Materials and Processes for New Propulsion Systems with Reduced Environmental Impact

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ABSTRACT

Aeronautics research at NASA Glenn Research Center includes development, characterization and modeling of high temperature, lightweight materials and fabrication processes for aircraft propulsion systems with increased efficiency and reduced emissions, fuel burn and noise. Current materials research includes Ceramic Matrix Composites with Environmental Barrier Coatings, Polymer Matrix Composites and Additive Manufacturing processes. This presentation will summarize recent progress and plans in these areas.

Keywords: Materials; Propulsion; Ceramics; Polymers; Composites

1.0 BACKGROUND

This paper summarizes recent advancements in propulsion materials research at NASA Glenn Research Center. Progress is reviewed toward the development and demonstration of high temperature, lightweight materials and fabrication processes that will accelerate the implementation of these materials into more efficient aircraft engines.

2.0 CERAMIC MATRIX COMPOSITES

With the recent introduction of Ceramic Matrix Composites into commercial aircraft engines, a range of new opportunities is available for reducing the impact of aircraft on the environment. The capability of current state-of-the-art commercial CMC components to operate at higher temperatures (2400 °F) than metals will reduce cooling requirements for engine components, increasing overall efficiency with corresponding reductions in fuel burned and emissions generated.

The mission of NASA is to develop materials technologies that will enable the next generation of high temperature materials, beyond current state-of-the-art capabilities. To address that goal, Glenn Research Center has developed Ceramic Matrix Composites for 2700°F operation in turbine engine components for the next generation of efficient aircraft. System studies have shown that incorporating a 2700°F CMC into engine hot section components would result in a 6% reduction in aircraft fuel burn and 30% reduction in engine emissions, compared to an all-metal hot section. The NASA 2700°F CMC is enabled by a series of advancements to the fiber and matrix constituents.

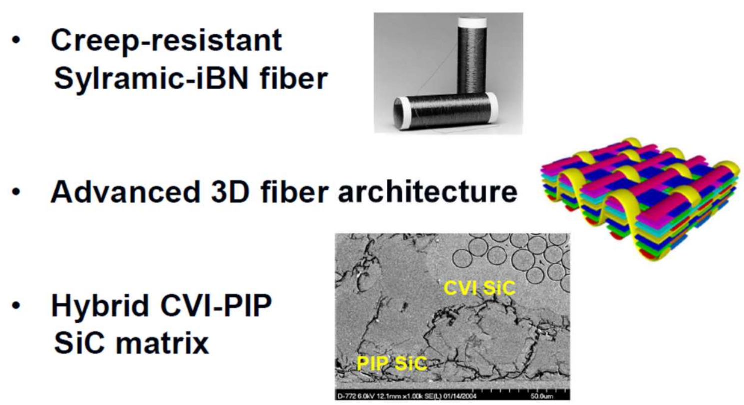
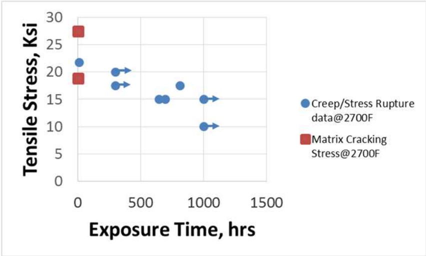


Figure 1: NASA 2700ºF Ceramic Matrix Composite incorporates advanced fiber & matrix constituents for increased operating temperature, reduced turbine cooling requirement and improved engine efficiency

These advancements include:

- Creep-Resistant “Sylramic-iBN” fibers [1]
- Strong and Damage-Tolerant 3-D woven fiber architecture [2]
- Durable “Hybrid” SiC matrix composition, using both Chemical Vapor Infiltration and Polymer Infiltration & Pyrolysis processes

High temperature durability tests conducted as part of the Transformational Tools and Technologies project in NASA’s Aeronautics Research Mission Directorate has demonstrated [3] that these three technology advancements can be combined to form a strong, durable Ceramic Matrix Composite with over 1000 hour life at temperatures up to 2700ºF under creep and fatigue loading up to 20 ksi.



