INVESTIGATION OF SPATIAL DISTRIBUTIONS OF DEFECTS IN CARBON FIBERS

UNIVERSITY OF DELAWARE | CENTER FOR COMPOSITE MATERIALS

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Introduction

Motivations

- Defects in fibers can control the fracture mechanism occurring among the brittle fibers in unidirectional composites.
- Brittle failure of a fiber in these composites is a locally dynamic process which induces stress concentration in the interphase, matrix and the neighboring fibers
- Generated stress waves travel at high speed and can trigger fractures of the neighboring fibers and clustering of fiber breaks is dependent on size and location of defects in these fibers.
- Experimental mapping of surface defects in brittle fibers are required for prediction of tensile failure of unidirectional composites.

Objectives

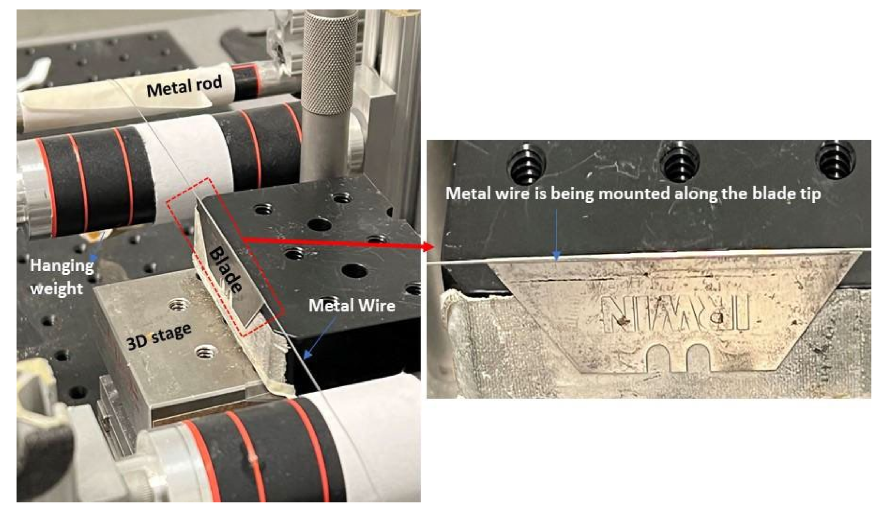
- To use the continuous fiber bending test method for investigation of the spatial defects in Carbon-AS4 fiber over a wide range of length scales.
- To establish the map of defect size / spacing between the defects.

Material

- **Carbon fibers AS4 were evaluate**

Property	Carbon fiber AS4
Radius (µm)	3.5
Modulus (GPa)	231
Elongation at break	1.8%
Critical stress intensity factor KIC (MPa m1/2)	1.67

Mounting Procedure of the Metal Wire on the Blade Tip



- A micron-precision 3-axis stage was used to mount the stainless-steel wires on to the tip of the blade. Then, the wire was adhered to the polished blade tip using Loctite 430 adhesive.
- The diameters of the mounted wires are 700 µm, 500 µm, 200 µm, 150 µm, 100 µm and 50 µm

Sample Preparation

- A 25 cm long of single carbon fiber was sandwiched between Kapton film and tape (see the schematic below).

Sample cross-section

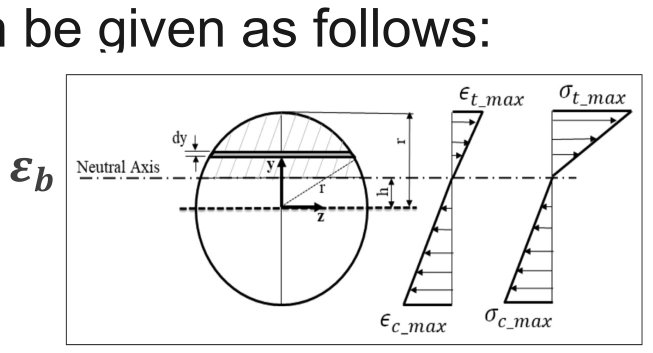
Bending test samples

Calculations of Maximum Bending Stress and Strain

- Max. strain (ε_t) and max. stress (σ_t) in tension mode experienced by the fiber surface during bending can be given as follows:

