Fall 11-9-2015

3D printing of composites with controlled architecture

Brett Compton
Oak Ridge National Laboratory, comptonbg@ornl.gov

3D Printing of composites with controlled architecture

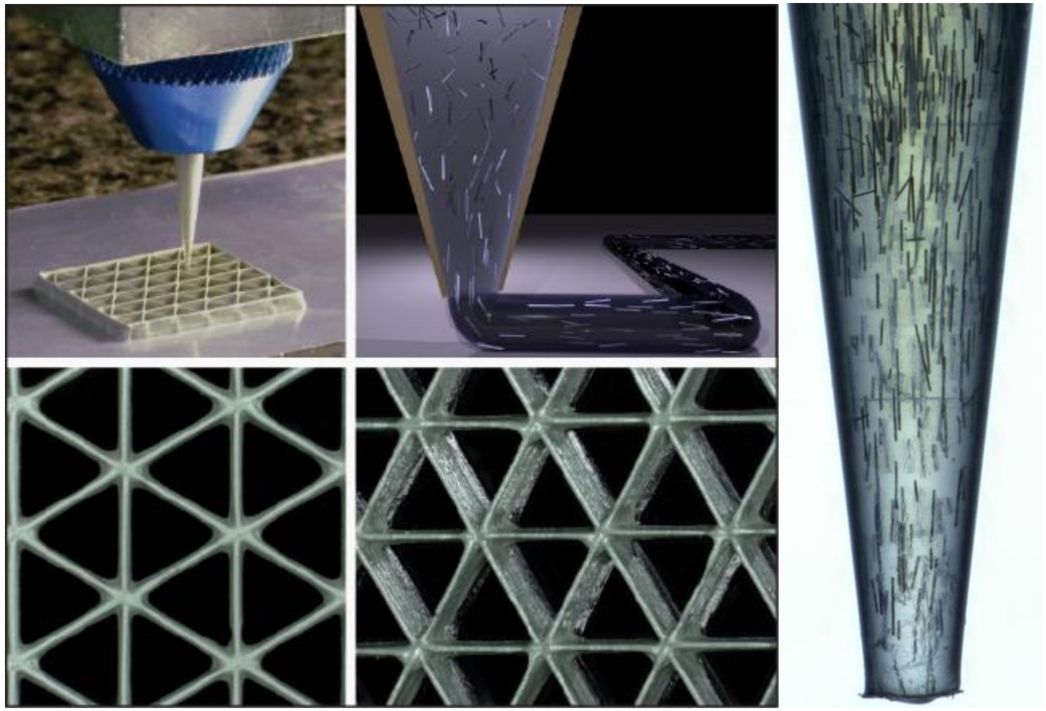
Brett G. Compton

Assistant Professor

Mechanical, Aerospace, and Biomedical Engineering Department

University of Tennessee - Knoxville

bcompto1@utk.edu



*Most of this work completed as a post-doc in Prof. Jennifer Lewis's group at Harvard University

Overarching research motivation

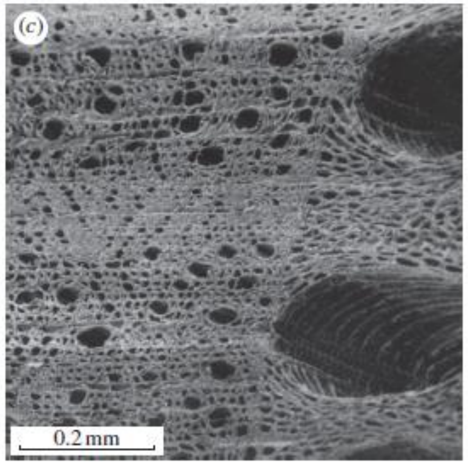
Better materials are needed! (Stronger, tougher, lighter, stiffer…)

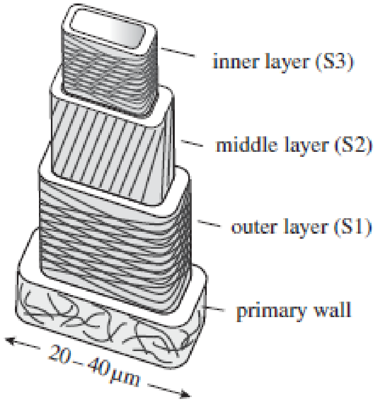
Inspiration:

Nature utilizes materials efficiently through control of **architecture at multiple length scales**.

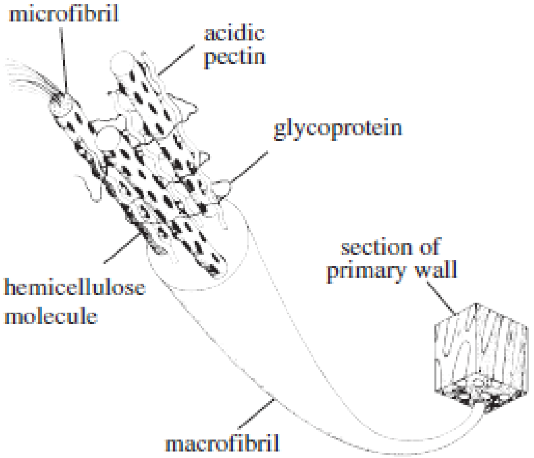
Wood utilizes **highly aligned cellulose fibrils** in a **cellular architecture** to maximize strength and stiffness with minimal weight.

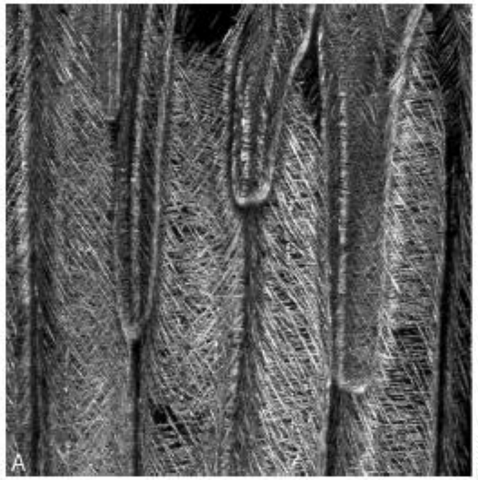
Balsa wood rivals the best monolithic engineering materials in terms of specific bending stiffness and strength.





Gibson, *J. R. Soc. Interface*, 2012

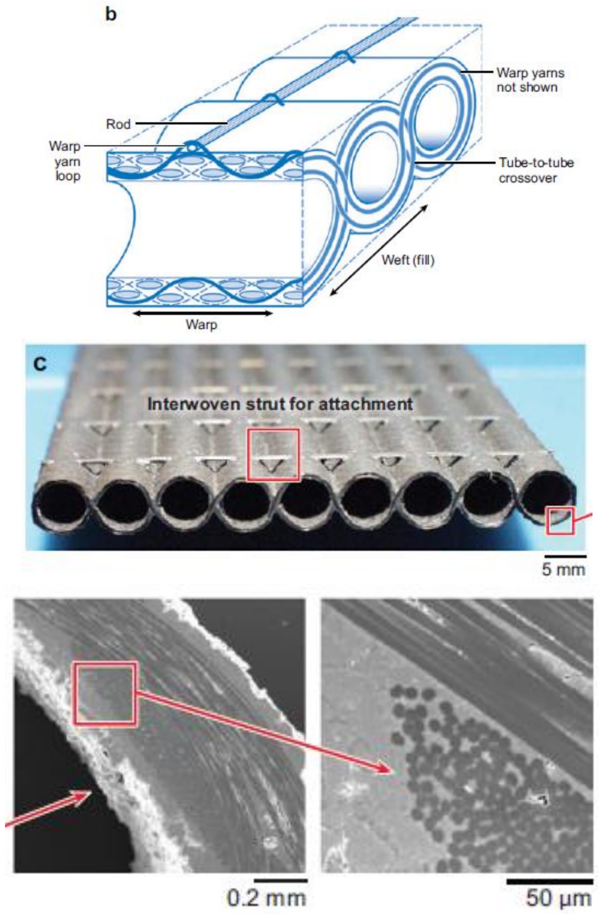




Donaldson, *IAWA Journal,* 2008

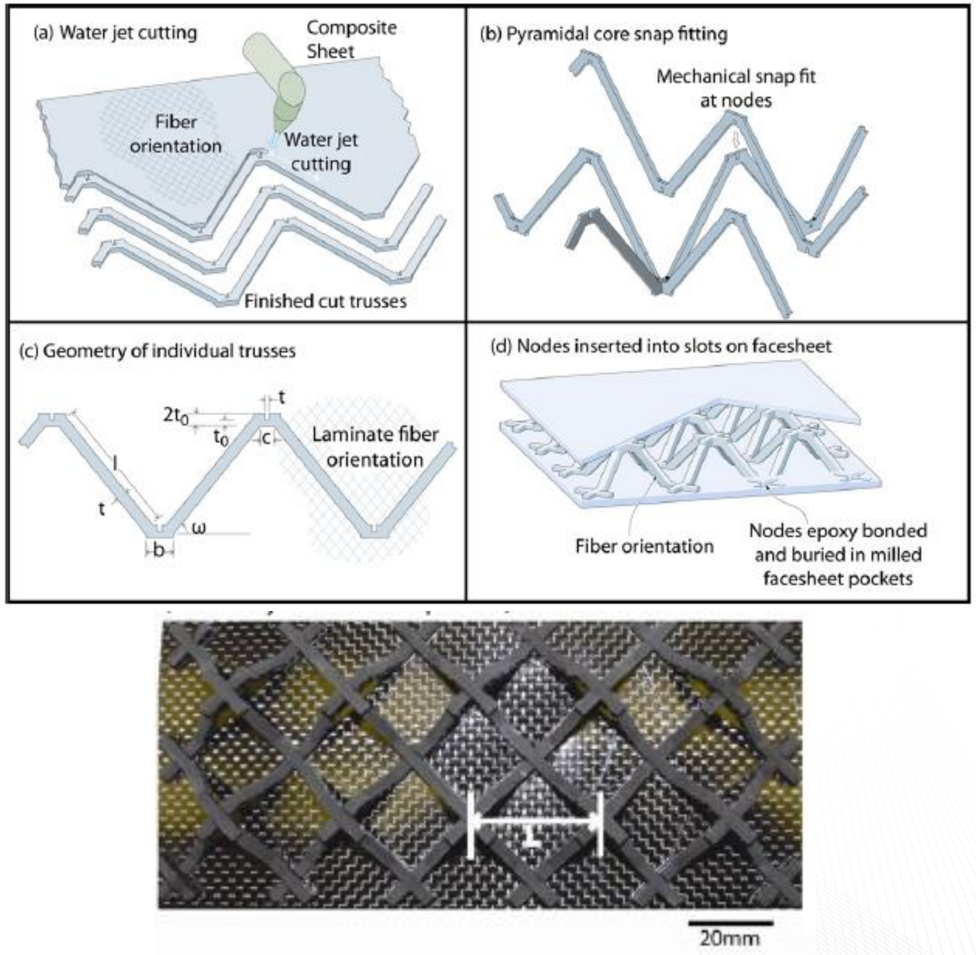
Existing approaches are promising, but complicated.

3D woven ceramic textiles



Marshall and Cox, 2008

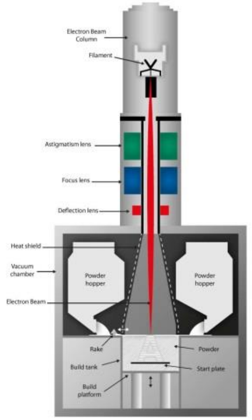
Assembled carbon fiber lattices



George et al. *Composites: Part A*, (2013)

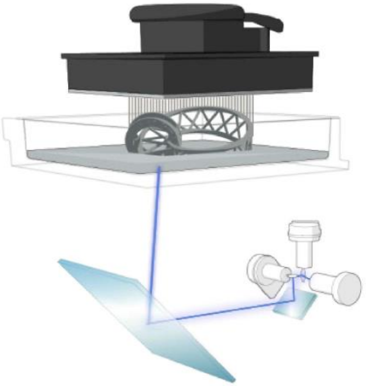
Additive manufacturing technologies

Powder bed methods (EBM, SLM)



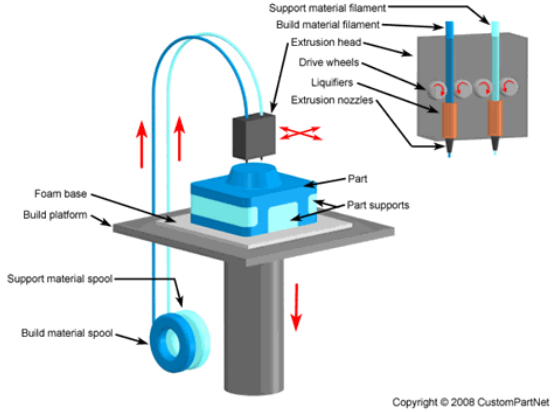
www.arcam.com

Stereolithography (SLA)



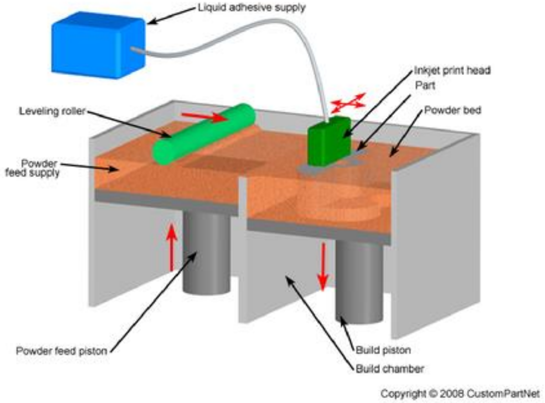
formlabs.com

Fused-deposition modeling (FDM)



