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Advanced Manufacturing Research Centre

BOEING

Science and Manufacturing: Ingredients for Innovation

Professor Alma Hodzic
AMRC Research Director
17th December 2013
AFOSR, Washington DC

Composites At Sheffield.

Composite Systems Innovation Centre

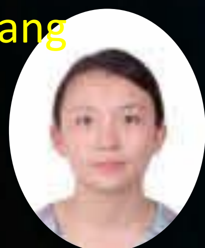
Advanced Manufacturing Research Centre

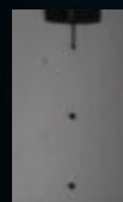
Self-ameliorating inkjet printed composites for higher survivability

Programme Managers: Dr Lee “Les” Byung-Lip, Sc. D. and Lt Col Randall "Ty" Pollak, PhD

PhD Candidates

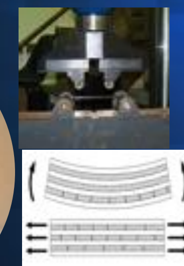
Yi Zhang
ME





IJ printing & IJPC analysis

Andrew
Cartledge
ME



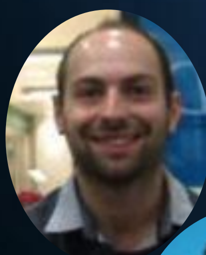
Fatigue tests & FEA

Hannah
Crunkhorn
AMRC

Machining & characterisation

Research Fellows

Dr Jonathan
Stringer, ME



Dr Richard
Grainger, AMRC

Supervisors

Patrick Smith, ME

Alma Hodzic, AMRC

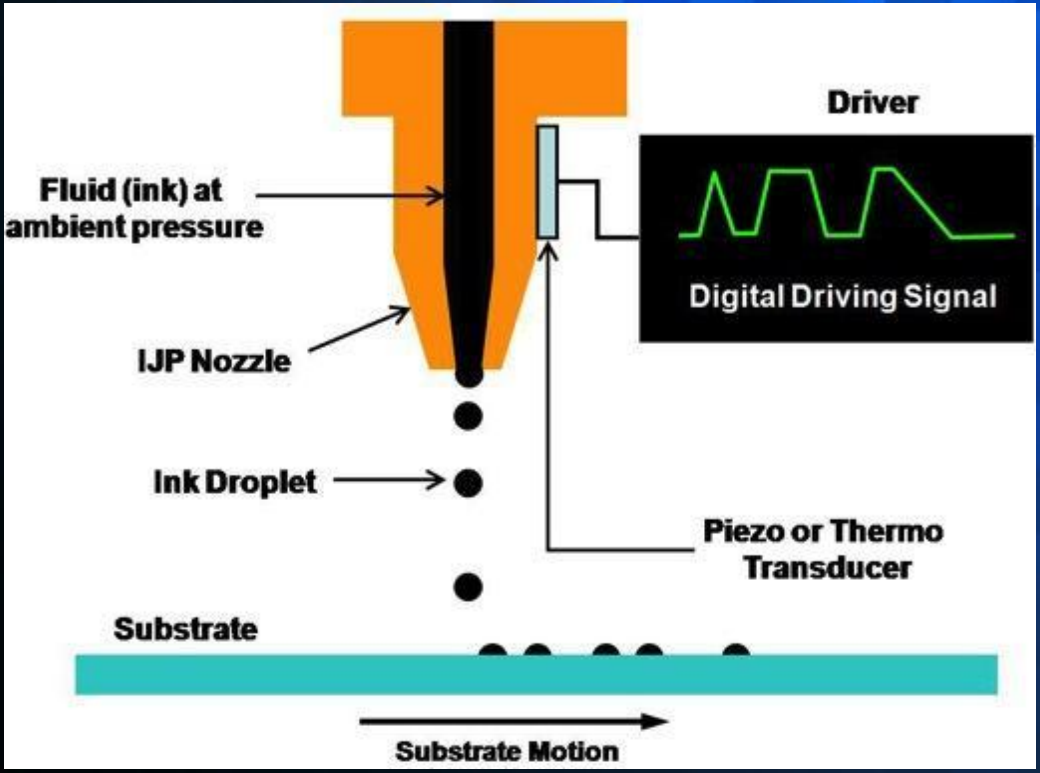
Christophe Pinna, ME

Richard Scaife, AMRC

www.sheffieldcomposites.co.uk

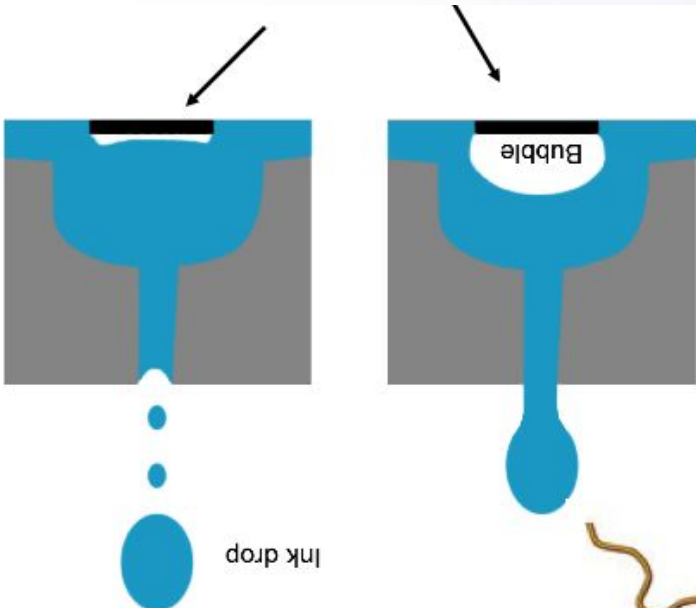
Benefits of Inkjet Printing

- Direct write technology (no masks needed)
- Additive technology
- Droplets of ink ejected from a nozzle to pattern substrate
- Computer-aided which can pre-define patterns according to requirements
  - Rapid changing between patterns (no down-time)
- Non-contact deposition method (reduces/removes risk of contamination)