$$\varepsilon_t = \frac{r-h}{Rc}, \quad \sigma_t = E_t\,\varepsilon_b$$

$$h = \frac{4r}{3\pi}\left[\frac{E_t - E_C}{E_t + E_C}\right]$$



Effective radius of curvature, R_C = Rw+ r + t

Where:
Rw: Wire radius
t: Kapton fil thickness
Et: Modulus in tension
EC: modulus in compression
h: distance of the neutral axis from the fiber center

Using the parameters:

r (µm)	3.5
h (µm)	0.060
Et (Gpa)	231
Ec (Gpa)	213
t (µm)	13

Surface Defects Size Calculations

- Surface crack size (a) in a solid cylinder in bending mode, can be given as:

$$a = \frac{1}{\pi}\left(\frac{K_c}{F_1\sigma}\right)^2, \ \sigma \text{ is the bending stress}$$

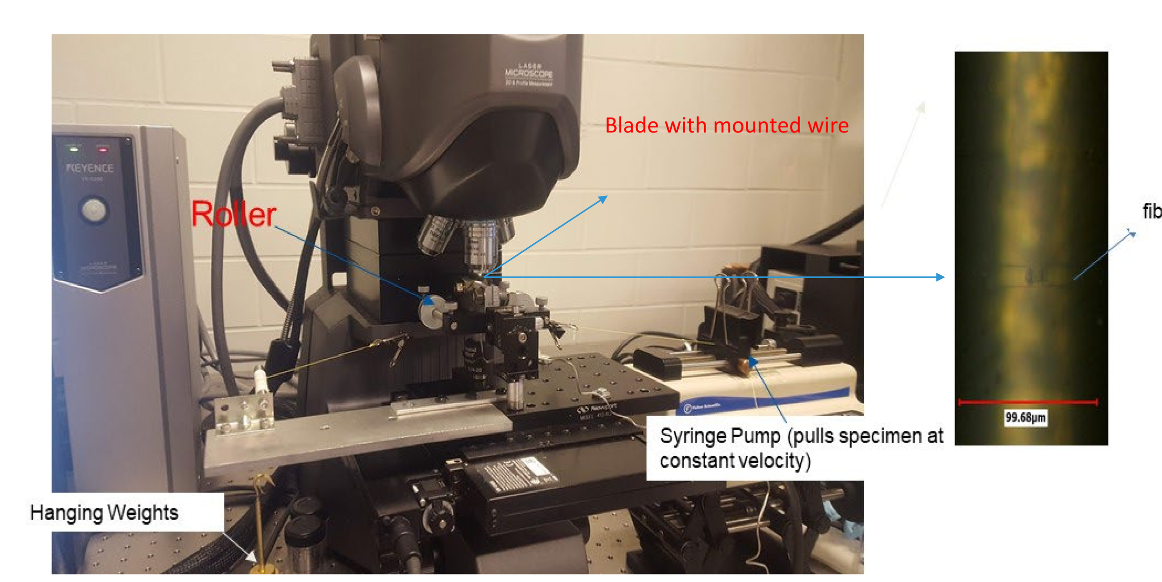
Where the parameters, such as F1=0.6 and Kc=1.67 MPa. m[2].

Calculated Defect Size (a) and Max. Bending Stress

Wire Diameter (µm)	Max. Bending stress (GPa)-Tension	Max. Bending Strain - Tension	Defect size (nm)
700	2.17	0.94%	514
500	2.98	1.29%	272
300	4.77	2.07%	106
200	6.82	2.95%	52
150	8.68	3.76%	32
100	11.95	5.17%	17
50	19.15	8.29%	7

- Defects size ranging from 7nm to 514 nm.
- Max. Bending stress ranges from 2.17GPa to 19.5 Gpa.