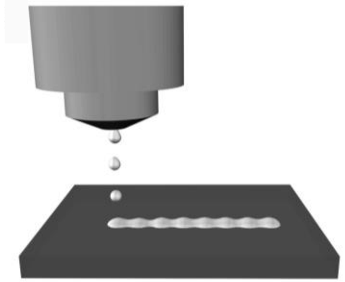
www.custompartnet.com

Binder jet powder bed



www.custompartnet.com

Inkjet



Direct-write extrusion

Lewis, *Curr. Opin. St. M.* (2002)

Additive manufacturing technologies

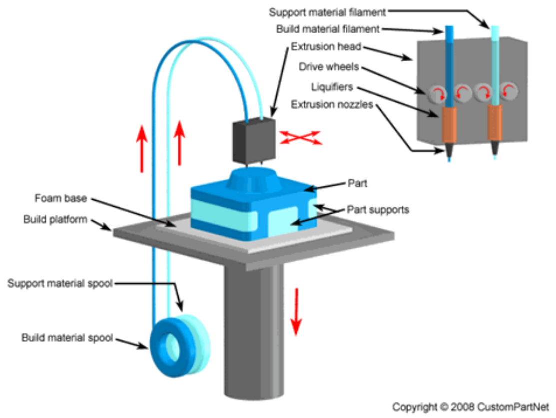
Powder bed methods (EBM, SLM)

Stereolithography (SLA)

Fused-deposition modeling (FDM)

Extrusion-based methods

- Thermoplastic or viscoelastic ink
- ~1-1000 μm feature size
- Can be parallelized for high throughput
- Suitable for multi-material deposition
- Greatest range of materials with direct-write
- Extrusion aligns fibers



www.custompartnet.com

www.arcam.com

formlabs.com

Binder jet powder bed

Inkjet

Direct-write extrusion

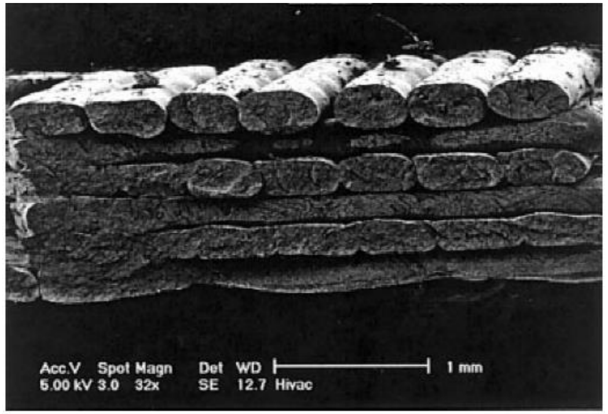
Lewis, *Curr. Opin. St. M.* (2002)

www.custompartnet.com

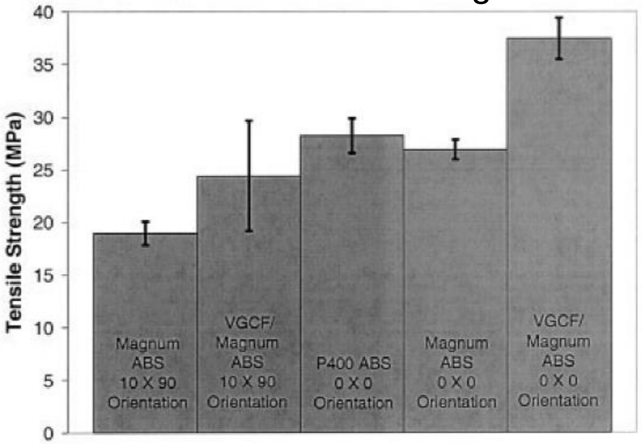
Background: Printed composites via FDM

ABS/carbon nanofiber

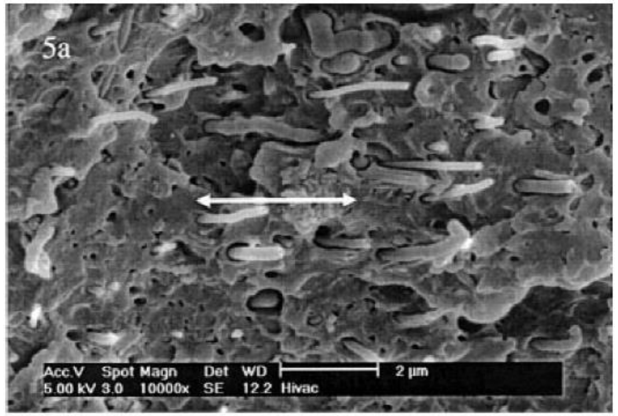
Tensile bar fracture surface

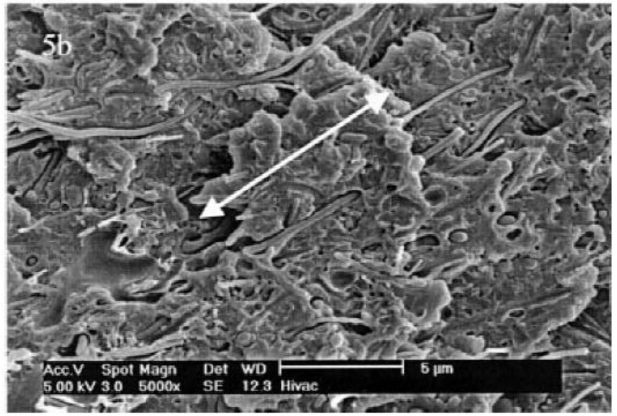


2x increase in strength



Fracture surfaces of printed ABS/carbon nanofibers



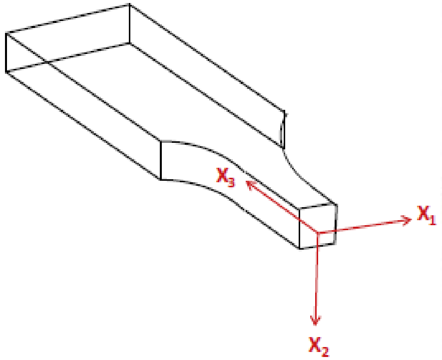


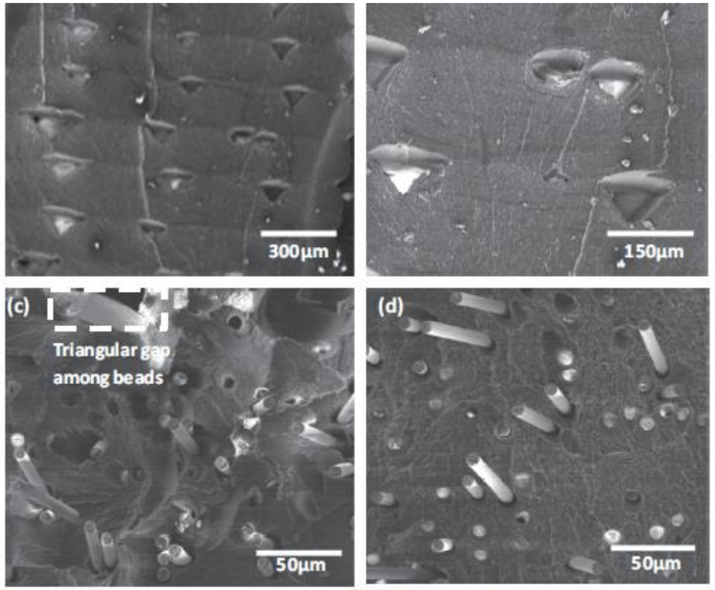
Longitudinal orientation

Transverse orientation

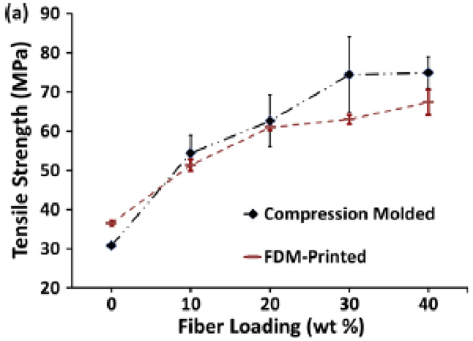
Shofner et al., *Journal of Applied Polymer Science* (2003)

ABS/carbon fiber

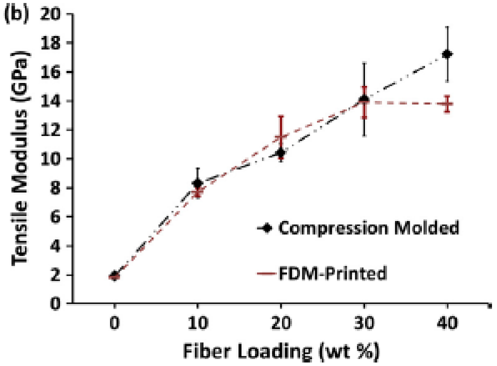




2x increase in strength



7x increase in stiffness



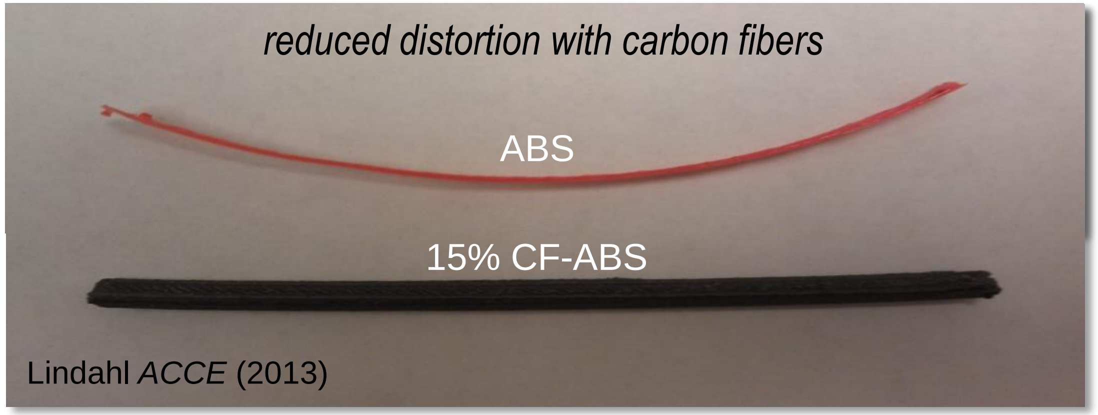
Tekinalp et al., *Composites Science and Technology* (2014)

Challenges with FDM

- Significant distortion possible due to thermal stresses from repeated addition and cooling of molten layers.

- Poor inter-layer/inter-filamentary adhesion and coalescence due to deposition of molten filaments onto cool structure.

- Challenges may be mitigated with thermoset feedstocks.



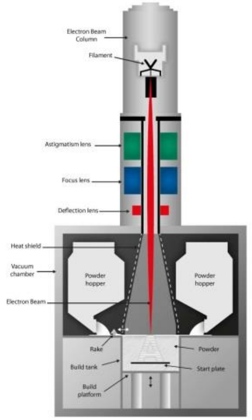
Lindahl *ACCE* (2013)

Platform	*Sx* (MPa)	*Sz* (MPa)
Makerbot replicator 2X[1]	21.04 ± 0.62	20.95 ± 1.3
CubeX[2]	29.31 ± 0.68	7.61 ± 2.91
Afinia[3]	28.09 ± 0.53	14.91 ± 0.96
Solidoodle 3[4]	24.08 ± 1.12	16.75 ± 4.56
Solidoodle 3 with 13% CF/ABS	70.69 ± 4.01	7.00 ± 2.59

Love et al. *J. Mater. Res.* (2014)

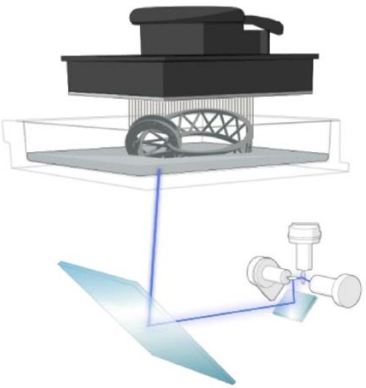
Additive manufacturing technologies

Powder bed methods
(EBM, SLM)



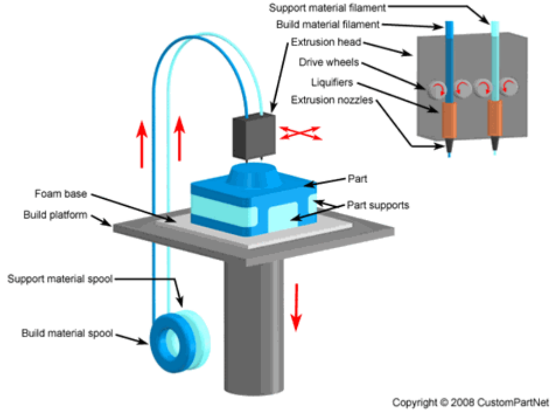
www.arcam.com

Stereolithography
(SLA)



