Epoxy and quench training of superconducting magnets: A dedicated study

Shijian Yin, Tengming Shen

Lawrence Berkeley National Laboratory

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Problems – the long quench training, the loss of training memory, and the unpredictability of superconducting magnets

- **Nb-Ti superconducting magnets of several of recent U.S. DOE projects are short of delivering performance, jeopardizing or failing the entire project, due a large part to a lengthy quench training plus, in some cases, a poor memory.**

- **LARP Nb_3Sn quads, CERN 11 T dipoles, and MDP CCT dipoles have a lengthy quench training and a good memory.**
  - **Future Nb_3Sn magnets will need to work at <80% SSL.**

- **All above mentioned magnets are epoxy impregnated and it has been suggested that epoxy is playing an important role.**

Hypothesis – epoxy cracking is a primary mechanism for premature quenches of superconducting magnets

Epoxies have defects, are easy to crack whereas magnets experience high-stress and strain.

Epoxies have a low thermal conductivity.

Experimental and theoretical investigation of mechanical disturbances in epoxy-impregnated superconducting coils. 3. Fracture-induced premature quenches

Y. Iwasa,* E.S. Bobrov,* O. Tsukamoto,† T. Takaghi** and H. Fujita††

Francis Bitter National Magnet Laboratory and Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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Heat generation from epoxy cracks and bond failures