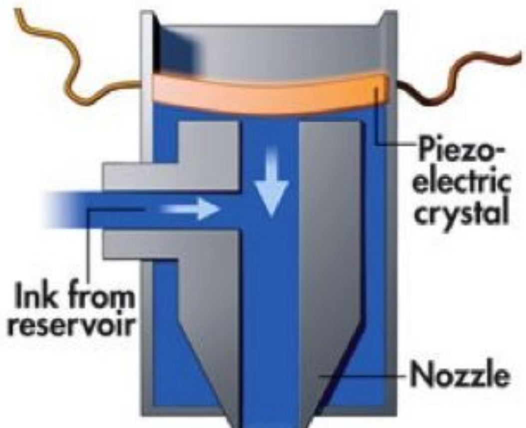


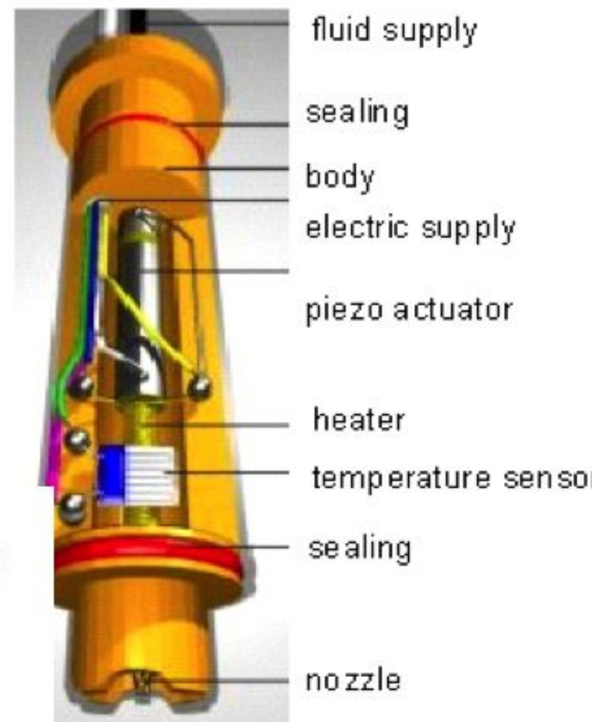
Drop on Demand Printheads

Heater



Thermal Inkjet



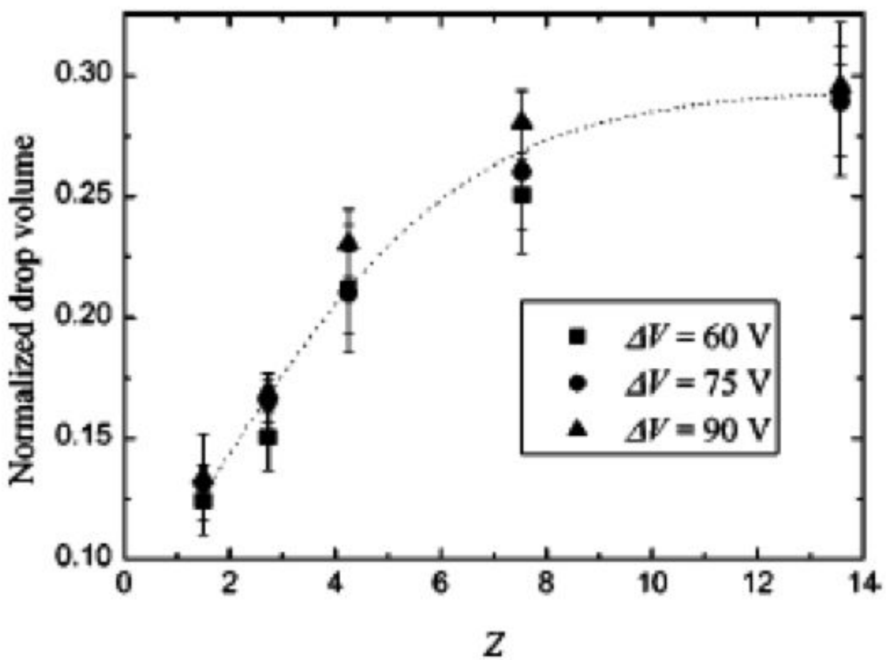


Piezo Inkjet

Effect of Z on Droplet Volume

1 < Z < 10 Optimum printing

$$\frac{Re}{We} = \frac{(\gamma\rho a)^{1/2}}{\eta}$$



Reis, Derby J. Appl. Phys. 2005, 97, 094903

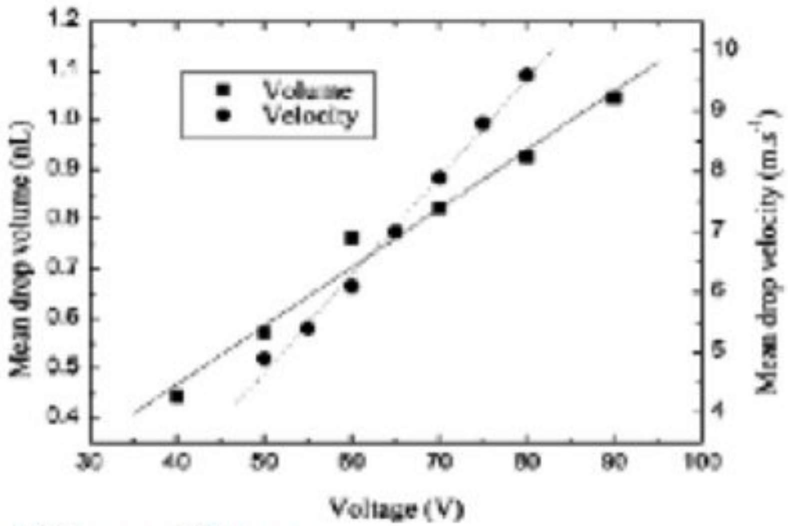
Droplet volume increases Z as predicted by Fromm

$Z = (d\rho\gamma)^{1/2} / \mu$

Droplet volume is normalised to the volume displaced by the actuator at different driving voltages

By varying the ink's rheology (viscosity or surface tension), we can vary the size of the ejected droplet

Influence of Voltage on Droplet Volume



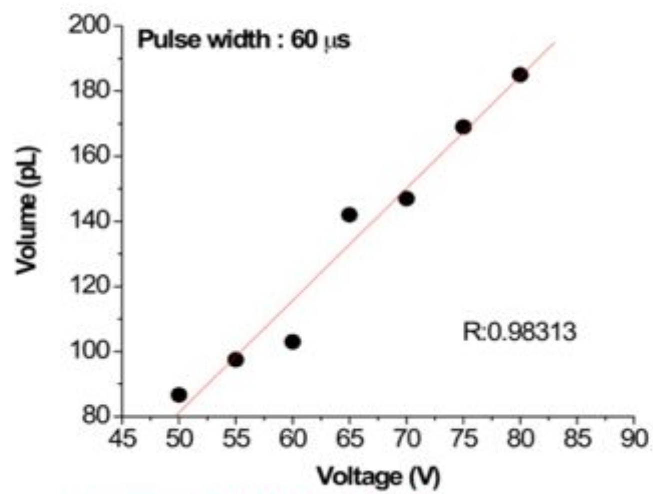
Molten paraffin wax

Reis, Derby, J. Appl. Phys. 2005, 97, 094903

By varying voltage,
we can vary the size of the ejected droplet

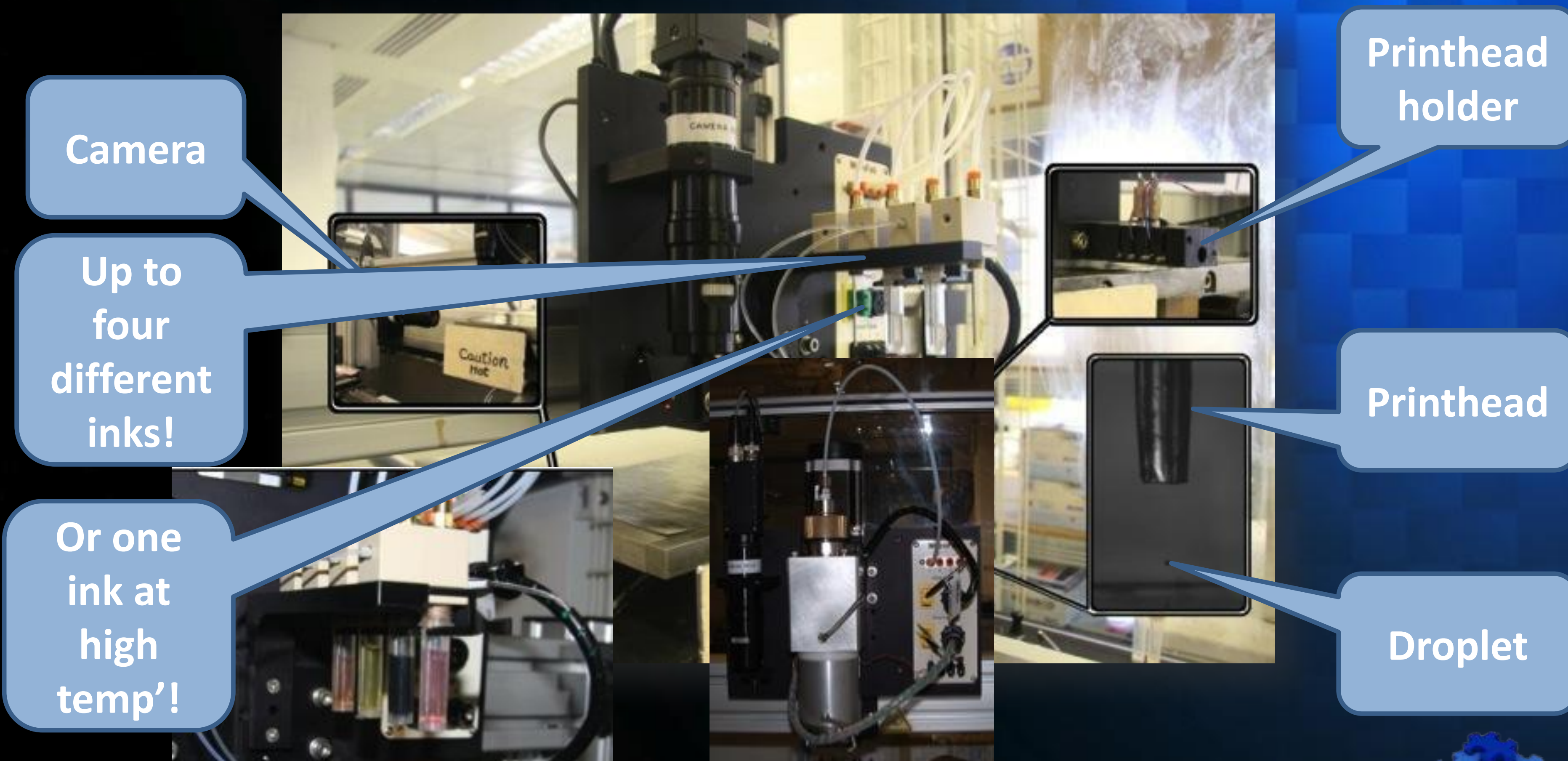
Applied voltage is proportional to droplet volume

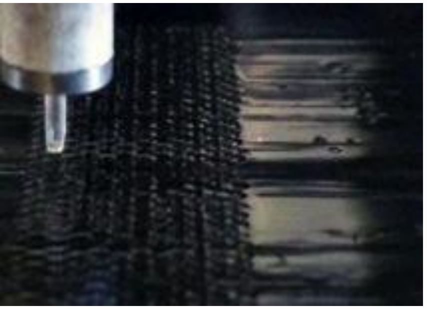
Increased Voltage = Increased Droplet Volume



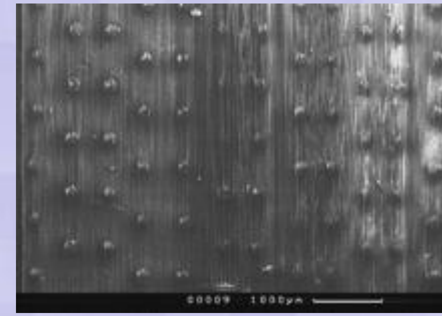
Aqueous PEDOT solution

Inkjet printer in Sheffield (MicroFab 4, piezoelectric DOD)