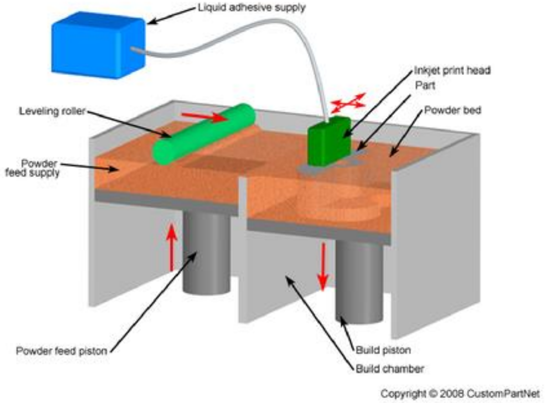
formlabs.com

Fused-deposition
modeling (FDM)



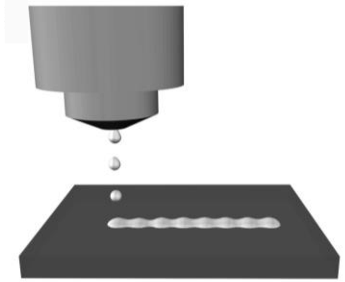
www.custompartnet.com

Binder jet powder bed



www.custompartnet.com

Inkjet



Direct-write extrusion

Brett G. Compton
Composites at Lake Louise, November 2015

Printed epoxy composites

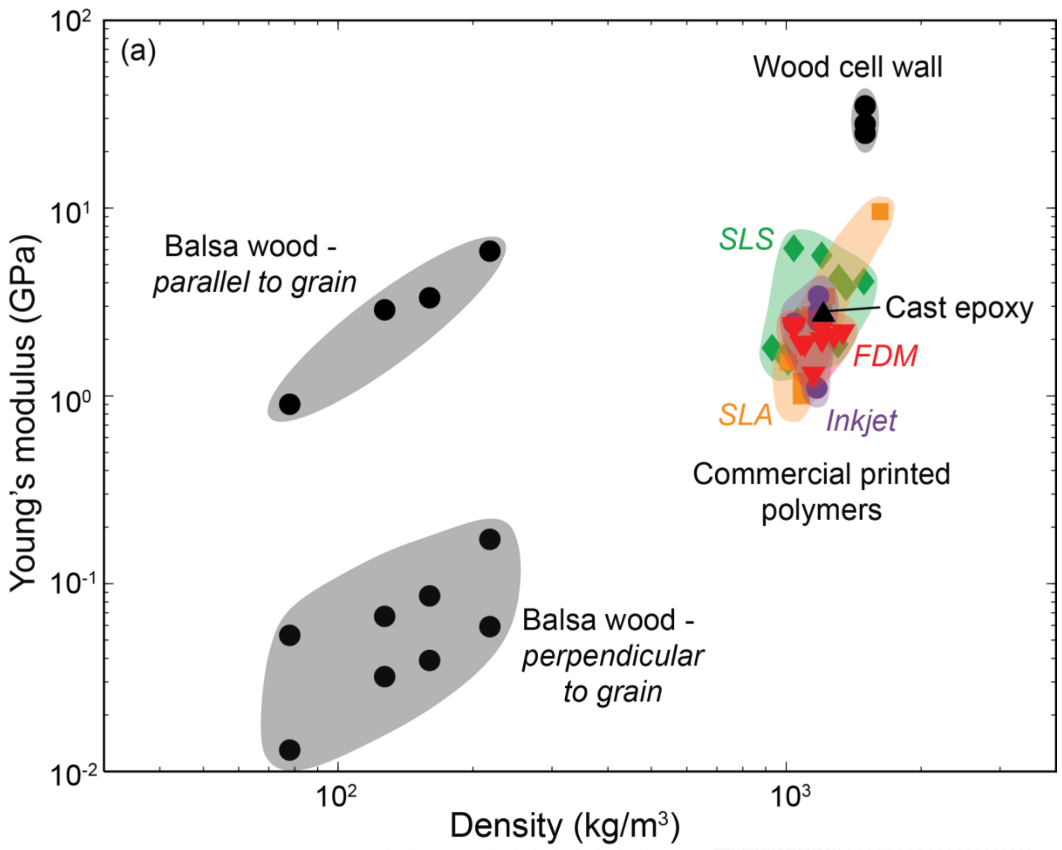
<u>Objectives:</u>
-Develop epoxy-based inks suitable for 3D-printing of lightweight cellular composites.

- -Minimal warping
- -Good inter-filamentary bonding

-Characterize mechanical properties of 3D-printed structures.

- -Young's modulus
- -Failure strength
- -Material orientation and effects of print direction

Mechanical property targets



Brett G. Compton

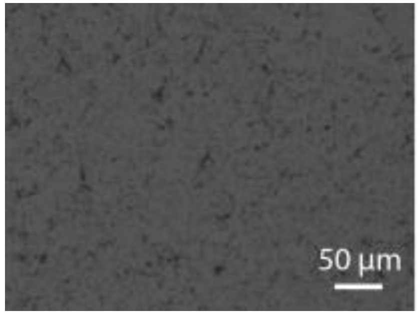
Materials

Resin: Epon 826 epoxy
resin

Viscosifier: Nano-clay platelets

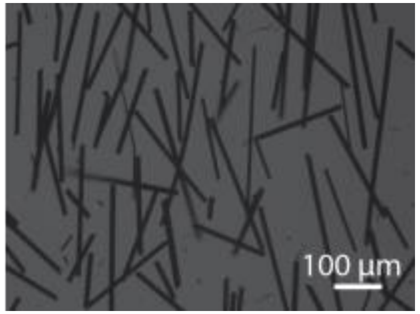
Structural
Fillers: SiC whiskers
Carbon fibers

SiC whiskers

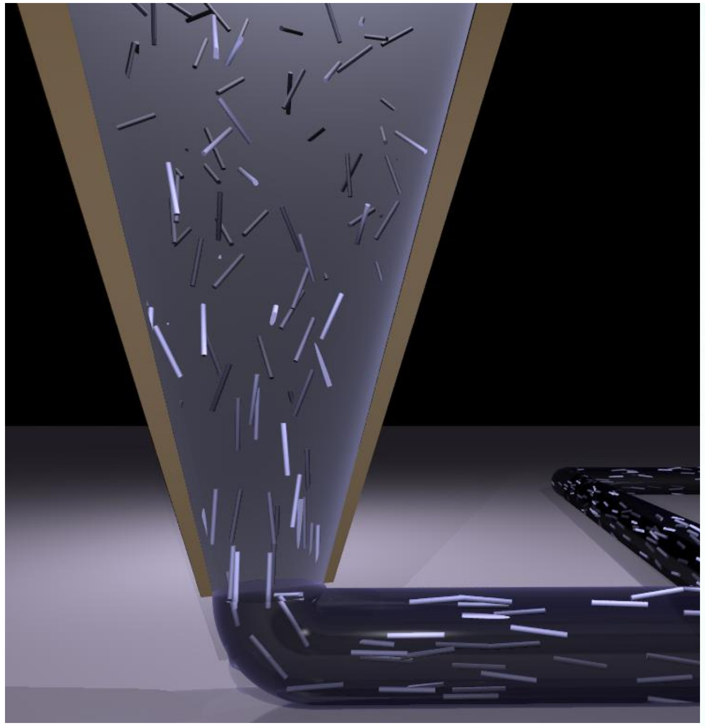


0.65 x 15 µm

Carbon fibers



10 x 220 µm



During extrusion, **high aspect ratio fillers become highly aligned**, resulting in superior properties along the print direction.

Alignment is critical to effective structural reinforcement

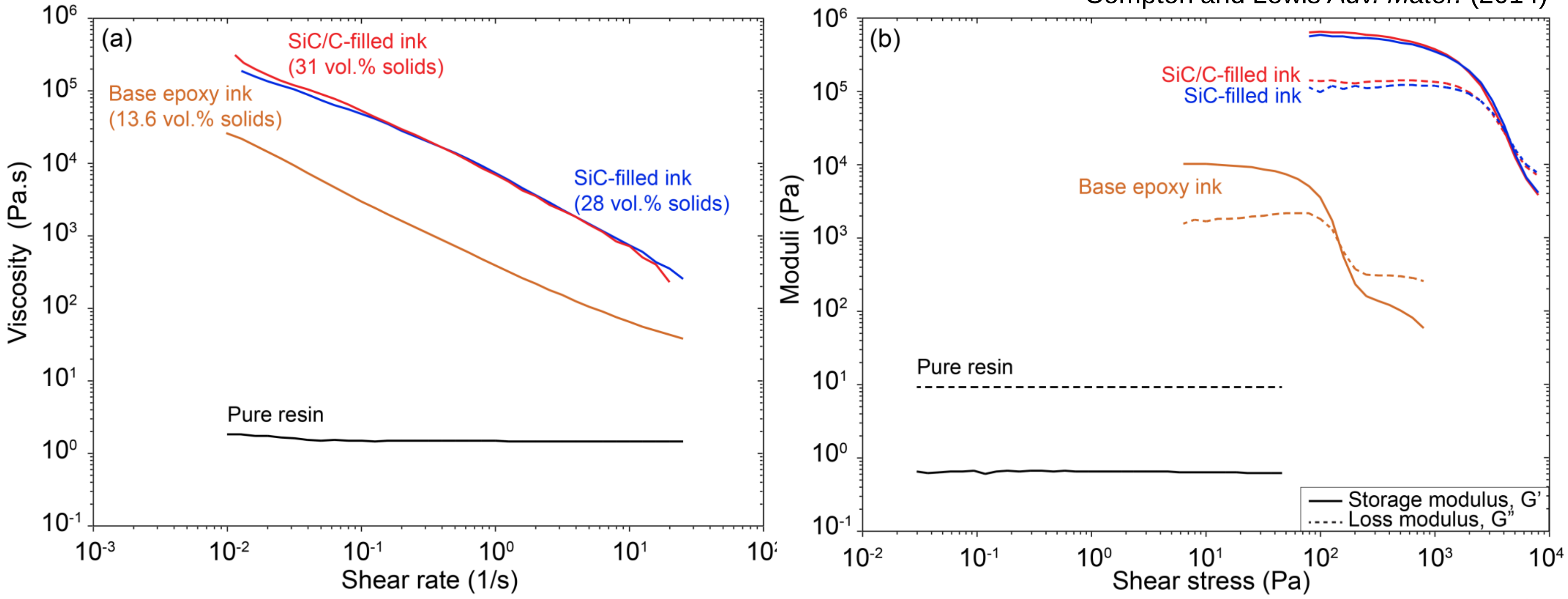
Ink formulations

Ink Constituents	Epoxy+ clay (g)	SiC-filled ink (g)	SiC/C-filled ink (g)	Epoxy+ clay (vol.%)	SiC-filled ink (vol.%)	SiC/C-filled ink (vol.%)
Epoxy (resin)	30	30	30	86.4	71.5	68.9
Cloisite nano-clay	8	8	8	13.6	11.2	10.8
SiC micro-rods	0	20	20	0	17.3	16.7
Carbon fiber rods	0	0	3	0	0	3.6

*All inks contain a latent curing agent, BASF Basionics VS03, at 5 parts per hundred by weight resin (phr) and DMMP antiplasticizer at 10 phr. Inks are cured at 100°C for 15 hours, followed by 2 hours at 220°C.

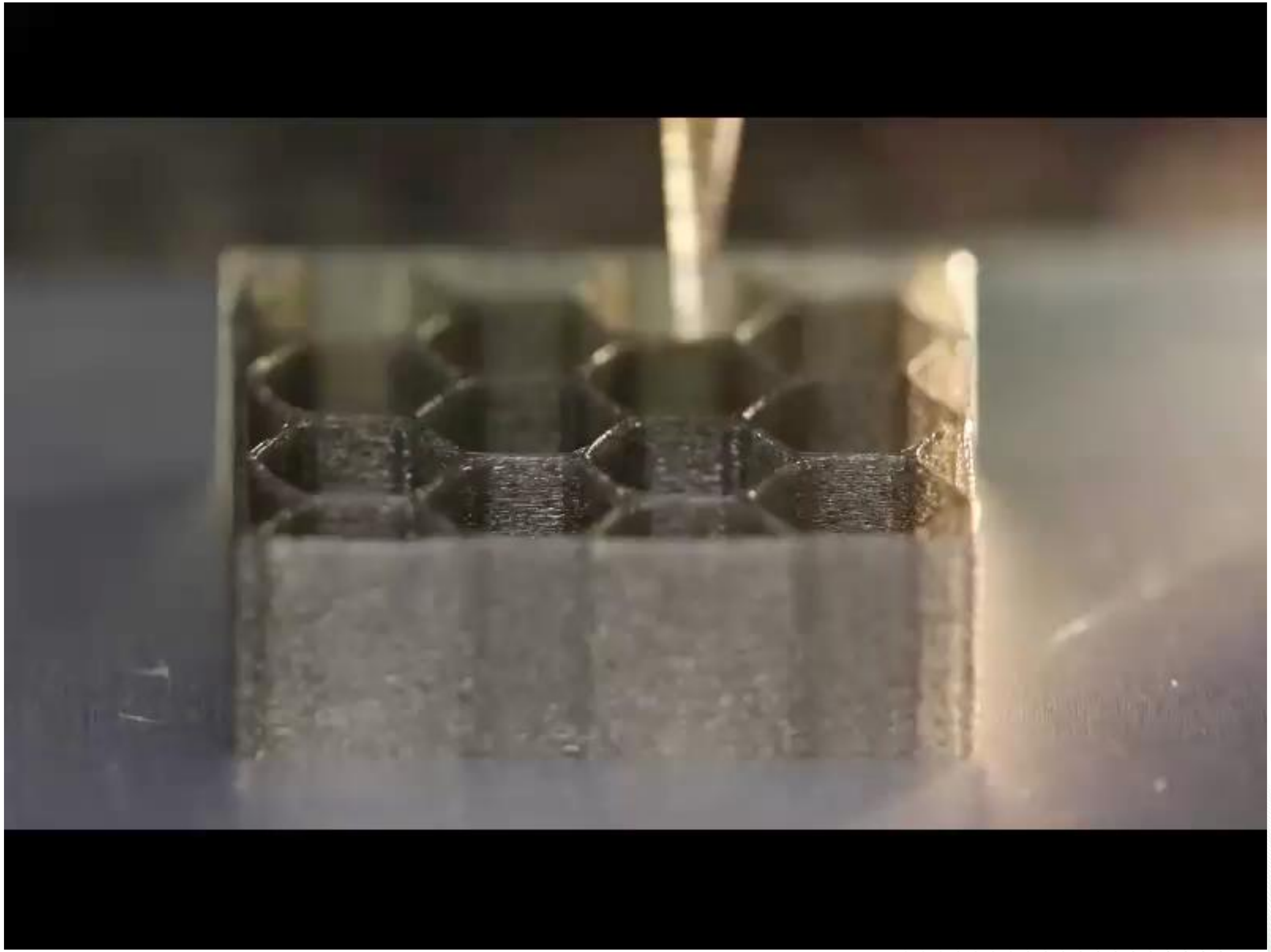
Ink rheology

Compton and Lewis *Adv. Mater.* (2014)