H. Maeda and Y. Iwasa

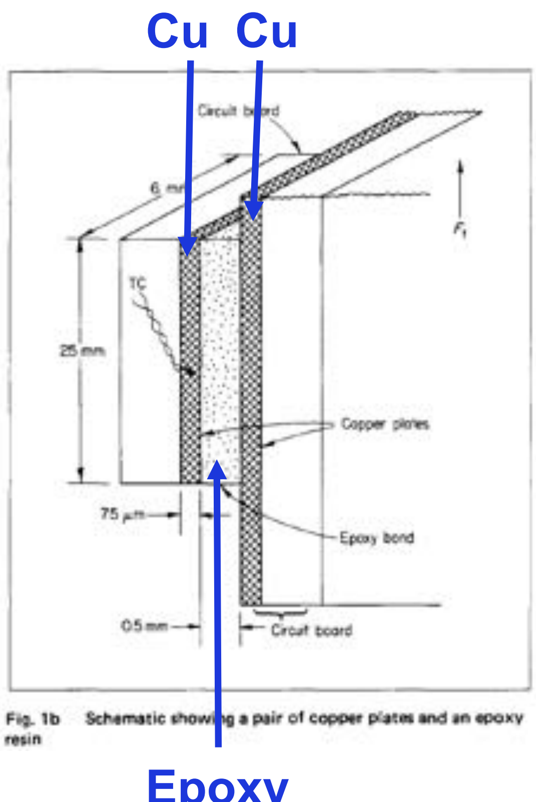


Fig. 1b Schematic showing a pair of copper plates and an epoxy resin

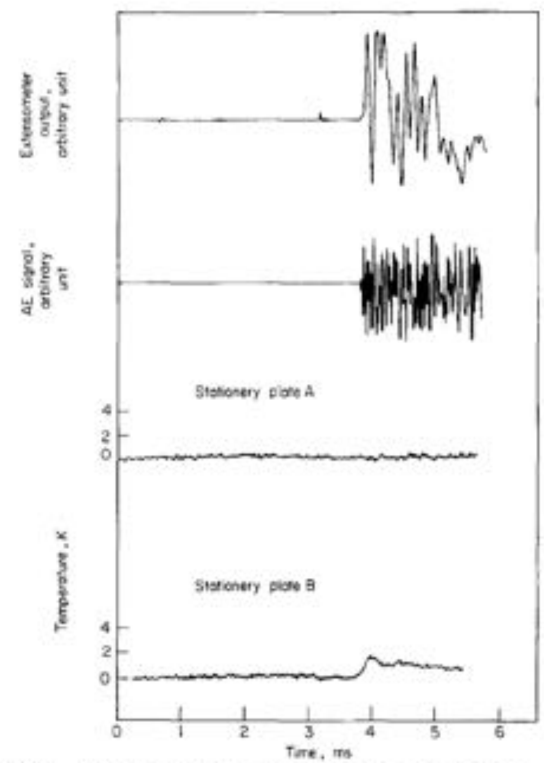
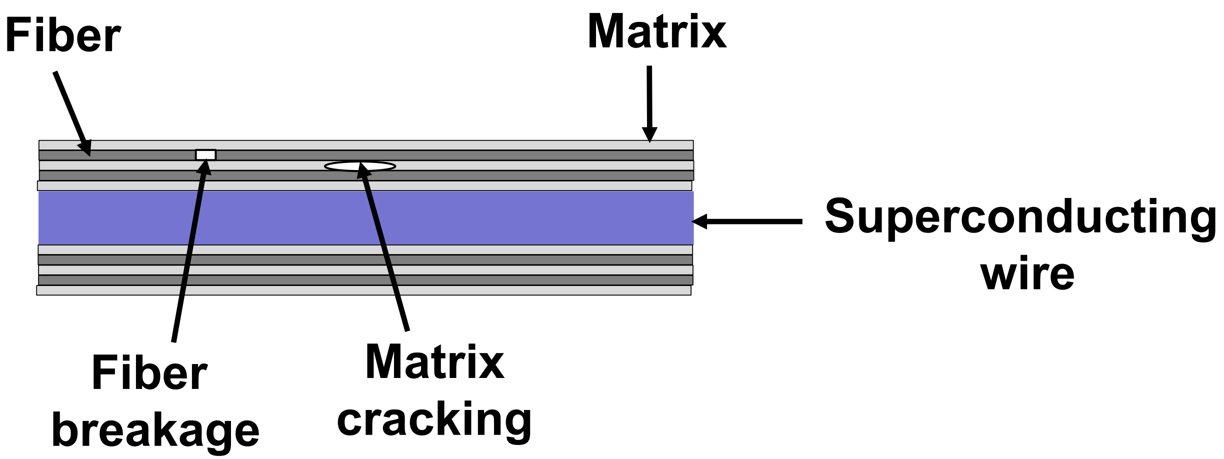


Fig. 2 Extensometer output, AE, and thermocouple outputs for both plates, all vs time for an epoxy crack event

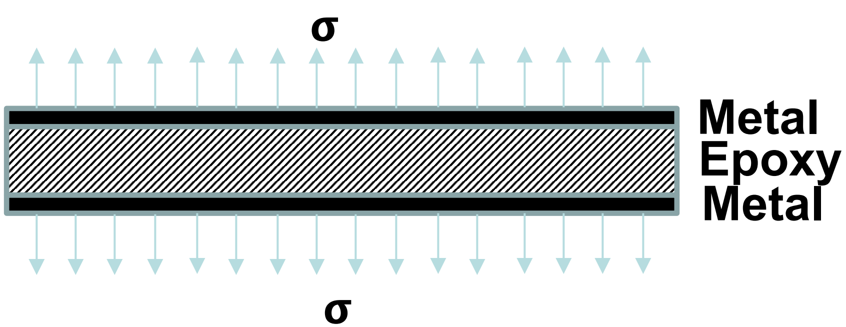
Failure mechanisms in fiber reinforced plastics and superconducting wire composite



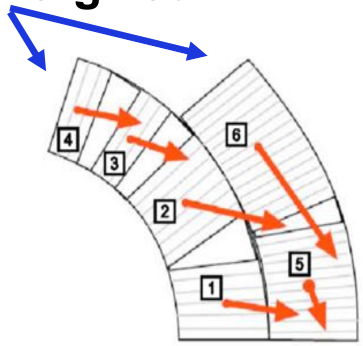
- Matrix cracking
- Fiber breakage
- Interfacial failure

Examples of interfacial failures in accelerator superconducting magnets

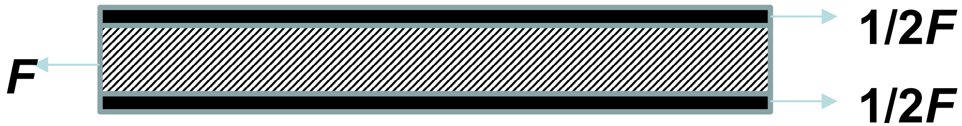
Crack, debonding or tear-off under normal stress



