MANUFACTURE AND THERMOFORMING OF CARBON FIBRE REINFORCED THERMOPLASTICS TAPES, USING WASTE POLYMER BLENDS

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CENTRE FOR ADVANCED MATERIALS MANUFACTURING & DESIGN

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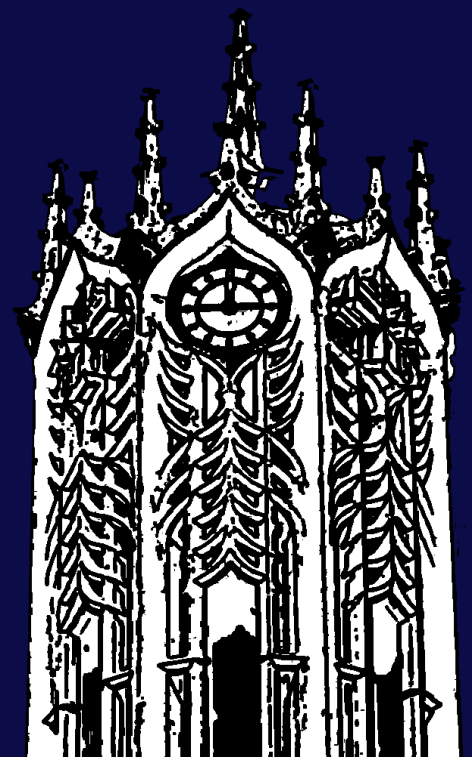

Challenges for a Plastics Circular Market in New Zealand

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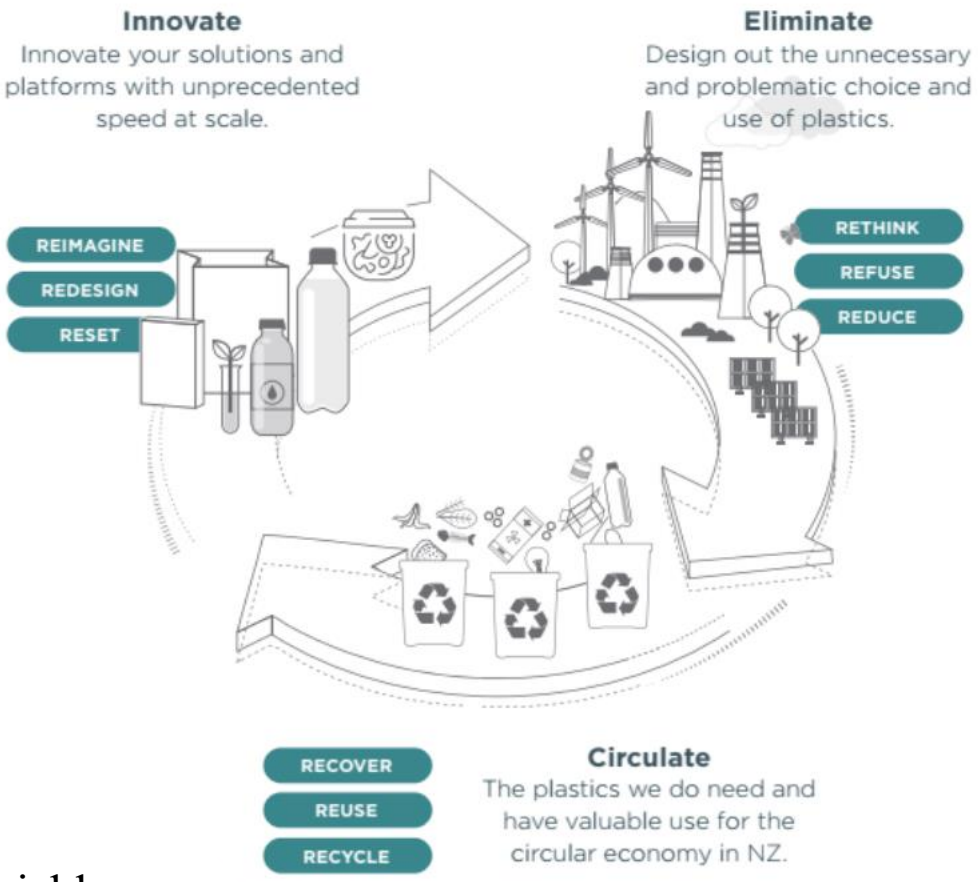
Annually in New Zealand, **540,000 tonnes** of plastic is imported. It is estimated that…

- **380,000 t** is landfilled, and **60,000 t** is discharged to the environment or stockpiled.
- Only **35,000 t** is recycled domestically, and **22,000 t** exported for recycling.

This is primarily a linear plastics market.

New Zealand aspires to a working circular plastics market to recycle, upcycle, and make new goods from plastic waste. We have challenges…

- A relatively small population, and economy.
- A distributed population, spread amongst many small centres.



A 5-year research program has been funded to create:

- **Business and design solutions** to create a connected, transparent and viable circular market.
- **Additional technical recycling solutions**, with potential for hard or impossible to separate mixed plastic waste streams.

MBIE Endeavour Research Program

Shaping a circular market system for plastics in New Zealand

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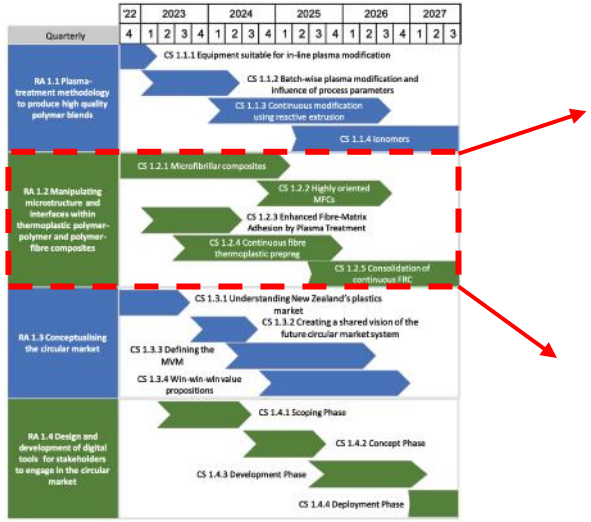
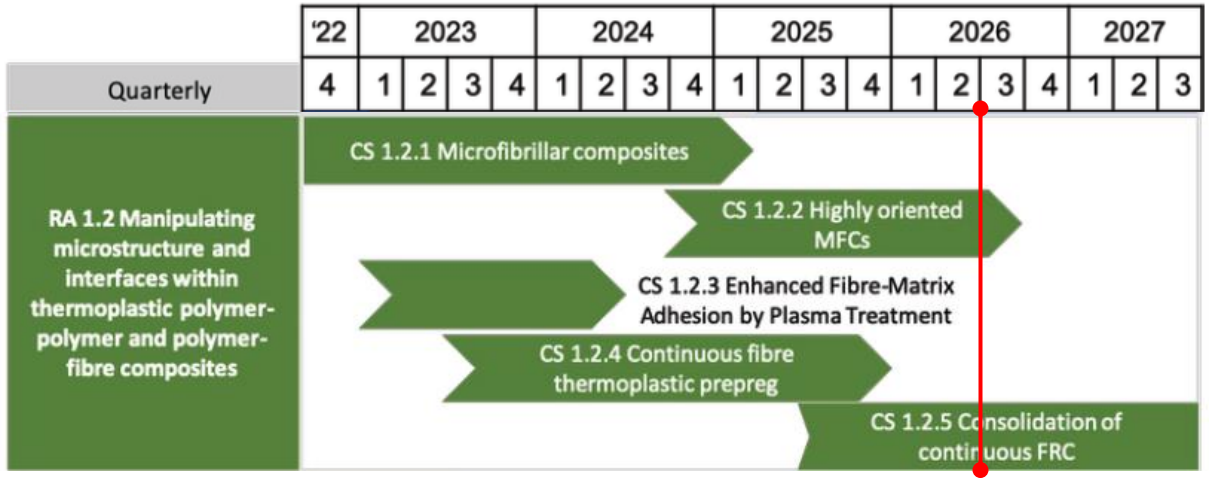
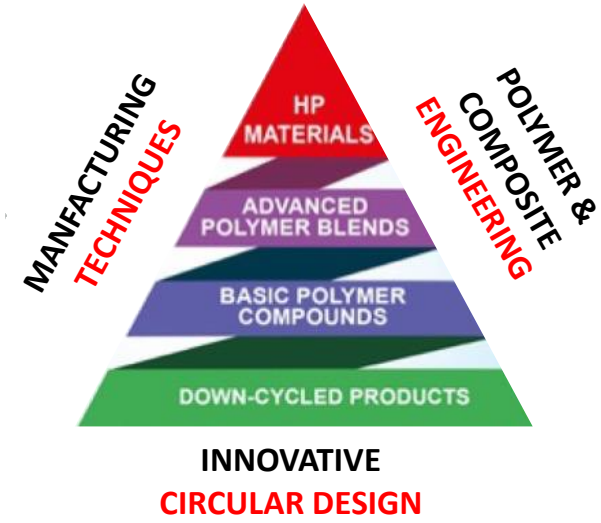




Research Aim 1.2 is focussed on creation of novel, high performance thermoplastic polymer composites.

- Two main streams of work, highly interactive with RA1.1
- Advanced polymer blends (MFCs) and fibre reinforced polymers
- Utilising complex waste streams, to create materials with high performance, for long term applications



Overview – Carbon fibre-reinforced PA6/PP tapes

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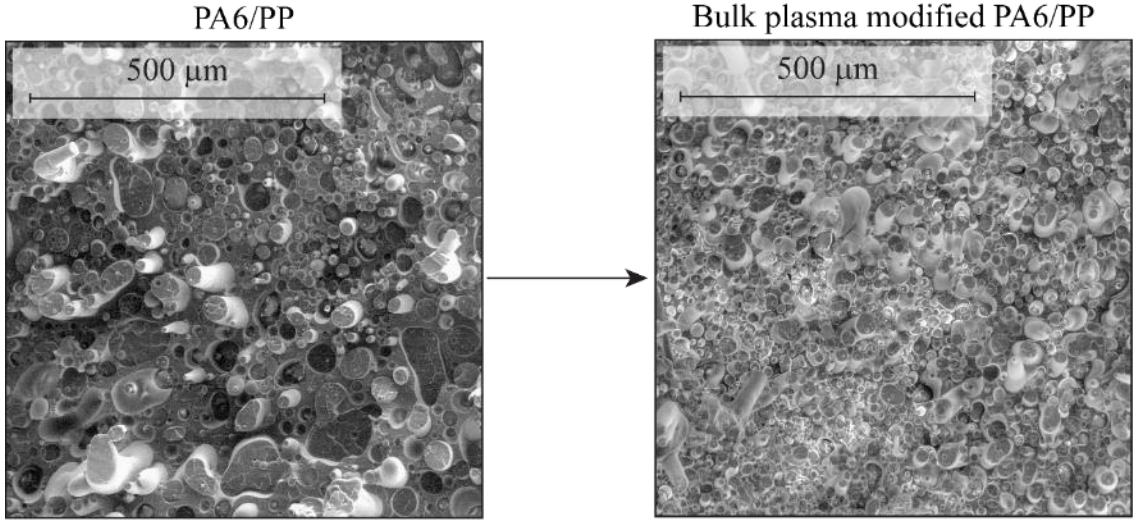
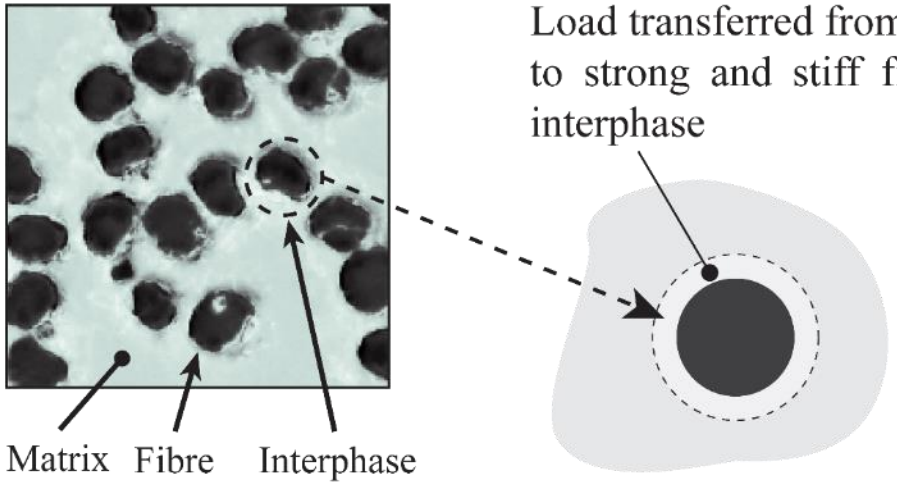
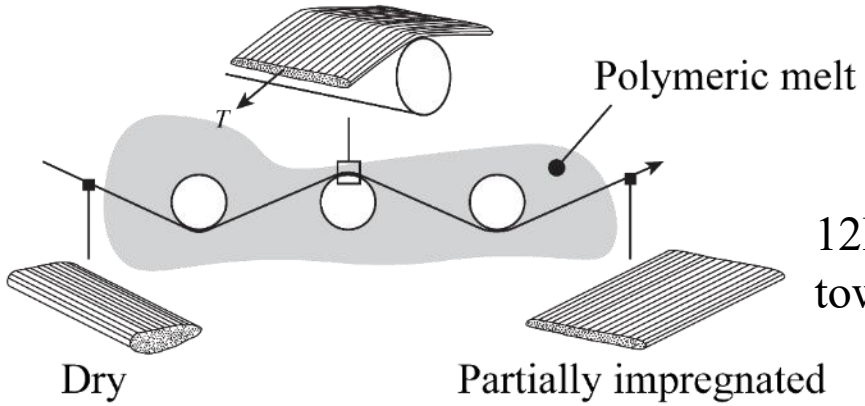
Polymer blend compatibility



Interface/interphase tailoring



Continuous plasma modified carbon fibre impregnation



12K unsized carbon fibre tow (Hyosung, Korea)

Why plasma?