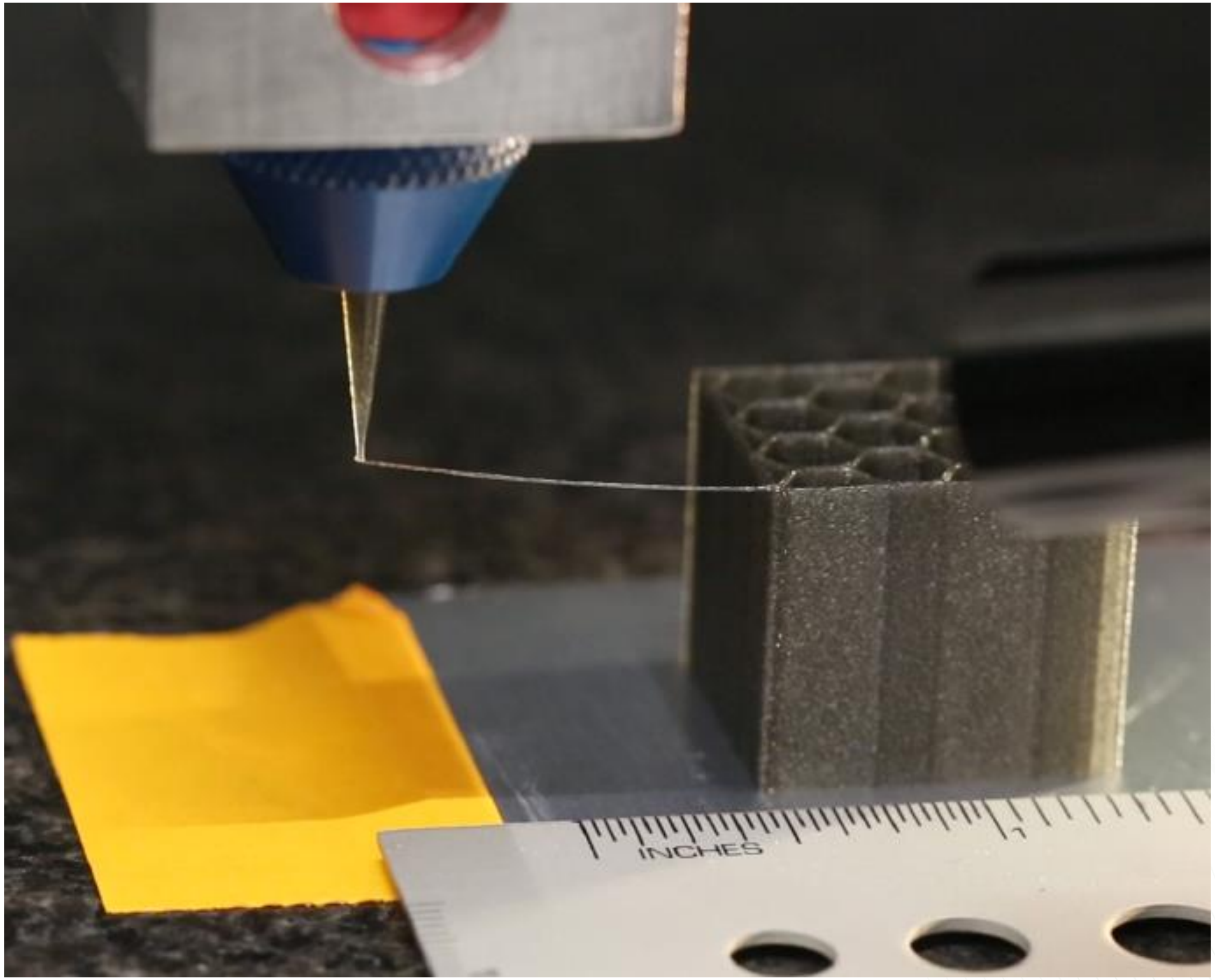


- **Nano-clay platelets** impart the **shear thinning, stiffness, and yield strength** required for 3D printing.
- **SiC whiskers** provide additional stiffness and yield strength to the ink, and act as **effective structural reinforcement** in the final composite.
- A small amount of milled **carbon fibers** provide **excellent structural reinforcement** without significantly affecting the rheology of the ink.