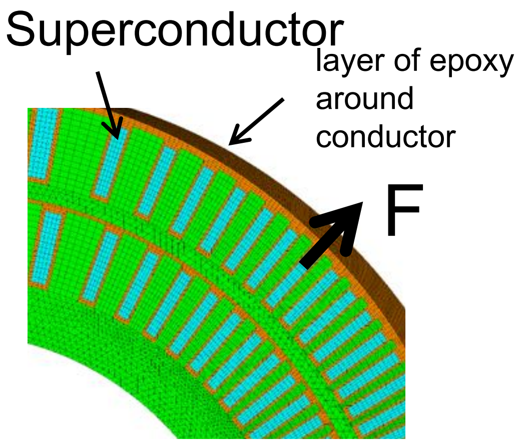
At the interface with pole island for CT when energized



Fracture (or crack) under shear stress



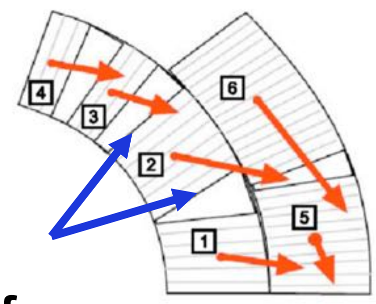
CCT – every conductor channel



Failure modes of epoxy in superconducting magnets: At the interfaces with other elements of superconducting magnets

Fracture (crack) under tensile stress

Differential thermal contractions of epoxy and metal (during the cooldown)



At the interface with phosphor bronze wedges

Three tasks

- **Determine engineering properties of epoxies for superconducting magnet systems.**
- **Investigate characteristic cracking events and energy release of fiber reinforced epoxy/superconducting wire system determined by monitoring acoustic events during dedicated mechanical tests**
- **High-thermoconductivity, high-strength epoxy for superconducting magnets through nano additions**

Table 1 Properties of epoxy resin at 4.2 K

Symbol	Property	Value
α	Thermal contraction from 293 to 4.2 K	0.010 — 0.012
E	Young's modulus	8000 MPa
μ	Poisson's ratio	0.36 — 0.37
G	Shear modulus	2200 — 2500 MPa
σ_f	Fracture strength in tension	145 — 200 MPa
ε_f	Tensile fracture strain	1.9 — 2.4%
γ	Fracture energy release rate	100 — 210 J m^{-2}
ρ	Radius of fracture deformation zone	5 — 9 μm
K_{Ic}	Mode I fracture toughness	1.2 — 1.5 MPa $m^{0.5}$
K_{IIc}	Mode II fracture toughness	4.6 — 5.4 MPa $m^{0.5}$
τ_f	Fracture shear	1 — 6 MPa

Reduced by fillers such as glass fibers to match that of metal/superconductor.

Which one of these following parameters are important for minimizing quench training?

- **Modulus**
- **Tensile fracture strain**
- **Fracture toughness**
- **Fracture shear**
- **Thermal conductivity**

Summarized by Yuki Iwasa with work done especially by David Evans at Rutherford lab

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Test design

- **Four epoxies: (1) Stycast 2850, (2) CTD-101K, (3) NHMFL-61, and (4) Matrimid**

- **Three mechanical tests:**
  - **Tensile**
  - **Compression**
  - **Fracture toughness**

- **Two low temperature physical property measurement: Thermal conductivity and specific heat**

- **AE measurement and microscopy**

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Tooling development

- **Vacuum impregnation epoxy mold designed and fabricated.**
- **2-layer design capable of fabricating 20 samples with each VPI run.**