Application of Atmospheric Pressure Plasma Jets (APPJ)

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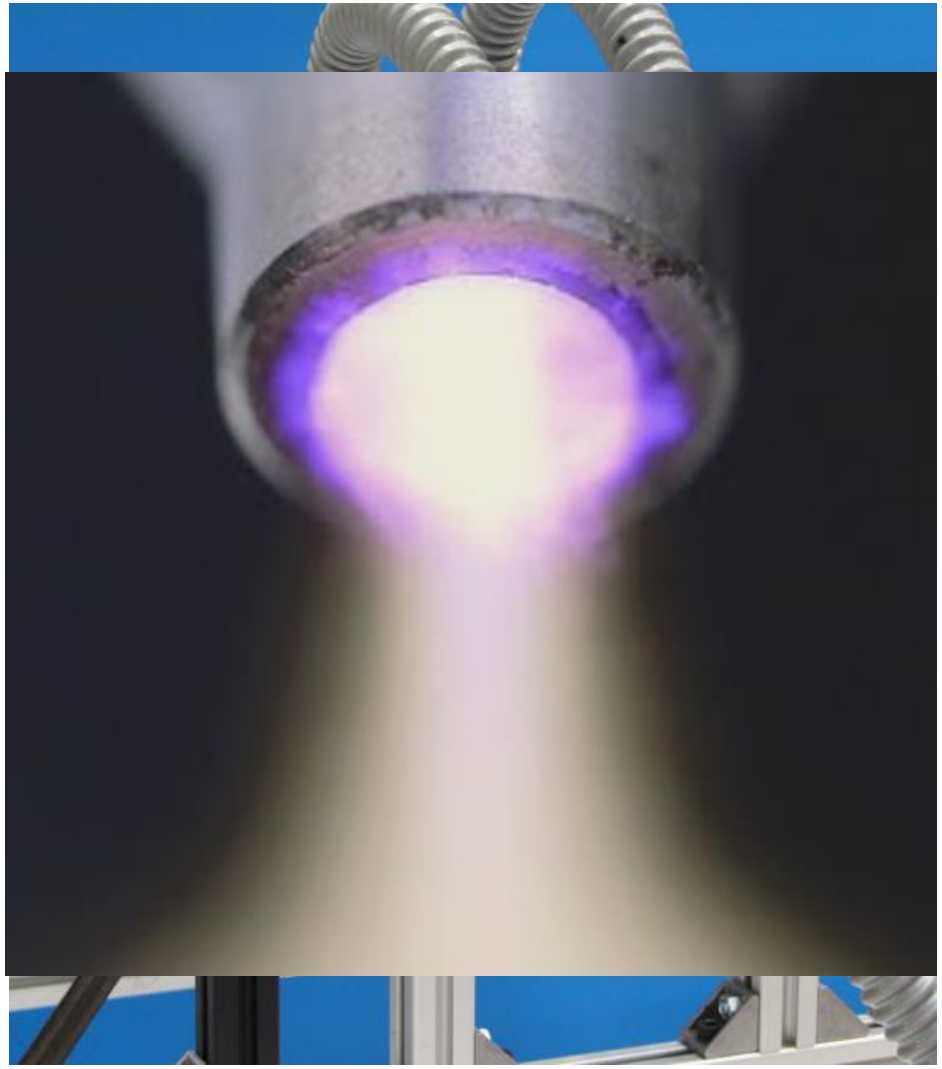
Plasma is a highly energetic quasi-neutral ionized gas composed of a complex mixture of electrons, ions, molecules, and other reactive species, exhibiting collective behavior.

Atmospheric Pressure Plasma Jets are:

- Easy to operate, and have low running costs
- Seamlessly integrated into production lines
- Energy efficient
- Able to employ a wide range of carrier gases, providing varying chemical functionalities to polymers or fibres



In this program APPJs are being applied for **bulk modification of polymers and polymer blends**, and for **surface modification of reinforcing fibres**.

Melt impregnation tape manufacture

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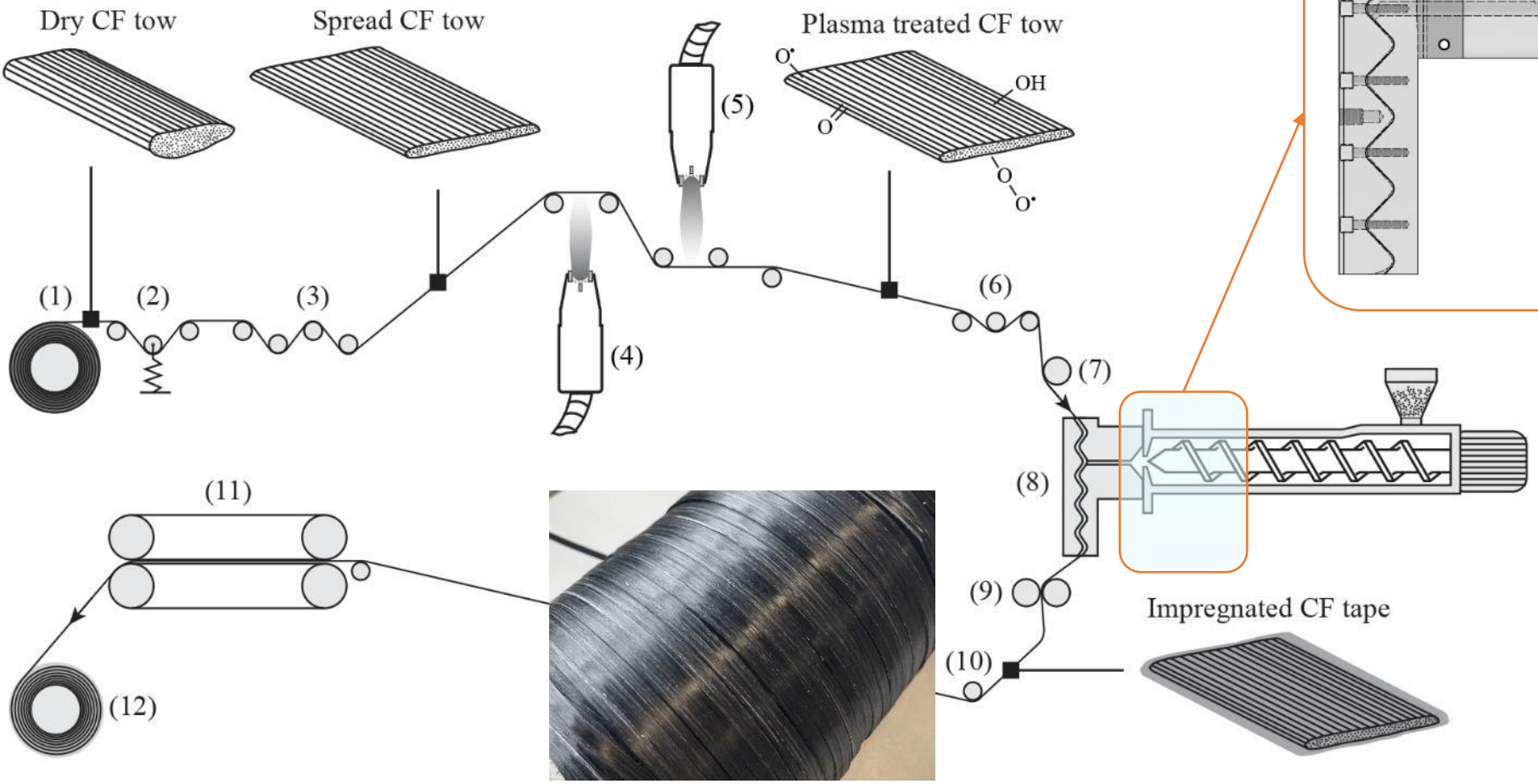