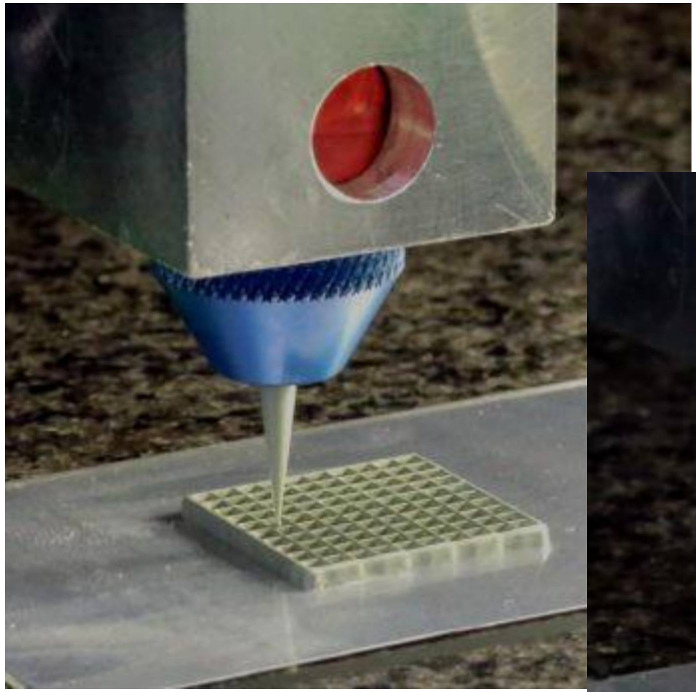
Printing cellular structures



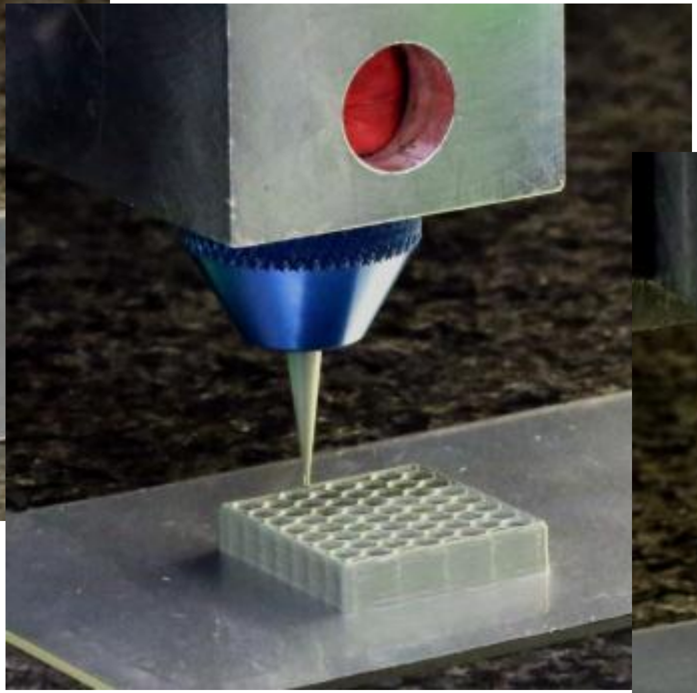
Printing cellular structures



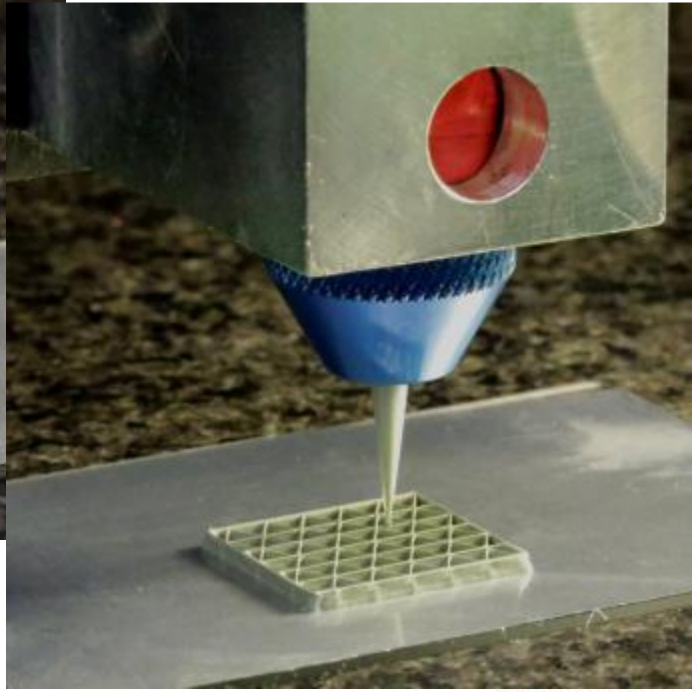
Printing cellular structures



Square honeycomb



Hexagonal honeycomb



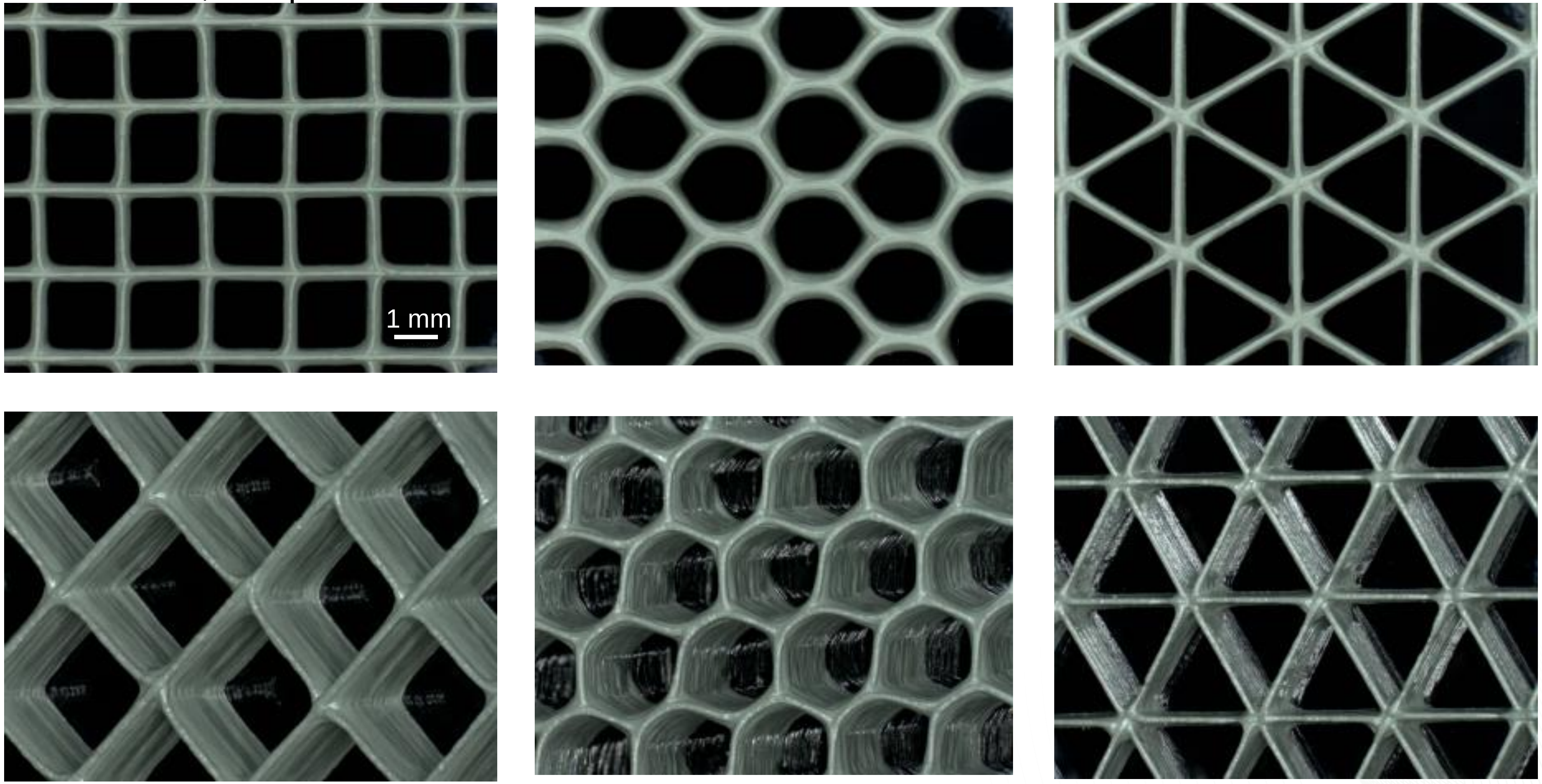
Triangular honeycomb

SiC-filled ink,
200 µm nozzle

Brett G. Compton
Composites at Lake Louise, November 2015

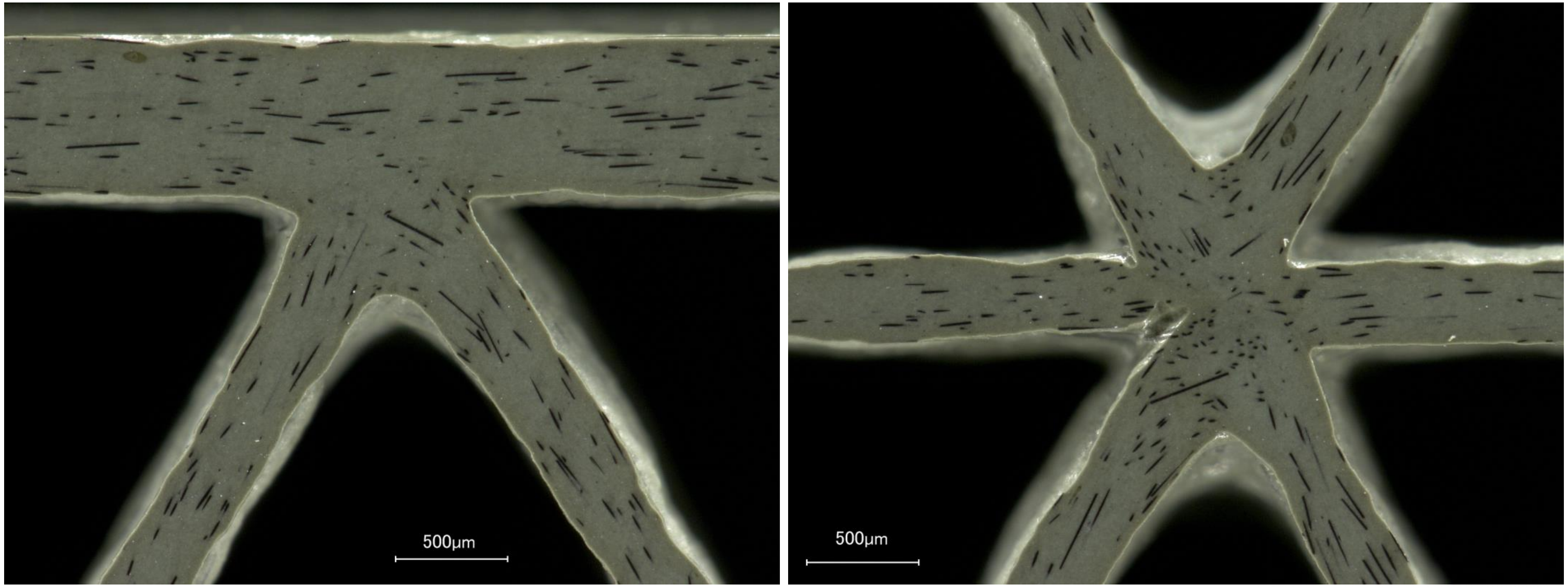
Printed cellular structures

SiC-filled ink, 200 µm nozzle



Square Hexagonal Triangular

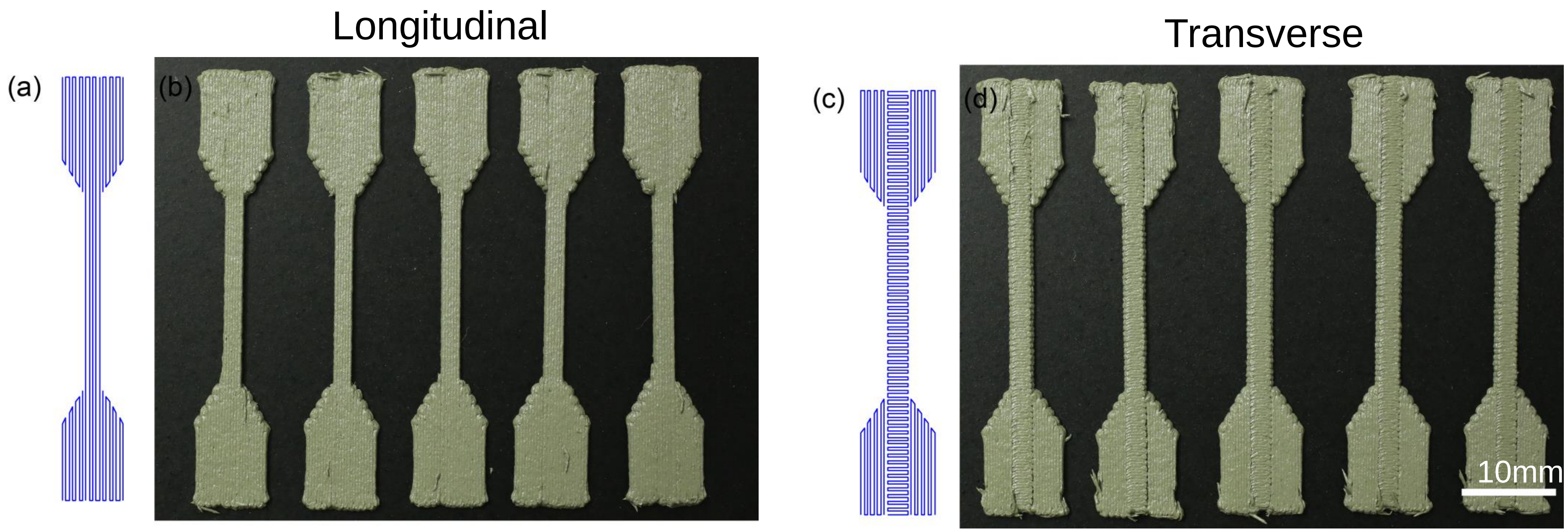
Printed cellular structures



The addition of carbon fibers visually demonstrates the high degree of alignment achieved with extrusion-based printing.

Filaments and nodes coalesce nearly completely.

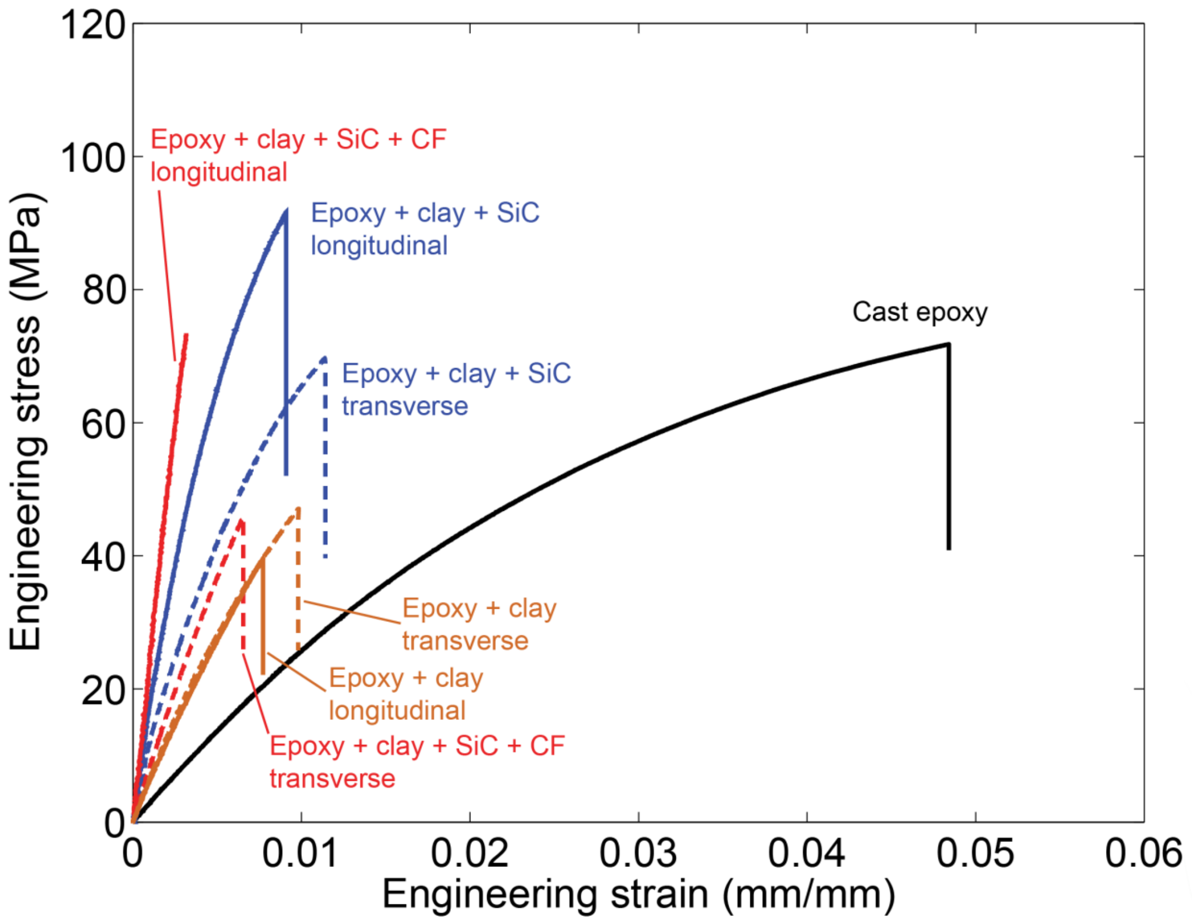
Printed tensile specimens



Orthogonal build directions allow the assessment of extrusion-induced anisotropy.

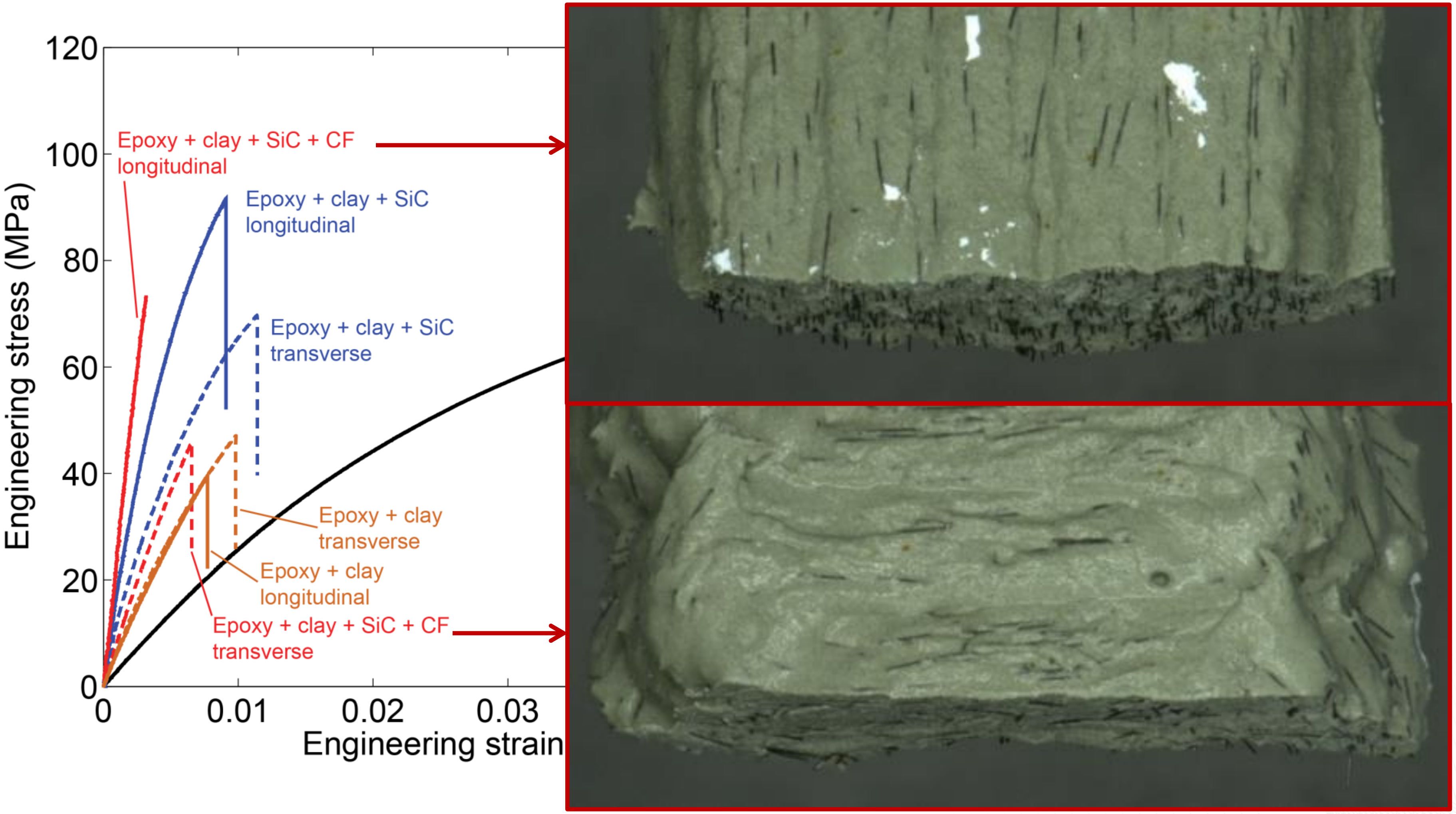
Brett G. Compton
Composites at Lake Louise, November 2015

Tensile tests



When high aspect ratio fillers are present, print direction strongly influences the mechanical properties. Without fiber fillers, isotropic properties are achieved.