Accuracy & repeatability



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Materials & method

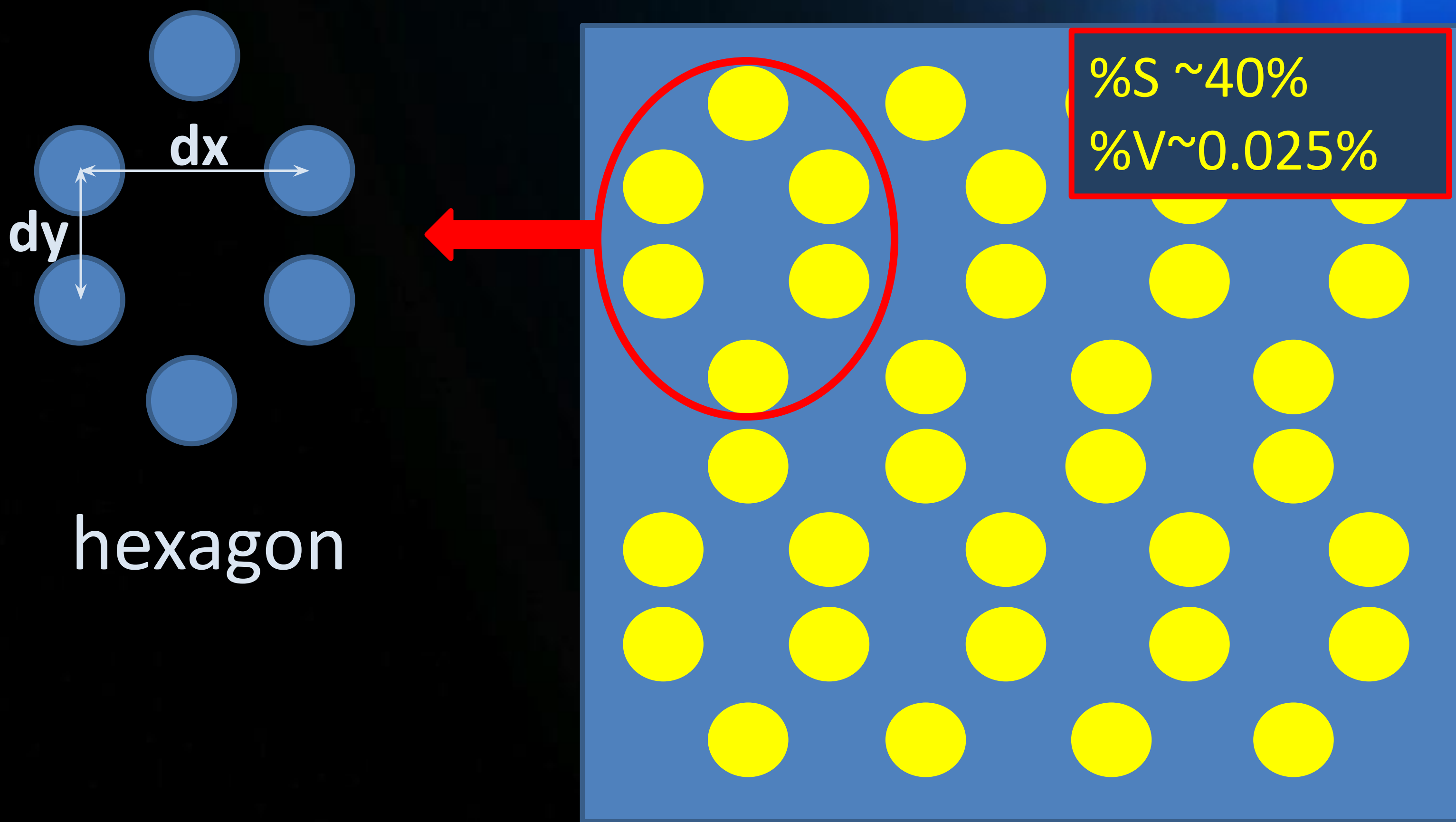
Group		Composition of ink			Diameter of printhead / µm	Pattern	Parameters of pattern		Substrate
		Solute	wt %	Solvent			dx / µm	dy / µm	
PU	Ink 1	PEG[1]	50	DMF	60	Hexagon	0.4	0.2	977-2
	Ink 2	IPDI/BiNeo	74/1	DMF					
PEG		PEG[2]	5	Pure Ethanol	60	Hexagon	0.4	0.2	977-2
PMMA		PMMA	5	DMF	60	Hexagon	0.4	0.2	977-2

PU: polyurethane
PEG[1]: poly(ethylene glycol) Mn = 400
PEG[2]: poly(ethylene glycol) Mn = 20,000
IPDI: Isophorone diisocyanate

DMF: N,N-Dimethylformamide
BiNeo: Bismuth neodecanoate
PMMA: poly(methyl methacrylate)

Substrate: Carbon fibre pre-impregnated with resin (prepreg) was obtained from Cytec (CYCOM 977-2-35-12KHTS-268-300, Cytec Industries Inc., New Jersey, USA)

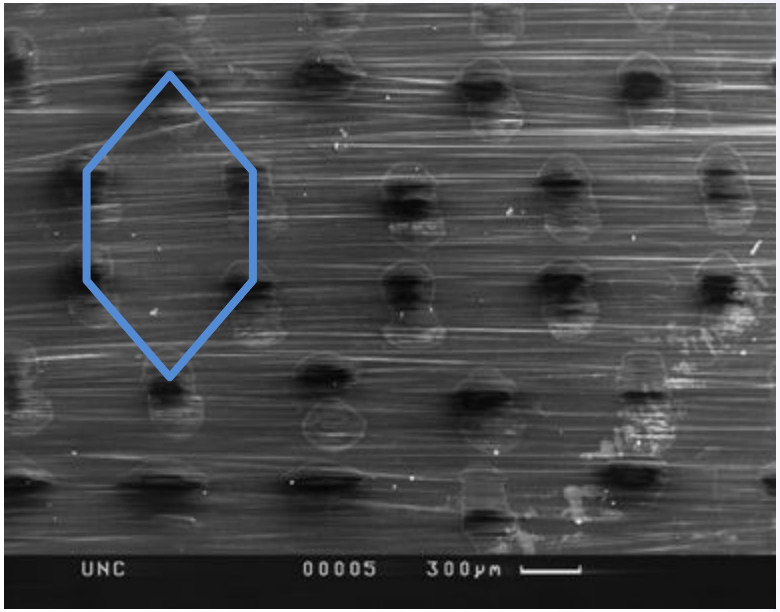
Pattern – Hexagon



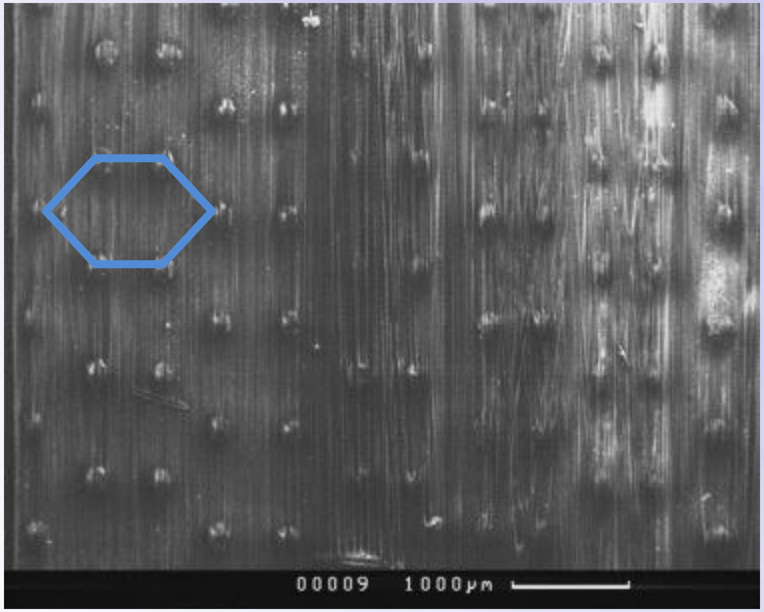
hexagon

Morphological analysis

PU dots on 977-2 pre-preg



a. Before curing

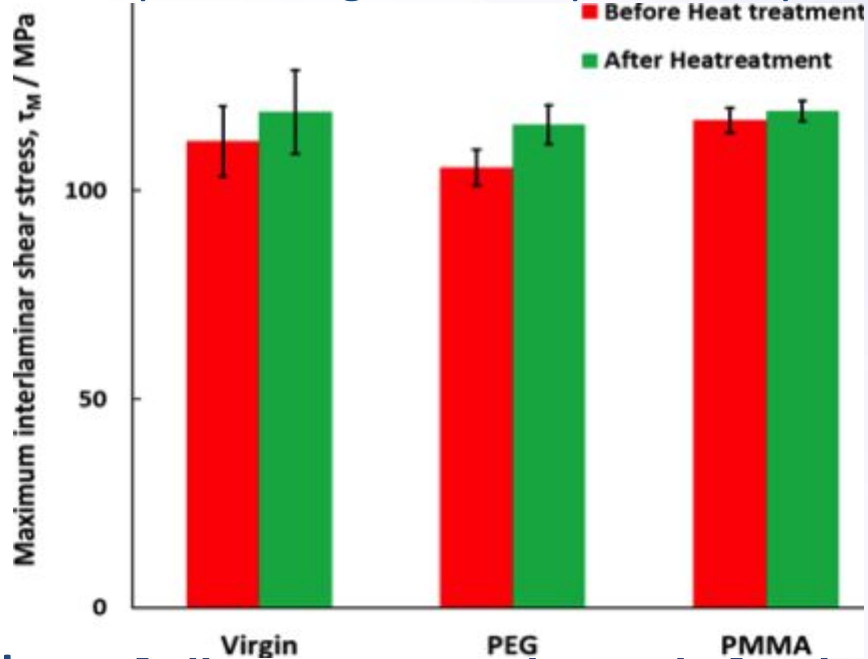


b. After curing

PU droplets are double-printed and polymerised in situ on pre-preg, and keep the printed hexagon pattern after curing cycle. (PU not subject to IP due to limited results – here used only for demonstration of printing accuracy. Synthesised in-situ from two polymer parts.)