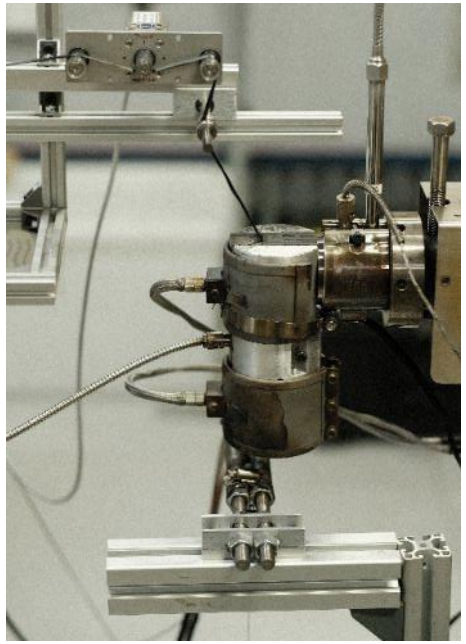

1.5 metres/min production rate

Presentation content

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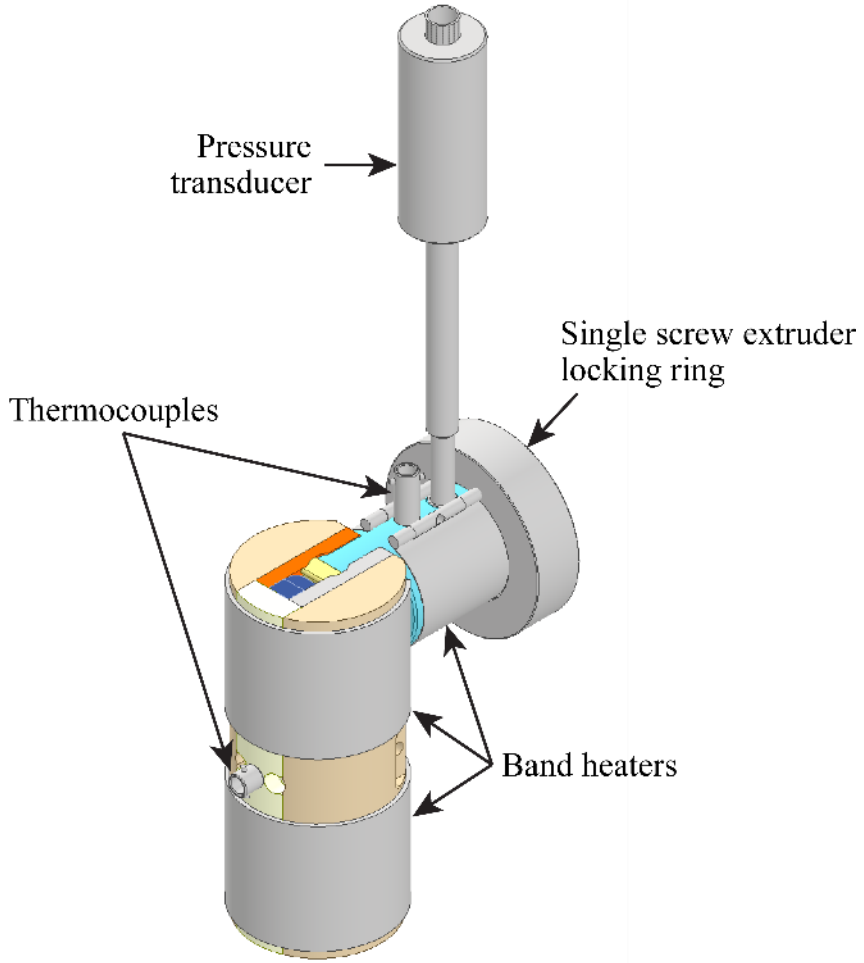
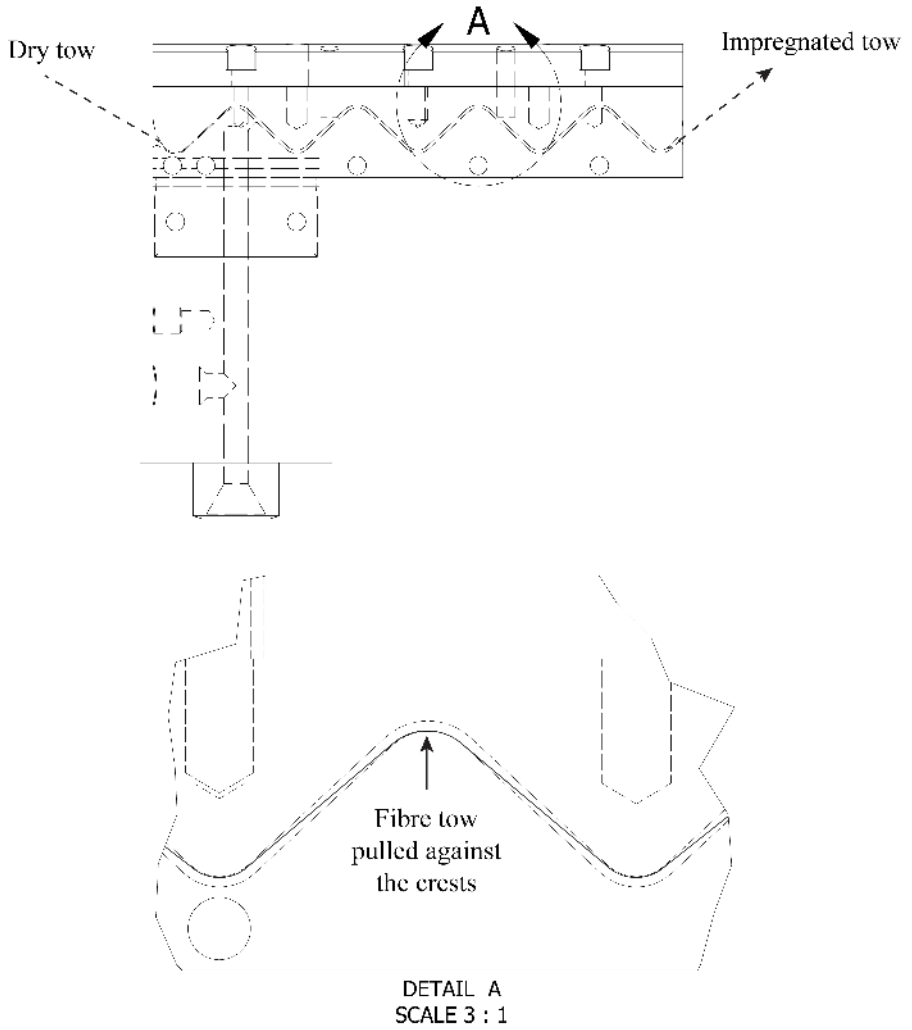
- Motivation and Introduction
- Wavy Slot Impregnation Die – Modelling
- Wavy Slot Impregnation Die – Carbon Fibre Blended Matrix Composites
- Scaling Manufacture – Automated Layup and Forming
- Scaling Manufacture – Composite Laminate Characterisation

Continuous thermoplastic prepreg melt impregnator

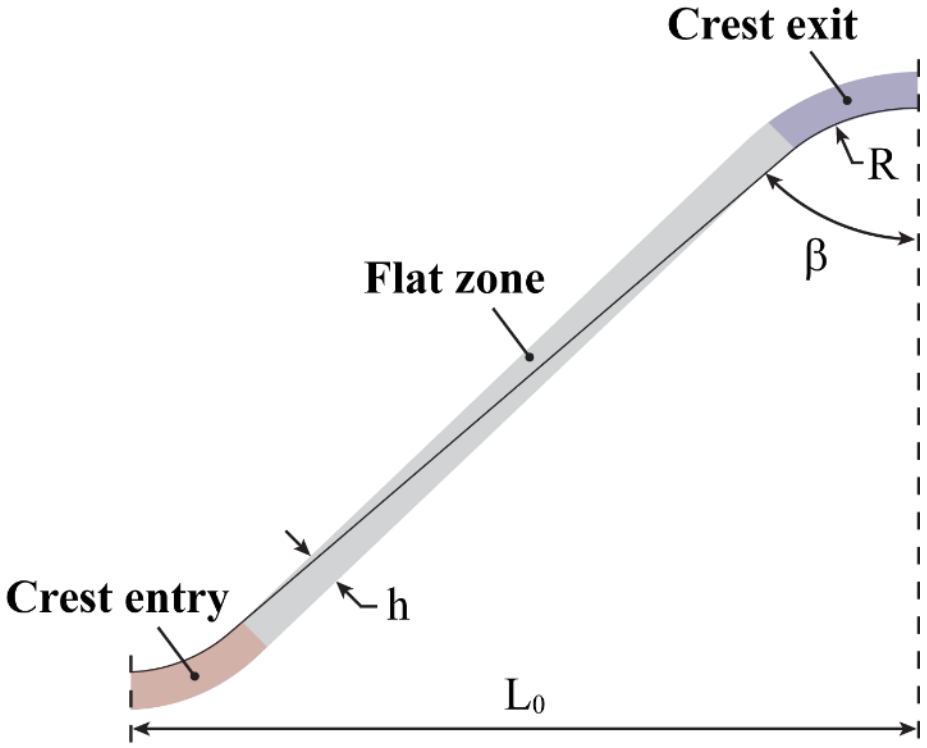
- Pin driven impregnation is a common continuous melt impregnation process
- To increase pressure and reduce melt degradation, Zhang et al. [1] introduced crest driven impregnation in a slot die





[1] Zhang et al. **"A novel slot die and impregnation model for continuous fiber reinforced thermoplastic UD-tape,"** *Applied Composite Materials,* 2023

Impregnation modelling approach - Overview



Polymer pressure within the developed model is assumed to be a combination of:

i. Static pressure — CFD with moving tow

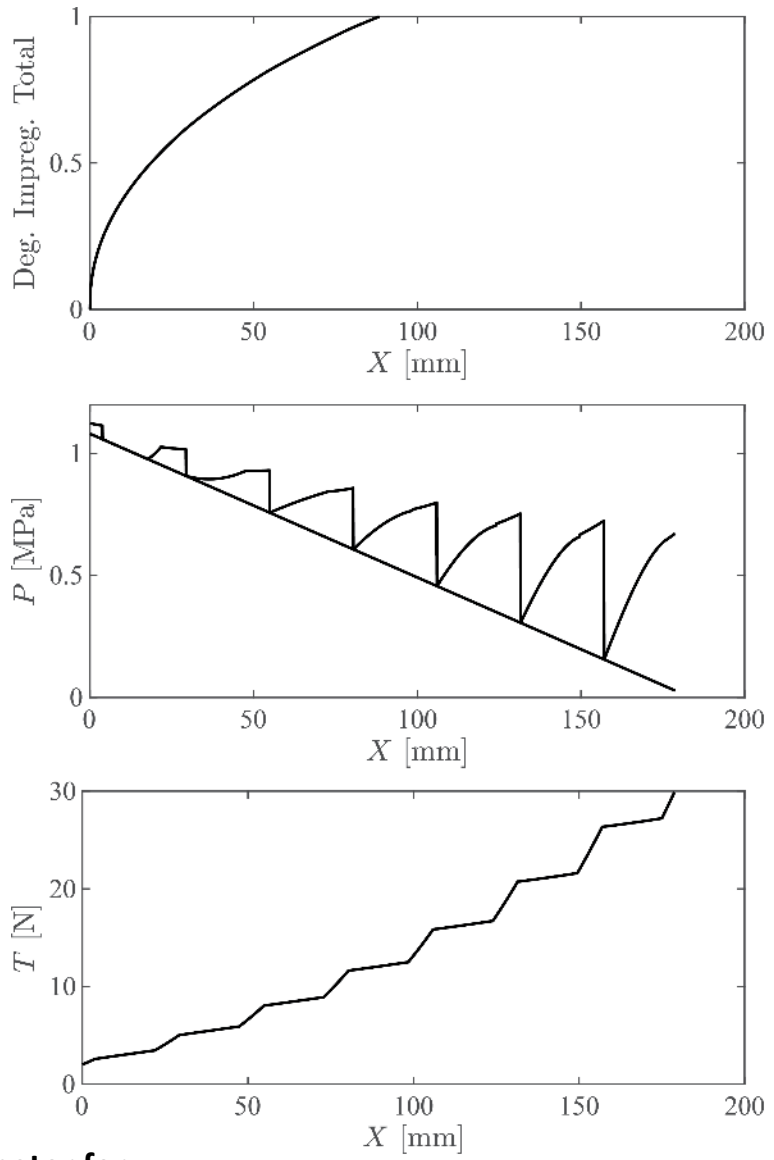
ii. Crest pressure from tow tension — Model by Bates and Zou [1]

iii. Wedge pressure from tow velocity and gap reduction — Adapted Bates and Zou [1]

[1] P. J. Bates and X. P. Zou, **"Polymer Melt Impregnation of Glass Roving: Modelling and Experimental,"** *International Polymer Processing* 17.4 (2002): 376-386

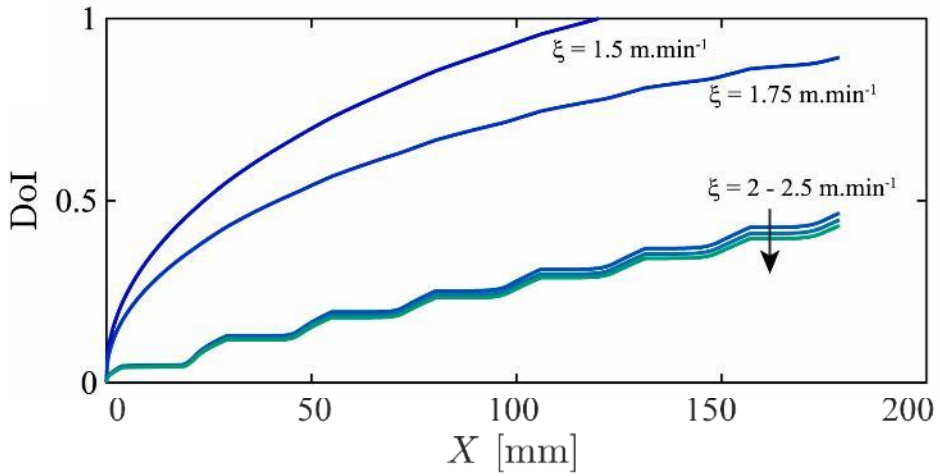
Impregnation model – Baseline model parameters

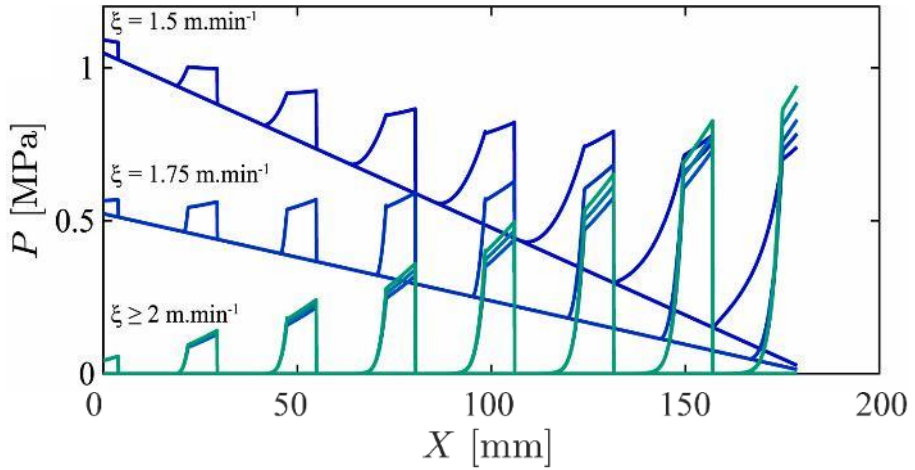
Tow thickness (mm)	0.3
Tow width (mm)	6.5
Crest length (mm)	20
Crest radius (mm)	5
Number of crests	7
Towing speed ($m.min^{-1}$)	1.5
Tow pre-tension (N)	2
Melt viscosity (Pa.s)	180
Melt inlet velocity ($mm.\ s^{-1}$)	1.5