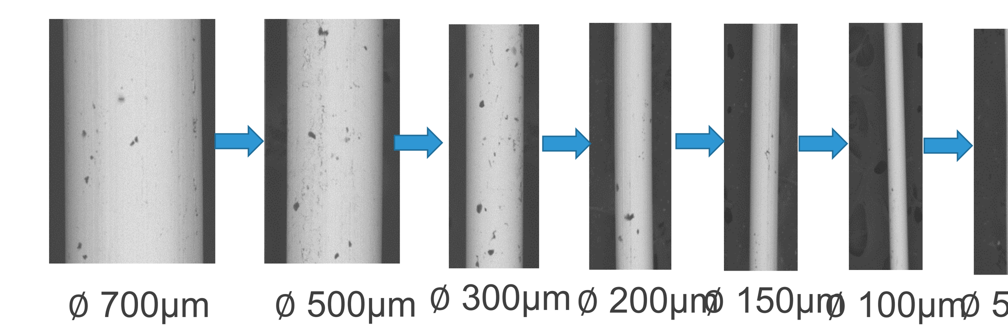
Bending Test Setup



- **Major parts**
- Syringe pump to pull the sample over the wire.
- 70g hanging weights, rollers, and microscope to ensure the curvature of fiber around the wire during the test.

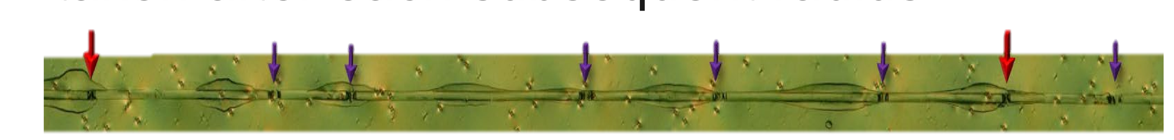
Continuous Bending Test Procedure

- The sample was allowed to move over the wire surface at 0.33 mm/min under constant load.
- Tests were done on each sample over 20 mm distance.
- Bending tests were perfumed at different radii of curvatures ranging from 350 um to 25 um on the same sample in sequential manner.



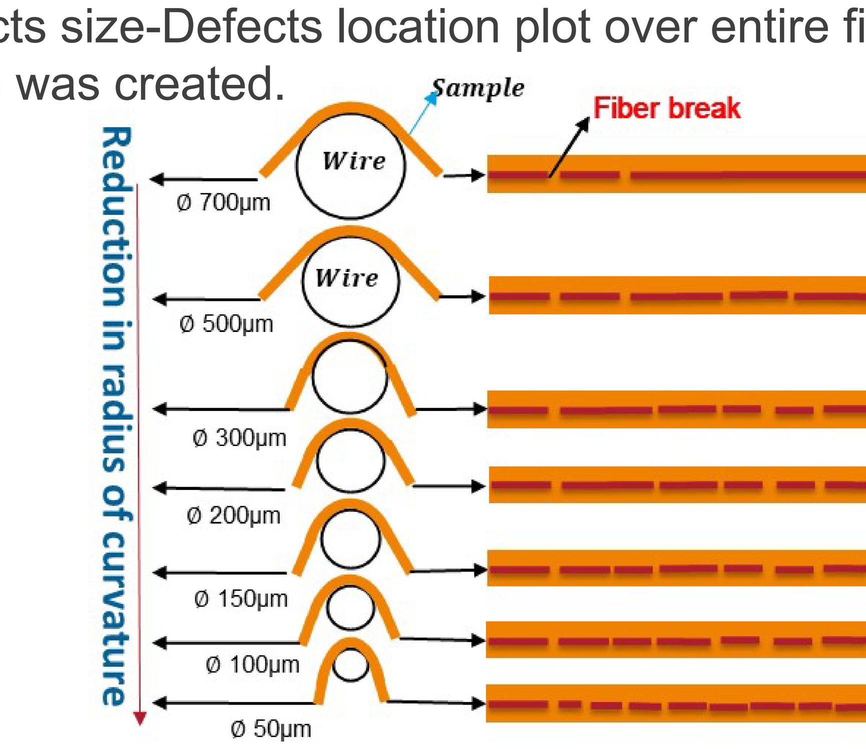
Progressive reduction in radius of curvature applied to same specimen