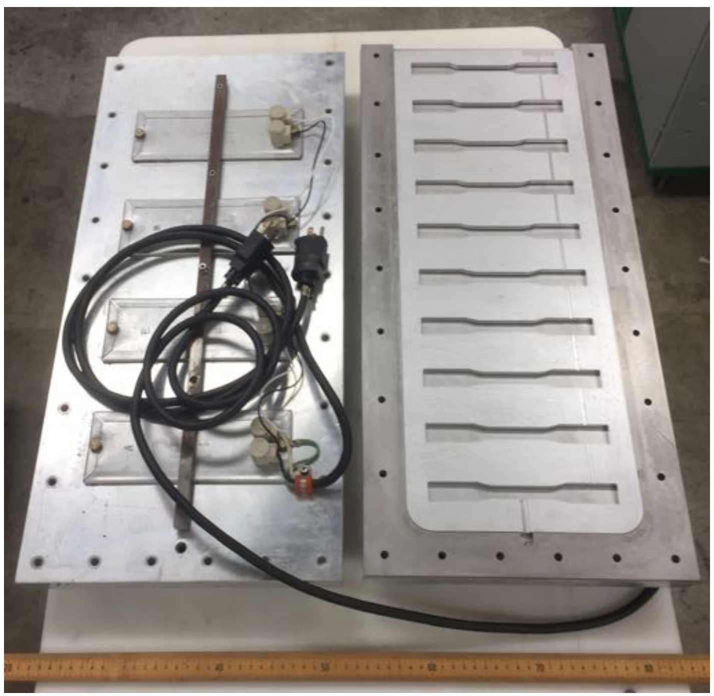


Fig. Heater plate and the first layer mold

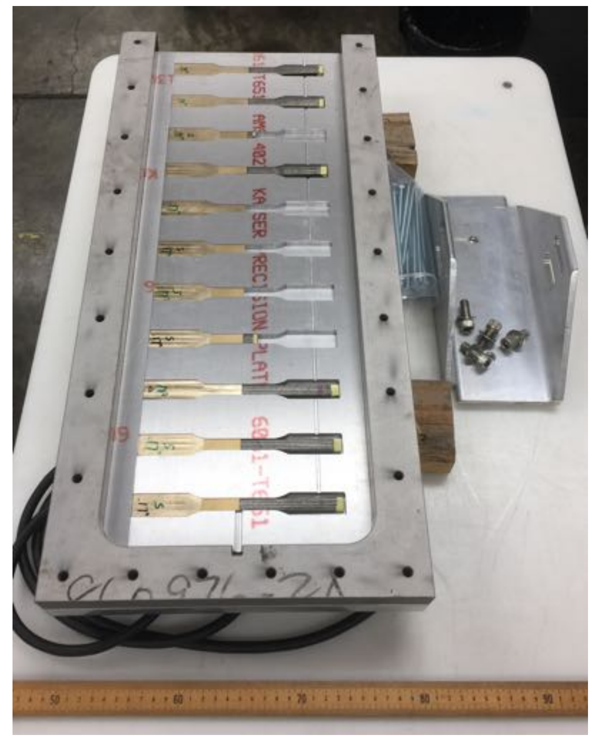


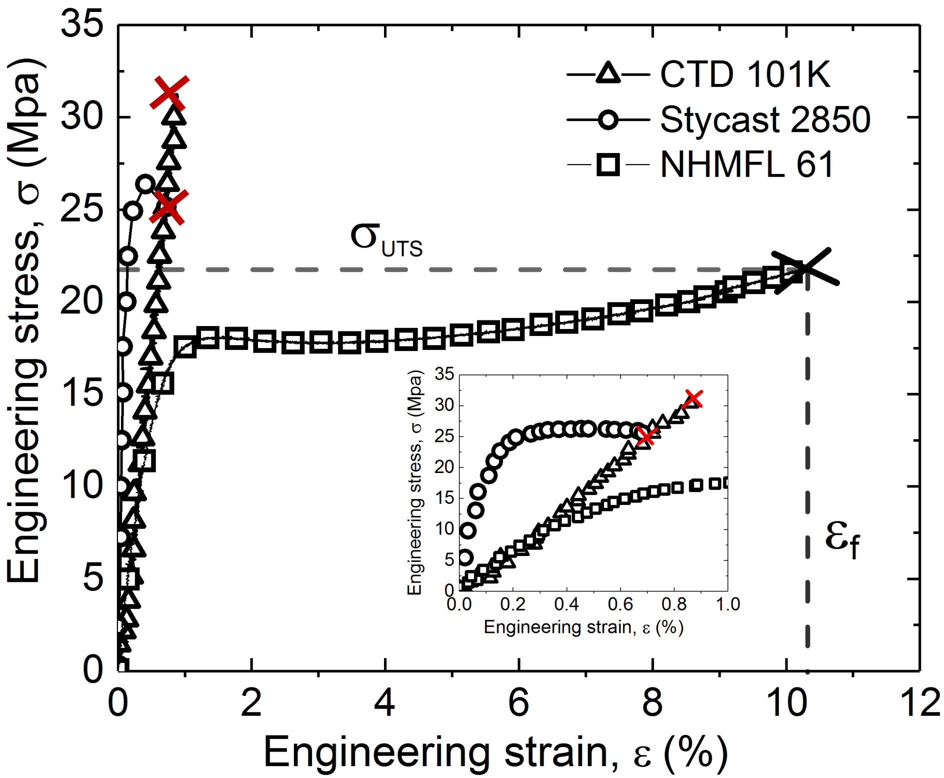
Fig. The second layer mold and legs

With inputs from Jim Swanson

Preliminary results – tensile tests of epoxy only samples

How does it correlate with magnet training behaviors?