Short beam shear test

- Maximum interlaminar shear stress (τ_M), each group contained 5 samples
- No damage introduced, investigation of undamaged parameters and placebo effect – postcuring effect of potentially un-crosslinked groups



Healing cycle: 177°C for 2 hours, harshest conditions

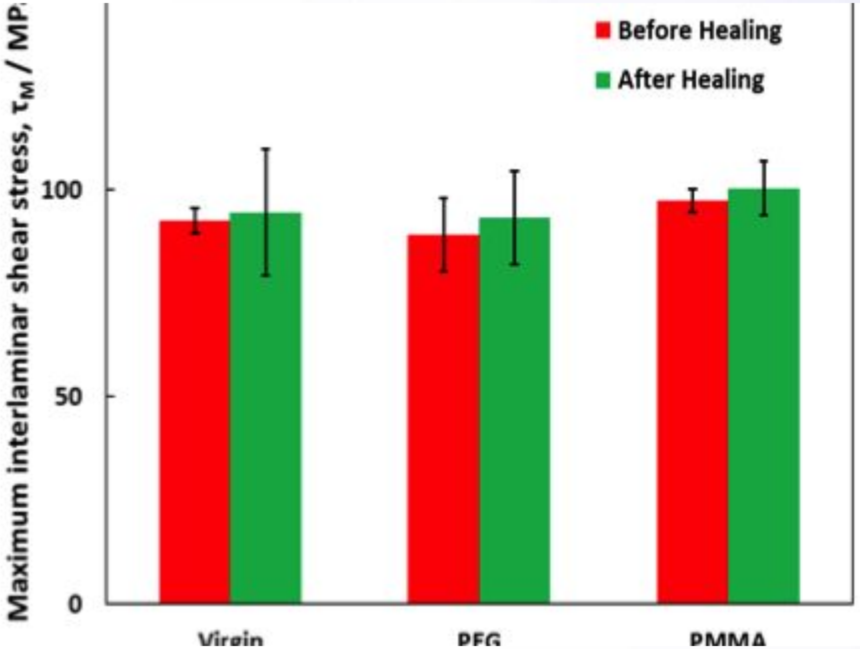
Purpose: to investigate any potential reduction of the shear strength, due to the presence of printed surface. Surprisingly, the structural integrity was improved with PMMA.

τ_M values of all groups are enhanced after healing cycle.

Note: error bar represents standard deviation, n = 5

Interlaminar shear strength

- Maximum interlaminar shear stress (τ_M) investigation
- Damage has been introduced this time in printed and virgin samples, before self-healing



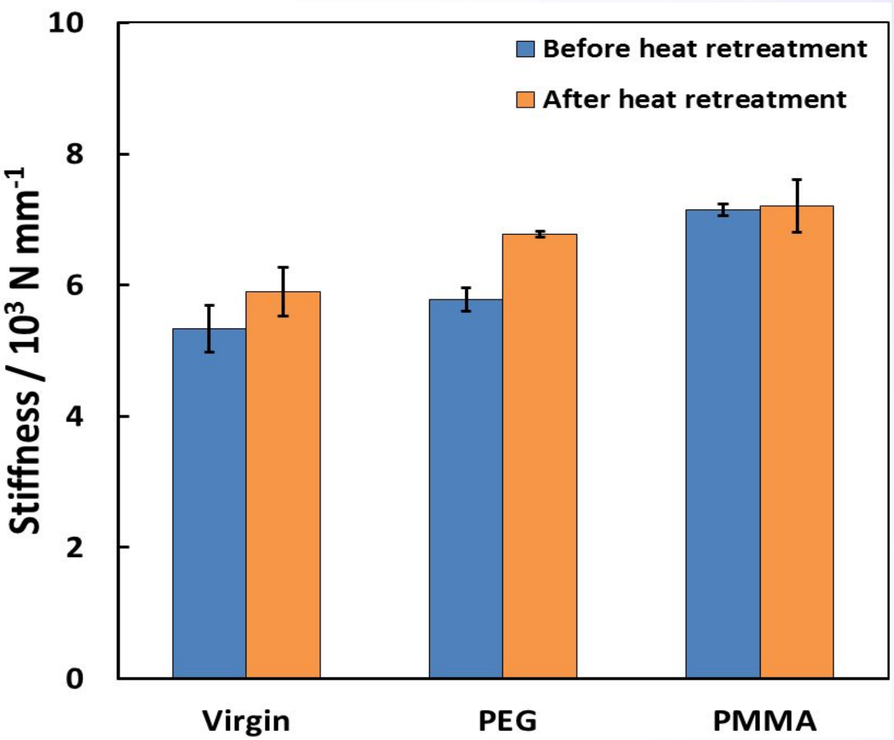
Healing cycle: 177°C for 2 hours, harshest conditions

Purpose: to investigate the total reduction in shear strength due to the introduced damage and to look for the effect of self-healing. PMMA again showed improvement in properties, where reduction was initially expected due to the severe damage.

τ_M values are reduced after damage. Enhancement in τ_M can be seen after healing cycle, and the printed M15P specimens showed the highest τ_M results.

Note: error bar represents standard deviation, n = 5

SBS test continued



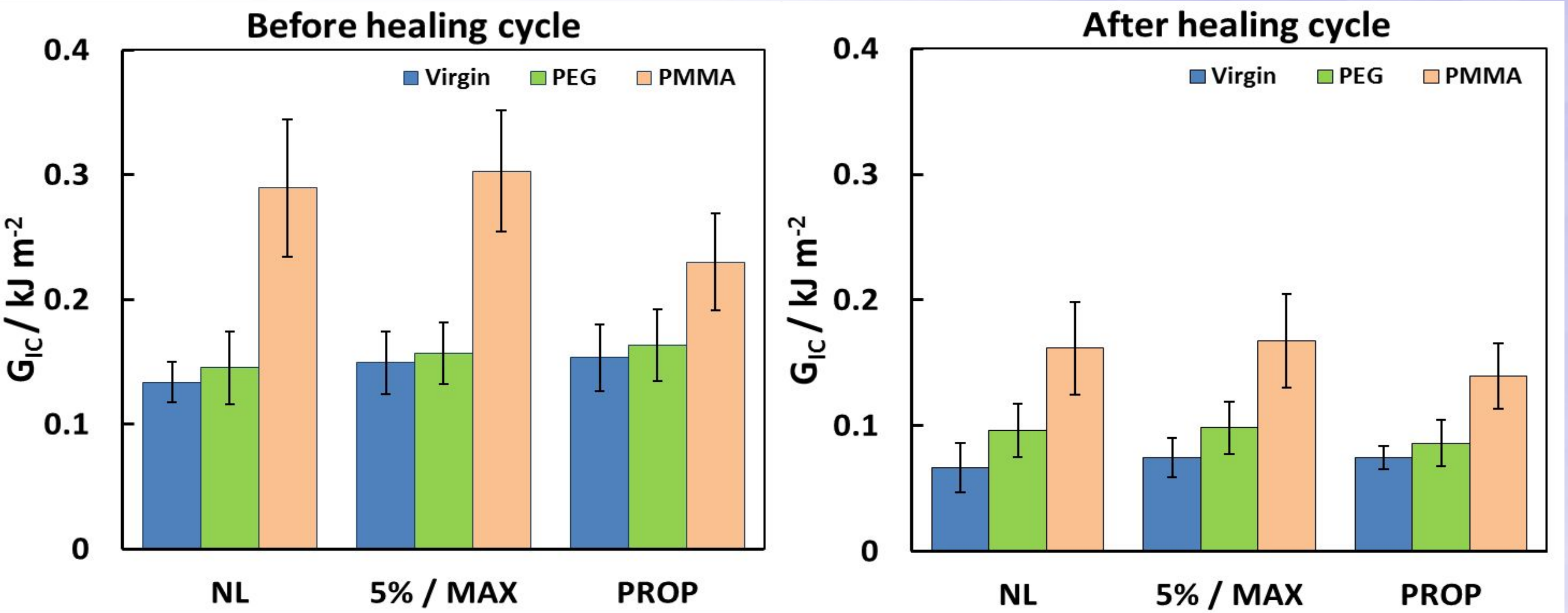
Healing cycle: 177°C for 2 hours, harshest conditions

Purpose: to investigate effect of self-healing on the material's stiffness. The effect achieved successfully. The printed surface noticeably increased the stiffness of the material both before and after the heat treatment.

With printed self-ameliorating agents, unidirectional fibre-reinforced plastic composite has higher stiffness than that of the virgin system.

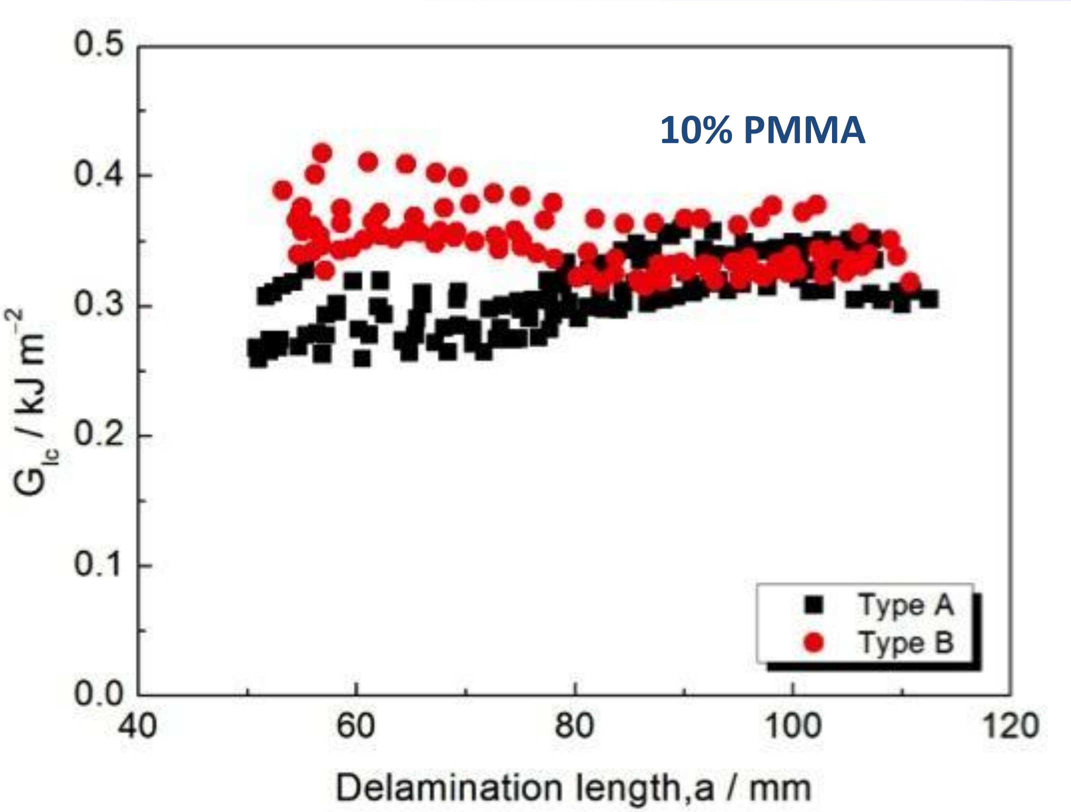
Note: error bar represents standard deviation, n = 5

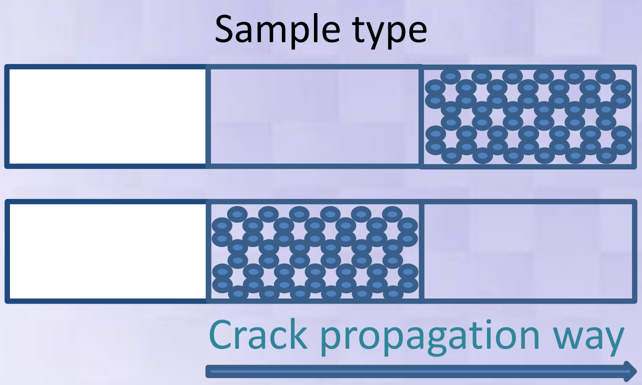
Mode I interlaminar fracture toughness (G_{IC}) test



The fracture toughness, obtained by the most destructive interlaminar test, showed approximately the double increase in value both before and after self-healing for printed PMMA material. To arrest crack propagation at this level implies even stronger capability to arrest the crack in normal service levels.

