Boron Nitride Materials Development for High Voltage Power Transmission

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High-Voltage Materials for Advanced High Power Electrical Applications Focus Session

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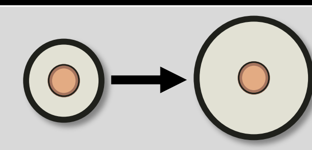
Power Requirements for Electric Aircrafts

Engineering Challenge:

- Future high attitude large class Electric Aircraft will need high power (< 10-20 MW) and safe sustainable high voltage transmission systems
- Two of the many ways of achieving the needed high power:
  - Increasing conductor size, also increasing conductor weight
  - Decreasing the conductor size while going at higher voltage will reduce conductor weight, but will increase insulation thickness, volume, weight and the conductor temperature
- High Voltage (HV) requires thicker insulation with enhanced performance in dielectric strength, breakdown voltages, thermal stability and long-life performance
- The most promising materials for HV operation are fluoropolymers which are currently being regulated and restricted for harmful environmental impacts

Heavy High Voltage DC Cable

Terrestrial SOA cables *cannot* solve aeronautics problems.



Increase in V = Increase in insulation thickness

How to Select Power Supplies for High-Altitude Applications. Advanced Energy Industries, Inc. Application Note-AN1701.
Mazzanti, G.: High voltage direct current transmission cables to help decarbonization in Europe: recent achievements and issues. *High Volt.* 7(4), 633– 644 (2022).

High Voltage Power Transmission: Insulation Materials

High Voltage Insulation Requirements:

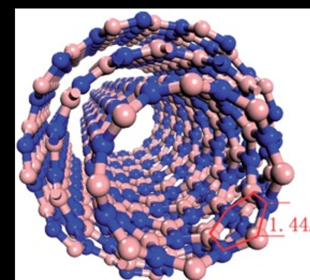
- ✓ Thermal conductivity > 1 W/m·K
- ✓ Maintain functional operating temperature >200 °C
- ✓ Push temperature >260 °C if possible
- ✓ Must be compatible with other component materials
- ✓ Retain dielectric strength of state-of-the-art materials
- ✓ Increased resistance to partial discharge and corona effects

<u>Goal</u>: Development of a material that combines chemical inertness, lightweight and high strength with high electrical resistivity and high thermal conductivity for the insulation component of high voltage power transmission

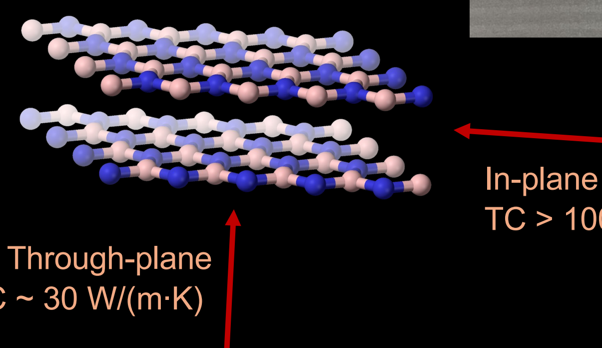
Hexagonal Boron Nitride (*h*-BN) Materials

- **Good Electrical Insulation Properties**
  - ✓ Constant wide band gap above 6 eV
- **Good Mechanical Strength and Rigidity**
- **Low Density**
  - ✓ *h*-BN: ~2.1 g/cm^3
  - ✓ BNNT: 2 - 2.5 g/cm^3
- **High Thermal Conductivity**
  - ✓ Thermal Conductivity (W/(m·K)): *h*-BN in plane > 100, *h*-BN through plane ~ 30, BNNT ~ 600
  - ✓ Ability to dissipate heat in nanoelectrics
- **Stability**
  - ✓ Chemical stable
  - ✓ Oxidation in air above 1000 °C
  - ✓ Hydrophobic