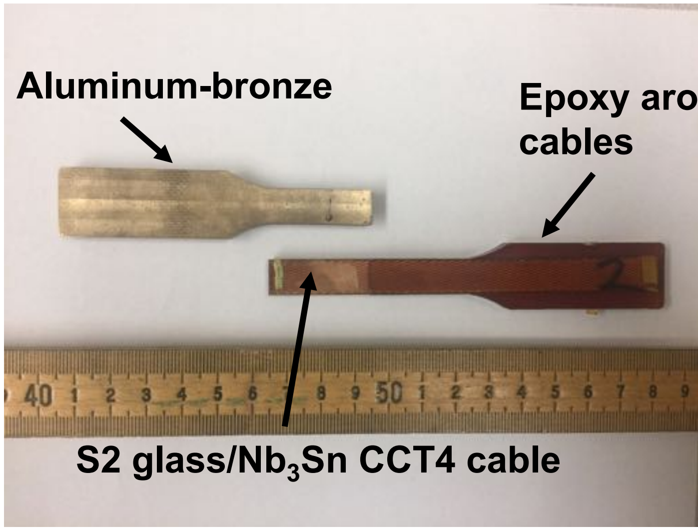
- Anecdotally wet winding with Stycast 2850 reduces training (e.g. C. Taylor and B. Wang, ALS superbend mangets)