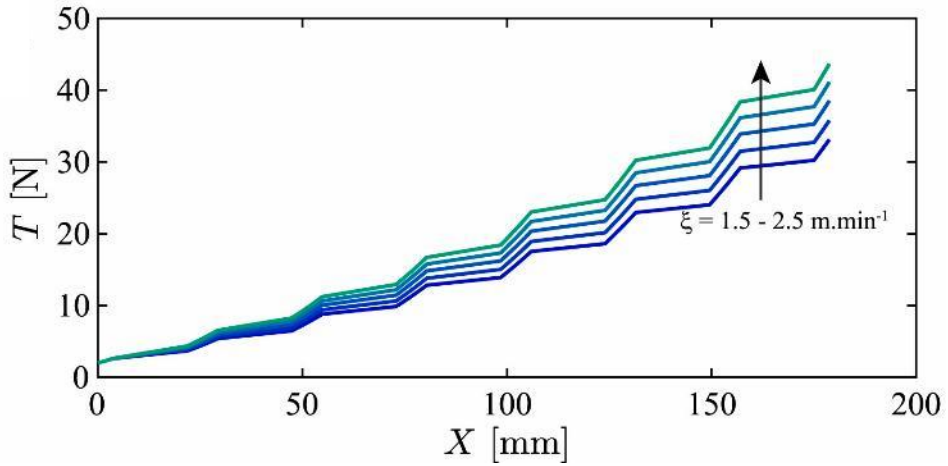


M. Pitto, et al., **"Parametric simulation study of a wavy slot channel thermoplastic melt impregnator for carbon fibre-reinforced prepreg tape production,"** Composites Part A *200* (2026)

Impregnation model results – Towing speed

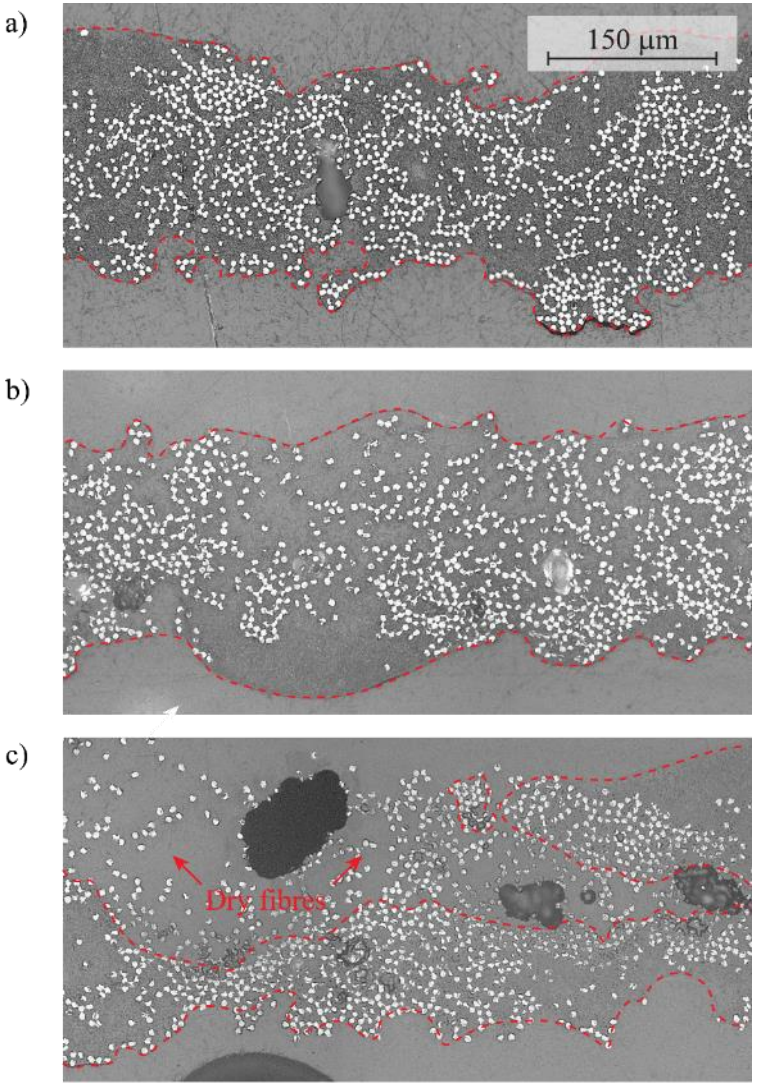


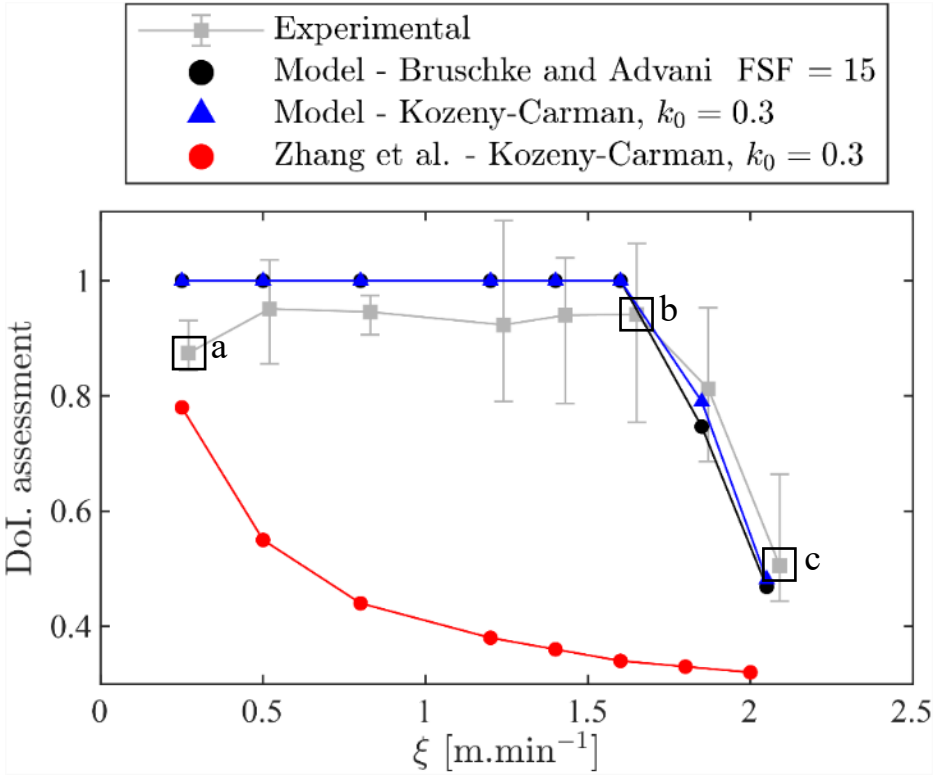




M. Pitto, et al., **"Parametric simulation study of a wavy slot channel thermoplastic melt impregnator for carbon fibre-reinforced prepreg tape production,"** Composites Part A *200* (2026)

Tape quality against pulling speed – Model validation

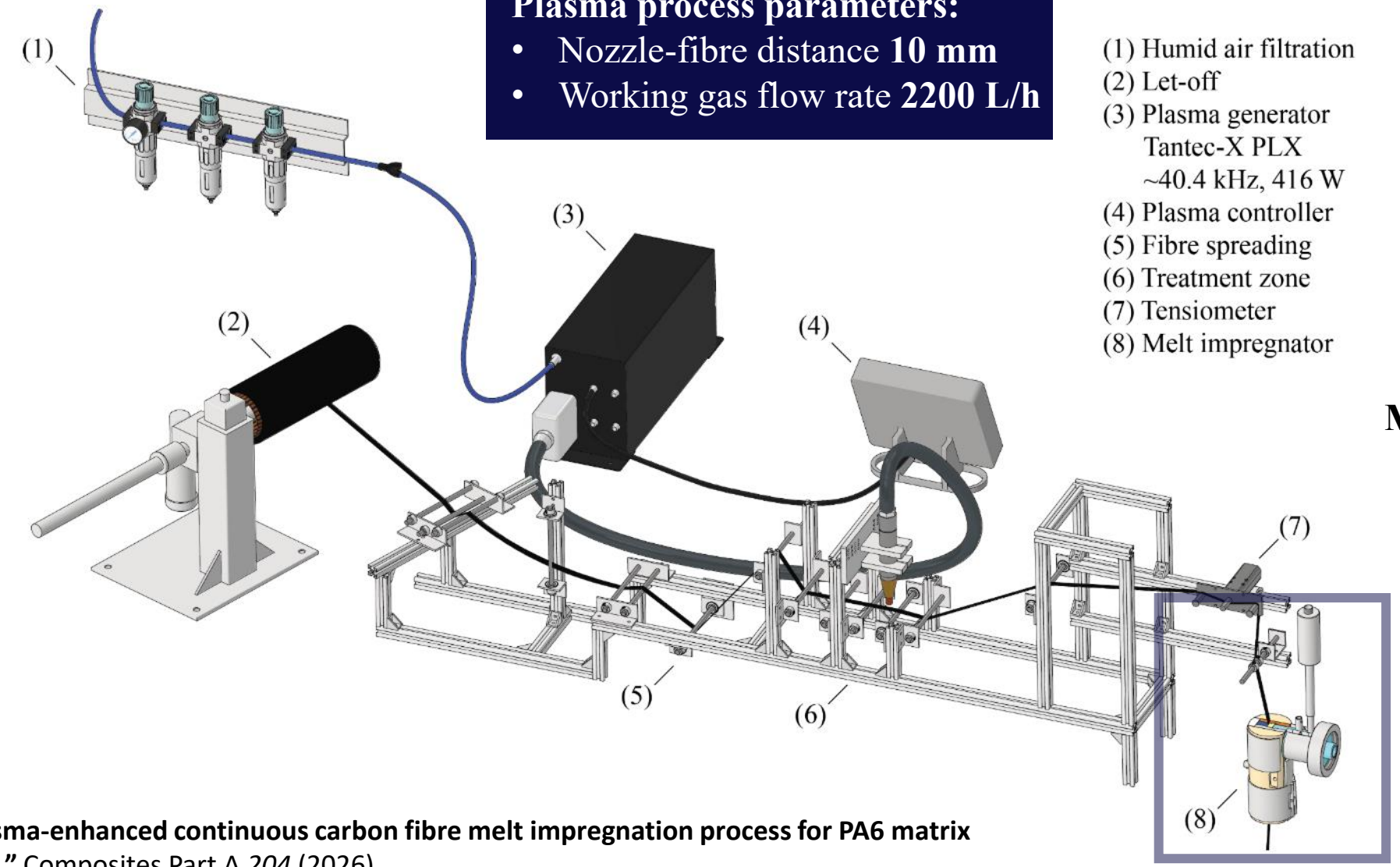




M. Pitto, et al., **"Parametric simulation study of a wavy slot channel thermoplastic melt impregnator for carbon fibre-reinforced prepreg tape production,"** Composites Part A *200* (2026)

Interface tailoring by continuous plasma treatment

Plasma process parameters:
- Nozzle-fibre distance **10 mm**
- Working gas flow rate **2200 L/h**



(1) Humid air filtration
(2) Let-off
(3) Plasma generator
Tantec-X PLX
~40.4 kHz, 416 W
(4) Plasma controller
(5) Fibre spreading
(6) Treatment zone
(7) Tensiometer
(8) Melt impregnator

Melt impregnation

M. Pitto, et al., **"Plasma-enhanced continuous carbon fibre melt impregnation process for PA6 matrix tape manufacturing,"** Composites Part A *204* (2026)