BNNT, 1-D

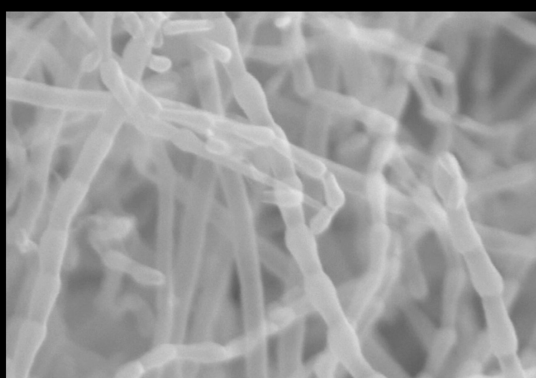


***h*-BN, 2-D**



GRC's Boron Nitride Nanotubes

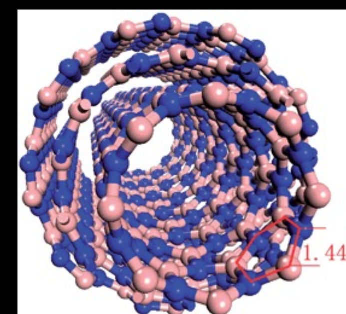
221ap 6.0kV 9.5mm x4.50k SE(M) 10.0um



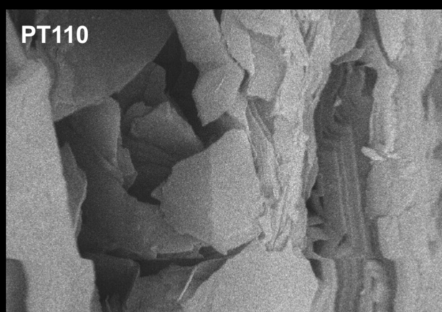
221ap 6.0kV 9.5mm x60.0k SE(M) 500nm

GRC developed a modified Chemical Vapor Deposition methodology to successfully and reproducibly synthetize BNNTs

- ✓ 1-2 gram batches are being synthesized per day; scalable process
- ✓ Synthesis evolved to prepare different structures to target different applications
- ✓ A preponderance of bamboo structured nanotubes could be achieved by careful additions of catalyst materials and control of processing conditions



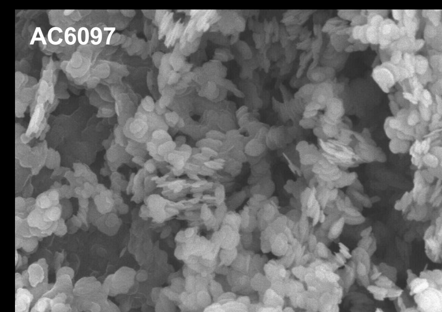
Exfoliation of Commercial *h*-BN Developed at GRC



PT110 10.0kV 5.8mm x25.0k SE(M) 12/4/2019 2.00um

Momentive PT110:

- Particle size: ~45 μm
- Surface area: 0.6 m^2/g



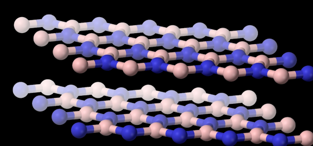
AC609A 6.0kV 11.7mm x25.0k SE(M) 2.00um

Momentive AC6097:

- Particle size: ~0.50 μm
- Surface area: 31 m^2/g

Exfoliation by Iron Chloride Intercalation

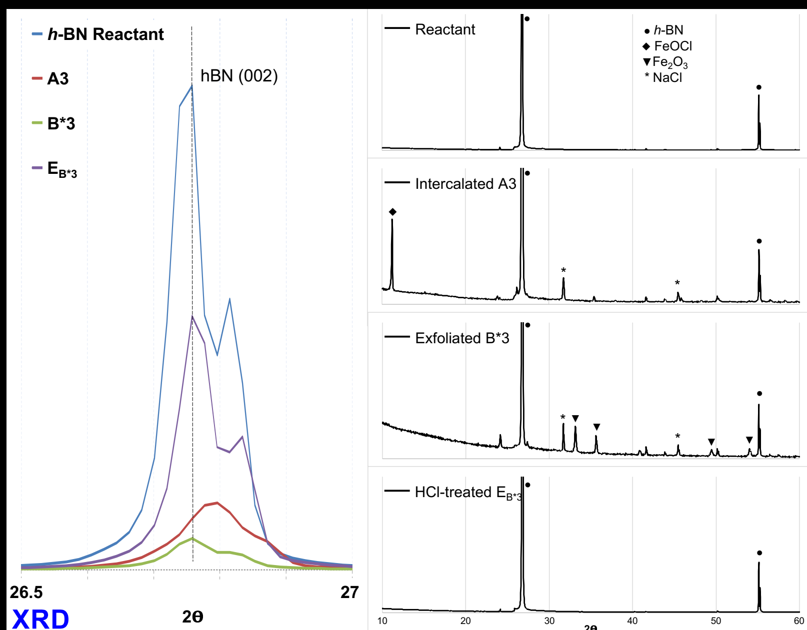
- ✓ Activation agent: *NaF*
- ✓ Intercalation and exfoliation happen on reactions (1) and (2), respectively
- ✓ HCl is done to remove impurities and intercalates