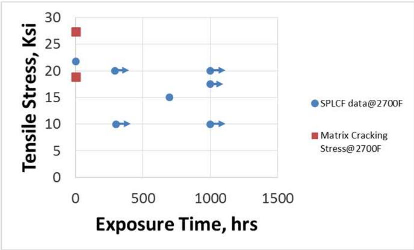


Figure 2: CMC has 1000+ hours durability at 2700ºF and 20 ksi in creep (left) and fatigue

Ceramic Matrix Composites require an Environmental Barrier Coating for long-term operation in a turbine engine environment. Therefore, an essential element of a feasible CMC material system for turbine engine applications is an Environmental Barrier Coating capable of protecting the underlying CMC from environmental attack during long-term engine operation.

3.0 ENVIRONMENTAL BARRIER COATINGS

Extensive development of SiC/SiC CMCs has led to the introduction of turbine hot section components such as CMC shrouds, combustor liners, and vanes into commercial engines with blades soon to follow. Dense slow-growing silica scale is responsible for the excellent oxidation resistance of CMCs, however volatilization of SiO_2 scale by water vapor generated during jet fuel-air combustion and the resulting rapid surface recession have proven to be a potential show-stopper. Environmental Barrier Coatings continue to be the enabling technology required to protect CMCs from surface recession.

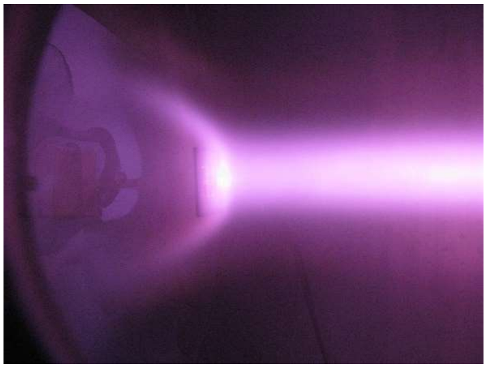


Figure 3: Plasma Spray Physical Vapor Deposition processing

Since the late 1990s, the first generation of EBCs were being developed at NASA using a three-layer silicon/mullite/barium-strontium-aluminosilicate (BSAS) coating, followed in the 2000s by a second generation of EBCs based on rare-earth silicates. Today, that development continues as new EBCs seek enhanced performance for next-generation gas turbine engines. The primary challenges of next generation EBCs include oxidation and recession resistance, CMAS resistance, and temperature capability. In addition thermo-mechanical stability, erosion resistance, and foreign object damage also must be considered. Robust EBC life models and relevant testing capabilities to validate the life models must be developed. Overall, oxidation is the key EBC failure mode, and the upper temperature of current EBCs is limited by the melting point of the silicon bond coat and environment interactions (H_2O recession and CMAS degradation) with the EBC topcoats. With today's CMC/EBC systems having an upper use temperature of approximately 2400°F, the key NASA EBC goals are developing a 2700°F capable non-silicon bond coat while improving topcoat stability.

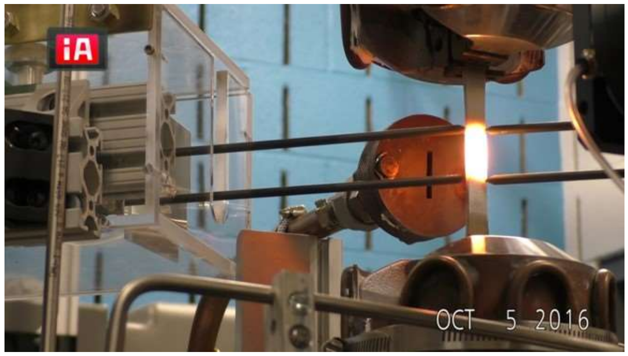
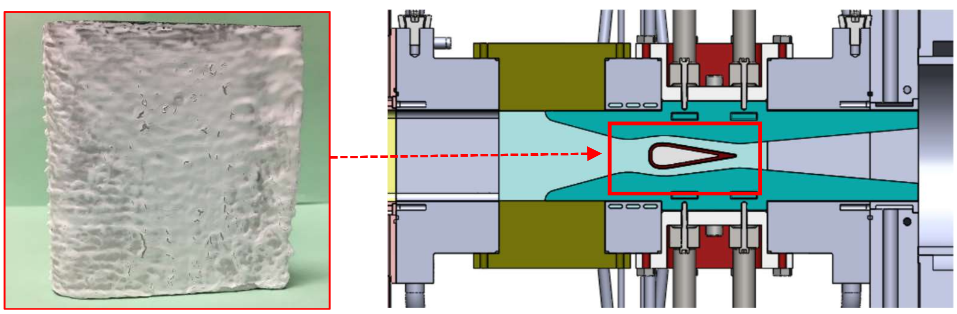