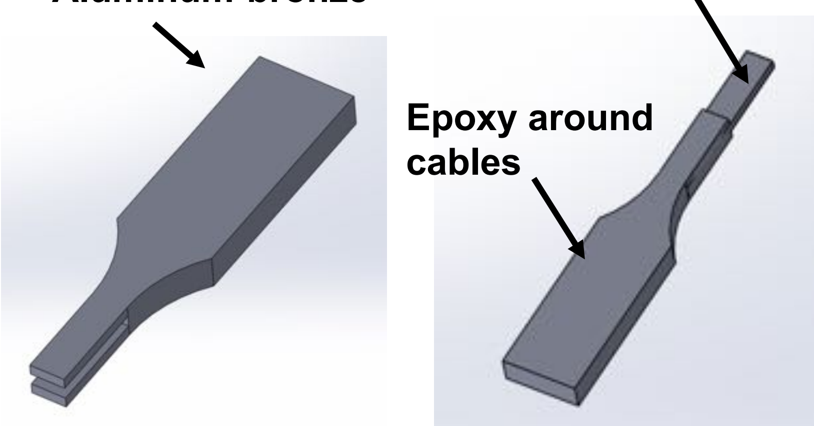


NHMFL 61 mix

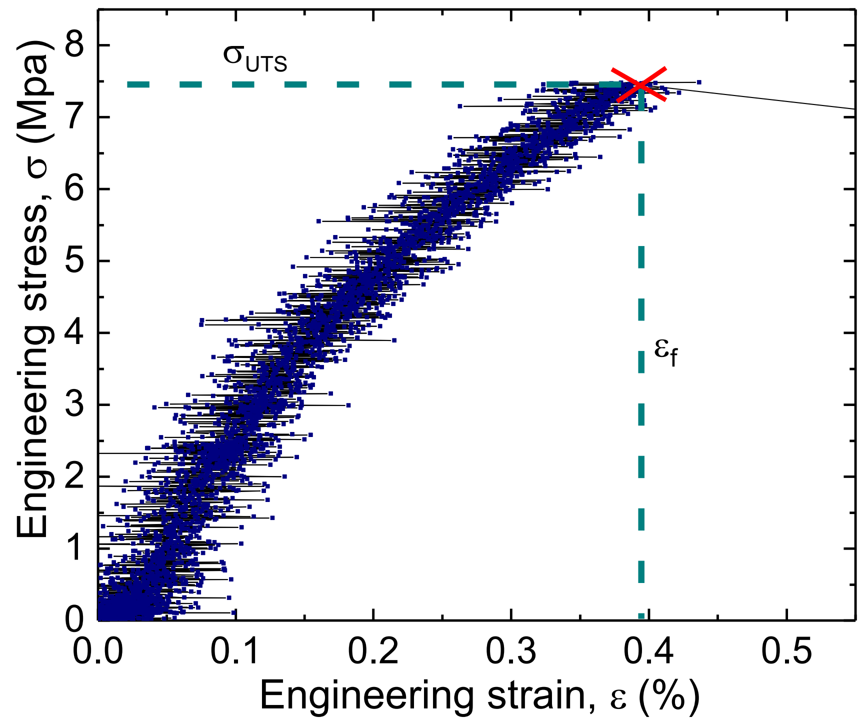
RT, test standard - ASTM-D638

Preliminary results – fracture shear stress is low – double-lap shear test



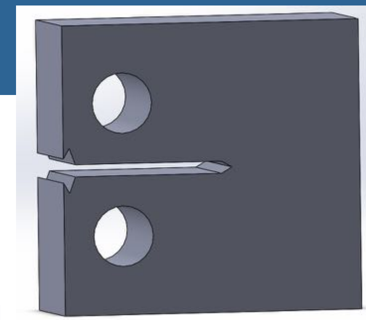


Fracture shear stress test of CTD101K/954/Nb_3Sn Rutherford cable at RT

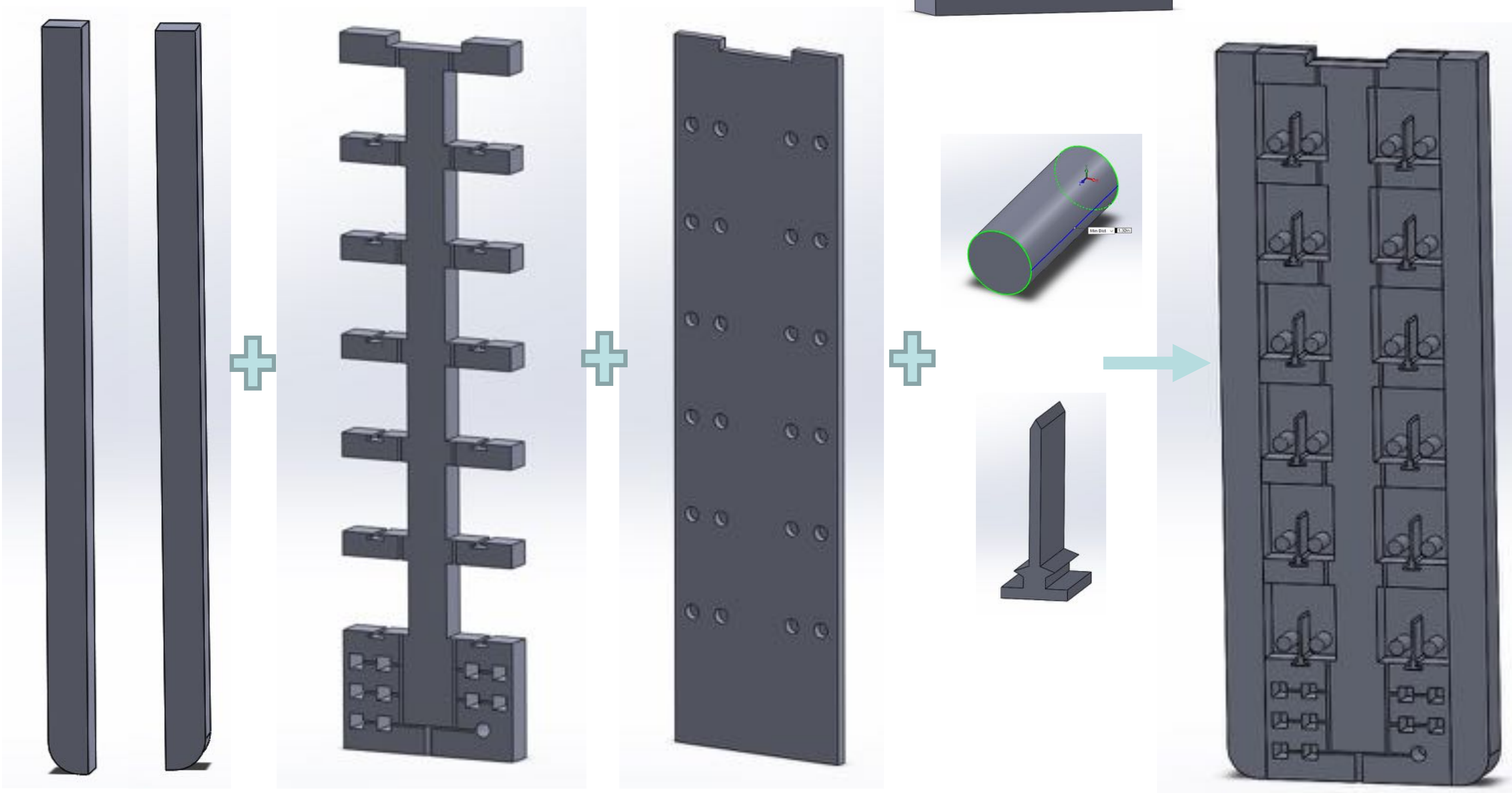


- **How does fracture shear stress of epoxy change with surface treatment such as sand-blasting?**