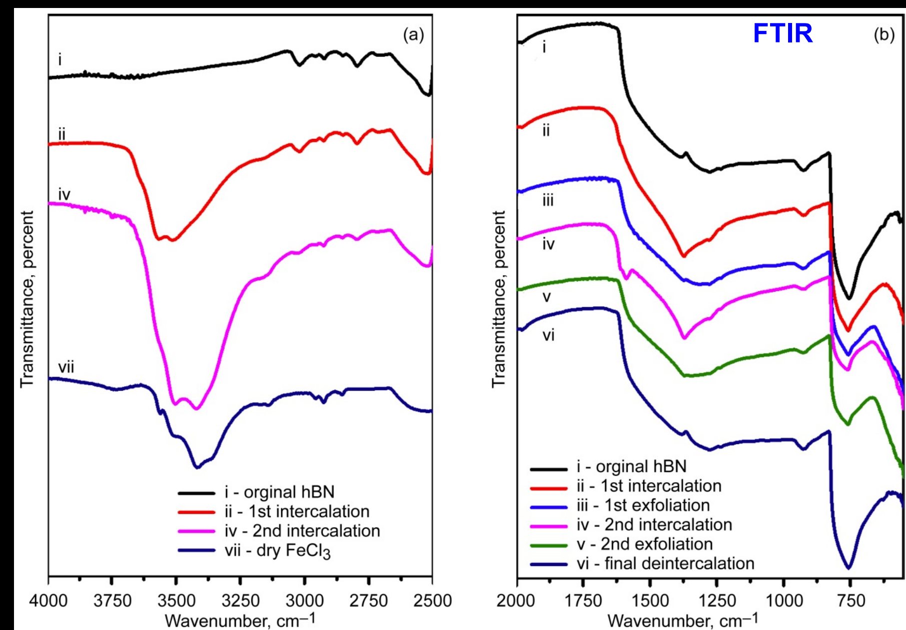


hBN + $FeCl_3$	—Activation Agent, Heat→	A	(Intercalated Product)	(1)
A —Heat→ B*	—Rinse with Water→	B	(Exfoliated Product)	(2)
B + $FeCl_3$	—Activation Agent, Heat→	C	(Intercalation)	(3)
C —Heat→	—Rinse with Water→	D	(Exfoliation)	(4)
A, B, C, or D	—HCl→	E_A, E_B, E_C, E_D		(5)

C.C. Hung, J. Hurst, D. Santiago, R. Roger, *NASA TM*-**2014**-218125

Intercalation/Exfoliation Structural and Chemical Changes

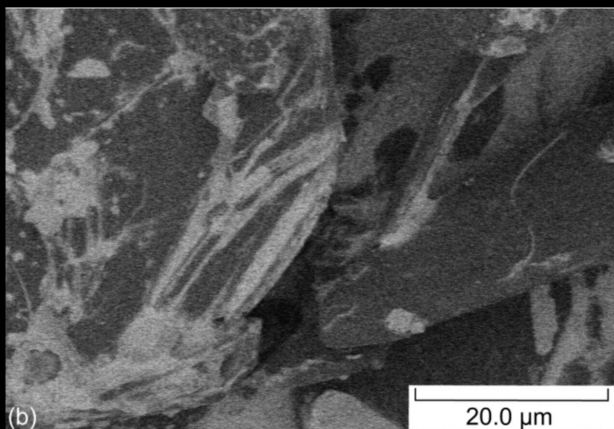




- (002) peak width becomes wider during intercalation and exfoliation process due to disorder into the lattice
- Cleaned exfoliated sample shows (002) peak more similar to *h*-BN reactant

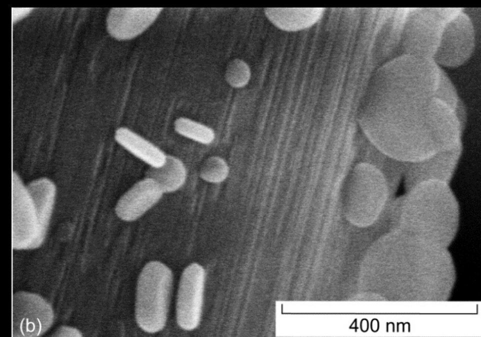
- BN stretching peak return to the original *h*-BN reactant after HCl treatment
- The B-N-B bending vibration peak seem to not be affected by the intercalation-exfoliation

