Development of Porous Silicon Nitride for Hypersonic RF Window Applications

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Abstract: Radomes protect the antenna from the harsh environment encountered when flying at hypersonic speeds. The radome material must have a low dielectric constant and loss to minimize reflection and attenuation of GHz 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. In this work, fabrication of a silicon nitride porous core using various methods, including extrusion concepts and pore forming agents.

Background and Application

Radomes must be able to protect the antenna it houses from the harsh environments experienced during high-speed flight as well as allow the electromagnetic waves to pass through to the antenna. Materials used in radomes must have low dielectric constants and low loss tangent values so that the reflection and absorption of electromagnetic waves is minimized.[1]

Radome Material Property Requirements

Radomes are used to protect microwave or radar antennas making it necessary for the radome material to be transparent to the radar waves of interest for the antenna to receive and transmit. The X, K_u, and K_a bands are of interest for radome applications.

Radar Frequency Bands		
Band Designation	Frequency Range	Typical Usage
VHF	50-330 MHz	Very long-range surveillance
UHF	300-1,000 MHz	Very long-range surveillance
L	1-2 GHz	Long-range surveillance, enroute traffic control
S	2-4 GHz	Moderate-range surveillance, terminal traffic control, long-range weather
C	4-8 GHz	Long-range tracking, airborne weather
X	8-12 GHz	Short-range tracking, missile guidance, mapping, marine radar, airborne intercept
K_u	12-18 GHz	High resolution mapping, satellite altimetry
K	18-27 GHz	Little used (H_2O absorption)
K_a	27-40 GHz	Very high resolution mapping, airport surveillance
mm	40-100+ GHz	Experimental
Source: AIAA (American Institute of Aeronautics and Astronautics)		

Radar Frequency Bands[2]

There are many material property requirements that radomes must meet due to the structural strength requirements and the radar requirements. Radomes must be able to withstand the high temperatures experienced as well as having low loss and dielectric constant. A material with a dielectric constant <4.0 and a loss tangent <0.01 would have excellent wave-transparency.[3]

Properties	Required
Service Temperature	Up to 1400°C
Dielectric Constant	<9.0 (5.0 preferred)
Temperature variation of dielectric constant to 1260°C	<7.0%
Loss Tangent to 1260°C	<0.1
Bending Strength (4 point)	>35 MPa

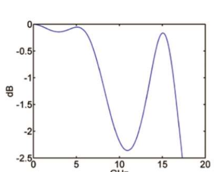
Radome material property requirements[1]

Silicon Nitride as an RF Material

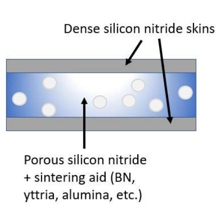
Silicon nitride ceramics have become of increasing interest for radome applications because of their excellent mechanical and thermal properties and potential for high-temperature application. Silicon nitride ceramics have high wave-permeability, thermal shock resistance, corrosion resistance, and fracture resistance. Dielectric constants for α-Si_3N_4 and β-Si_3N_4 are 5.6 and 7.9 respectively at room temperature.[1] In order to lower the dielectric constant to improve radar transmission porosity is introduced. A balance between adding porosity to lower the dielectric constant and maintaining mechanical strength is important.

A-Sandwich Radome Design

The A-sandwich radome is a commonly used wall design. It is composed of a low dielectric foam or honeycomb core with thin laminates of high dielectric on either side. The core is designed to be 0.25 wavelengths thick for the frequency of interest.[4] For an 18 GHz signal (16 mm wavelength) the core should be 4 mm thick.



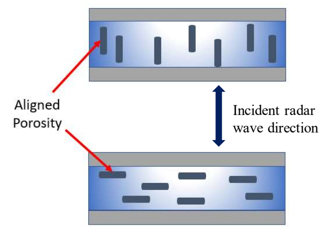
Reflections versus frequency in an A-sandwich radome . The core is designed to be 0.25 wavelengths at 5 GHz, providing maximum performance at <7 GHz.[4]



A-Sandwich design for silicon nitride

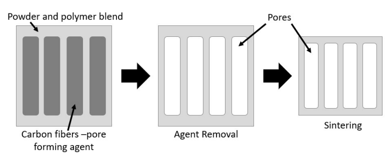
Fabrication of Porous Core

Extrusion and pore forming agents are being used to create aligned porosity in silicon nitride to study if the amount and direction of alignment of pores affects the dielectric properties. Alignment of porosity perpendicular to the skins has the potential to give better transmission compared to porosity aligned parallel to the walls.