Melt impregnator and pin-driven post consolidation

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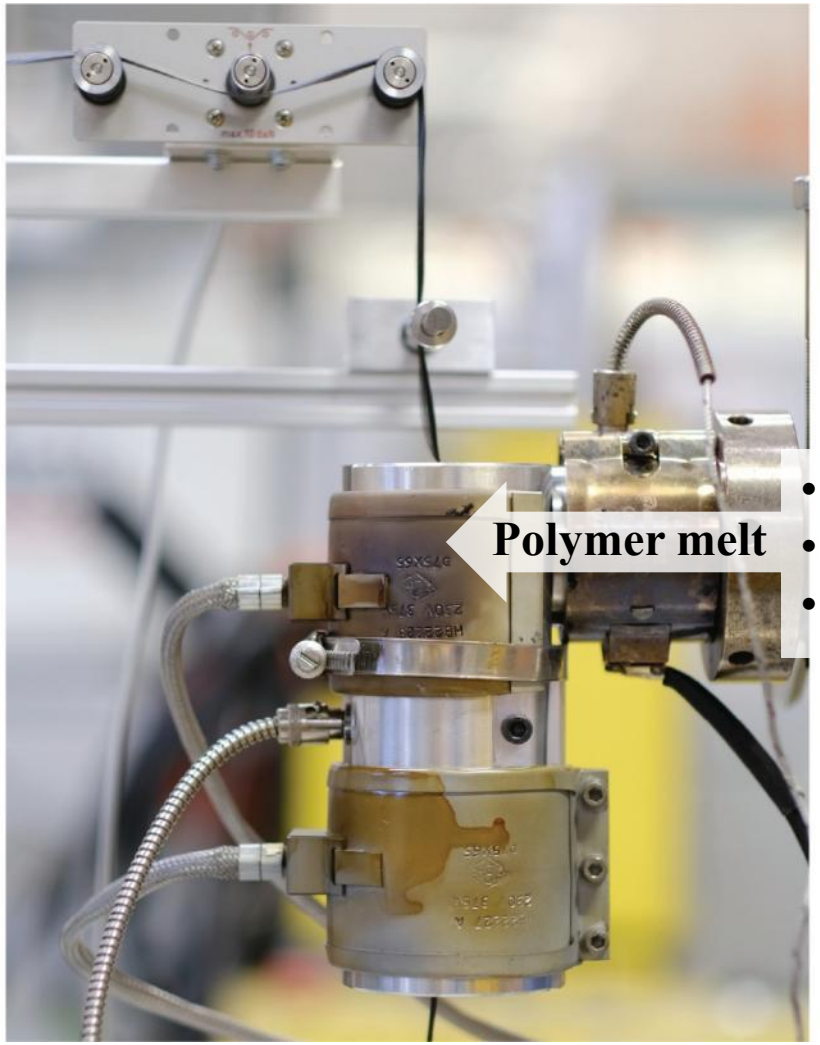
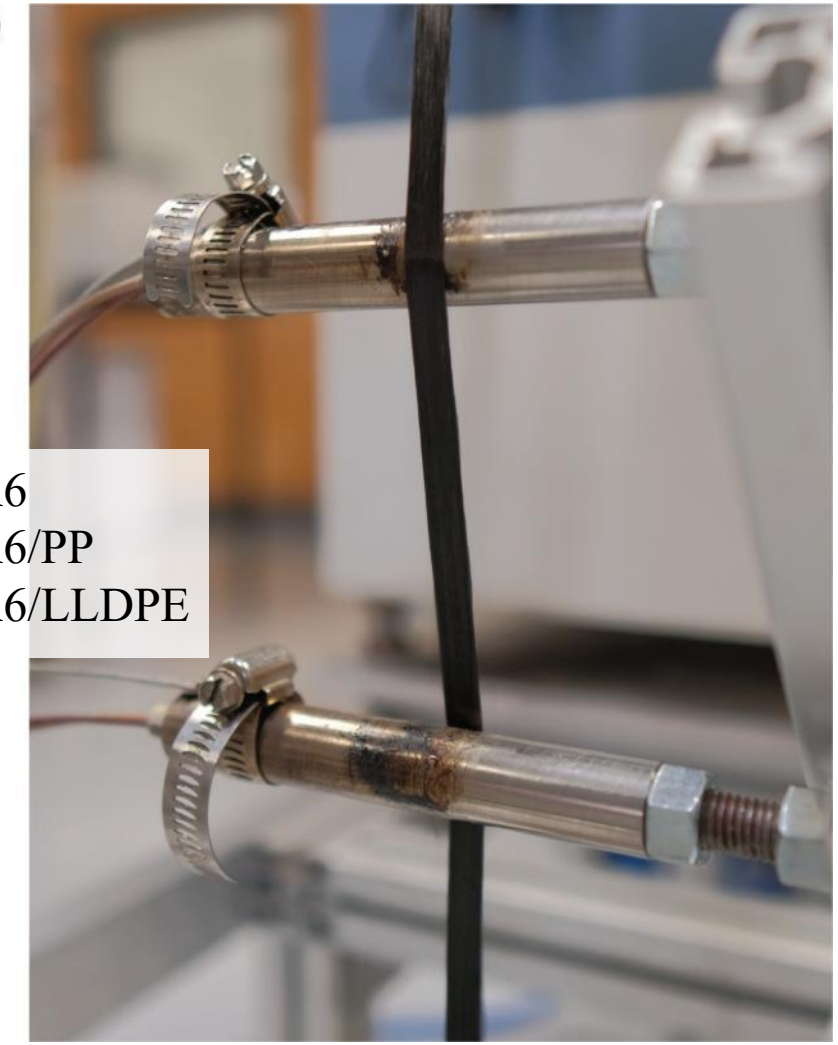
a)



b)



- PA6
- PA6/PP
- PA6/LLDPE

M. Pitto, et al., **"Plasma-enhanced continuous carbon fibre melt impregnation process for PA6 matrix tape manufacturing,"** Composites Part A *204* (2026)

Blended matrix preparation – PA6/PP

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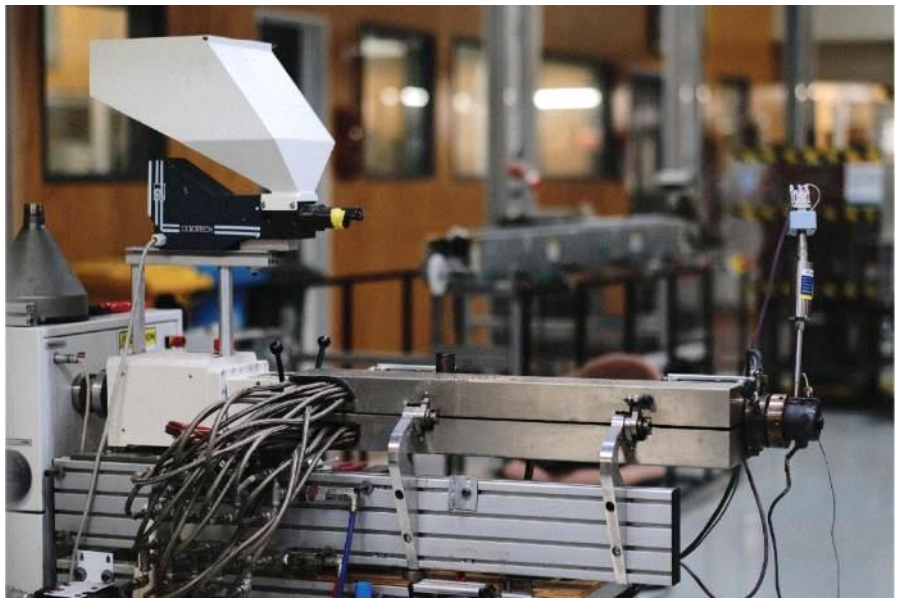
Extrusion $T = 190 – 200 – 210 – 220 – 230 – 240°C$

Virgin PA6 and PP →



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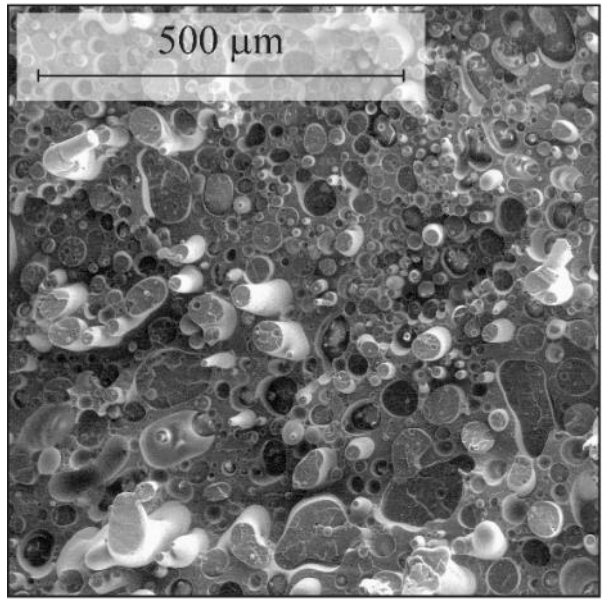
Blended dispersed morphology [1]



[1] J. Ashraf, et al., **"Plasma-Induced Reactive Compatibilization of Polypropylene/Polyamide 6 Blends,"** ACS Applied Polymer Materials (2025).

Blended matrix preparation – rPA6/rLLDPE

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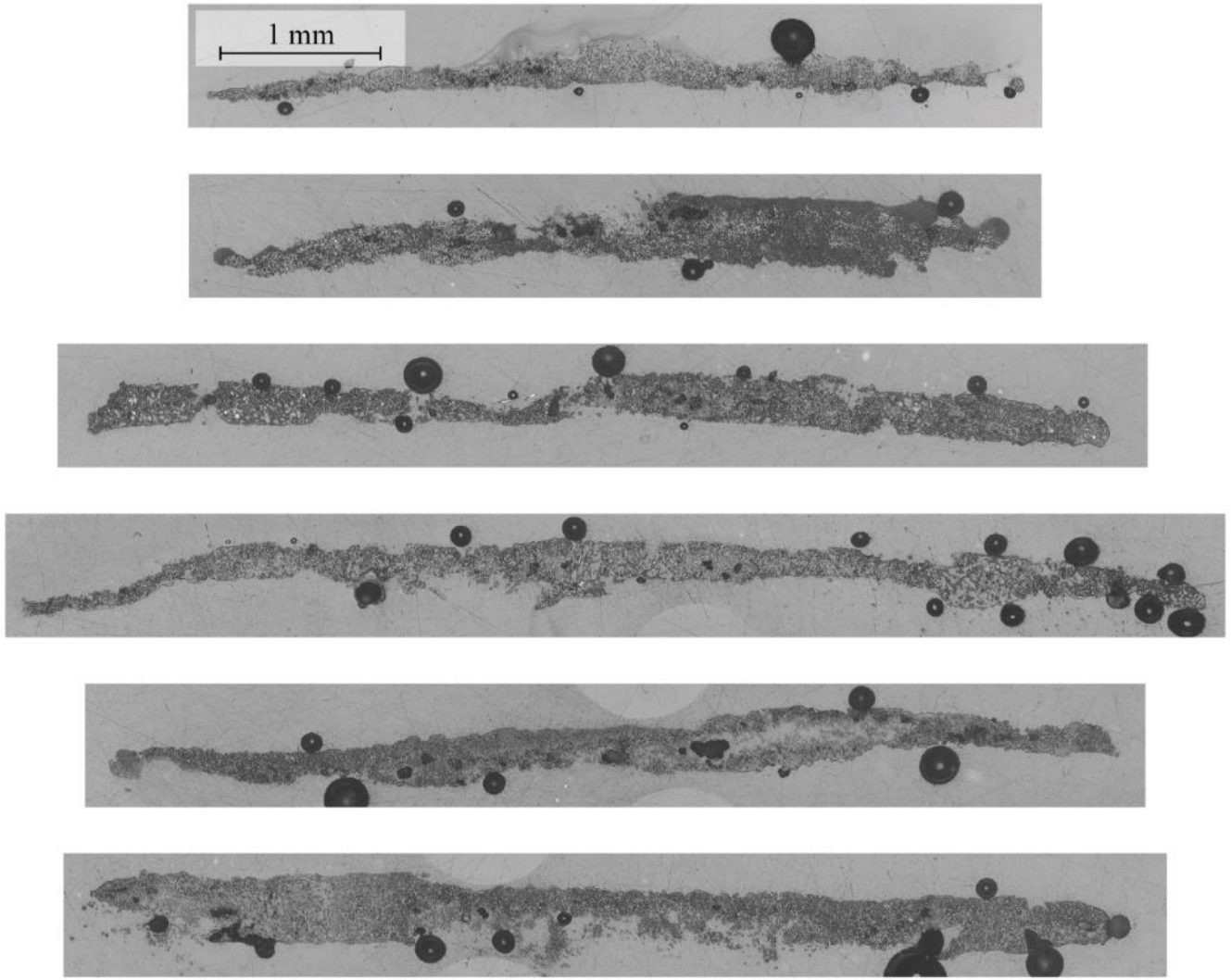
rPA6/rLLDPE waste film