- Defect locations are captured from the images taken after each subsequent radius



Steps of Defects Map Generation

- Bending tests were perfumed by pulling the same sample over the wires with different diameters ranging from 700 um to 50 um in sequential manner.
- Defect locations are captured from the images taken after each subsequent radius.
- Same steps were repeated for 42 samples
- For each individual stress level, the cumulative locations of the defects were determined. From this data, defect map was established.
- Defects size-Defects location plot over entire fiber length was created.



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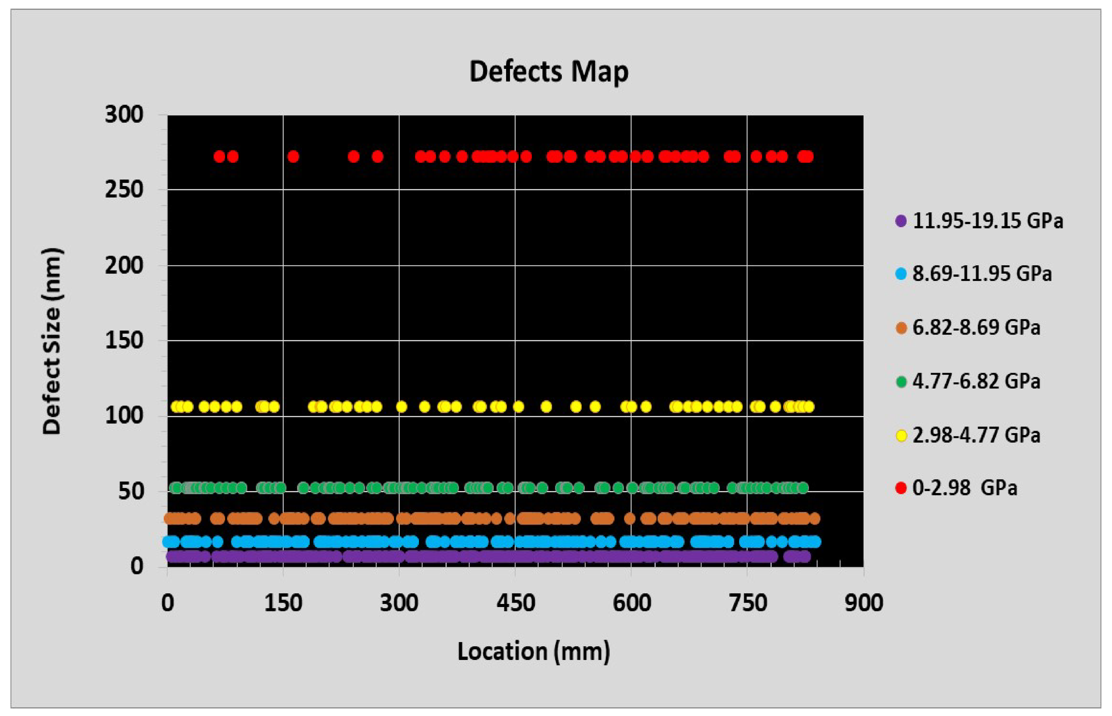
Spatial Distribution of Surface Defects

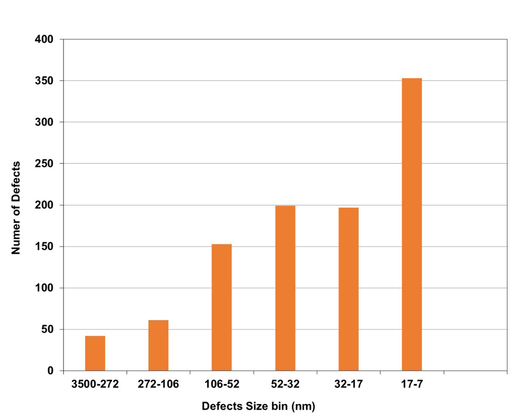
- Defect map was established (see Figure below).