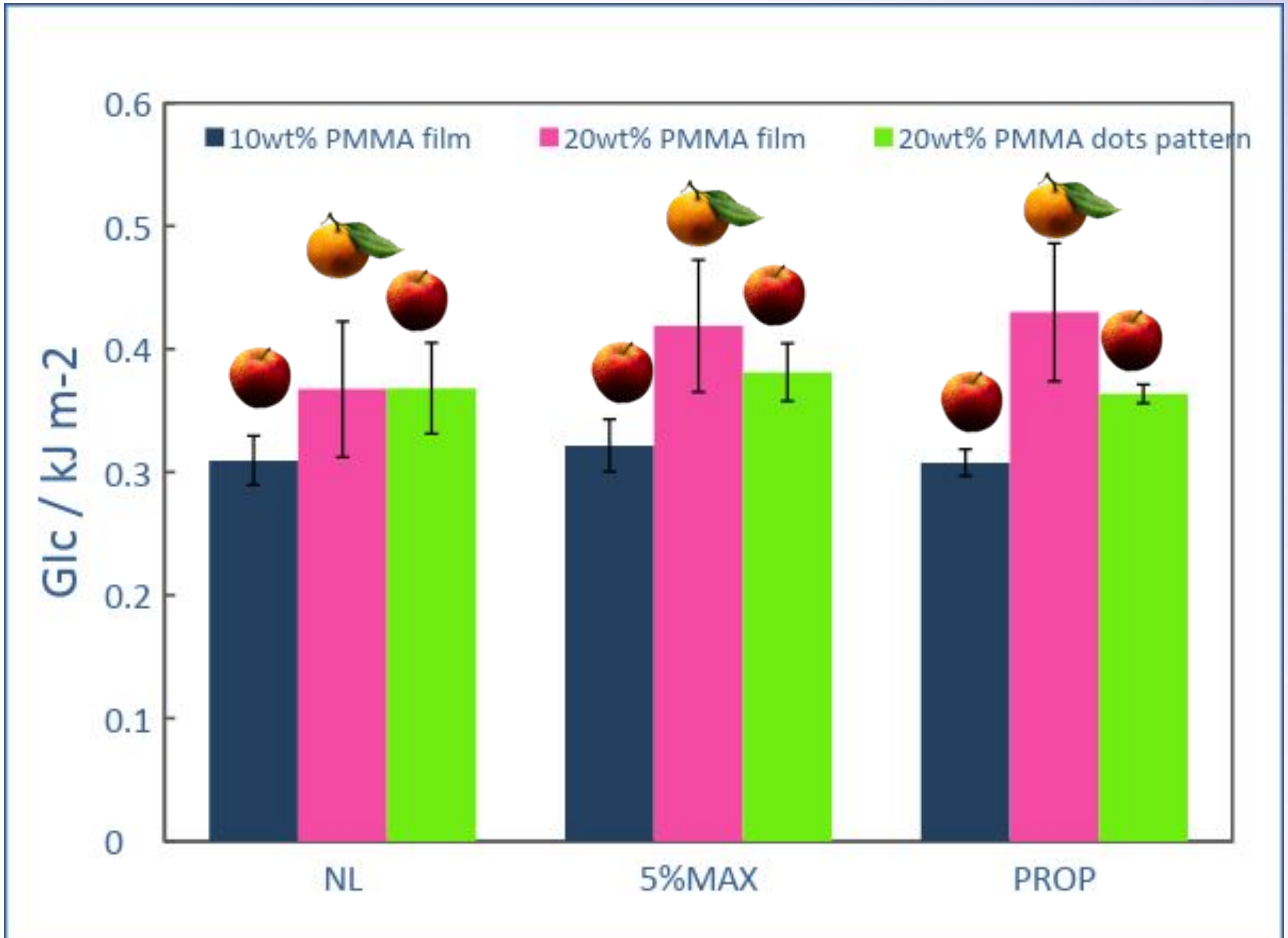
Functional gradation of properties





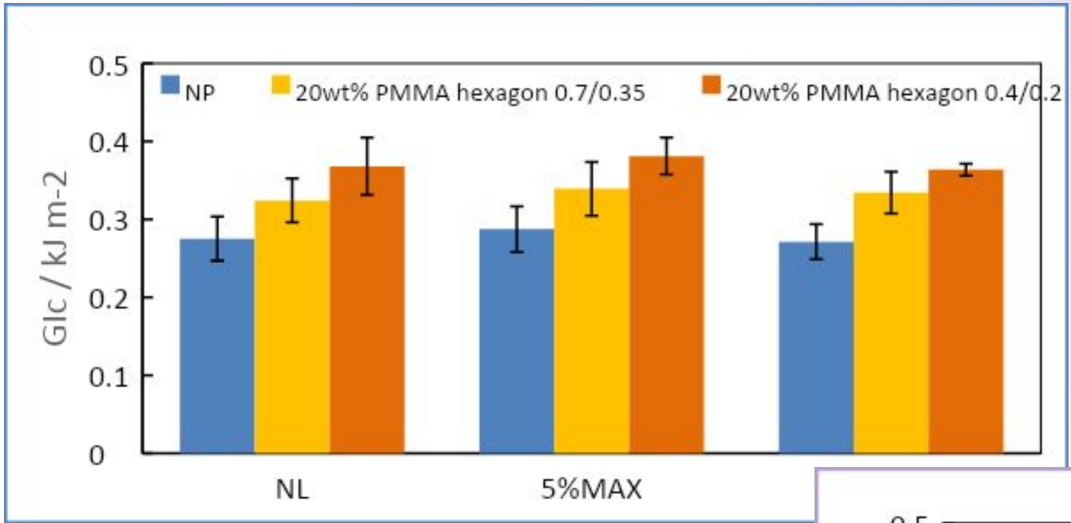
G_{Ic} (fracture toughness) values of polymer printed areas are comparatively higher than unprinted areas, which means inkjet printing can be applied to delicate material design work, and manufacture property graded multifunctional materials.

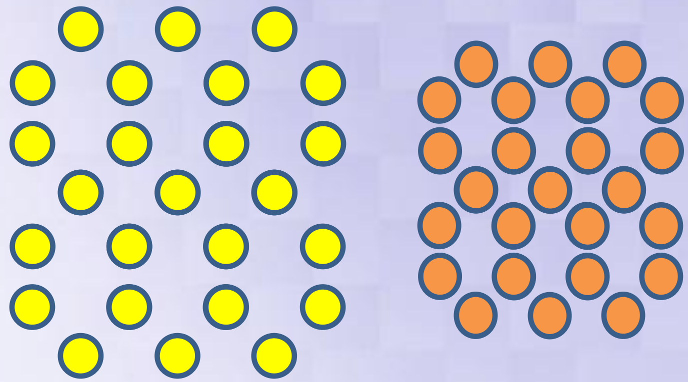
Discrete and film patterns

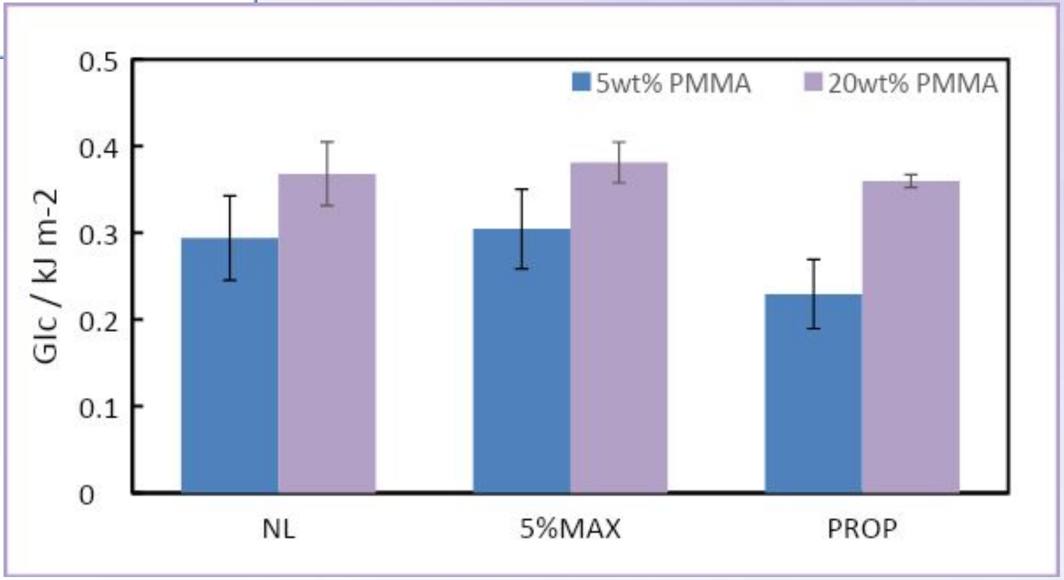


G_{Ic} (fracture toughness) values of discretely printed areas have comparatively higher fracture toughness values and higher predictability than fully printed surfaces with the same amount of PMMA (20% dots = 10% film by V_f). Adding more polymer to film (20% film equivalent to 40% dots) resulted in the loss of engineering predictability.