Figure 4: High heat flux combined thermo-mechanical testing of CMC/EBC system

Glenn Research Center is developing that capability, recently demonstrating and patenting a new EBC composition capable of long-term operation at 2700°F. Development of the new EBC material has required separate technology advancements related to thermochemistry and modeling, advanced coating processing, and unique combined testing capabilities. Thermochemistry and modeling utilizing experiments and a model-based approach have determined reaction chemistry and stability of prospective EBCs that reduce recession rates of CMCs by 70 percent. Significant enhancements have also been made by developing new phase diagram modeling and database capabilities, along with new thermodynamic properties measurement techniques such as drop solution calorimetry. Advanced coating processing has included the in-house development of both Plasma Spray Physical Vapor Deposition and Slurry Casting methods, and development of combined test capabilities has included a suite of thermo-mechanical high heat flux laser fatigue test facilities and unique materials combustion test capabilities.



Slurry-processed 2700°F EBC on CMC airfoil   Test rig developed by Pratt & Whitney

Figure 5: A Durable CMC/EBC (left) was demonstrated in a 2700°F turbine environment

This past year represented the culmination of these two parallel material development efforts, in that the first "System-Level" material validation was conducted by testing a representative CMC/EBC turbine vane test article in a test rig that created a realistic (Technology Readiness Level 5) turbine section environment. Both CMCs and EBCs functioned effectively during this test, through a series of progressively more challenging test conditions. The TRL 5 test demonstrated, for the first time, the effectiveness of the combined CMC and EBC functioning together as a durable 2700°F material system. Since that demonstration, efforts have been focused on optimizing the chemistry and processing for improved environmental durability and continue today.

4.0 POLYMER MATRIX COMPOSITES

4.1 Improved Damage Tolerance

Application of polymer matrix composite materials for jet engine fan blades is becoming attractive as an alternative to metallic blades; particularly for large engines where significant weight savings are recognized on moving to a composite structure. However, the weight benefit of the composite of is offset by a reduction of aerodynamic efficiency resulting from a necessary increase in blade thickness; relative to the titanium blades. Blade dimensions are largely driven by resistance to damage on bird strike. The reduction in thickness over the state of the art composite blades is expected to translate into structural weight reduction, improved aerodynamic efficiency, and therefore reduced fuel consumption. Further development of the composite material is necessary to allow composite blade designs to approximate the dimensions of a metallic fan blade. A materials development effort at NASA Glenn yielded a promising approach to improve composite damage tolerance and allow for design of composite blades with improved aerodynamic efficiency [4].

Glenn Research Center recently demonstrated an impact screening test method for a blade leading edge subcomponent structure and identified material solutions to improve composite impact performance and allow for thinner fan blade structures. IM7/8551-7 uni-directional prepreg from Hexcel was used for leading edge fabrication. A thermoplastic polyurethane (TPU) veil was incorporated into the leading edge structure to evaluate its influence on composite damage tolerance. Test articles containing three layers of a TPU veil interleave were prepared to evaluate impact resistance imparted by increased inter-laminar strain capability of the structure. As shown in Figure 5**Error! Reference source not found.**, the toughening veil was 22.9 cm (9 in) long and placed in the midsection of the part's length. Two of the layers were 7.6 cm (3 in) wide and the other was 5.1 cm (2 in) wide. The veil placement was chosen to cover a significant portion of ply terminations, thus reducing free edge stresses.

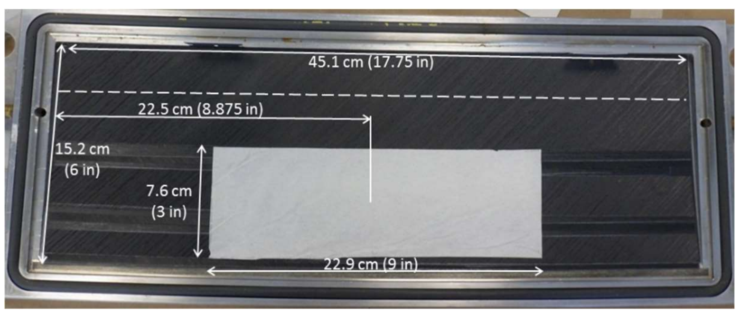


Figure 5: Placement of 7.6 cm (3in) thermoplastic polyurethane veil layer with leading edge subcomponent.