Porosity alignment options in A-sandwich radome

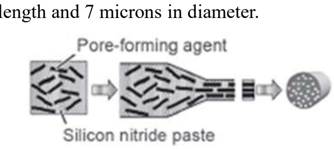
Carbon fibers are used as pore forming agents or sacrificial fugitives. This creates pores where the fibers once were after they are burned out from the ceramic part.



Function of pore forming agents[5]

Alignment Through Extrusion

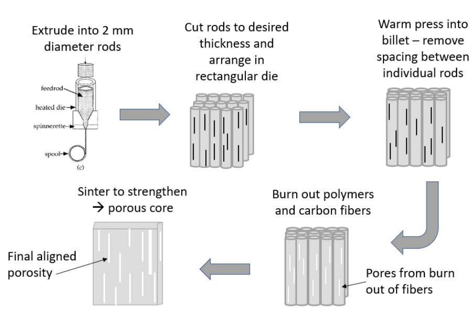
High aspect ratio particles like carbon fibers tend to align when extruded through a smaller channel. A 2 mm die is being used to create extrudates with carbon fibers aligned parallel to the extrusion direction. Fibers being used are 3 mm in length and 7 microns in diameter.



Alignment during extrusion of carbon fibers[6]

Complete Extrusion Process

Silicon nitride powders and sintering aids are mixed into a blend of thermoplastic polymers along with the pore forming agent, carbon fibers. This blend is then able to be extruded at 150°C into continuous rods. These extrudates are then cut down to size, stacked, and laminated together. A burnout of the polymers and carbon fibers leaves only the silicon nitride powers and porosity behind. Sintering is completed to increase strength as the final fabrication step.



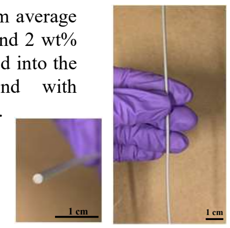
Processing route to form porous core with aligned porosity[7]

Current Results

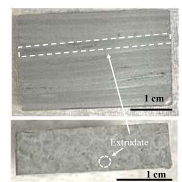
Silicon Nitride Extrudates

Silicon nitride powder (0.5 µm average diameter) with 6 wt% yttria and 2 wt% alumina sintering aids is mixed into the thermoplastic polymer blend with powder loading up to 52 vol%.

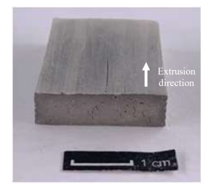
Processing variables include percentage of carbon fibers, powder loading, lamination temperature, and sintering temperature.



2 mm diameter extrudate composed of thermoplastic polymers, 45 vol% powder, and 5 vol% carbon fibers



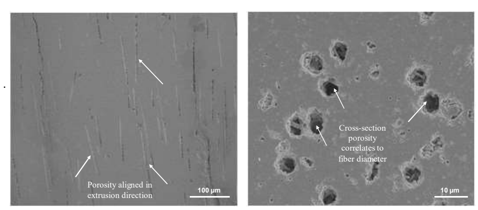
Bundled and warm pressed extrudates – green body



Sintered core with aligned porosity from fugitive fibers

Evidence of Aligned Porosity

Channeled porosity created by the fugitive carbon fibers is observed through SEM imaging. Carbon fibers were originally 3 mm in length, but the aggressive mixing of the thermoplastic and ceramic particle blend causes fibers to be broken into smaller lengths. Porosity is consistent with the fibers 7-micron diameter.



SEM images of aligned porosity parallel to extrusion direction (left) and perpendicular (right)

Future Work

Optimization of the fabrication process of the porous A-sandwich cores is still ongoing as well as studying the effects of increased amounts of carbon fiber additives. Further work on fabrication of dense skins to complete the A-sandwich design will be done once processing and testing of the porous core has been completed. Joining of the skins and core will be important to maintain strength throughout the structure as well as designing the wall thickness for the desired radar transmission.

Acknowledgements

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