Patterns and polymer loadings





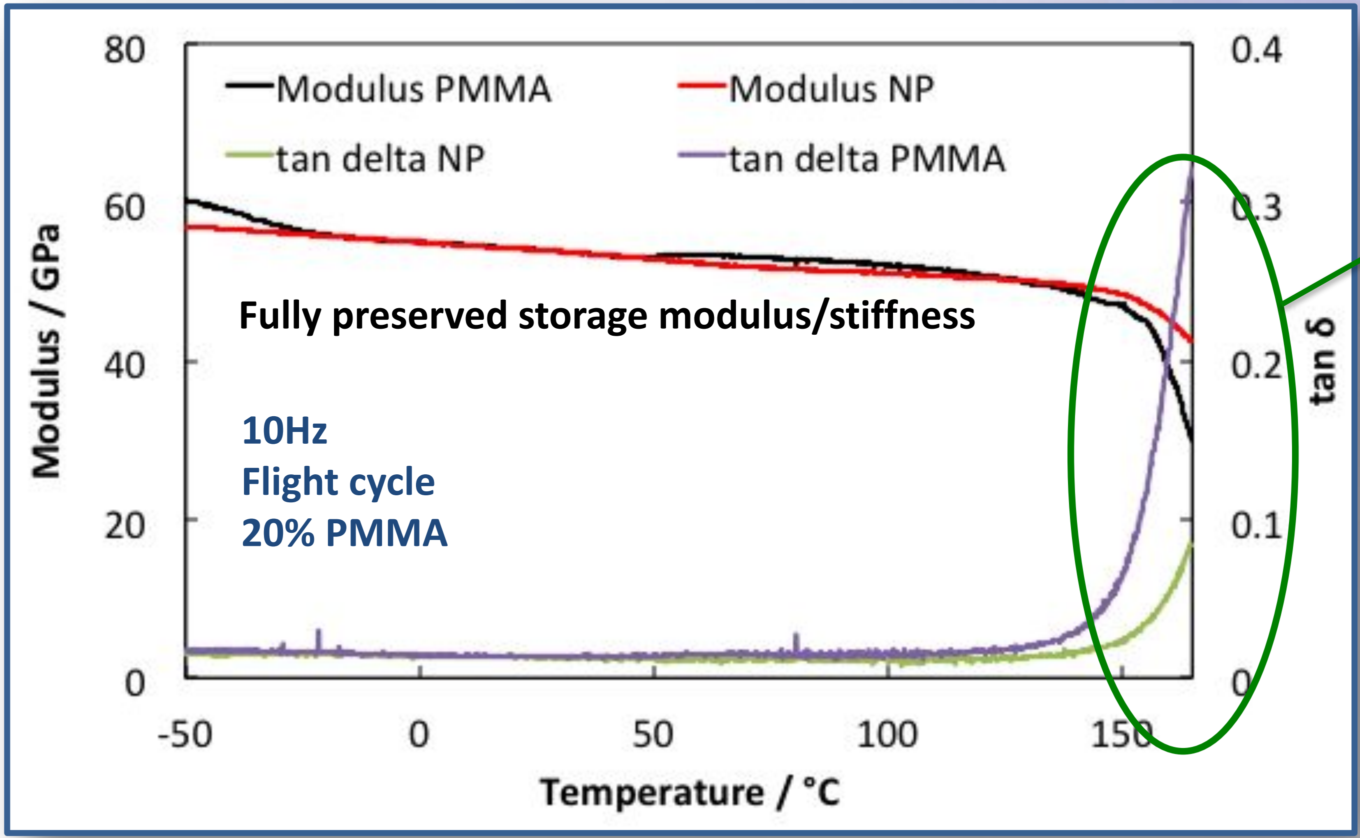


%PMMA ⇑

G_{Ic} ⇑

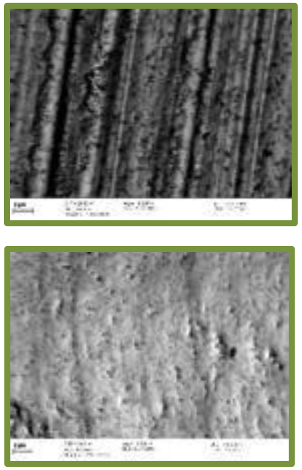
Repeatability ⇑

Dynamic mechanical properties preservation

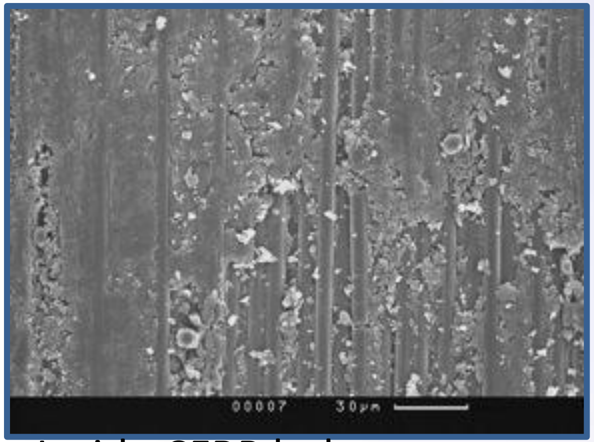


This zone is important in the machining process

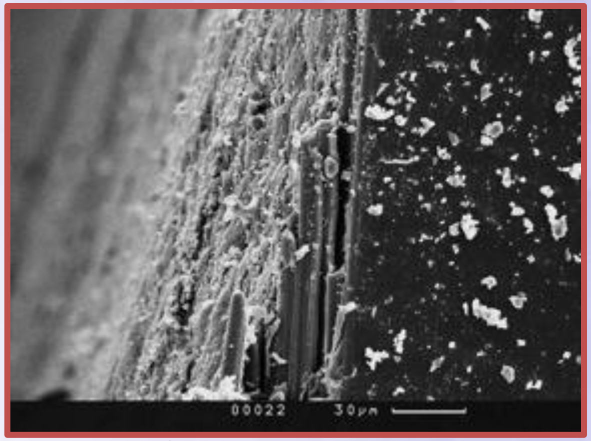
Machining quality improvement



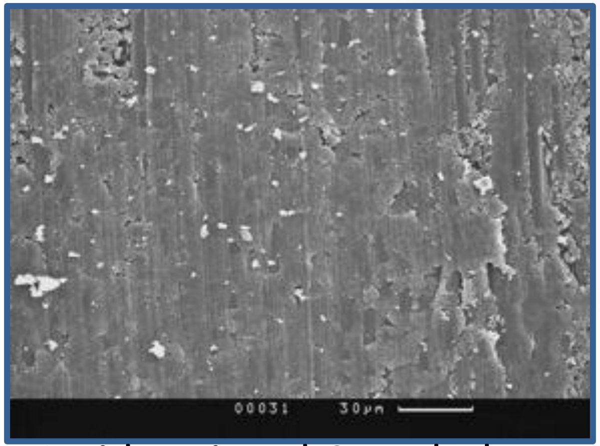
Typical tool wear in CFRPs



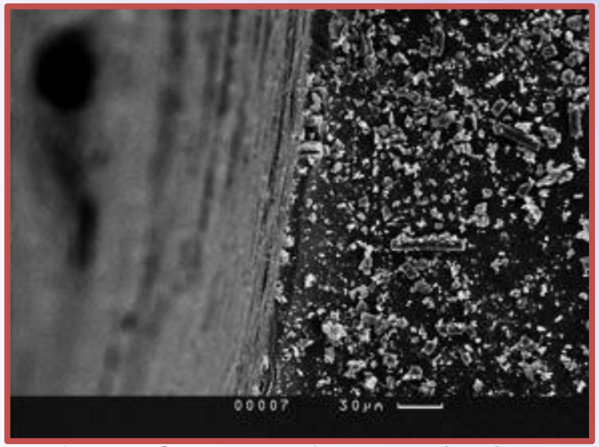
Inside CFRP hole



Edge of CFRP hole



Inside printed CFRP hole



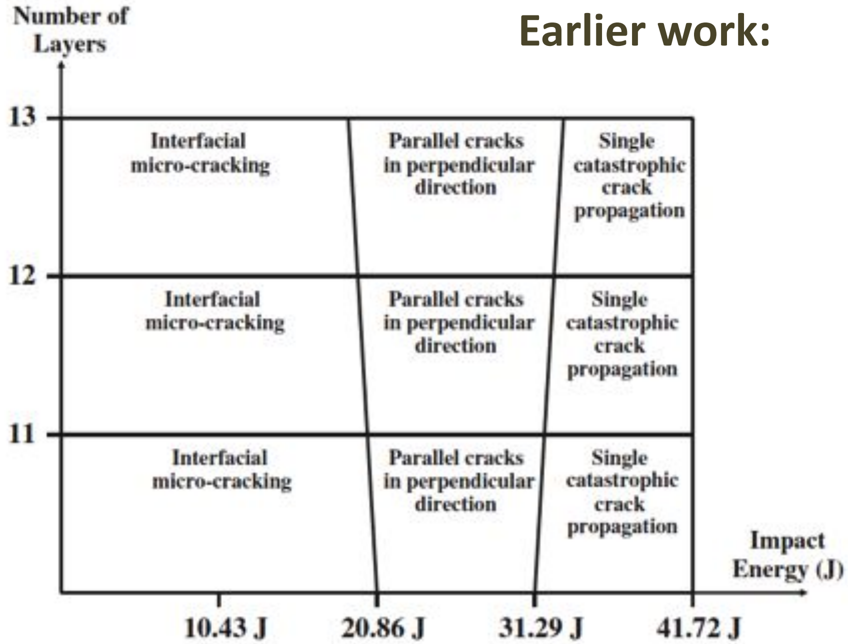
Edge of printed CFRP hole

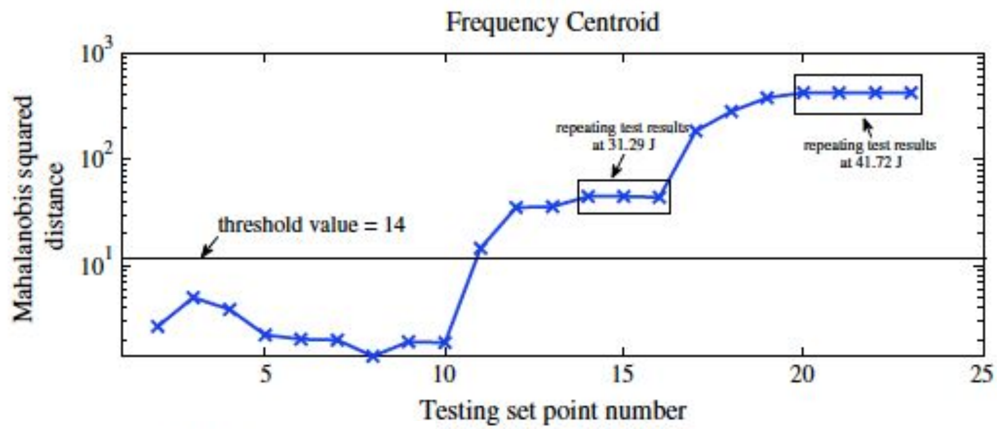
Composites At Sheffield.

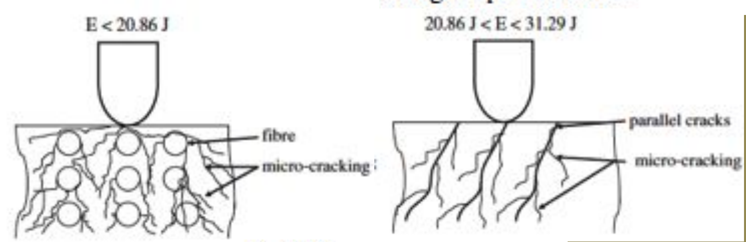
A plan to develop BVID detectable by SHM…

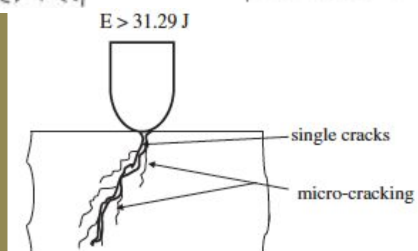
…ended up with 1J impact only in our UD specimens

Earlier work:









Sultan MTH, Worden K, Pierce SG, Hickey D, Staszewski WJ, Dulieu-Barton JM, Hodzic A, On impact damage detection and quantification for CFRP laminates using structural response data only, Mechanical Systems and Signal Processing 25(8): 3135-3152, 2011.

X-ray tomography @ Southampton

Aim:

Investigate BVID crack formation and SH

Impact CFRPs and IJ printed CFRPs with 1J

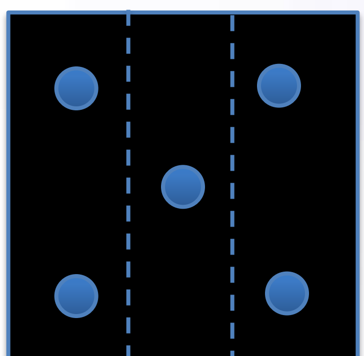
8 layers UD