Impact testing was performed in the Ballistics Impact Laboratory at NASA Glenn Research Center to simulate the material response from bird strike at the leading edge. A gelatin bird simulant was used as the projectile in this project. For the impact testing, a single-stage gas gun was used, consisting of a 7 m barrel and a 0.35 m^2 pressure vessel. The pressure vessel was loaded to a pressure of 1.2 MPa (175 psi), and the pressure was released using a burst disk. The projectile was housed in a cylindrical sabot for protection at the initial pressure release. Both were accelerated through the barrel by the release of pressure. The sabot was halted at the end of the barrel by a sabot arrestor and the projectile continued into the test specimen. High speed cameras were used to capture the impact of the projectile on the test article and determine the estimated speed. These tests were performed at speeds between 305-350 m/s (1000-1150 ft/s).

The projectile velocity and orientation of the leading edge test article were derived from computer simulation of the relative motion of a fan blade and bird during a bird strike event. The blade was clamped along the axial direction at the flat section for cantilevered impact testing. The leading edge specimen and fixture set up for impact testing is shown in Figure 6. The impact location was at the leading edge of the blade where the angle of impact was measured as 66^o from the perpendicular to the projectile path at the thickest part of the blade. The blade tip was oriented approximately 24^o off of the projectile's path. Between the blade and the fixture there is a 15.2 cm (6 in) section of clay added to reduce additional pressure loading on the fixed portion of the blade.

Figure 6: Impact testing fixture secured in impact chamber

Baseline, composite only, blade test articles were labeled as C006 and C007. The TPU toughened blade was labeled as C008. As shown in Figure 7, there was very little visual damage to the TPU toughened (C008) test article. No delamination at the leading edge was noted in the interleave region. As with many of the test articles, a small delamination was observed near the tip of the leading edge in an unmodified region due to flexural wave reflection. This failure mode was observed in many of the leading edge tests and is considered an artifact of boundary conditions, occurring after the initial impact.

Figure 7: Post-impact images of baseline and TPU toughened blades

In this test program, the influence of ply configuration and test set-up were evaluated such that impact data would reflect selected material modifications. An interleave toughening approach was taken in an effort to reduce damage on impact and enable a reduction of composite blade thickness. It was found that incorporation of the lightweight TPU veil provided considerable benefit to the damage tolerance of the composite parts tested in this program.

4.2 Lightweight "Hybrid" Gear Application

NASA Glenn Research Center and the U.S. Army Research Laboratory have been investigating hybrid (composite/steel) gear technology for use in vertical lift drive systems. The hybrid gear concept replaces the structural portion of a gear between the shaft and the gear rim with a lightweight carbon fiber composite, in an effort to reduce the overall weight of a gear and increase the drive system power density. One hybrid gear design that has been evaluated is shown in Figure 8. In this design, a carbon fiber/epoxy composite material is used for the web portion of the gear, and conventional gear steel is used for the hub and rim. Load is transferred through lobe-shaped mechanical interlocks between the middle composite layer and the steel hub and rim sections. Additional composite layers in the shape of annular rings are located above and below the middle layer to prevent axial displacement of the middle interlocking layer. The composite is made using multiple plies of triaxial braid prepreg having a 0/+60/-60 fiber architecture and equal fiber volume in each direction. An advantage of this approach is that each ply is quasi-isotropic, which simplifies layup of the laminate and results in a gear web having the same stiffness in all in-plane directions.

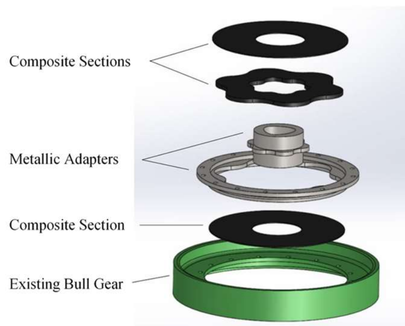


Figure 8: Exploded view of hybrid gear design

A series of hybrid gears with various web designs have been tested using the High-Speed Helical Gear Rig [5] at the NASA Glenn Research Center shown in Figure 9. The facility is a closed-loop, torque-regenerative testing system. It consists of back-to-back identical test and slave gearboxes that are mirror images of each other. Each gearbox has an input gear, three idlers, and one bull gear. The gearboxes are joined together through the input gears and bull gears via shafting. The large bull gear at the left end of the test gearbox is a bolted assembly with a steel gear rim bolted to an integrated steel hub/web piece having a keyed attachment to the shaft. In order to test the hybrid gears, the bearing structures were modified and the shaft connection was change from a keyed attachment to a polygon.