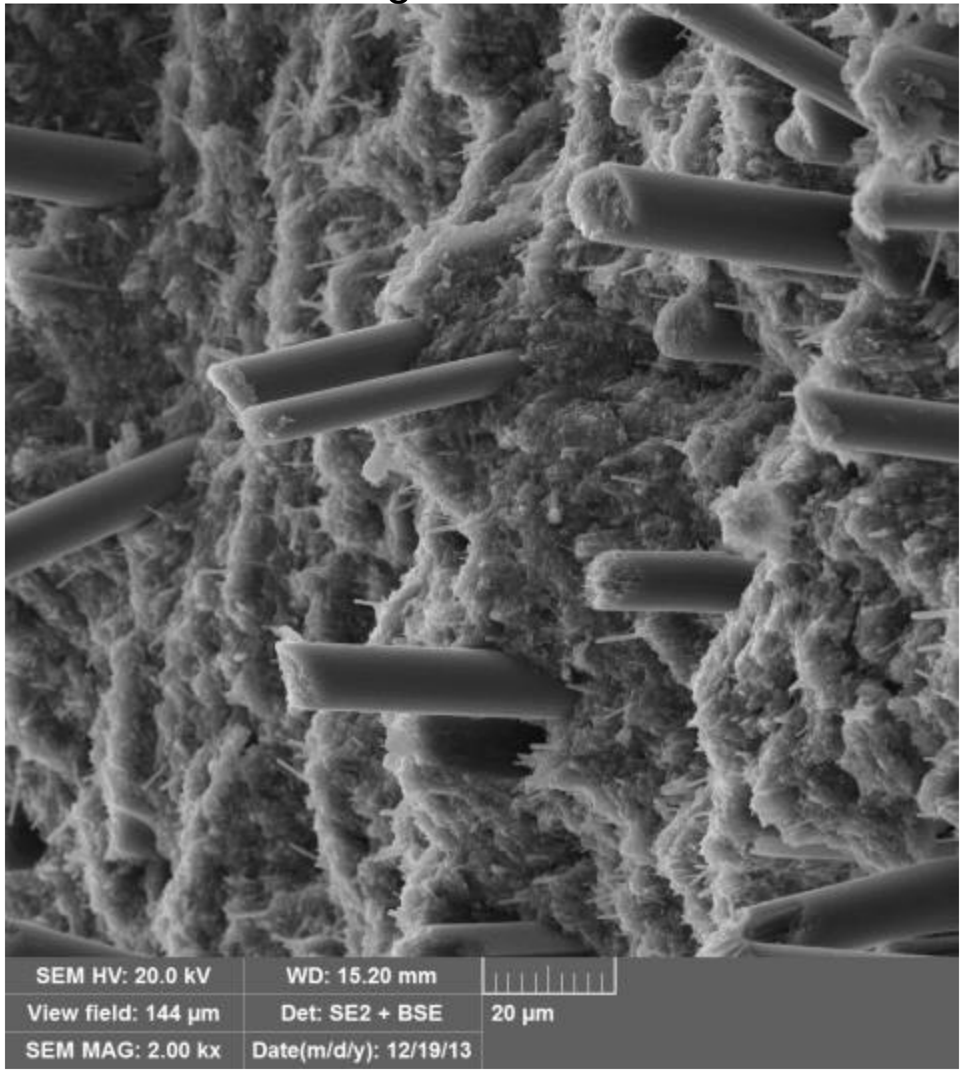
Fracture surfaces



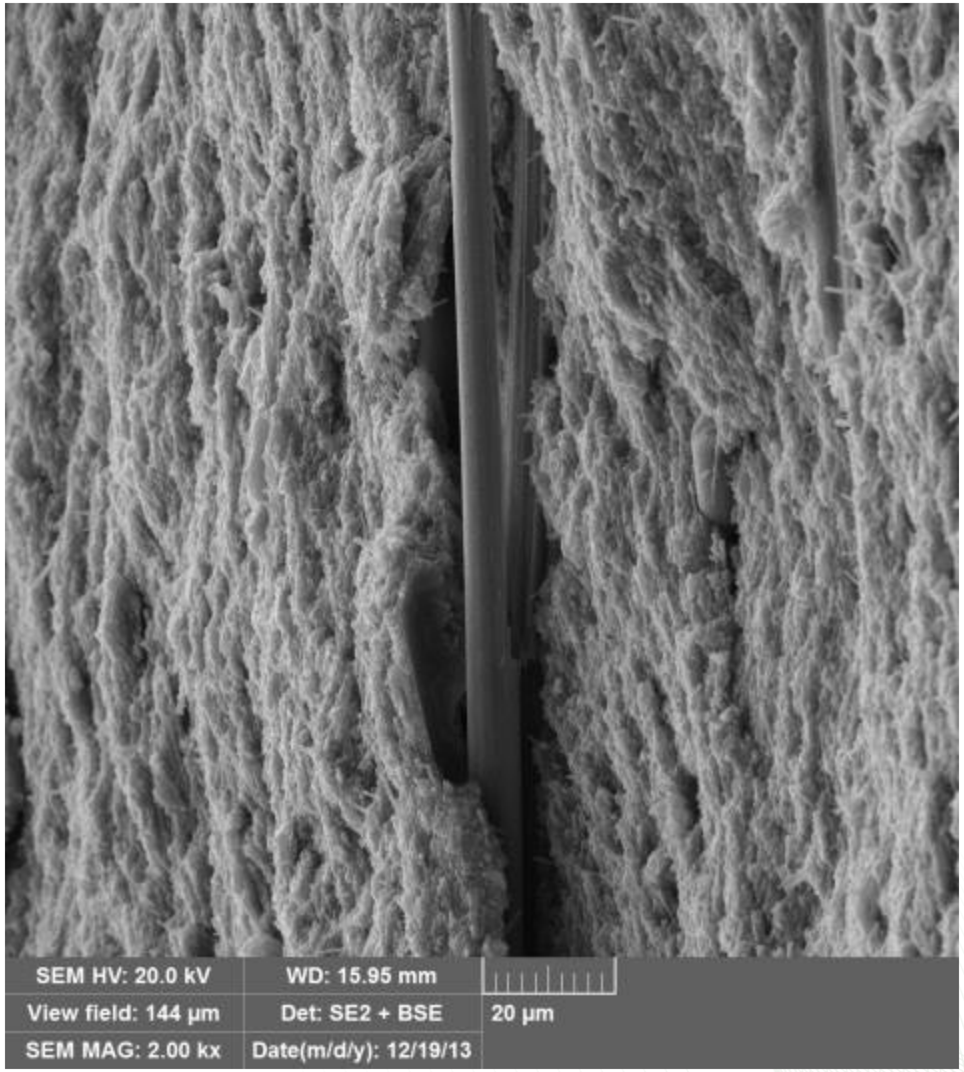
Brett G. Compton

Fracture surfaces

Longitudinal



Transverse

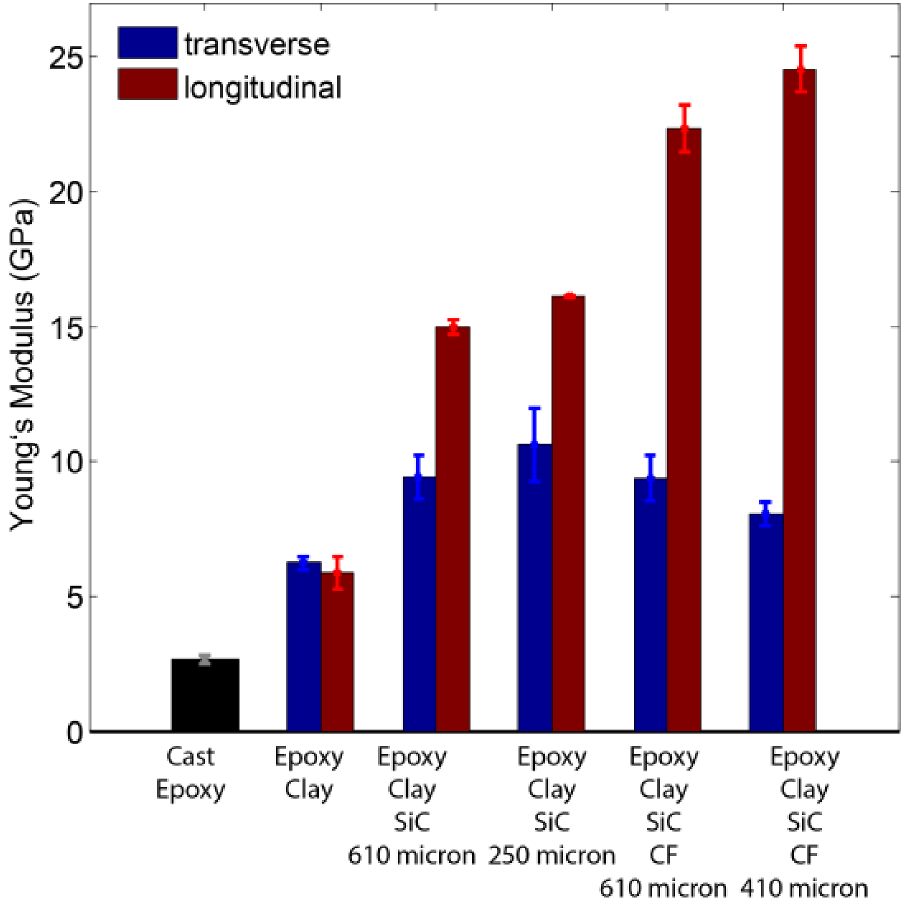


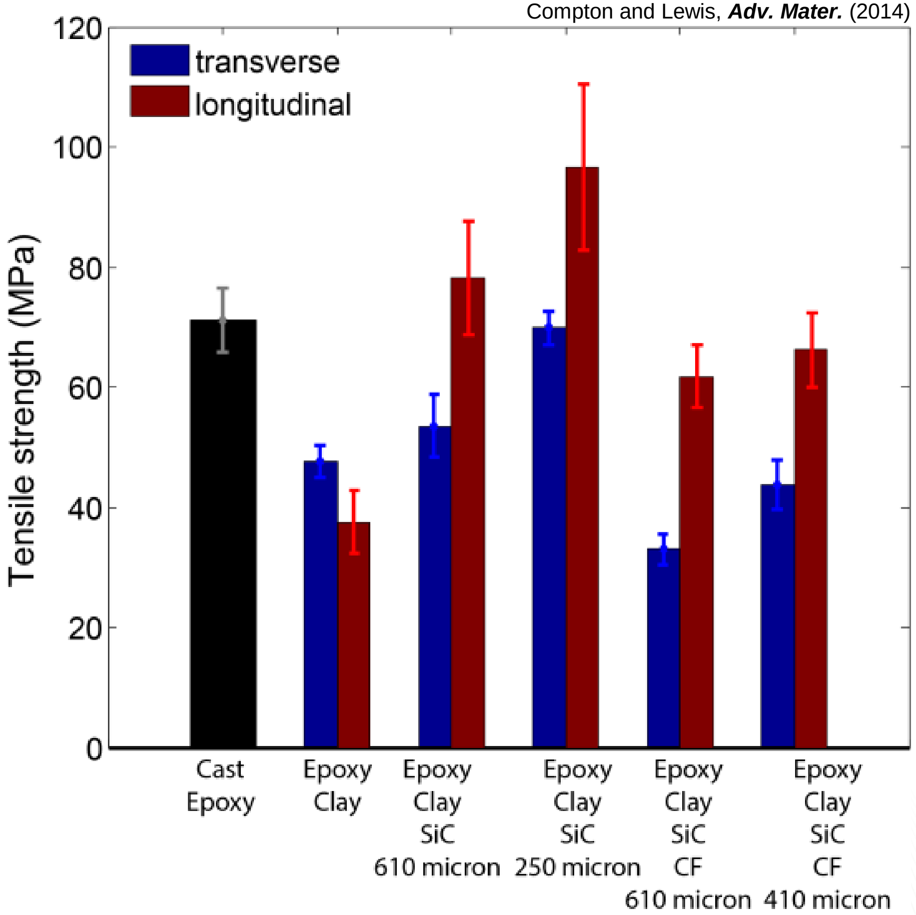
Fracture surfaces show **high fiber alignment** and **pullout at multiple length scales**.