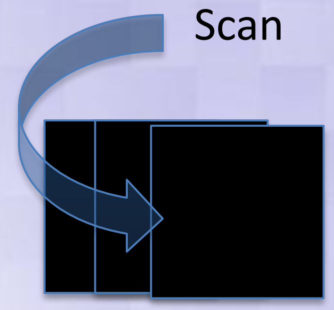
Scan the samples, heat-treat and scan again.

Achieved?

Still trying to make cracks in 20% PMMA printed CFRPs

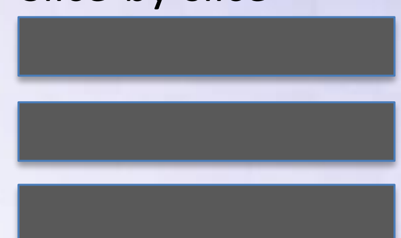
A very happy team celebrating Xmas and increasing impact force.





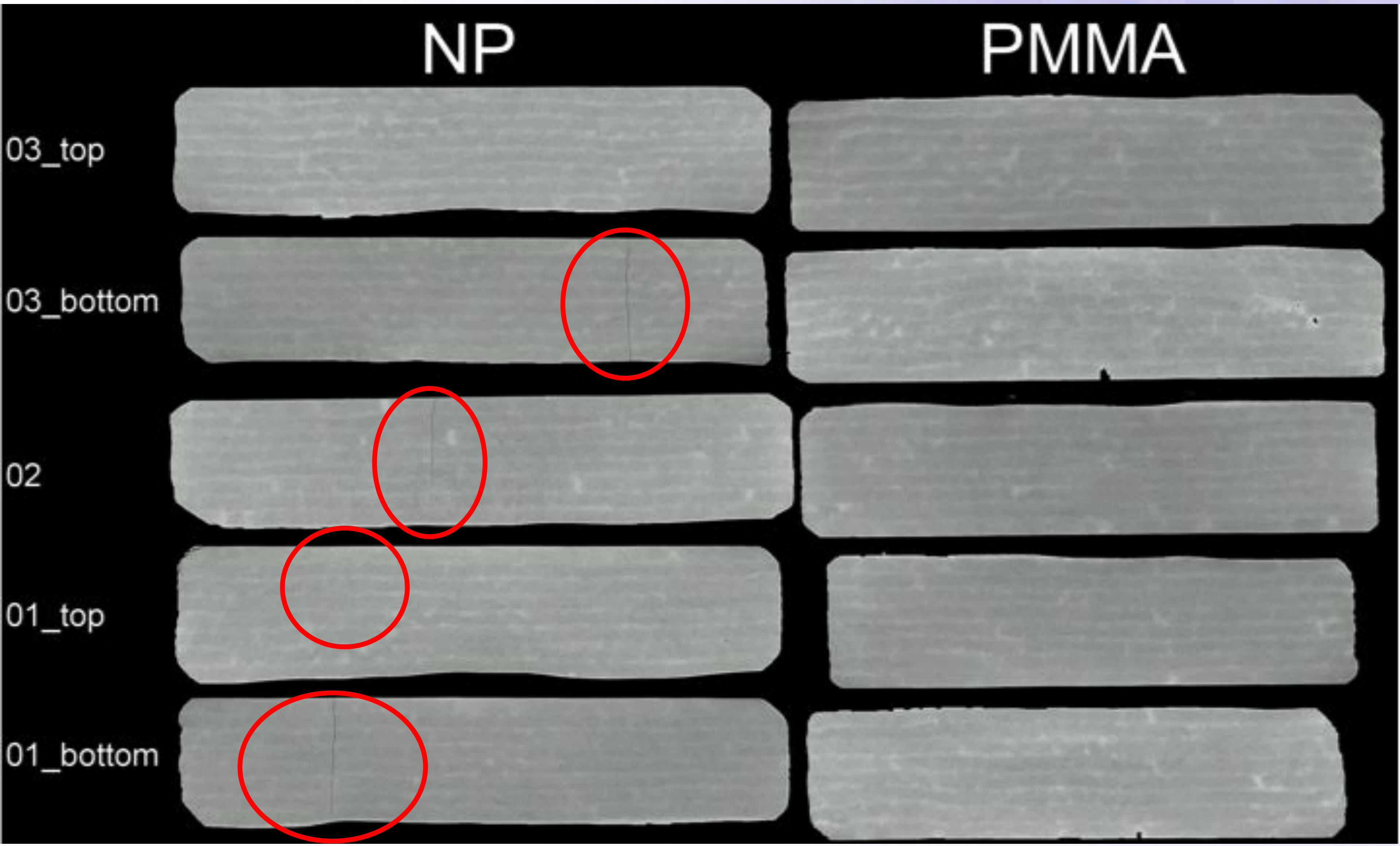
Through-thickness

Slice-by-slice



X-ray tomography @ Southampton

- System: Custom design Nikon/Metris dual source high energy micro-focus walk-in room system
- This scan used the 225kV source with and 1621 PerkinElmer cesium-iodide detector
- To enhance contrast a Mo target was used and peak voltage was set at 55kV, with no pre-filtration
- The current was set at 157uA (8.6W) and the panel brought forwards so that the source-imaging distance was ~700mm. At this power, the focal spot is spread slightly to prevent melting of the target - however, since the voxel size at this magnification was 7.6microns, we could afford to gain flux at the expense of focal spot size, without affecting the resolution of the reconstruction.
- 3142 projections were taken over the 360 degree rotation, with 4 frames per projection being averaged in order to improve signal to noise
- Exposure time of each projection was 354ms and the gain set to 30dB
- To reduce the effect of ring artefacts, shuttling was used with a maximum displacement of 5 pixels