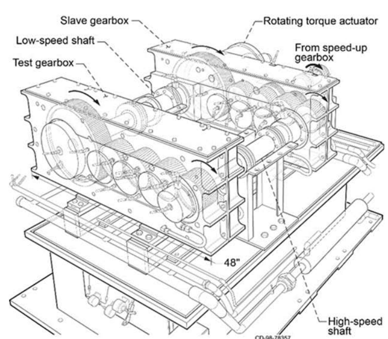


Figure 9: High speed helical gear test rig

The gear, shaft, and bearing assembly is shown in Figure 10. Each component, and the full assembly, were balanced prior to testing. The same double-helical steel gear rim (green part in Figure 8) was used for all tests. A double-helical gear design should apply primarily torsional loading with minimal axial loading [6]. The initial hybrid gears were designed for this load condition.

Figure 10: Gear, bearing, and shaft assembly

A series of tests were performed with various composite layups and interlocking features. Vibration levels were monitored using accelerometers, and the orbit of the gear was monitored using proximity probes [7]. In the initial tests the torque and speed were limited to avoid a failure in the test rig. In the most recent test, the goal of operation at a power level of 5,000 hp (3,730 kW) by applying 58,400 in-lb (6600 N-m) torque at 5,400 RPM was achieved. Further endurance testing at 5,000 hp was then begun with a goal of 1,000,000 cycles. The endurance testing was discontinued after 500,000 cycles because of a shift detected in the gear orbit. Post-test ultrasound inspection indicated an internal delamination. The cause of the delamination is being investigated. A likely cause is that the test article had an unintended axial displacement between the metal hub and rim adapter (see Figure 8). An attempt to correct for this within the gearbox resulted in an unintended axial load applied to the hybrid gear in a first attempt at assembling the gearbox. Corrections were made to eliminate the axial load, but damage during the first assembly or the presence of a small overturning moment during the test are possible causes for the delamination. In spite of the presence of the delamination, the hybrid gear continued to carry full load after the shift in orbit load was detected allowing a safe shutdown of the test rig. The unintended offset of the metal adapters has been corrected in a subsequent test article, but tests have not yet been completed.

5.0 ADDITIVE MANUFACTURING

As the world-wide aviation community pursues revolutionary reductions in the environmental impact of aircraft power and propulsion systems, NASA's initiatives toward More Electric aircraft and small, personal air vehicles that will advance "Urban Air Mobility" goals in congested cities is motivating the development of high power-density electric motors for these applications. This research is essential to meet longer-term goals for increased performance and efficiencies, and reduced emissions.

The Compact Additively Manufactured Innovative Electric Motor (CAMIEM) project is utilizing additive manufacturing methods to achieve new motor designs that have significantly higher power densities as well as other performance and manufacturing benefits [8]. CAMIEM is supported by the Convergent Aeronautics Solutions Project and the NASA Transformative Aeronautics Concepts Program. New motor components enabled by additive manufacturing technologies were designed, built, and tested. Performance gains are being evaluated against a baseline motor configuration. Partners include NASA Glenn, Langley and Armstrong Research Centers, LaunchPoint Technologies, and the University of Texas El Paso.

In order to obtain higher power densities and/or efficiencies, new manufacturing approaches are needed to achieve innovative electric motor designs that cannot be obtained through conventional manufacturing methods. Additive manufacturing offers the potential to radically change motor designs compared to the current state-of-the-art. New motor topologies with greater geometric complexity, compact designs, multi-material components, innovative cooling, and optimally designed and manufactured components are possible. Additional benefits include the elimination or reduction of extensive machining, expensive tooling and design changes, high labor, and material waste of conventional manufacturing.

The baseline motor and the innovations applied to the design are for an axial flux motor configuration also known as a “pancake motor.” The baseline motor design by LaunchPoint Technologies is shown in Figure 11. The motor is considered state-of-the-art because of its high power density due to its compact design, highly efficient air-cooling, and an innovative halbach array of magnets, which Launchpoint uses in the rotors. The baseline motor is 19.5 cm (7.5”) in diameter and weighs only ~1.8 g (4 lbs). The performance of the baseline motor is rated > 7 kW continuous output at 7500 RPM with ~ 94% efficiency and a power density of 3.93 kW/kg at well below the maximum allowable temperature and 10 kW at 7500 rpm with a power density of 5.5 kW/kg at the maximum allowable temperature.