Different Exfoliation Processes

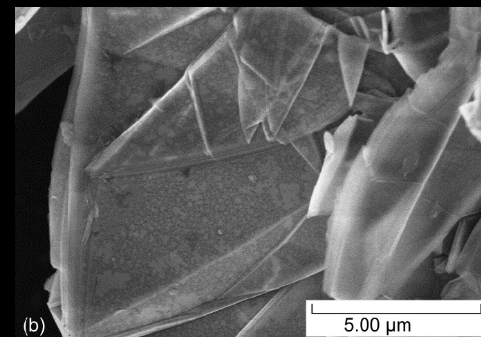


***h*-BN particles intercalated with $FeCl_3$**

✓ BSD highlights the location of the heavy element (Fe) at the edges and sides

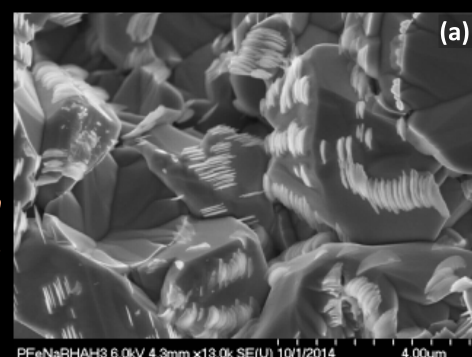


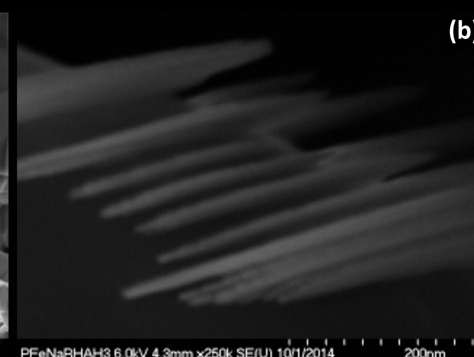
Slow oxidation produces Fe_2O_3 nanoparticles and split into layers about 20 to 30 nm thick



Quick oxidation formed micron-sized Fe_2O_3 particles and after HCl rinsing, shows exfoliation

Quick oxidation after hydration formed micron-sized Fe_2O_3 particles with exfoliated *h*-BN imbedded in the iron oxide particles





Boron Nitride Nanosheets (White Graphene)

For "stand alone" *h*-BN sheet, this process need to be repeated several times:

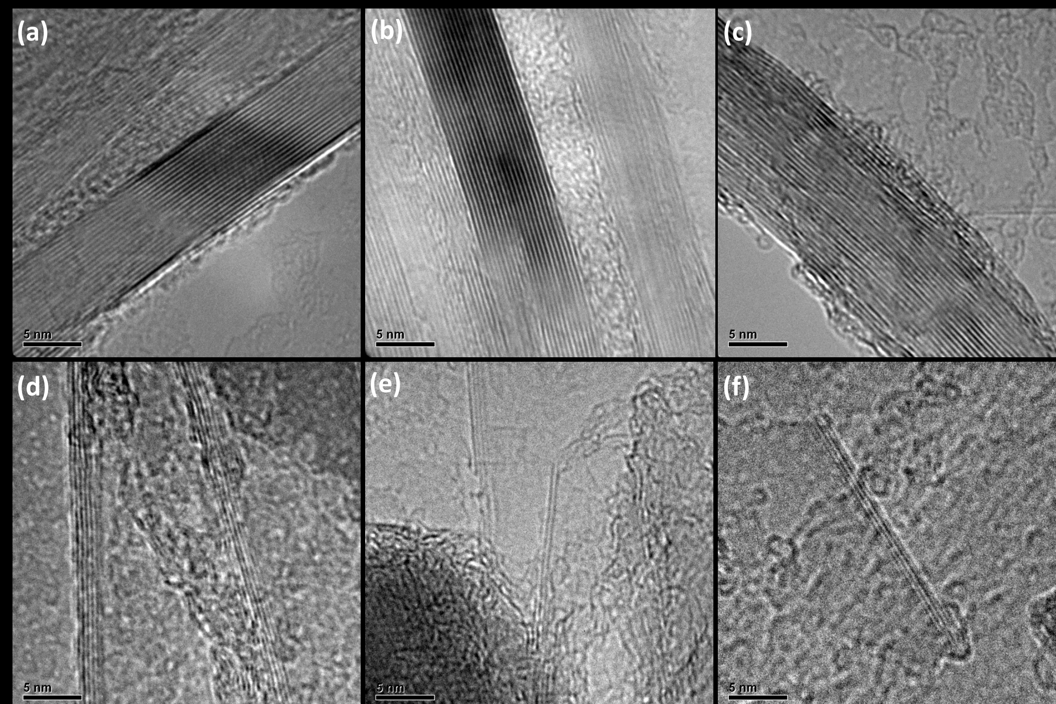
$$hBN + FeCl_3 \xrightarrow[\text{Heat}]{\text{Activation Agent}} A \quad \text{(Intercalated Product)} \qquad (1)$$