NP
PMMA
03_top
03_bottom
02
01_top
01_bottom

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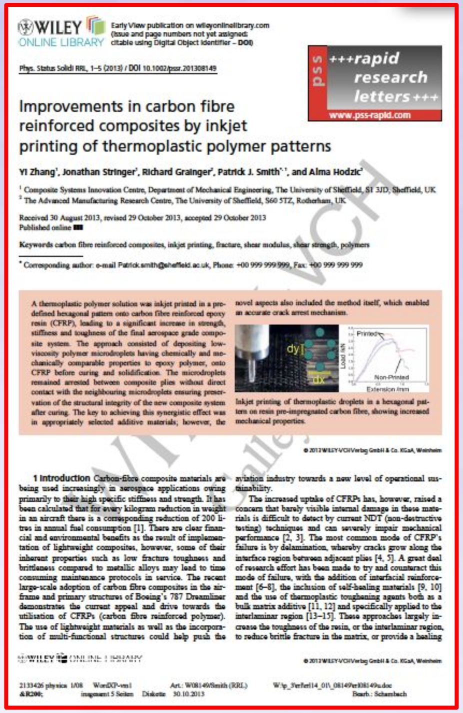
In nuce

(In pursuing the original task: to quantify the SH effect)

- **Can we accurately print thermoplastics in AE accredited CFRPs?** □
- **Are there compatible SH polymers in the incompatible families?** □
- **Are structural static and dynamic properties preserved?** □
- **Is damage tolerance improved?** □□
- **Are discrete patterns more desirable?** □
- **Are shear properties improved?** □
- **Is there improvement after 2nd thermal treatment?** □
- **Is machining qualitatively improved?** □
- **Did we manage to avoid adding any parasitic weight?** □
- **Did we conform to the existing supply chain?** □
- **Did we increase the value of the product?** □
- **Did we pioneer a new improved system?** □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Phys. Status Solidi RRL, 1–5 (2013) / DOI 10.1002/pssr.201308149

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Improvements in carbon fibre reinforced composites by inkjet printing of thermoplastic polymer patterns

Yi Zhang[1], Jonathan Stringer[2], Richard Grainger[2], Patrick J. Smith[*,1], and Alma Hodzic[1]

[1] Composite Systems Innovation Centre, Department of Mechanical Engineering, The University of Sheffield, S1 3JD, Sheffield, UK
[2] The Advanced Manufacturing Research Centre, The University of Sheffield, S60 5TZ, Rotherham, UK

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Keywords carbon fibre reinforced composites, inkjet printing, fracture, shear modulus, shear strength, polymers

* Corresponding author: e-mail Patrick.smith@sheffield.ac.uk, Phone: +00 999 999 999, Fax: +00 999 999 999

A thermoplastic polymer solution was inkjet printed in a pre-defined hexagonal pattern onto carbon fibre reinforced epoxy resin (CFRP), leading to a significant increase in strength, stiffness and toughness of the final aerospace grade composite system. The approach consisted of depositing low-viscosity polymer microdroplets having chemically and mechanically comparable properties to epoxy polymer, onto CFRP before curing and solidification. The microdroplets remained arrested between composite plies without direct contact with the neighbouring microdroplets ensuring preservation of the structural integrity of the new composite system after curing. The key to achieving this synergistic effect was in appropriately selected additive materials; however, the novel aspects also included the method itself, which enabled an accurate crack arrest mechanism.

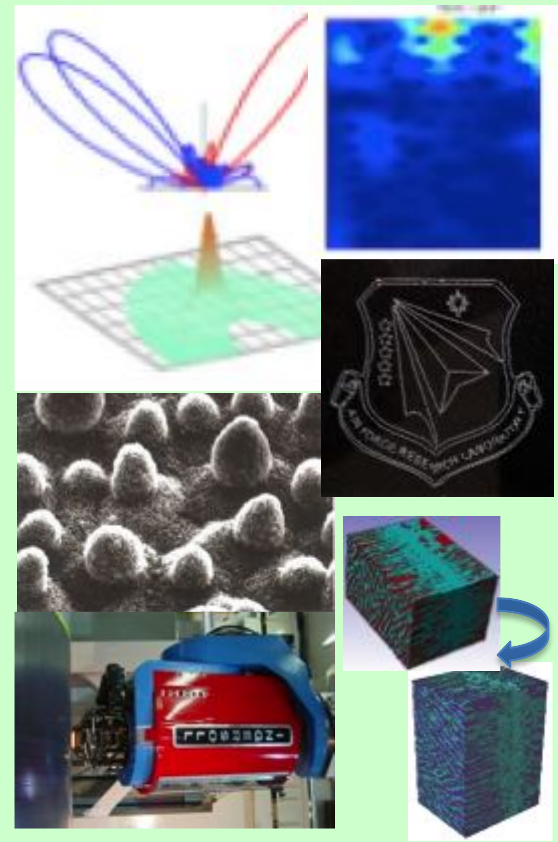
Inkjet printing of thermoplastic droplets in a hexagonal pattern on resin pre-impregnated carbon fibre, showing increased mechanical properties.

With massive thanks to

International roadmaps for IJPCs

Sheffield, Bristol, South Carolina (McNair) and Clemson:

- **R1: manufacturing of novel IJPCs**
  - (Smith, Hodzic, Scaife, Tarbutton, van Tooren)
- **R2: embedding novel sensors in IJPCs**
  - (Giurgiutiu, Tarbutton, Smith, Hodzic)
- **R3: grafting novel polymers for IJPCs**
  - (Luzinov, Kornev, Smith)
- **R4: watermark composites**
  - (Smith, van Tooren, Majumdar)
- **R5: multiscale ultrasonic inspection in woven IJPCs**
  - (Banerjee, Giurgiutiu, Smith, Hodzic, van Tooren)
- **R6: developing FEA from x-ray tomography of IJPCs**
  - (Pinna, Deng, Majumdar, Smith, Hodzic, van Tooren)
- **R7: validation of damage models in IJPCs using SHM and 3D NDT**
  - CSIC (Hodzic, Smith, Pinna), DRG (Worden, Manson) from Sheffield and NDT (R. Smith) from Bristol – white paper submitted to AFOSR
- **R8: machining of IJPCs, influence on durability**
  - (Hodzic, Scaife, Pinna, Smith)
- **R9: integration of R1-8**



Innovation and Research
Manufacture/Characterization/Certification

Research

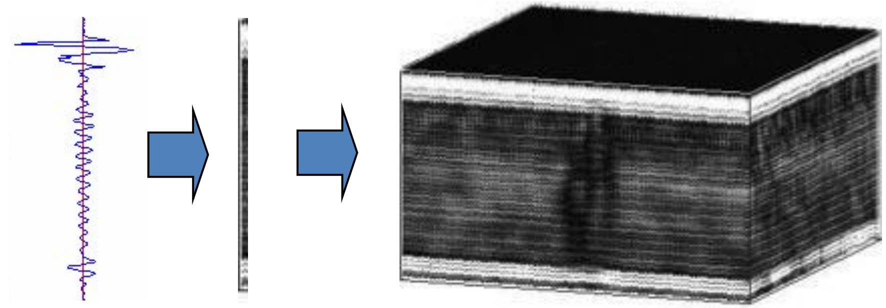
- Advanced Materials and Structures
  - Design
  - Development
  - Testing
  - Commercialization
  - Response to
    - extreme conditions
    - lightning
- Life Cycle
  - Monitoring
  - Remediation and Maintenance
- Systems design
- Fuel Cells/Power Sources
- Cyber security
- Supply Chain
  - Sustainability
  - Optimization
- Global Regulated Business Strategy

- Center for Mechanics, Materials, and Non-Destructive Evaluation
- Laboratory for Active Materials and Smart Structures
- Center for Friction Stir Processing, NSFI/UCRC
- Virtual Test Bed
- Condition-Based Maintenance Research Center
- Lightning Response Laboratory
- HetroFoaM Center
- Solid Oxide Fuel Cell Center
- Strategic Approaches to the Generation of Electricity
- May 2014: Advanced Composite Material Research Laboratory

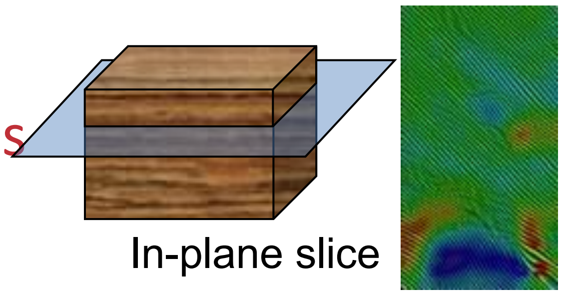
FW: NDT at high frequencies

Prof. Robert Smith

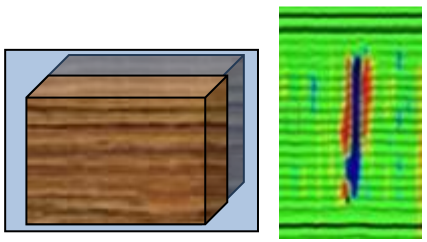
- 3D Characterisation of composite materials
  - Ultrasonic response
  - Inversion methods give actual material properties
- Fibre vector maps
- Fibre volume fraction
- Porosity
  - Frequency response
  - Distinguish between types



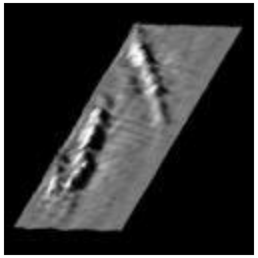
Full-waveform capture



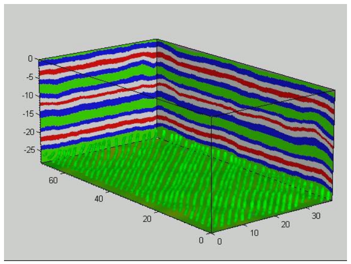
In-plane slice



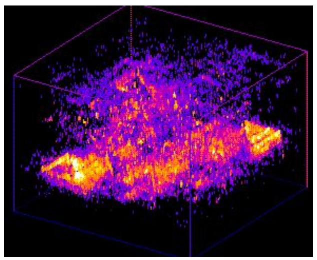
Out-of-plane slice



Wrinkle



Vector Map



Porosity