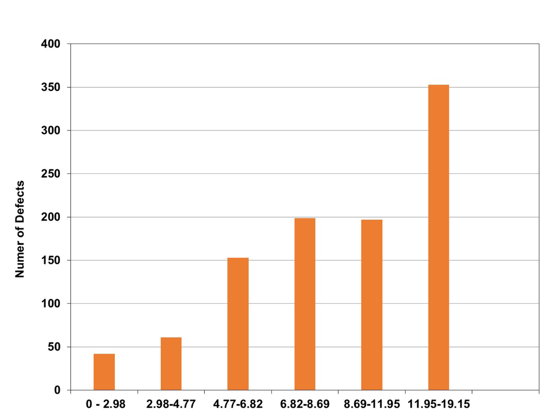
- As bending stress increases, smaller defects with smaller spacings on tension side of the fiber are activated.

Number of Defects-Bending Stress

➢Number of defects in each defect size bin

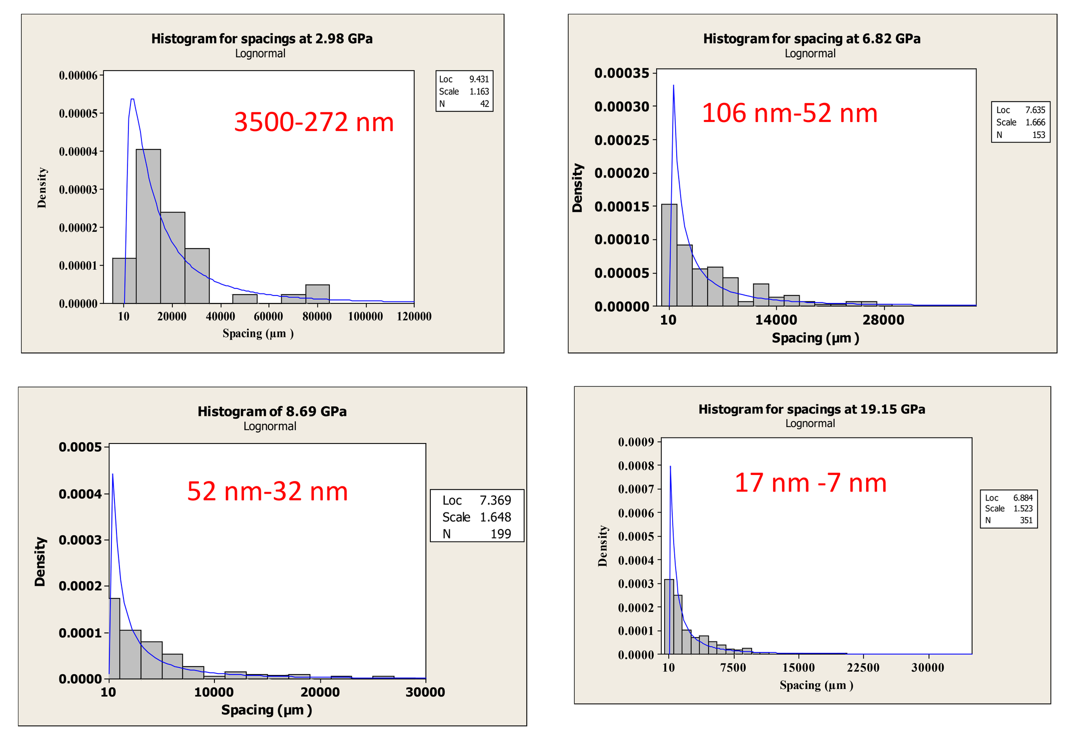


➢Number of defects in each bending stress bin



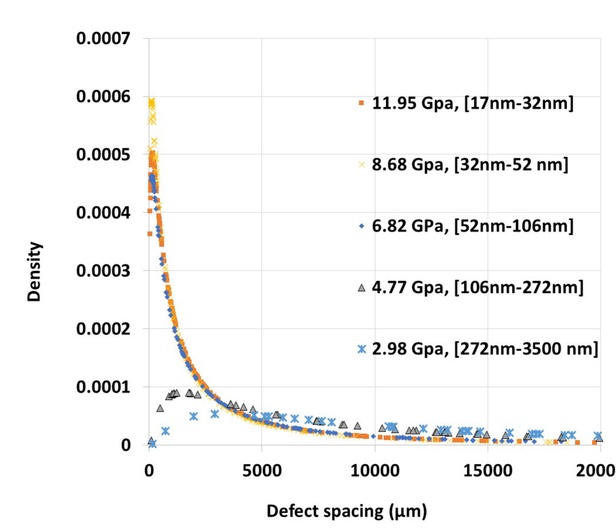
- As the defect`s size decreases, the number of defects increases.