$$A \xrightarrow[\text{Heat}]{} B^* \xrightarrow[\text{Rinse with Water}]{} B \quad \text{(Exfoliated Product)} \qquad (2)$$

$$B + FeCl_3 \xrightarrow[\text{Heat}]{\text{Activation Agent}} C \quad \text{(Intercalation)} \qquad (3)$$

$$C \xrightarrow[\text{Heat}]{} \xrightarrow[\text{Rinse with Water}]{} D \quad \text{(Exfoliation)} \qquad (4)$$

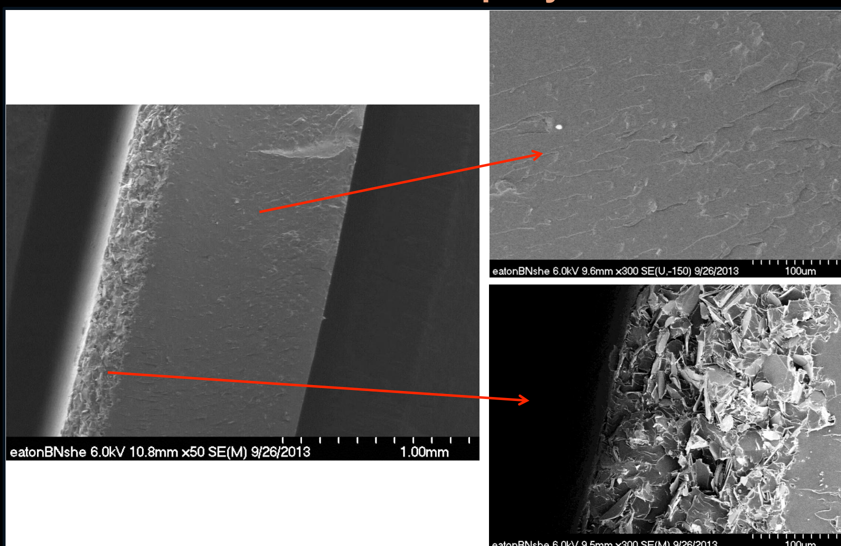
$$A, B, C, \text{ or } D \xrightarrow[\text{HCl}]{} E_A, E_B, E_C, E_D \qquad (5)$$



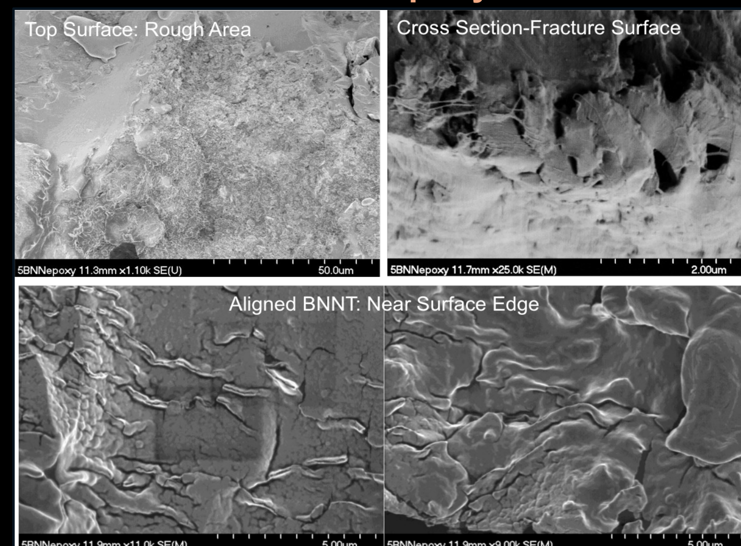
Initial BN Composites Challenges

Goal: Exploring the use of BN nanomaterials as filler on polymer composites for improved thermal conductivity and high electrical resistivity as a moldable nanocomposite

BNNS/Epoxy



BNNT/Epoxy

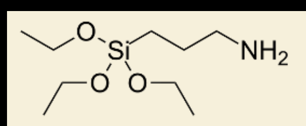


BNNS and BNNT were not well dispersed in the composite!