Shredded and dried rPA6/rLLDPE

Tape cross-sectional microscopy – Fibre volume fraction



Sample	Mean v_f
CF/PA6	0.34±0.04
pCF/PA6	0.28 ± 0.09
CF/PA6/PP (50:50 wt.%)	0.32±0.02
pCF/PA6/PP (50:50 wt.%)	0.29±0.06
CF/rPA6/rLLDPE (20:80 wt.%)	0.28±0.07
pCF/rPA6/rLLDPE (20:80 wt.%)	0.26±0.02

Short beam strength – Sample manufacturing – Representative example

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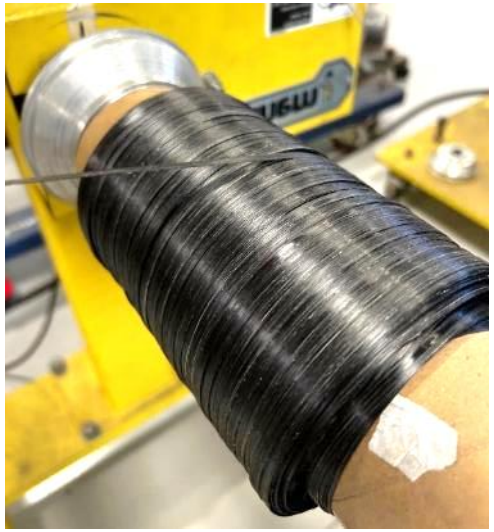
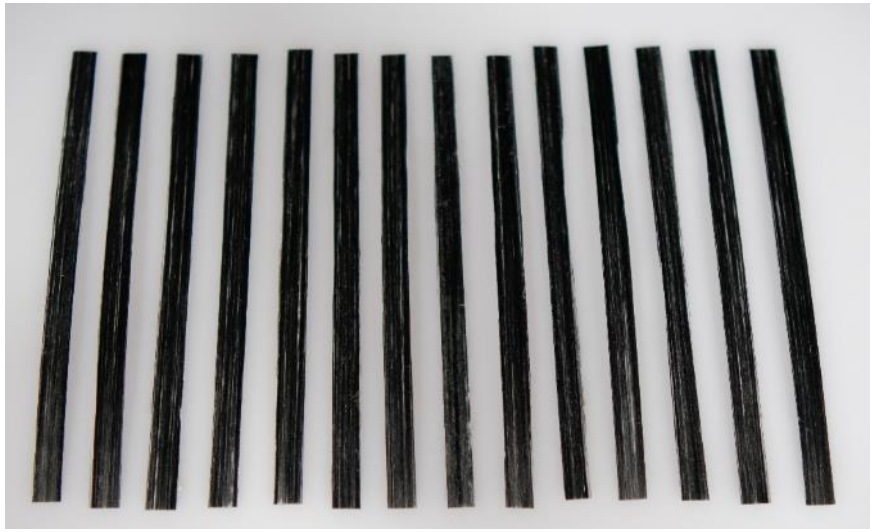
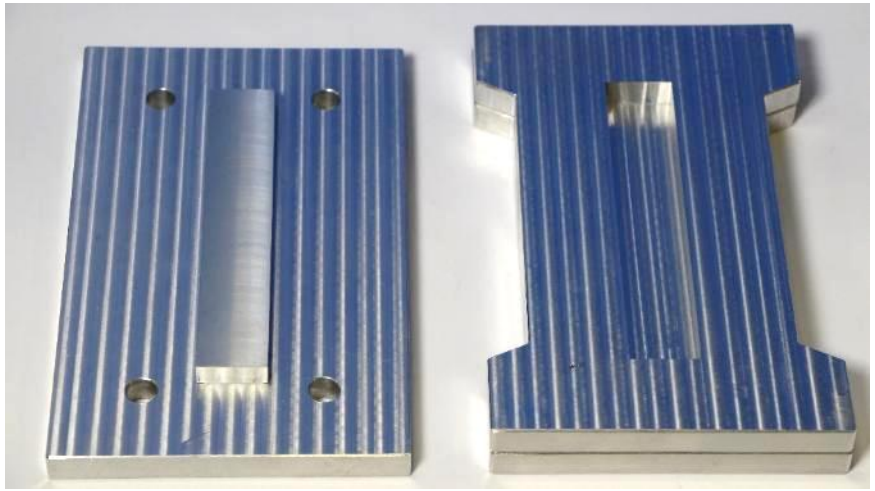
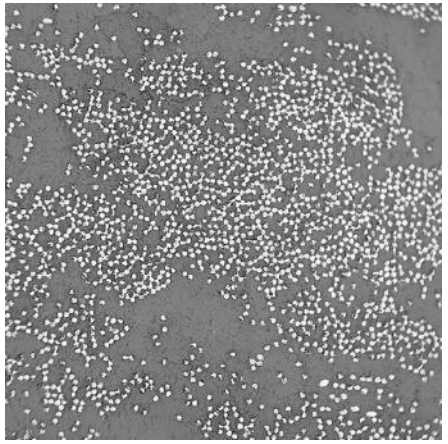


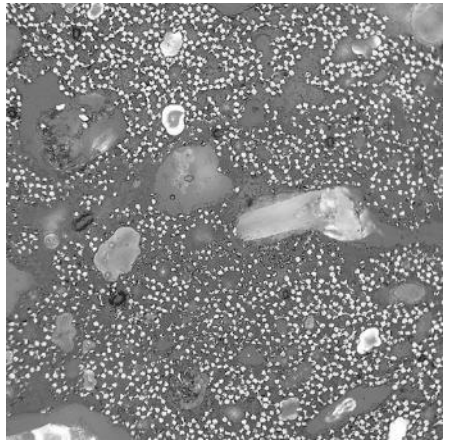




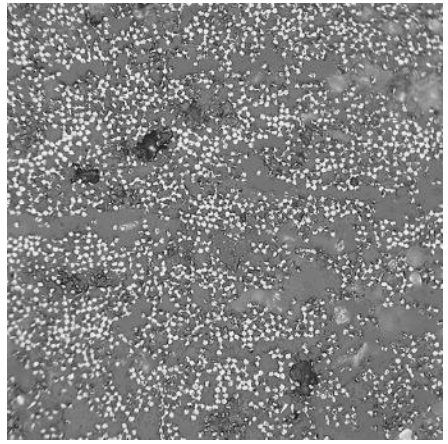
CF/PA6



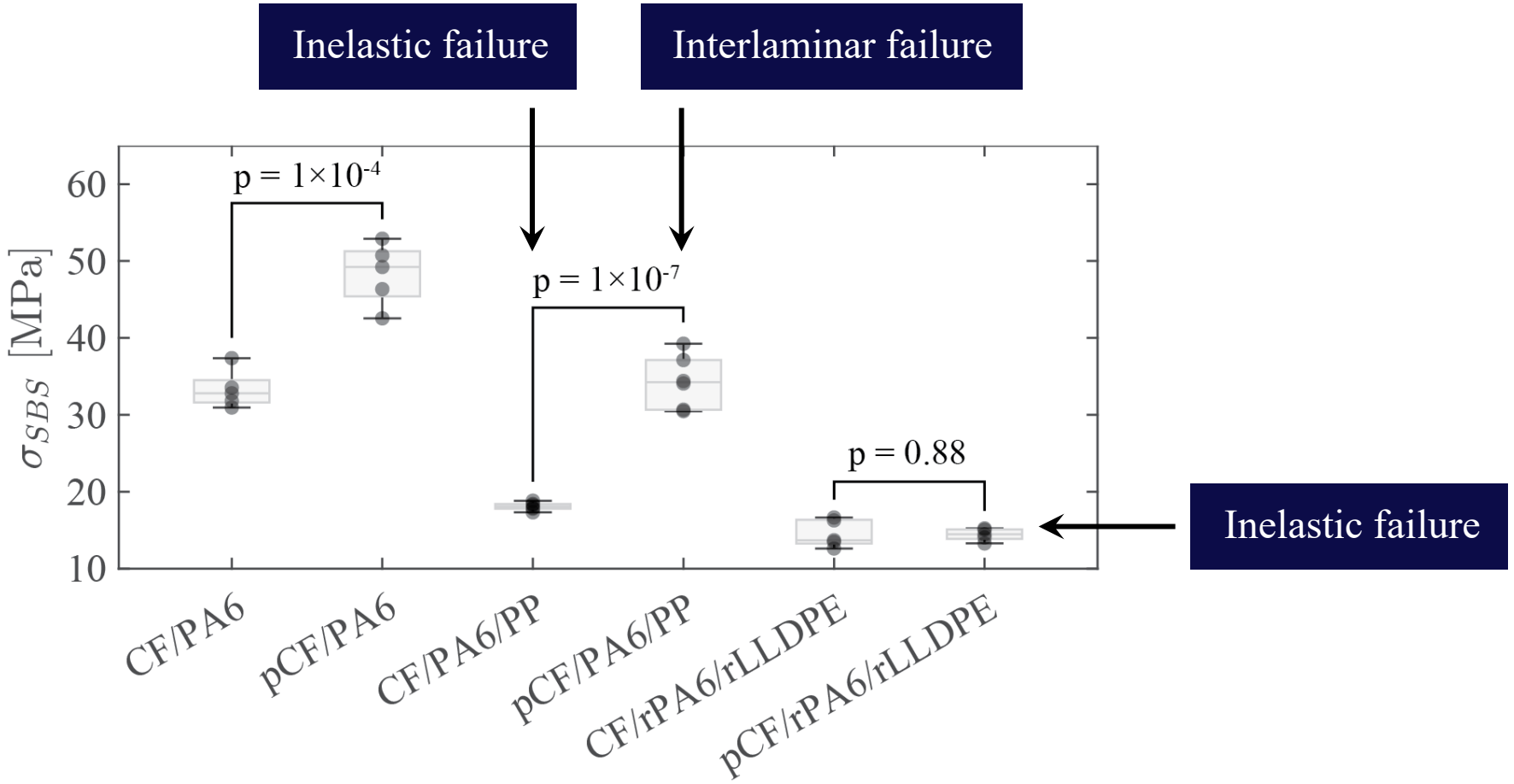
CF/PA6/PP



CF/PA6/LLDPE

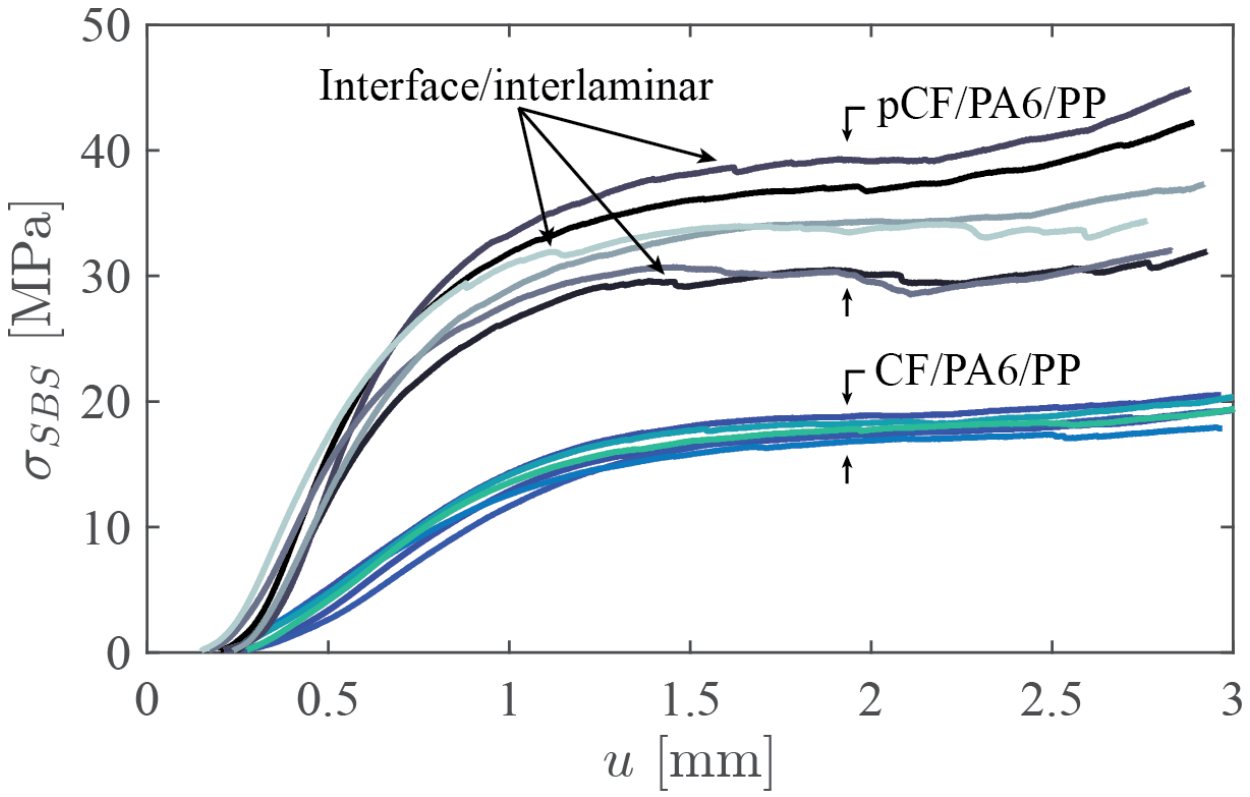


Short beam strength – ASTM D2344



Outcome: 36% oxygen surface content increase significantly enhanced bonding for composites containing significant quantities of the polar PA6.