- As the bending stress increases, the defects number increases.

Representative Histograms for Defect Spacings in Carbon AS4



➢Lognormal is the best fit function

Lognormal Fits of Spatial Distributions (PDF Curves)

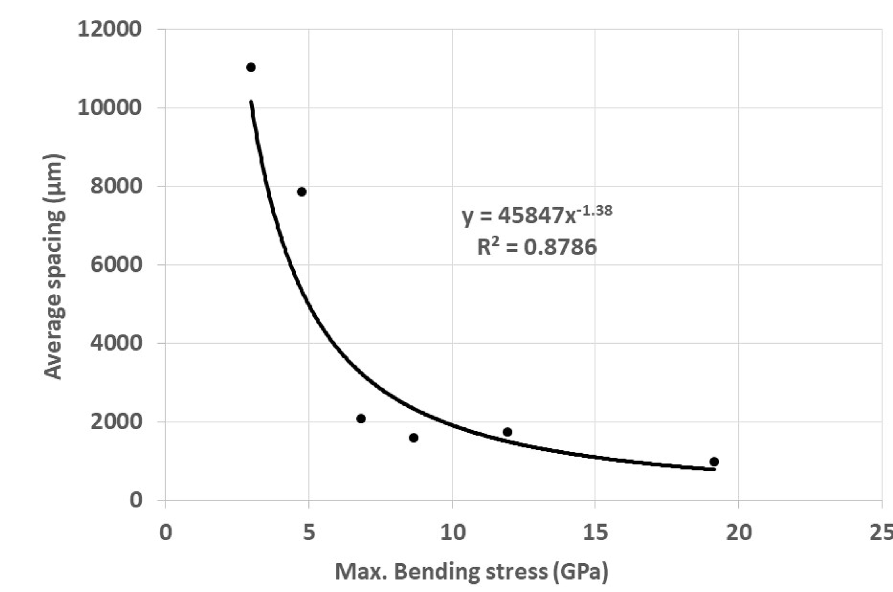


➢ Spacing at Max. Density of PDF Curves for Carbon fibers

Max Bending stress (GPa)	Spacing at max. Density (μm)
2.98	2913
4.77	1227
6.82	98
8.69	112
11.95	164
19.15	27