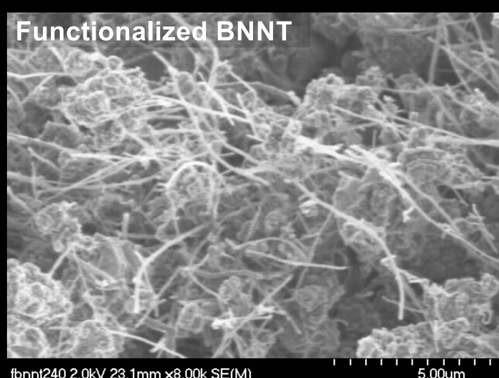
Boron Nitride Functionalization with APTES

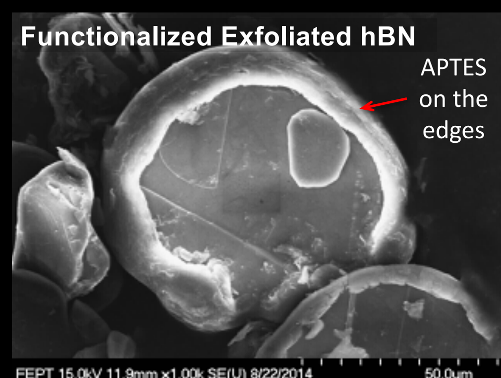
- ✓ BN is chemically inert and is difficult to mix in polymer composites
- ✓ Functionalization of BN helps with the dispersion

APTES (3-aminopropyl-trithoxysilane)



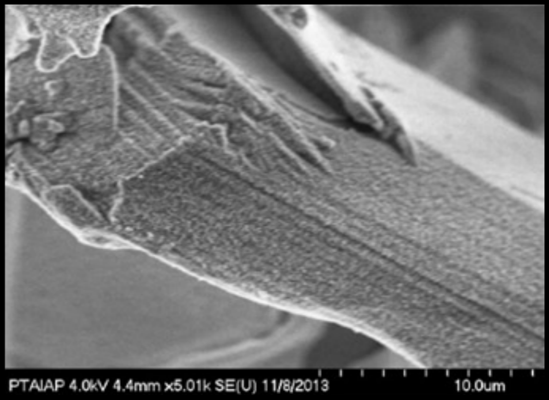
- BNNT (5 wt.%)/Ultem 1000 composite had an improved thermal conductivity of 67% by using functionalized instead of non-functionalized BNNTs
- f-BNNT (20 wt.%)/Kapton composite obtained a thermal conductivity of 1.6 W/mK
- Functionalization was effective but the process was tedious and produced small batches

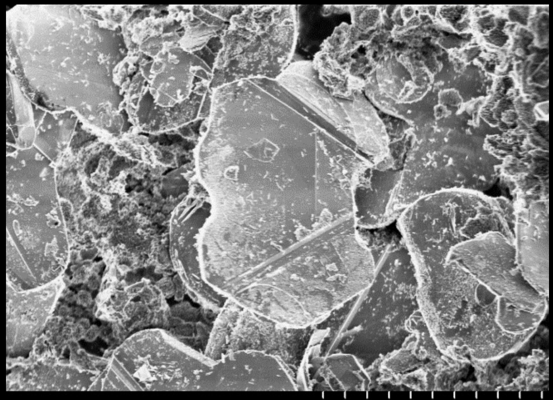


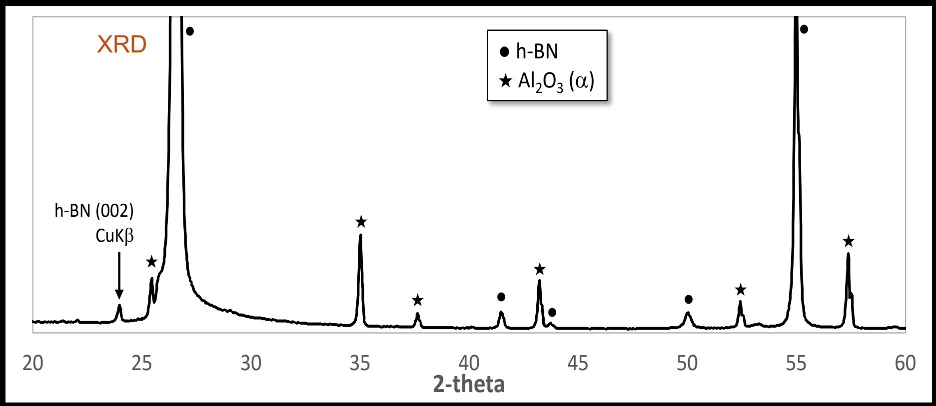


BN Intercalation with Aluminum Chloride

- ✓ $AlCl_3$ reacts like $FeCl_3$ with *h*-BN and an activation agent
- ✓ Produce an *h*-BN-Al_2O_3 mixture where nanosized Al_2O_3 particles are inside the *h*-BN platelets
- ✓ Alumina cannot be removed with HCl
- ✓ *h*-BN can also be coated by alumina, acting as a functionalized BN