Figure 11: Baseline motor design by LaunchPoint Technologies and with a propeller on the right.

Three of the CAMIEM partners are focused on new component designs for electric motors, which are enabled by additive manufacturing (AM) processes. The three AM partners include NASA LaRC, the University of Texas-El Paso (UTEP), and NASA GRC. NASA LaRC is focusing on metallic structural sub-elements with reduced mass and enhanced cooling across the stator (Figure 12). The highest payoff component for reducing mass was the housing, which was redesigned with a mass savings of 63% and was manufactured by selective laser sintering. Also, a rotor plate has been redesigned to include airfoil fan blades and air channels for better thermal management with improved airflow across the stator. The unique rotor plate design with its integration of tilted airfoils cannot be easily obtained with conventional manufacturing. There is also an AM finned cooling ring for integration to the stator to aid in cooling.

Figure 12: Additively manufactured metallic structural motor components include the housing (left), rotor (center), and finned stator cooling ring.

Two optimized stator design concepts are being developed in which advanced electrically conductive coils are fabricated using direct copper wire imbedding and direct silver printing methods (Figure 13). UTEP is using their Multi3D System, which is a hybrid manufacturing system where additive manufacturing is complemented with introduction of machining and wire embedding. The focus is on using the direct copper wire imbedding process in sub-components produced with material extrusion additive manufacturing to yield a stator. The additively manufactured stator, which offers an alternate lower cost fabrication method to the baseline stator is shown in Figure 13 (left). NASA Glenn is pursuing an innovative stator design (Figure 13, center) with a higher power density than the baseline stator. An nScrypt 3Dn-300 quad-head machine is used to direct print electrically conductive silver inks. The direct printing process allows for unique features in the coils such as conductor coils with varying widths and multi-layers which achieves higher packing. The integration of iron into the innovative stator design offers high coil packing and higher magnetic flux than the baseline. Also, material selection allows for higher temperature capability of 250°C instead of 180°C for baseline stator. The printed silver coils greatly exceeded requirements during uncooled testing under high current and temperature (Figure 13, right). The material and design improvements are projected to contribute to a 50% increase in power density for the motor.

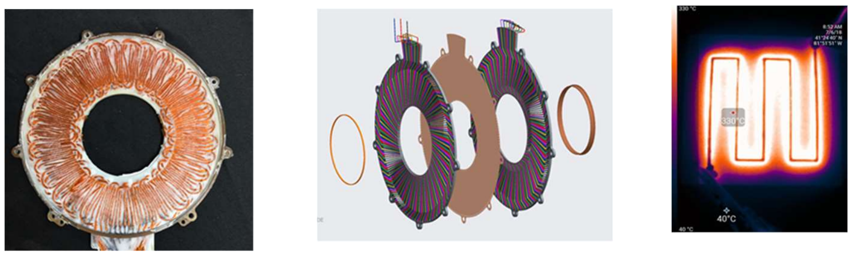


Figure 13: Multi-material stators to include a direct wire imbedded stator (left) and a direct printed stator design (center). Demonstration of greater than 300°C temperature capability of direct printed silver coils (right).

Several of the additively manufactured components were integrated into a modified motor configuration (Figure 14, left). The performance gains from the new components will be evaluated against the baseline motor using the dynamometer in the NASA Glenn Small Motor Test Facility.

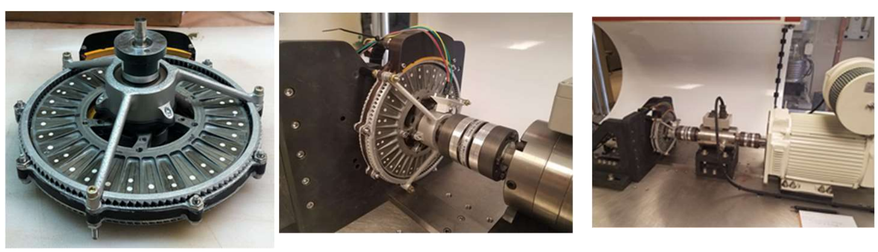


Figure 14: Additively manufactured components integrated into as electric motor configuration (left) and prepared for testing on a dynamometer at GRC (center and right).

The CAMIEM project has shown that additive manufacturing methods allow for innovations in electric motor design that are projected to double the powder density of the baseline motor.

ACKNOWLEDGMENTS

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