Short beam strength – ASTM D2344 curves for PA6/PP



Variability potentially caused by pCF surface heterogeneity

No bonding. Matrix dominated

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Automated tape laying and forming techniques

Multilayer
2D tape near-net shape layups

Press Moulding
Thermoforming of 2D blanks into complex 3D parts

SUT tape manufacture and ATL preparations

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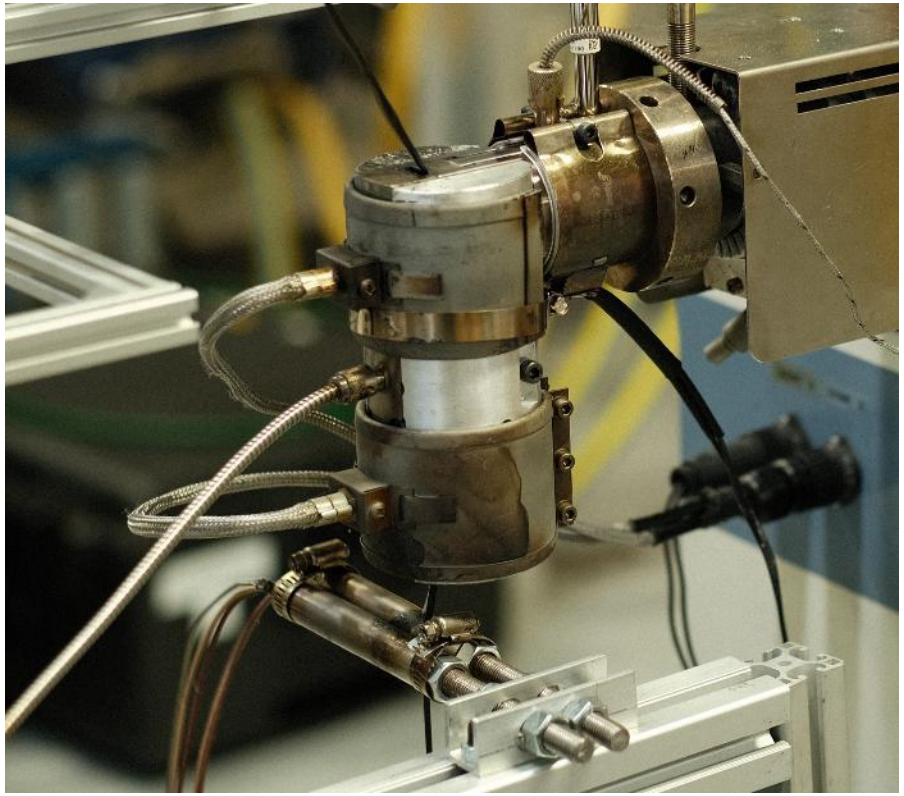
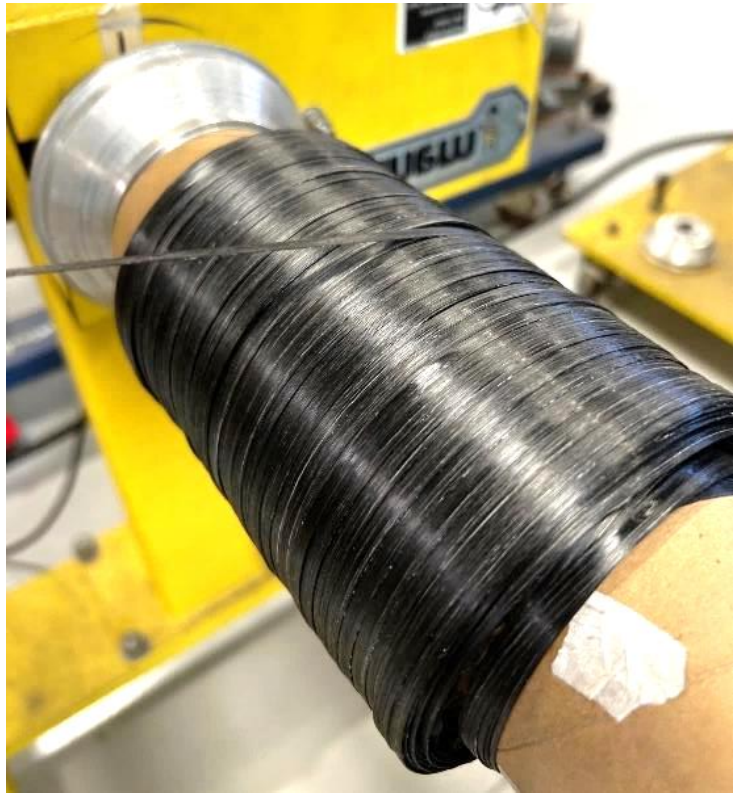
Continuous manufacture of PA6/PP matrix tapes



Tape haul-off on bobbin



Transfer to creel

Modified ATL for quarter-inch PA6/PP tapes

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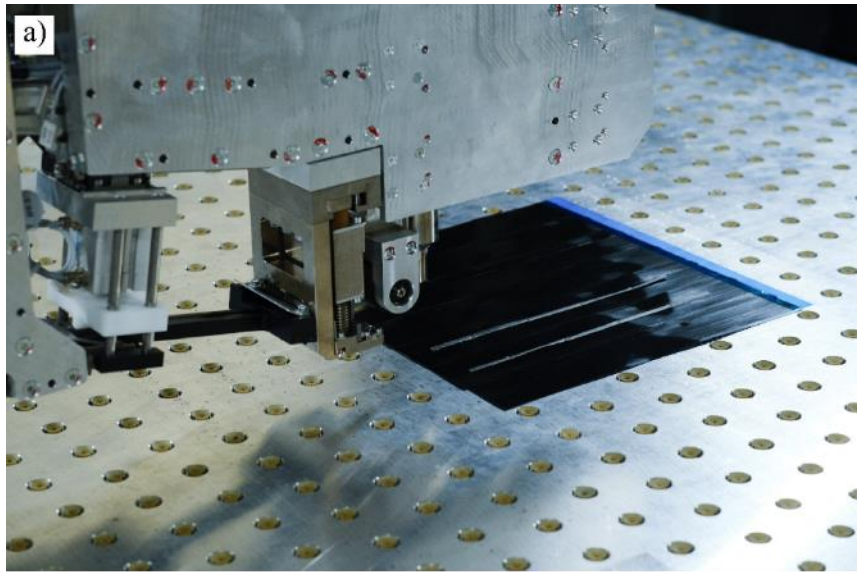

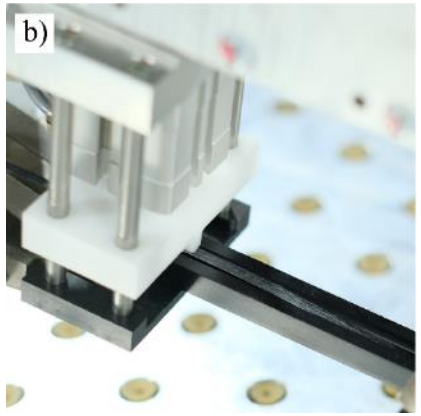

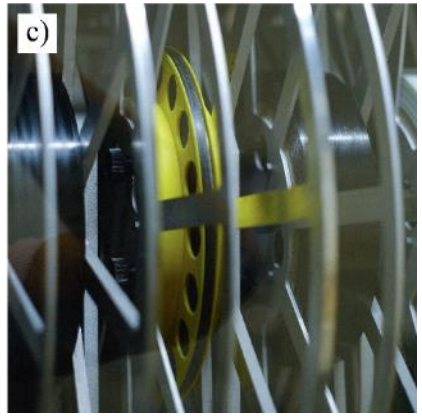

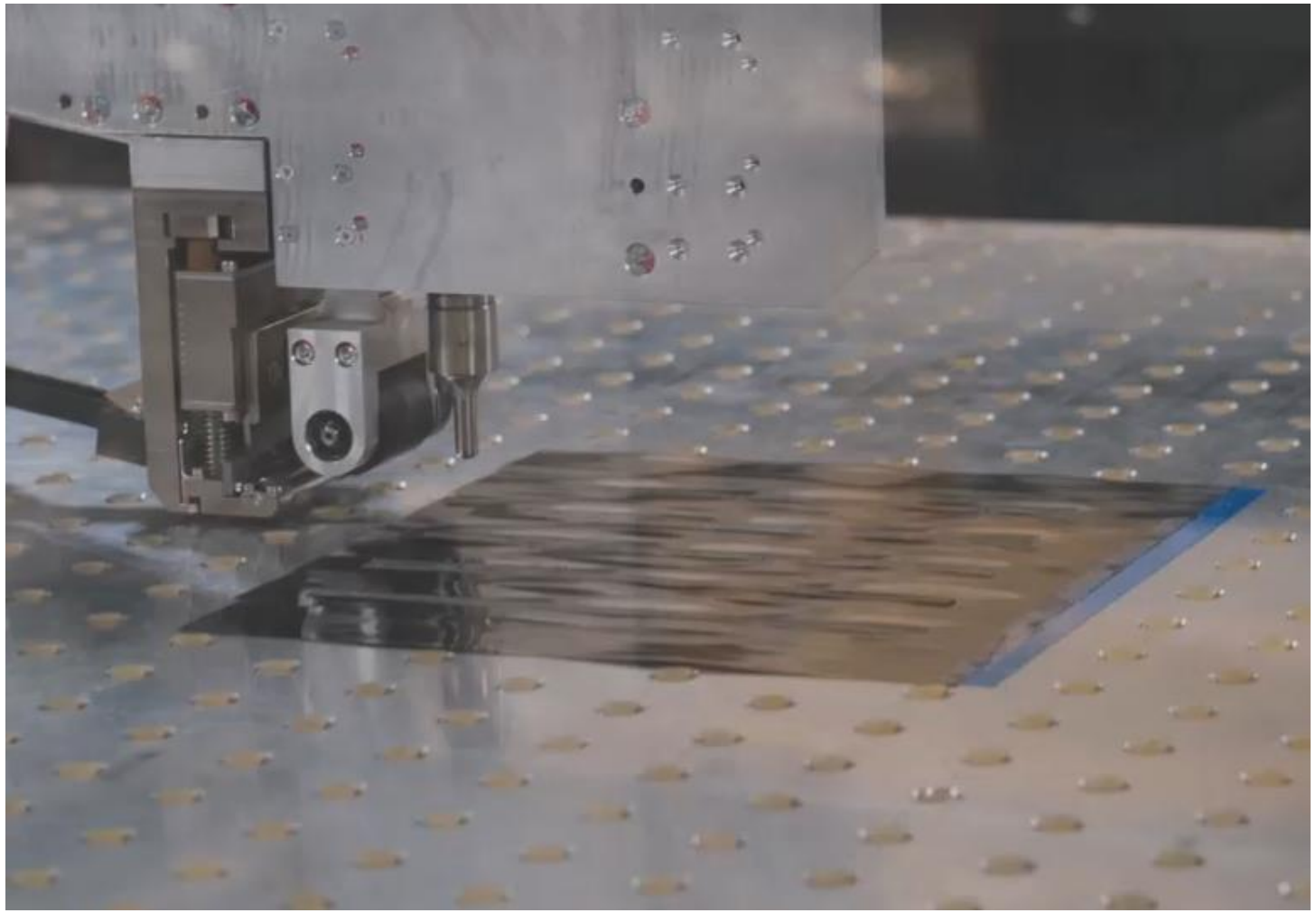

ATL, consolidation, and forming

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Compression moulding (240℃, 30 min, 170 kN)