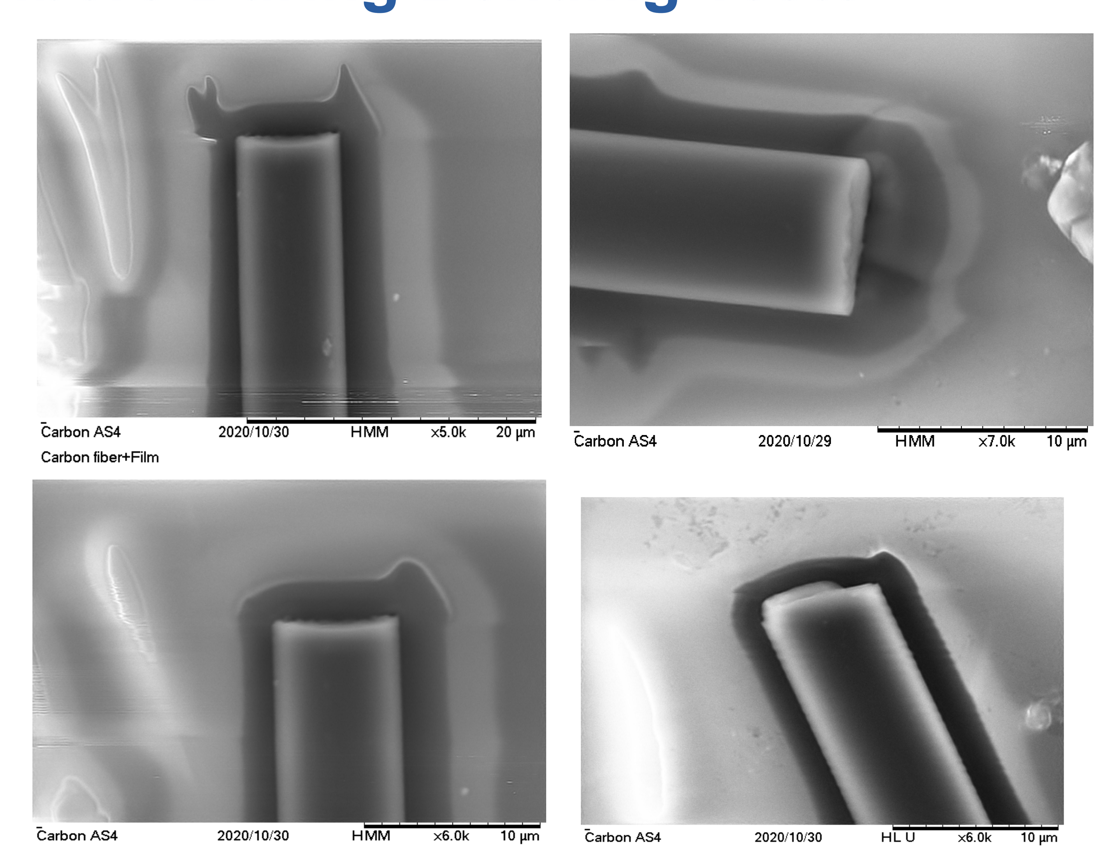
➢ Maximum density of spatial distributions exhibit shifts to lower spacings with increased bending stresses.

Average Spacing-Bending Stress



➢ From spatial distributions, average spacing between the defects can be estimated within bending stress with a range of 3Gpa-19Gpa.

Cross-Section of Fractured Carbon Fibers During Bending Tests



➢ Mostly the fractured surface of the fiber exhibits a circular cross-section showing that a tension dominant failure during bending.

Conclusions

- A novel continuous bending test method was used to establish the spatial distribution of the defects in Carbon AS4 over length of ~850 mm.
- The defect`s size-location map for AS4 was established. This map reveals that higher number of defects with smaller size are activated at higher bending stress levels.
- Spatial distributions of defects were generated at different stress and defect`s size intervals and their peak values exhibited shifts to smaller spacing values with increased stress levels.
- From SEM images, carbon AS4 fibers show a circular cross-section of fractured surfaces confirming a tension dominant failure of fiber during bending test.

Future Work

- From the defects map, flexural strength distributions will be generated at different gauge length (0.01mm-20mm).

Acknowledgements

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