Brett G. Compton
Composites at Lake Louise, November 2015

Summary of mechanical properties

Compton and Lewis, ***Adv. Mater.*** (2014)





Printed composites achieve up to **9x increase in Young's modulus** over cast epoxy while maintaining **comparable strength values.**

*Recent work has demonstrated printed composites with ~150 MPa strength using longer chopped fibers.

Printed epoxy composites

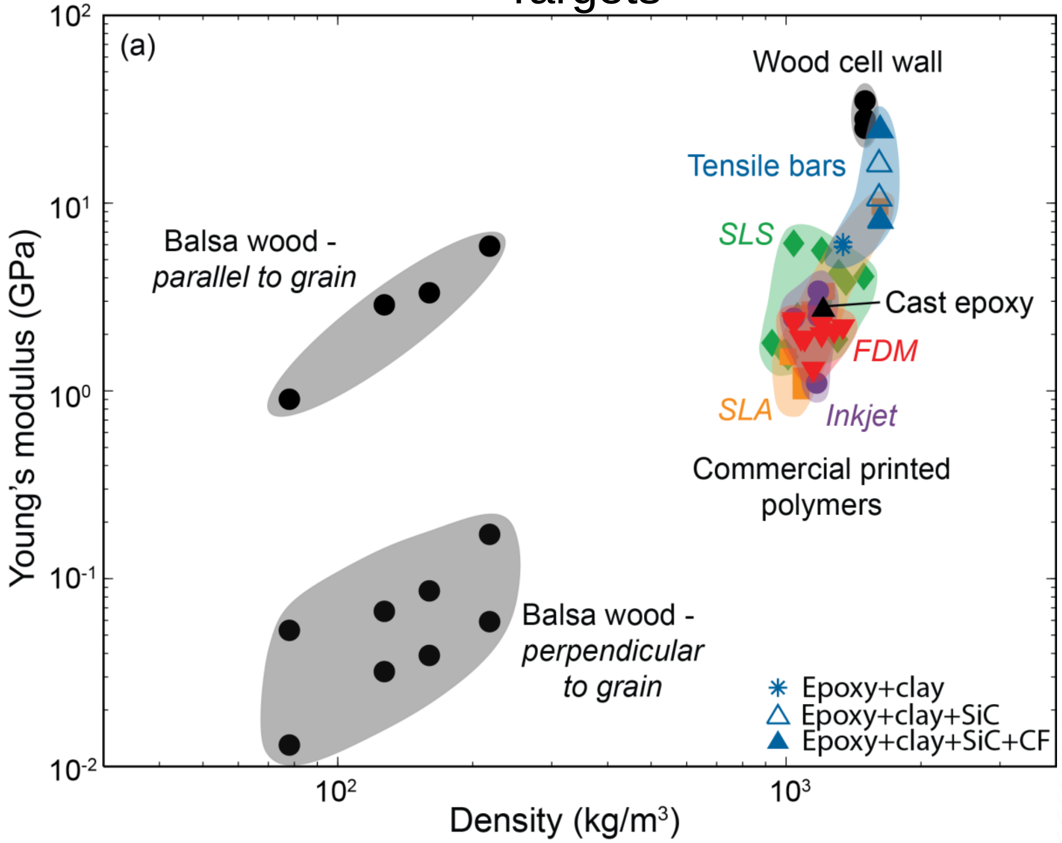
Objectives:

-Develop epoxy-based inks suitable for 3D-printing of lightweight cellular composites.

-Characterize mechanical properties of 3D-printed structures.

- -Young's modulus
- -Failure strength
- -Material orientation and effects of print direction

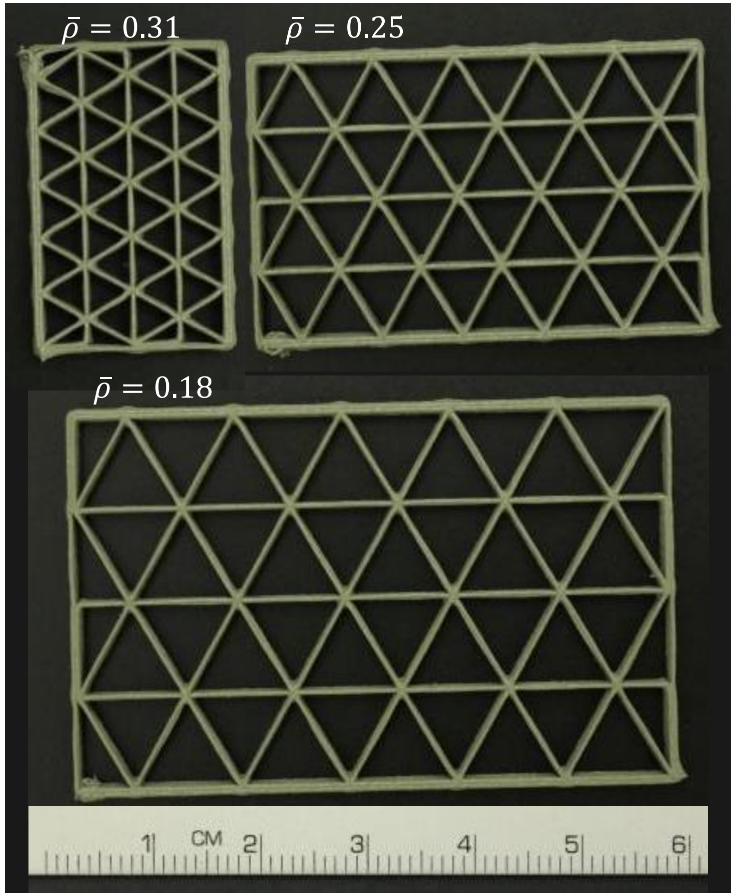
Targets

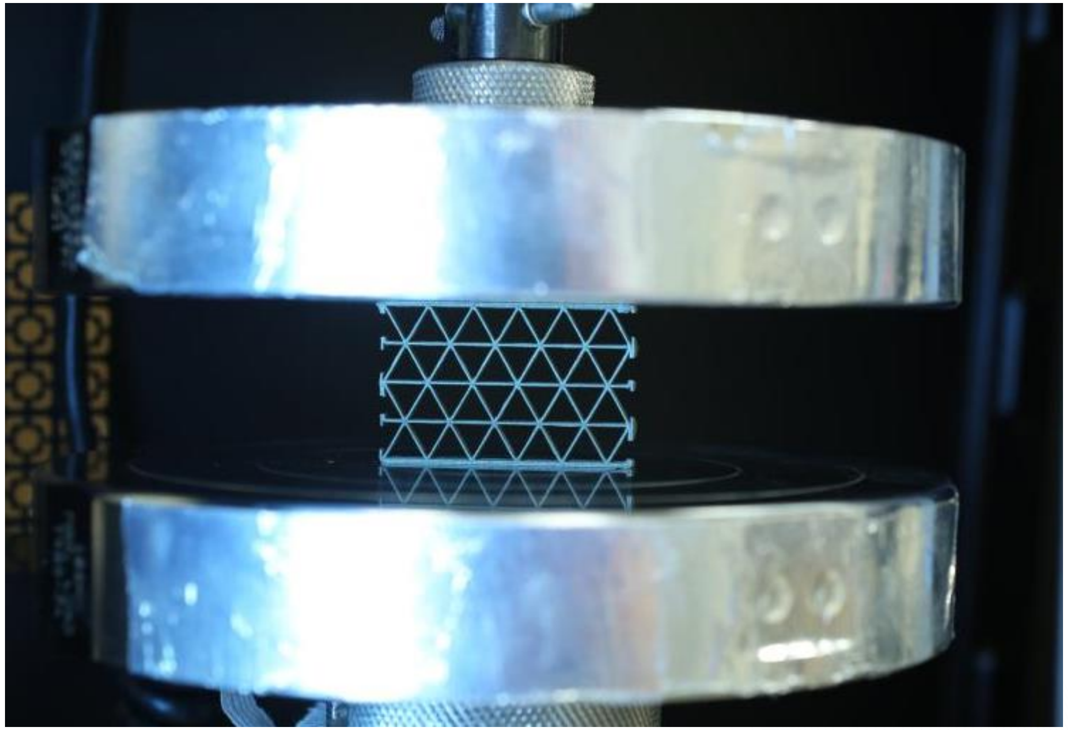


10x increase in modulus over most commercial printed polymers!

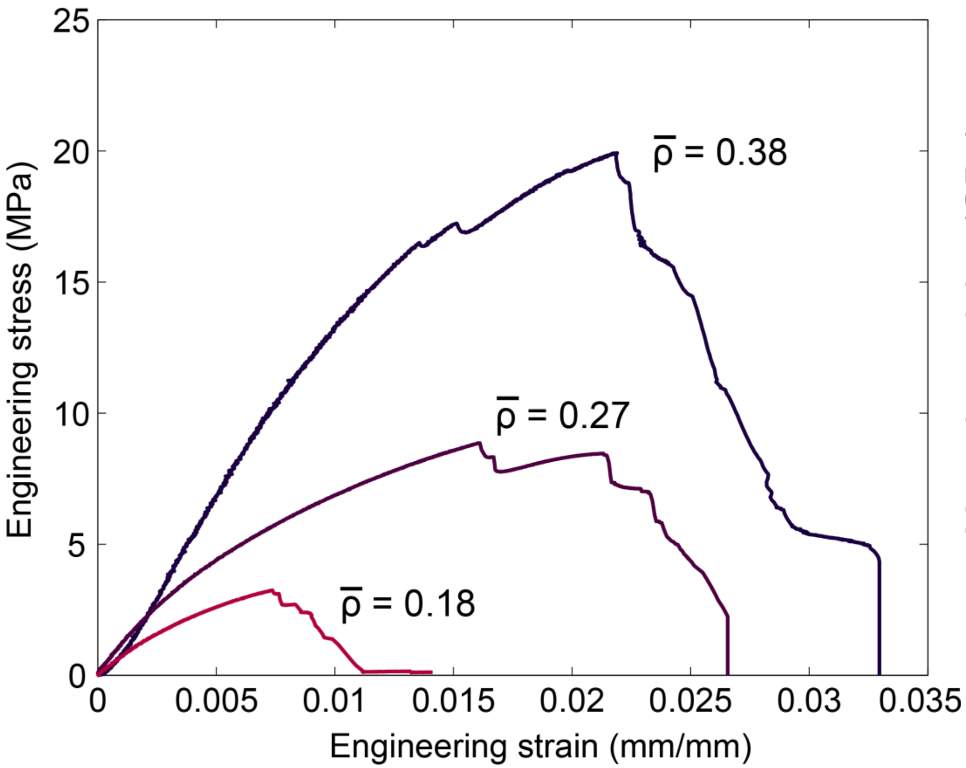
Brett G. Compton
Composites at Lake Louise, November 2015