Ceramic Composite

Benefits of using Alumina with *h*-BN for Ceramic Composite

- Alumina can help decrease the hot press temperature needed to make a ceramic composite with *h*-BN
- Alumina properties:
  - ✓ Chemical and physical stability
  - ✓ Thermal conductivity: 30 W/m·K
  - ✓ High heat resistance
  - ✓ High strength and hardness

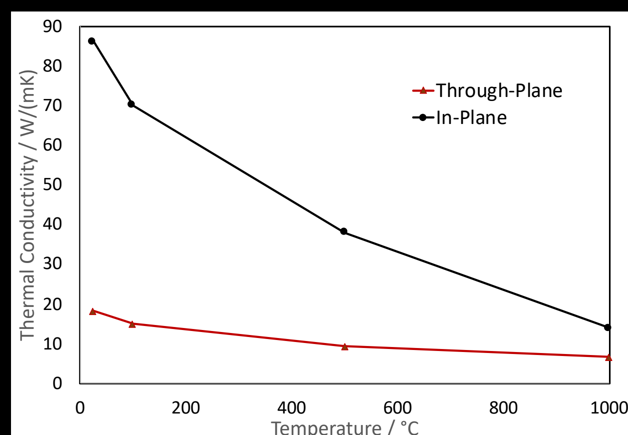
Thermal Conductivity Tests:

- *h*-BN/Alumina composite of 60 wt.% *h*-BN and 40 wt.% alumina
  - In-plane thermal conductivity > through-plane

***h*-BN**

***h*-BN intercalated and coated, or just coated with Alumina**

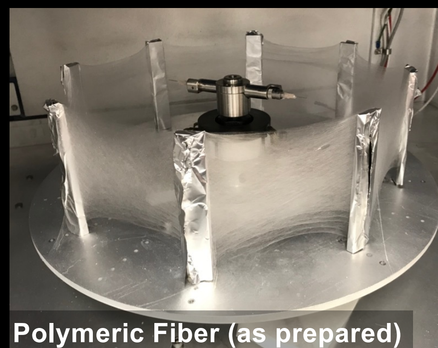
Hot Pressed at High Temperature & Pressure



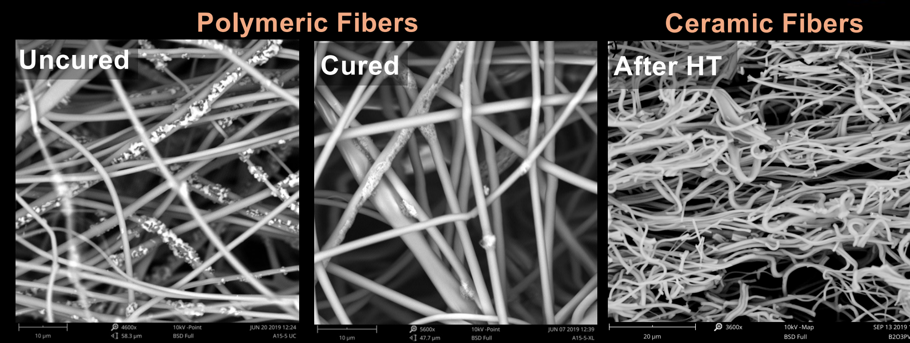
GRC started engineering BN by using intercalation and exfoliation and/or functionalization of other materials to target properties

