National Aeronautics and Space Administration

FY25 Strategic University Research Partnership (SURP)

Nonconductive Conductors: Heat Pipes for High Voltage Systems

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Strategic Focus Areas
Thermal Control Systems
Electric Propulsion

Background

Hall Effect Thruster (HET) performance is currently limited by thermal management, specifically the need to protect low-temperature components (e.g., magnetic coils < 500°C) and maintain electrical isolation between parts. These constraints preclude many traditional thermal solutions, creating a need for a high-thermal-conductivity, electrically insulating material to enable higher-performance, lower-mass designs.

Concurrently, ceramic additive manufacturing (AM), particularly Digital Light Processing (DLP), is a burgeoning field. DLP uses UV light to cure ceramic-resin slurries, producing complex, high-density (~99%) parts. This technology enables the fabrication of advanced non-oxide ceramics, like Aluminum Nitride (AlN), which offer high dielectric strength and thermal shock resistance, making them ideal candidates for these demanding aerospace applications.

Objectives

Existing high-thermal-conductivity heat transfer devices are also electrically conductive. Parts which must be electrically isolated (such as the anode and cathode in an electric thruster) require either layers of low-thermal conductivity electrical insulation or entirely separate thermal management systems, both of which increase complexity and reduce performance. AM Ceramic heat pipes would simplify and enhance thermal management between electrically isolated systems. This project will see the combination of JPL's knowledge of additive heat pipes and thermal management technology with Cornell's unique approach to printing high precision technical ceramics.

Approach & Results

We pursued two complementary strategies: (1) optimizing the binder system and (2) modifying the ceramic particle surface. We found the binder is not just a structural medium; it critically determines printability, sintering, and final mechanical/thermal properties.

To investigate debinding, single-monomer slurries were used to identify defect origins. We identified two types: interlayer delamination (Z-direction) and intralayer cracking (XY-plane), driven primarily by gas pressure from binder decomposition and thermal expansion mismatch.

Failure analysis showed that binder mechanical properties (eg, Young's modulus, elongation at break) govern stress development. Stiffer binders led to fine micro-cracks, while low elongation at break suppressed delamination.

This analysis yielded an optimized binder (20 wt% PPGDA, 30 wt% PEGDA, 50 wt% 2HEA) with minimal delamination. With alumina, this formulation achieved 96% relative density, 118 MPa flexural strength, and 18.88 W/m·K thermal conductivity (Fig. 1).

In parallel, we addressed the poor UV curing-depth of aluminum nitride (AlN) caused by its high optical absorption. A silane-based surface treatment (AAPS) was applied, improving particle dispersion, reducing slurry viscosity, and lowering optical scattering. This increased the curing depth by over threefold, enabling stable printing of larger components (Fig. 2).

Figure 1. Effect of PEGDA/2HEA ratio (with 20 wt% PPGDA constant) on cracking behavior, flexural strength, and thermal conductivity of alumina composites.