Compression testing of printed honeycombs

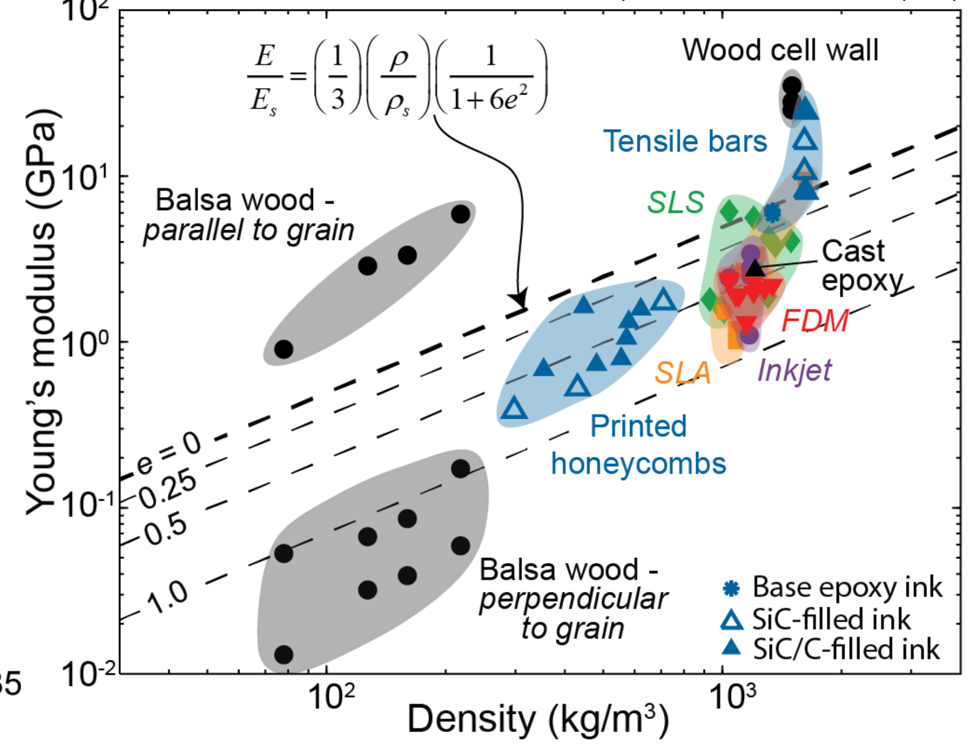




Mechanical properties of honeycombs



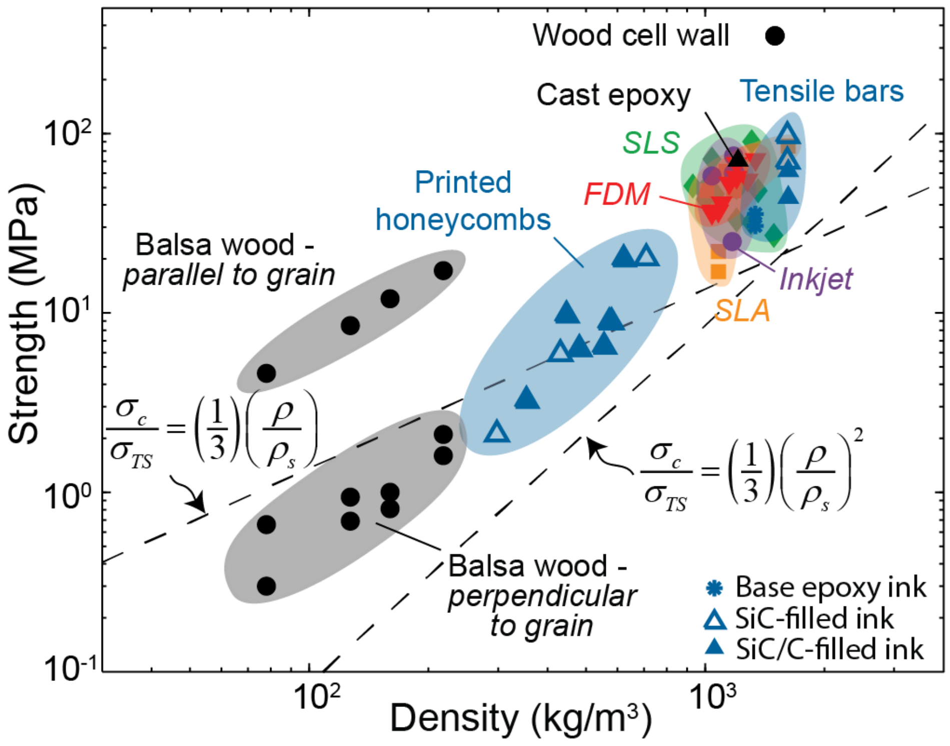
Compton and Lewis, ***Adv. Mater.*** (2014)

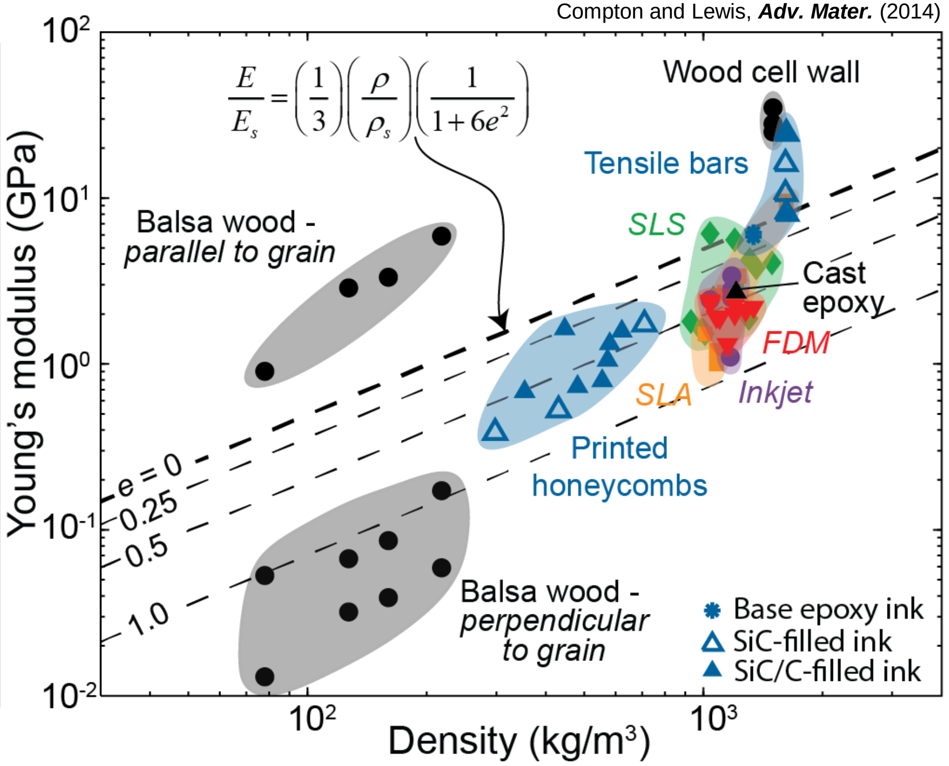


In-plane stiffness of printed honeycombs exceed that of balsa wood (in-plane) and matches that of commercial printed polymers at half the density.

Mechanical properties of honeycombs

Compton and Lewis, ***Adv. Mater.*** (2014)





In-plane strength of printed honeycombs matches that of balsa wood (albeit with higher density).

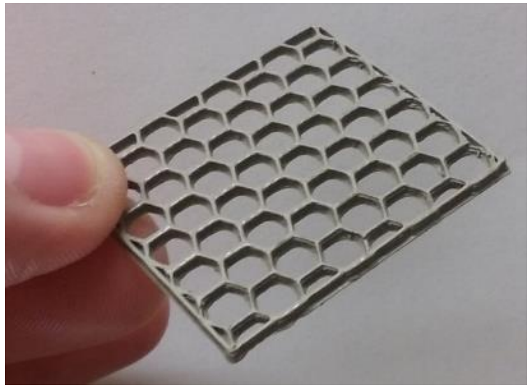
Summary

- Extrusion-based printing methods effectively align fiber reinforcements to create efficient short-fiber composites.
- Printed thermoset composites can achieve **Young's modulus values 10x-20x higher than commercial printed polymers** while maintaining comparable strength values**.**
- Printed thermosets demonstrate **strong inter-filamentary bonding**.
- Printed fiber composites are **well-suited for lightweight cellular structures** with fiber orientation that cannot be achieved in extruded honeycombs.
- **Anisotropy** within printed parts can be **controlled through print path** and choice of filler particles (size and aspect ratio).

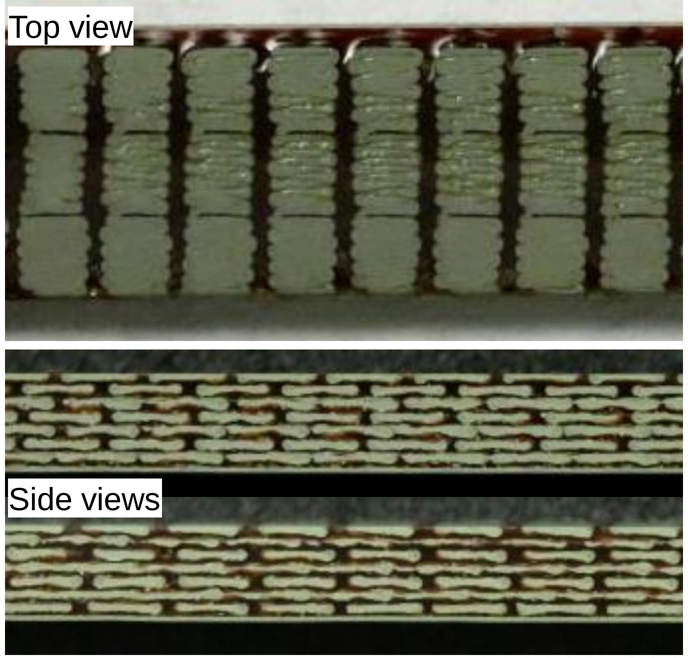
Future directions at UTK

- Additional high performance fillers/higher fiber loading for higher strength
- High temperature materials
- Bio-inspired hierarchical architectures and lattice structures
- Novel (and better) nozzle designs to tailor fiber orientation (coming soon!)

Ceramic precursor feedstocks

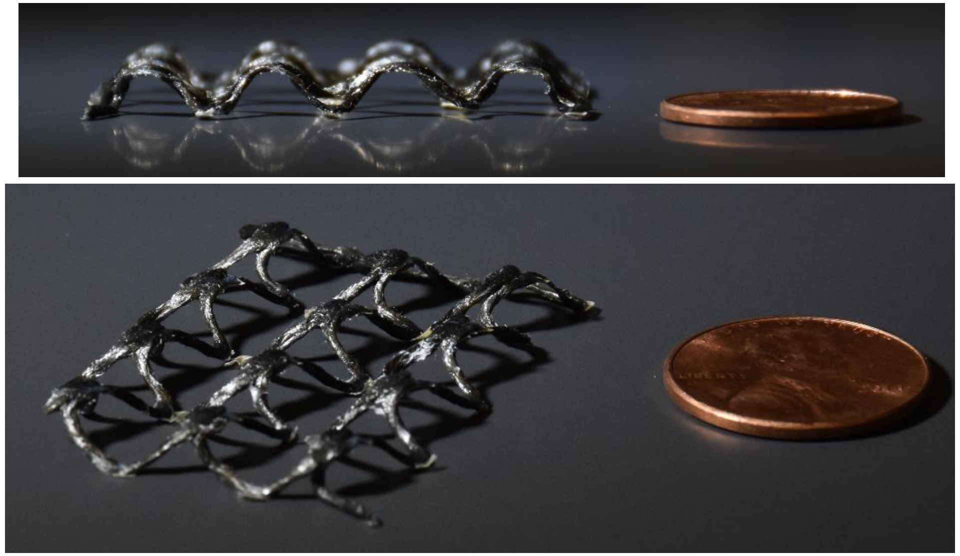


Hierarchical bio-inspired composites



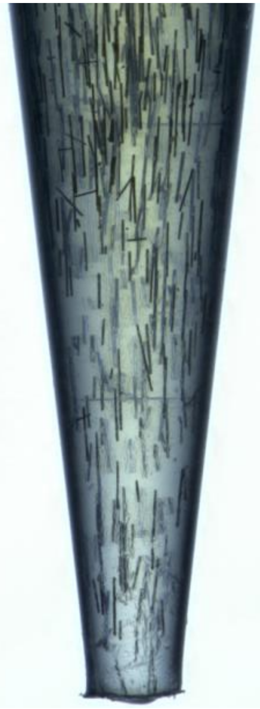
Compton and Lewis, ***unpublished*** (2013)

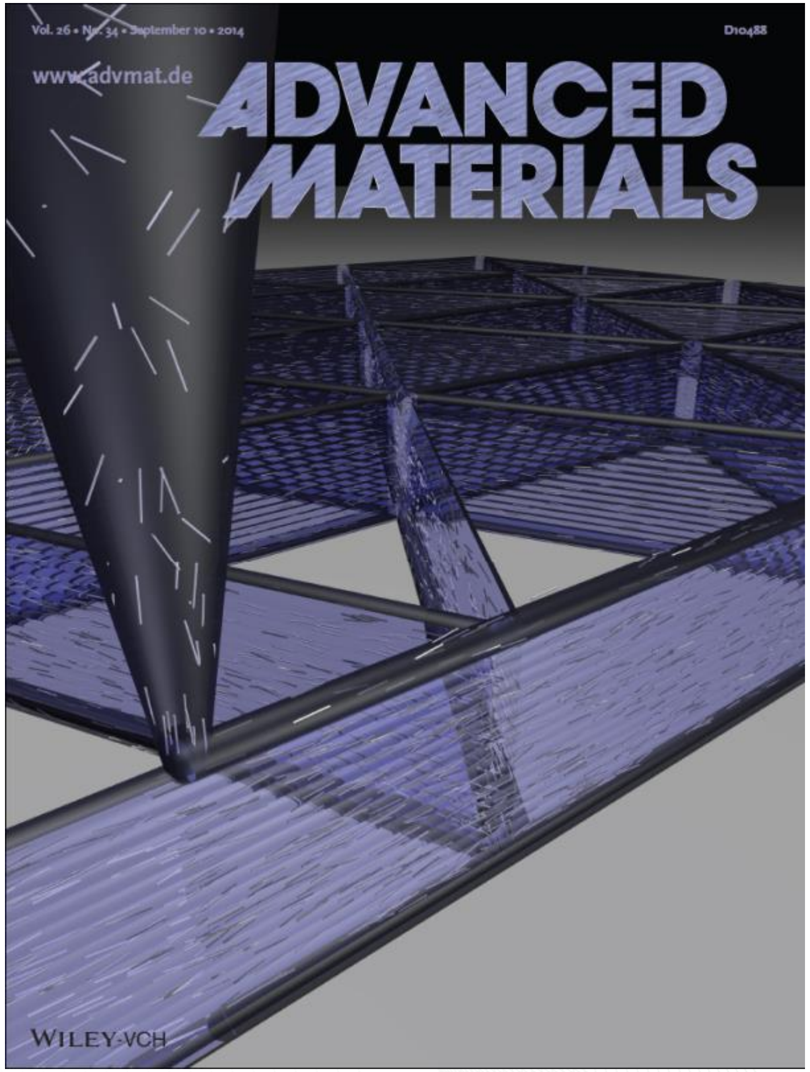
Out-of-plane printing of lattice structures



Printed bonded magnets

Thanks for your attention!





Compton and Lewis, ***Adv. Mater.*** (2014)

Contact:

bcompto1@utk.edu

http://mabe.utk.edu/peopletwo/brett-g-compton/

This project was supported by:

BASF The Chemical Company