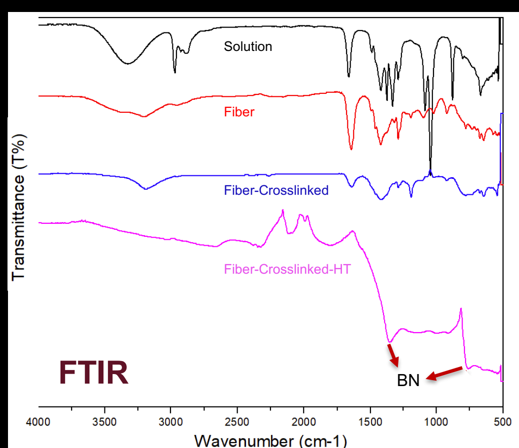
Boron Nitride Fibers

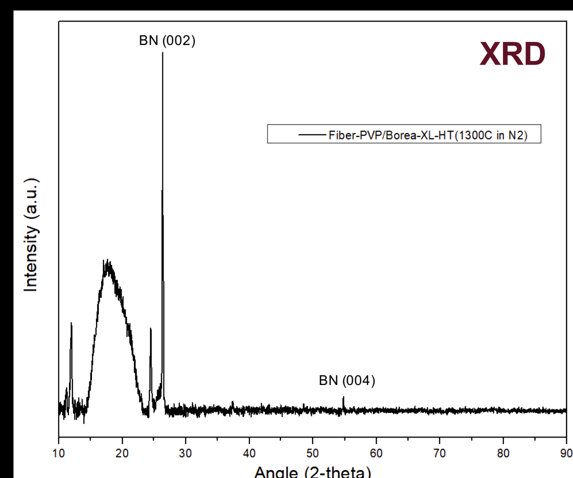
- Polyvinylpyrrolidone (PVP), C_6H_9NO
- Boron Oxide, B_2O_3



Polymeric Fiber (as prepared)



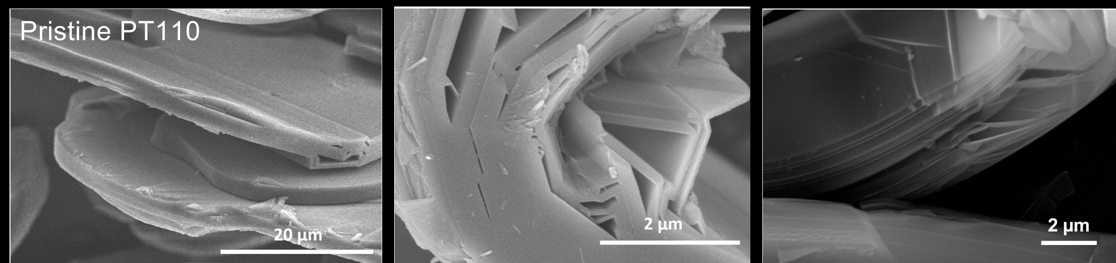


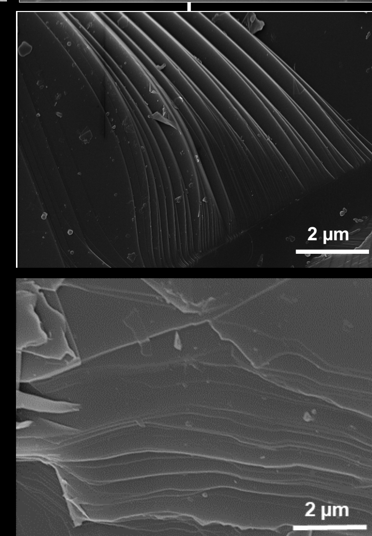


- FTIR and XRD confirmed heat-treatment process produced BN
- Proved feasibility

h-BN Intercalation/Exfoliation Process Optimization

Higher processing temperature





Longer processing time

- Activation Agent Study to optimize the intercalation and exfoliation process
  - NaF, KF, LiF, NaCl, KCl and LiCl to optimize the intercalation and exfoliation process.
- Processing temperature and time study

Next Steps to Prepare GRC Engineered Composites

Fabrication of BN Nanocomposites with Twin Screw Extrusion

- The goal is to prepare composites as close as the application processing parameters:
  - Tape/film take-up extrusion (for characterization)
  - Wire coating extrusion (application)

Automated Material Laboratory with Machine Learning

- The goal is to accelerate material discovery and optimization by continuous preparation of samples and analysis with minimum interaction from a researcher
- Initial setup can mix liquid and solids, synthesize materials, heat and cool, tape cast and software that allows incorporation of Machine Learning
- Modules are interchangeable and more can be added to adapt it to new processing

Summary

- Modification of commercial hexagonal boron nitride has been developed to be used as filler in composites
  - hBN intercalation / exfoliation by iron chloride or aluminum chloride
  - hBN coated with alumina
- Although functionalization of boron nitride nanomaterials using APTES was used successfully to help with their dispersion on polymer composites to obtain higher thermal conductivity, the process is tedious and not scalable
  - Scalable processes to engineered BN to target properties are being developed
- Intercalation and exfoliation process has been optimized with higher temperatures and longer processing time yielding better exfoliation
- Very high thermal conductivity of in-plane and through-plane of hBN-alumina composite was obtained
- ***A lot of work is still in progress, and our BN Research Team is making strides in developing new pure BN components and getting them engineered and incorporated in new ceramic and polymeric matrixes using extrusion and/or the Automated Materials Laboratory***

Acknowledgements

- Transformative Tools and Technologies (TTT)
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  - Ching-cheh Hung (retired)