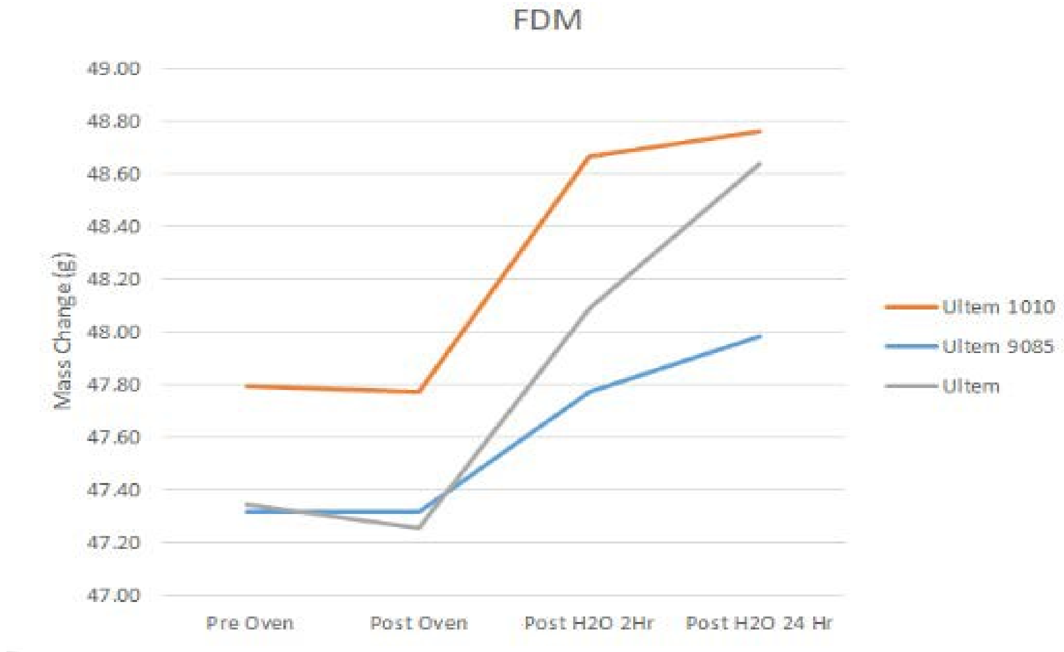

Figure 4. FDM Absorption Results

Figure 5. SLA Absorption Results

3.3 Goal 3: Publish the results for dissemination was an important activity for this grant. The RadSat board was taken to the SmallSat Conference in Logan, UT (in 2015) for demonstration purposes. Meetings were held at the 2016 CubeSat Workshop and the SmallSat Conference for NASA Ames and AFRL personnel to update them on current test results as well as plans ahead for future testing. Paper submissions were forwarded for the 2016 event but they were not accepted for full papers.

4. Results and Discussions

The team achieved the original objectives as well as going into other areas of investigation that were of interest to the space community as more and more spacecraft activities are looking to use 3D printing for satellite development. The outcome is that excellent advances have been made in the areas of 3D printing for space but that the ability to print space qualified and repeatable systems for future nanosatellite applications is still probably a decade in the future.

The team met established goals. There were no cost overruns on this activity.

5. Conclusions

The overarching conclusion to this work revolved around the understanding that additive manufacturing is not quite ready for use in government missions today for actual flight. There is specific merit in the printing process though. By 3D printing the prototypes, insight can be obtained in terms of measurements for cable lengths and for fit checks for the various components in the satellite system. Additionally, the ability to repeatably print space qualified items is questionable. By printing on printer "A" with material "B" and then qualifying the part for flight. If another identical part is printed with the same printer and material, there is no guarantee that the part will not have differences in dimensions and density to allow for mass production of modules to perform flight. Additionally, the ability to print wiring and electronics into the 3D printing process is still at the early stages. There are very few organizations that have the resources and ability to create the massive systems that will be required to remove an item at a specified point in the printing process, add chips and wiring, and then return the item to the printing process with the confidence that what will be completed will have the same quality of workmanship.

Acronyms

2D – Two Dimensional
3D – Three Dimensional
ABS – Acrylonitrile Butadiene Styrene
AFRL – Air Force Research Laboratory
AM – Additive Manufacturing
CAD – Computer Aided Design
FDM – Fused Deposition Modeling
MD – Molecular Dynamics
PCB – Printed Circuit Board
PLA – Polyactide
STL – Stereolithography
UNM – University of New Mexico

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