Fracture toughness sample mold being designed

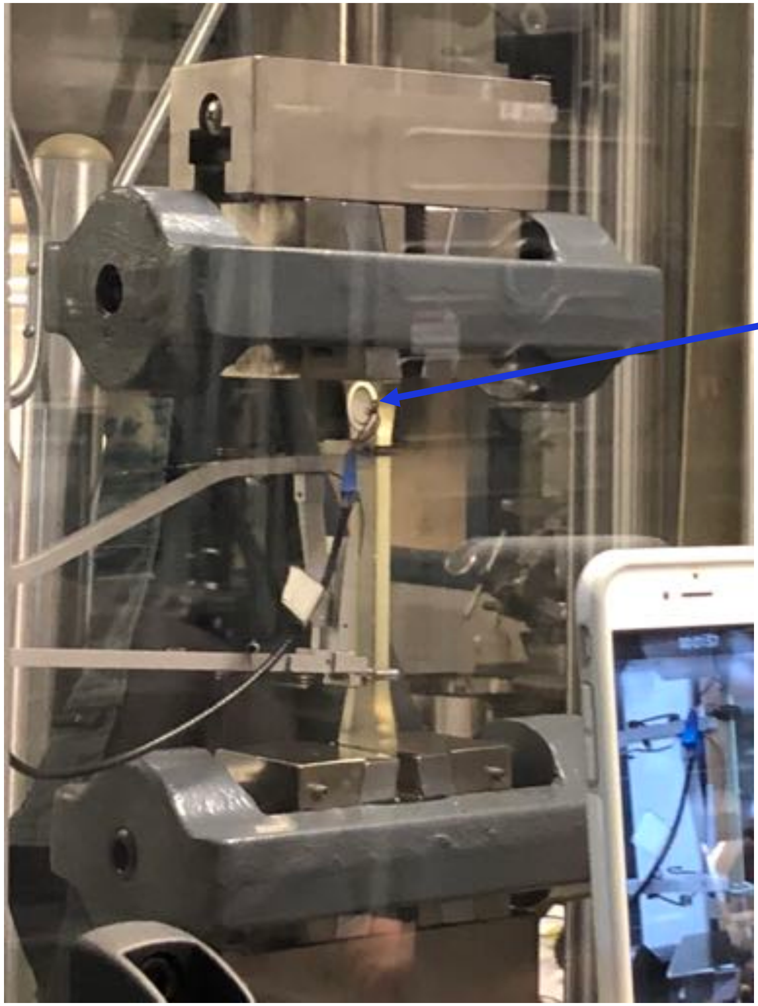


ASTM D5045



Monitor acoustic events during mechanical tests – just started

With Maxim Marchevsky.



AE sensor

With CTD/S-2 glass fiber/Nb_3Sn cable, cracking sounds can be hear by human ears.

Many complexities involved: how to distinguish epoxy fracture, from fiber breaking, and from bonding failure?

