Professor Trice's research focuses on structure–property-processing relationships of advanced ceramic materials. Direct ink writing, material extrusion additive manufacturing, and room-temperature injection molding processing approaches for forming carbon-fiber reinforced and silicon-carbide platelet silicon carbide composites, carbon/carbon composites and ultra-high temperature ceramics (UHTCs) into useful shapes is being studied. Preparation of high emissivity coatings to passively cool hypersonic vehicle leading edges is also explored. Methods for producing transparent aluminum oxide for hypersonic IR windows is being investigated. Development of ceramic and thermoplastic mixtures with silicon carbide and silicon nitride to build complex shapes by extrusion and compression molding is also studied.

**Research Overview**

**High-Emissivity Coatings for C/C CMCs**

The primary objective is to design materials with high emissivity so that they can be used to passively cool leading edges during hypersonic flight. In this program, cubic-zirconia ceramics stabilized with rare-earth oxide emissivity modifiers are being developed and evaluated in high-heat flux conditions. Finally, the goal is to develop sintering methods to reduce the grain size of the final sintered bodies to increase its mechanical strength and fracture toughness while retaining transmission at IR wavelengths.

**Development of Transparent Al₂O₃ for IR Sensors**

Aluminum oxide or alumina has the potential to replace single-crystal alumina, a.k.a. sapphire, for high-temperature IR window applications because of its improved strength, hardness, and corrosion resistance. By aligning crystallographic features it is possible minimize birefringence-based optical scattering in alumina to improve transparency in the optical regime from UV through short-wave IR. The figure below shows the in-line transmission for aligned grain platelet alumina and equiaxed alumina samples made by a recent graduate student of Prof. Trice and Prof. Youngblood compared to commercially available sapphire and polycrystalline alumina. However, significant grain growth occurred due to high sintering temperatures (1800°C) and long sintering times (7 hrs) which resulted in poor mechanical strength. With this in mind, our goal is to develop sintering methods to reduce the grain size of the final sintered bodies to increase its mechanical strength and fracture toughness while retaining transmission at IR wavelengths.

**Development of Si₃N₄ Ceramics for Hypersonic RF Windows**

Radar protection the antenna from the harsh environment encountered when flying at hypersonic speeds. The radome material must have a low dielectric constant and loss so as not to reflect and attenuate GHz frequency radar waves. Silicon nitride is being considered as a radome material because it meets these criteria, it also has high mechanical strength and toughness, low coefficient of thermal expansion, and high thermal shock resistance. The A-sandwich design is a common broadband radome design. It is constructed with a porous core and dense skins on each side of the core. Aligned porosity is created by extruding silicon nitride/polymer blends with high aspect ratio fibers through a narrow die. The polymer and carbon fibers are removed via burnout, creating the oriented high aspect ratio pores. As shown below, aligned porosity can be created using this approach which will ultimately lower the dielectric constant of the core.

**Ytterbium Disilicate EBC Materials for Gas Turbines**

Ceramic Matrix Composite (CMC) parts for gas turbines degrade at rates up to 0.25 µm/h by reacting with atmospheric water and silicates at operating temperatures. Therefore, environmental barrier coatings (EBCs) are required to extend the part lifespan. Ytterbium disilicate (YSDS) and monosilicate (YMS) EBCs are compatible with SiC parts, however, EBCs contain defects (right) that encourage cracking when annealed. Modelling with finite element software may reveal how defects in EBCs respond to heat treatments can be developed to reduce cracking in real coatings, and results can be experimentally verified with microstructural analysis and fracture toughness measurements.

**Additive Manufacturing of C/Composites**

Thermal manipulation of viscoelastic properties of thermoplastic polymers via extrusion deposition additive manufacturing allows fabrication of complex-shaped polymer matrix composites without external tooling and molds. Carbon/carbon (C/C) composites are one class of materials that can benefit from extrusion additive manufacturing due to the difficulties associated with forming complex carbon fiber architectures and a carbon matrix. Seven additively manufactured short carbon fiber-reinforced thermoplastic polymers including polyphenylene sulfide (PPS), polyether ketone (PEEK), poly sulfone (PSU), polyether sulfone (PESU), and polyetherimide (PEI) were investigated via carbonization tests in order to compare dimensional changes during pyrolysis. The results for 25 mm x 25 mm samples showed that slower heating rates minimized material distortion. The carbonization results for an additively manufactured rocket nozzle illustrate how fiber-reinforced polyphenylene sulfide can be used to perform shape and size-preserving initial pyrolysis processing for more complex geometries.

**Direct Ink Write Additive Manufacturing of C/SiC CMCs**

Current bulk ceramic forming processes are limited to simple structures or require secondary machining to add intricate features. Direct ink writing (DIW), a form of additive manufacturing (AM), can be used with aqueous ceramic-polymer suspensions with tailored rheological properties to produce complex geometries. Additionally, DIW can be used to preferentially align fibers or platelets. The following summarizes several ceramic materials including SiC, Al₂O₃, Si₃N₄, and ZrB₂, with our current efforts focused on SiC reinforced with both carbon fibers and SiC platelets.

**Development of Si₃N₄ Ceramics for Hypersonic Heat Exchangers by Co-Extrusion**

The walls and core are made of a mixture of either ceramic powder or carbon powder and mixed with a variety of polymers to create extrudable blends. By tailoring the rheology of these blends, simultaneous extrusion of both the core and walls occurs. The extruded feedrod can be rebundled and re-extruded again to further reduce the feature size. The extruded channels are then put in a binder burnout run and sintered to yield fully dense, porous channels. Sintered channels size are ≈ 100 micron. Note the 3 x 3 array of channel microstructures below.

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