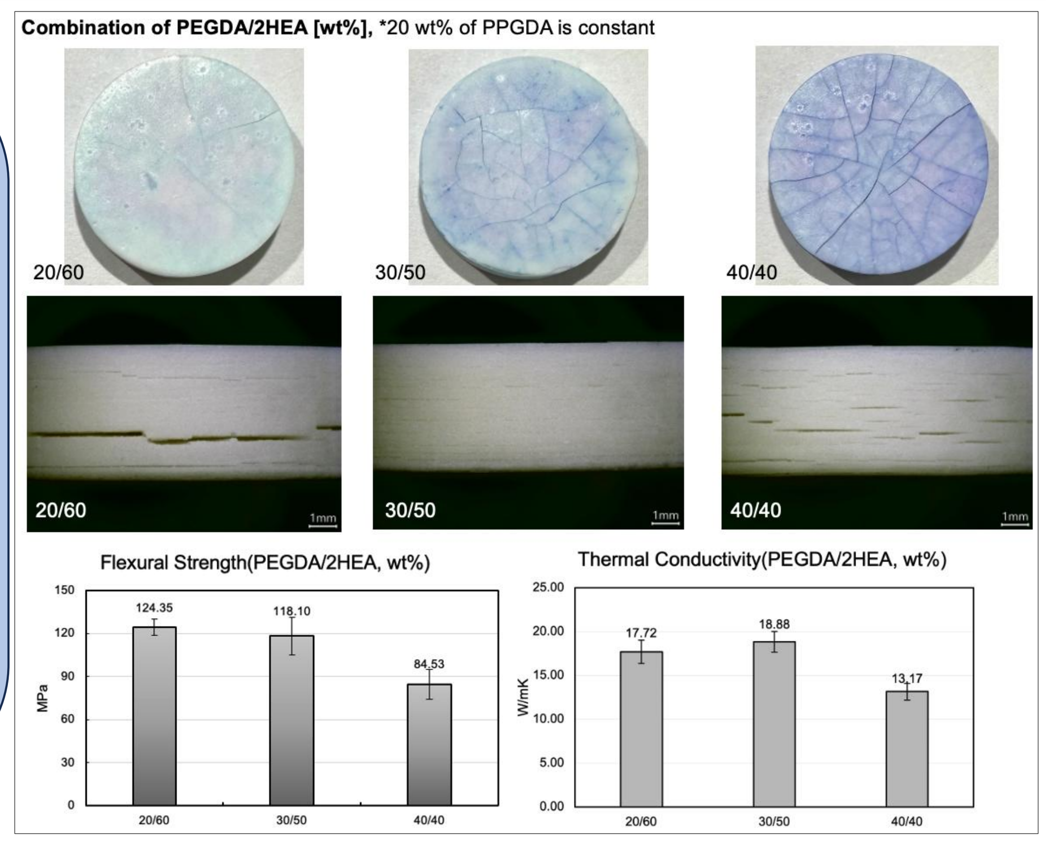
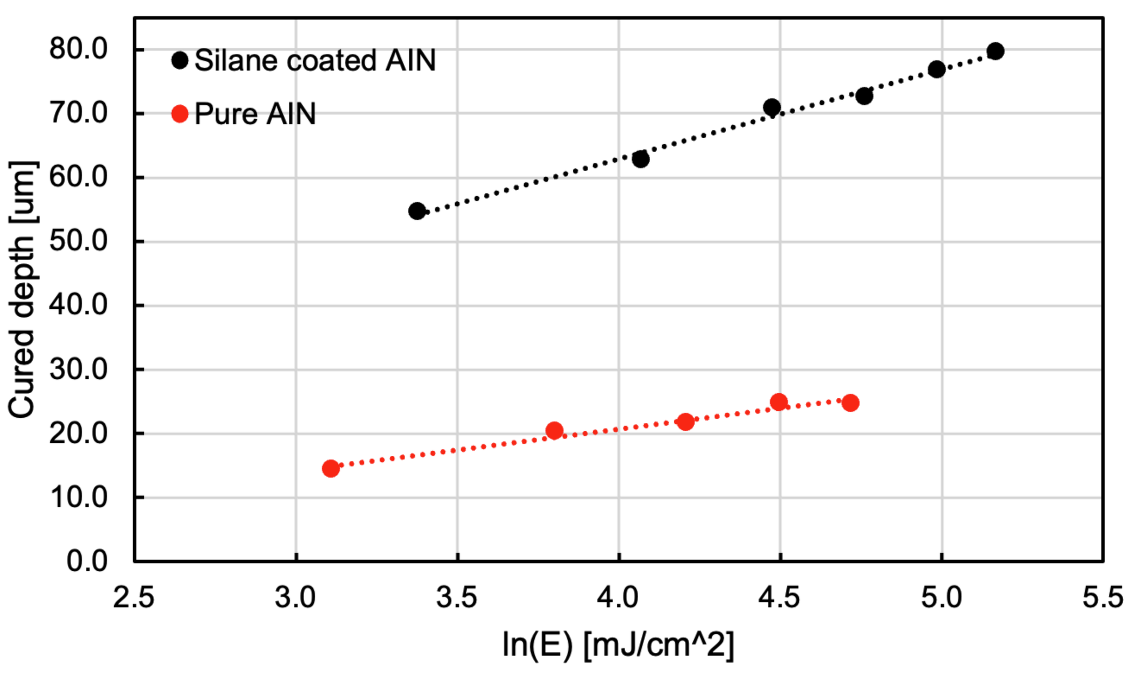


Figure 2. Comparison of cured depth as a function of exposure energy for pure and silane-coated AlN, showing over threefold improvement in curing depth after AAPS surface treatment.



Benefit to JPL & NASA

While JPL has previously flown 3d printed ceramics onboard its missions (a wire isolator onboard Curiosity), they are still seen as a high risk technology. This project will demonstrate the feasibility of fabricating engineering ceramics with high thermal conductivity (> 100 W/m-K) while performing as electrical insulators. On their own, these would greatly simplify thermal management of electrical systems, eliminating the need for electrically insulating layers or structures to prevent electrical shorting. However, this project will also demonstrate the feasibility of integrated heat pipes made from conductive ceramics. These will offer effective conductivities in excess of 5,000 W/m-K, providing an entirely new class of thermal management devices which can be integrated directly into structures. These technologies are not only interesting to JPL/NASA for electric propulsion systems, avionics thermal management, instrument systems, and low CTE thermal straps, but also to the department of energy for high temperature heat pipes, for managing fusion reactors or low temperature heat pipes for particle accelerators. One could imagine a future technology where a superconductor, e.g. YBCO, is printed by Cornell's process, along with internal heat pipe structures to also enable it to become an extremely good thermal conductor as well.

This project will also be complementary to JPL's current R&TD task on integrating oscillating heat pipes into electric propulsion systems. This project builds off of our expertise in additively manufacturing Hiperco, a Fe/Co alloy with high magnetic saturation. While these OHPs can offer two orders of magnitude improvement in thermal conductivity to the Hiperco itself, it still requires highly tortuous paths for heat flow, as the heat pipes must be fully contained within the anode or cathode. The ability to create an electrically insulating, highly thermally conducting bridge between the anode and cathode will simplify thermal design, allow for more direct heat flow, and continue to push JPL's EP systems to be world leading.

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None yet

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