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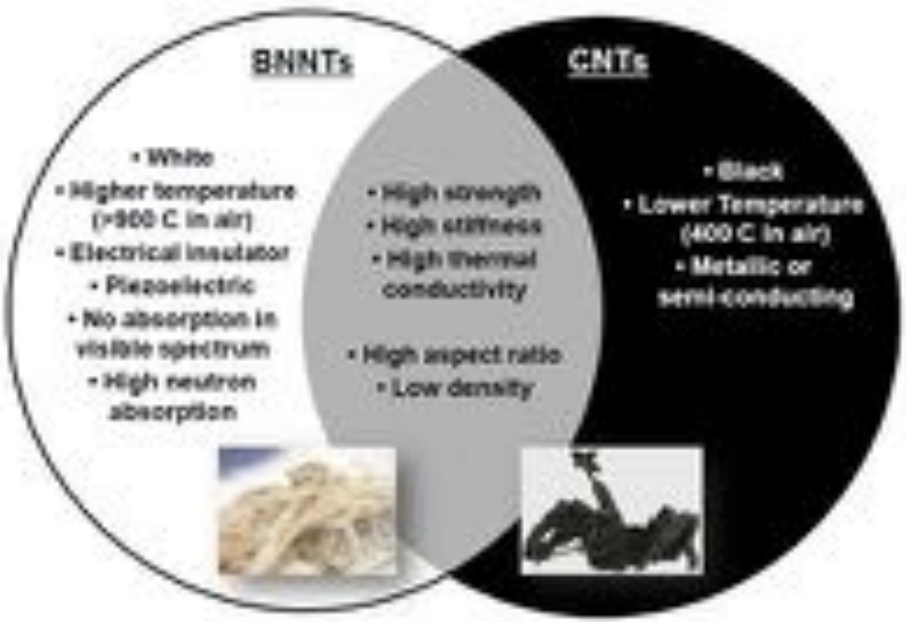
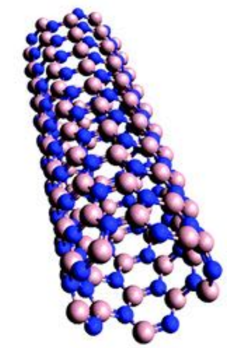
Improve properties of epoxy through nano additions

Boron nitride (BN) nano-materials possess a high thermal conductivity, electrical insulation property as well as excellent mechanical features.

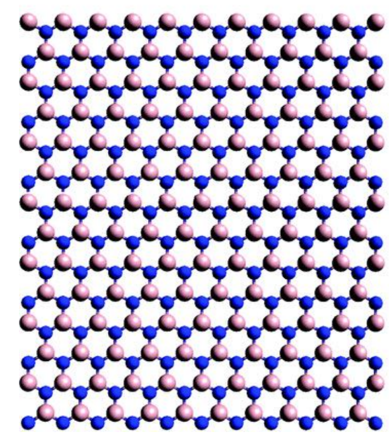
BN nanomaterials are potential fillers for impregnation resins which have a promising perspective to meet the requirement of superconductor magnets.



Nanotube



Nanosheet

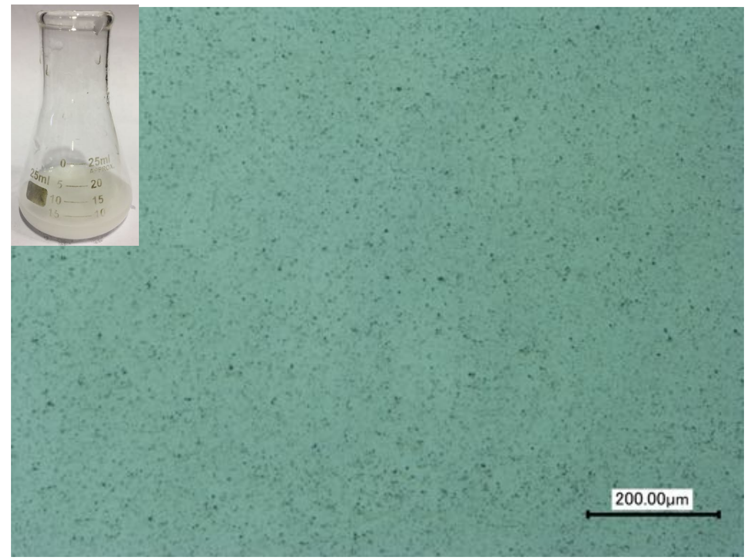


[1]

Jakubinek et al., *Polymer Nanocomposites Incorporating Boron Nitride Nanotubes*, Nanotech 2015 Conference: Washington, DC, June 2015.

Procedures to mix, disperse functioned BNNS into epoxy, and WPC are being developed

BNNS disperse in isopropyl alcohol



PBA-BNNS disperse well in IPA
After 3 h ultrasonic mixing

Concluding remarks

Dedicated mechanical tests and sample designs to explore patterns and roles of fracture of epoxy in superconducting magnets on their quench training behavior.

- Just started with some interesting findings.

Couple these tests with sub-scale magnets tests and high-field wire measurements will be rather useful.

Collaboration with universities, NHMFL, and Fermilab (compression tests) will be quite useful.