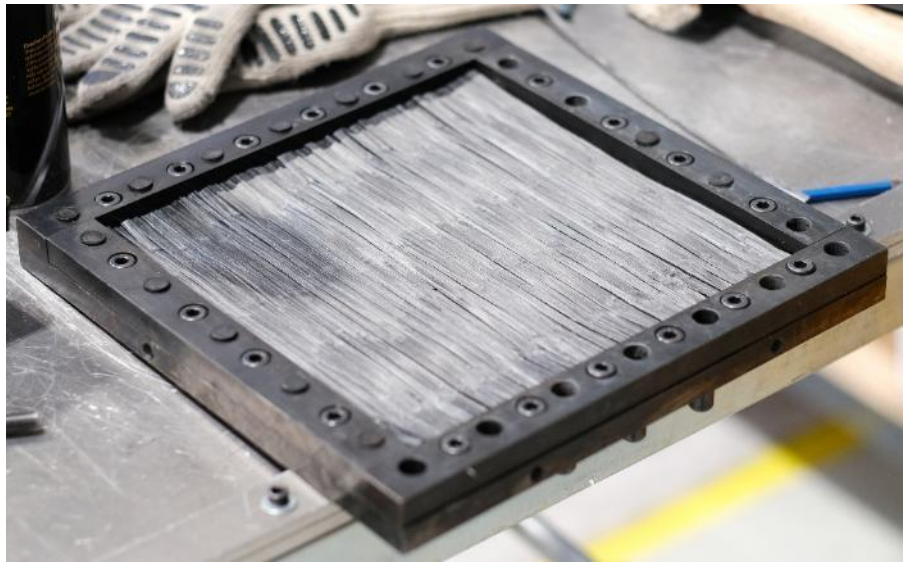
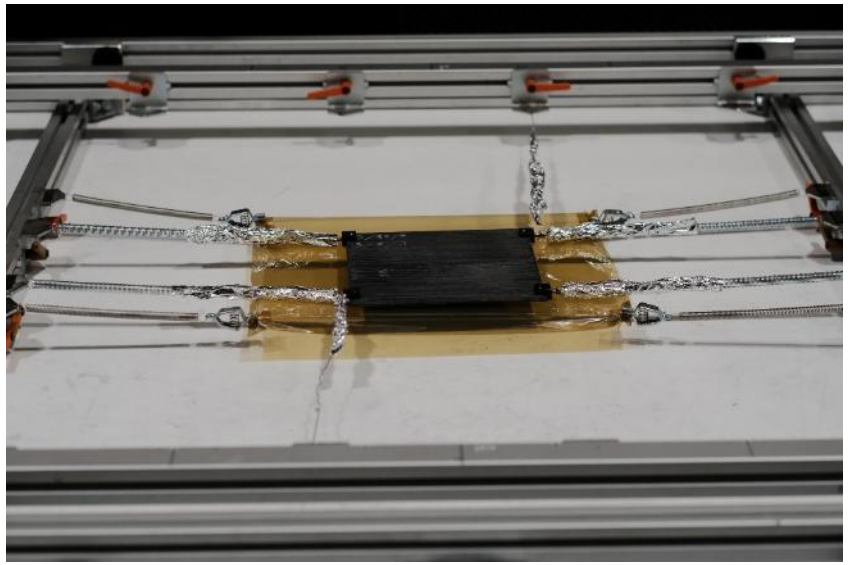
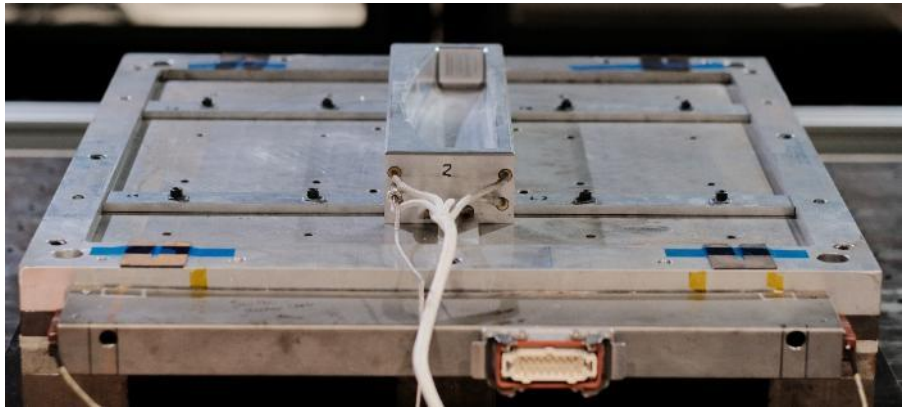


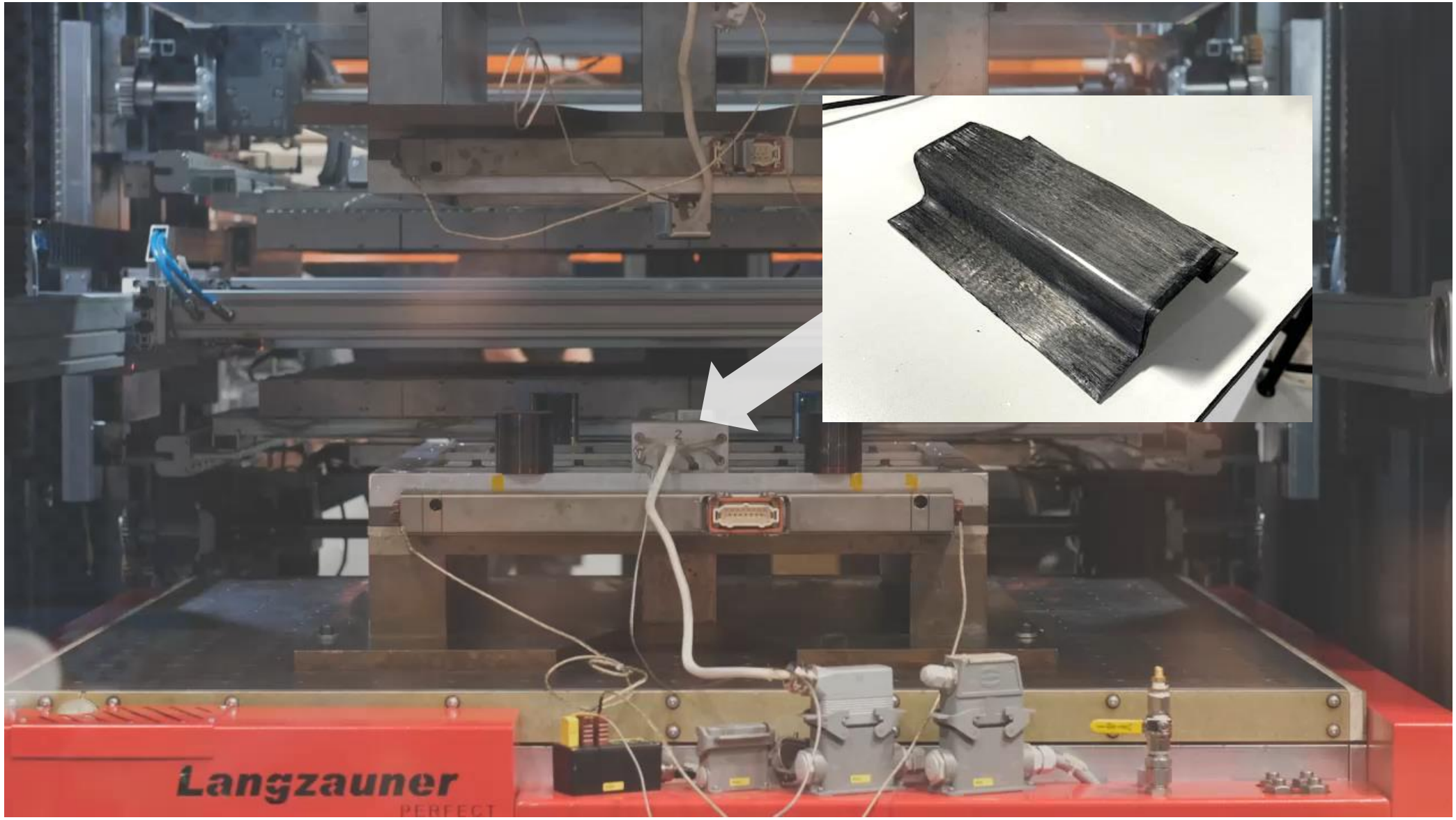
Plate suspension for IR heating (220℃, 60 s)



Thermoforming (200℃, 500 kN)



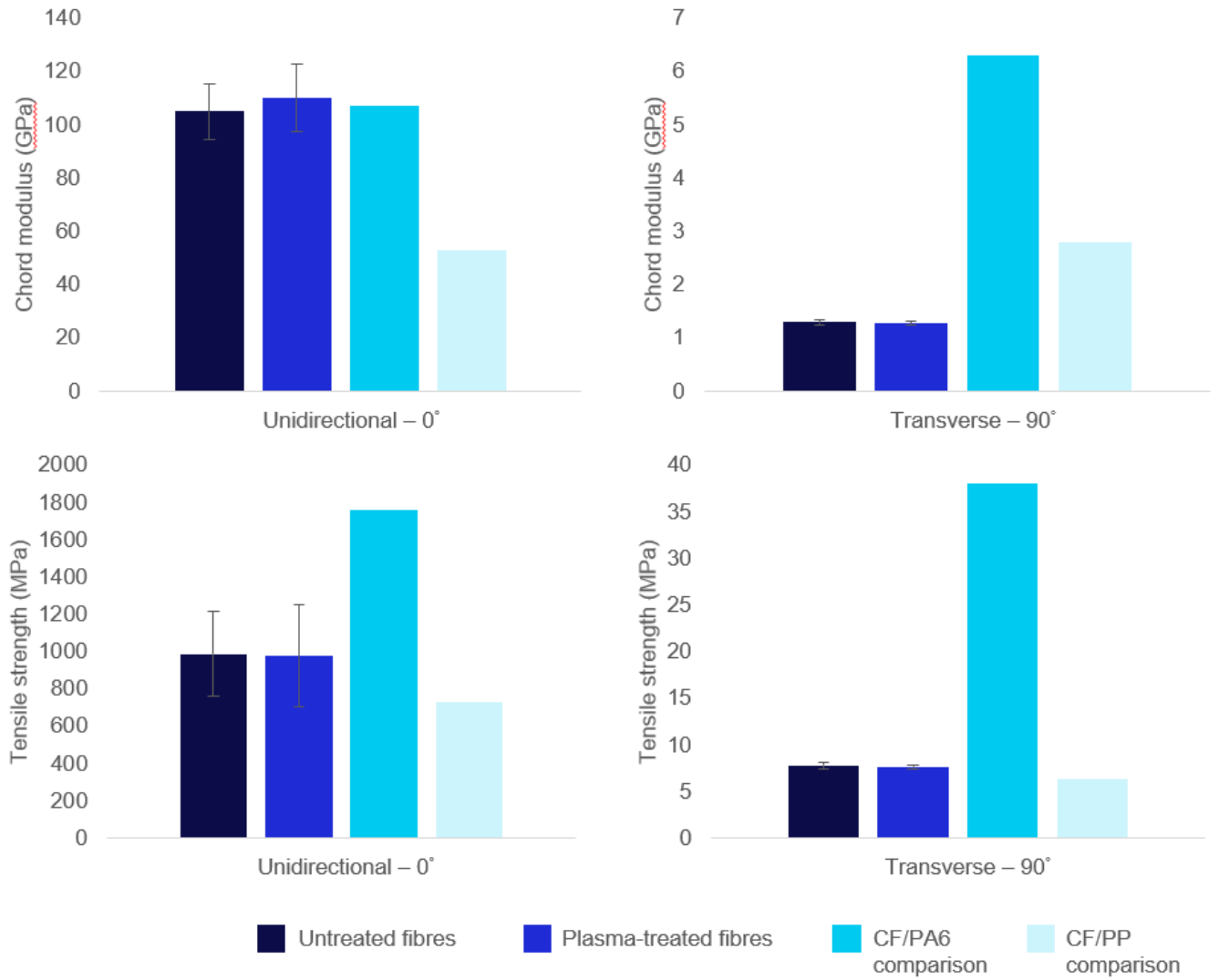
Automatic tape laying, consolidation, and forming



Characterisation – Composite tensile properties

- Tested according to ASTM D3039
- CF-PA6/PP = fibre volume fraction of 45%
- Data compared to CF-PA6 and CF-PP matrix laminates (*Matsuo et al. 2019*)

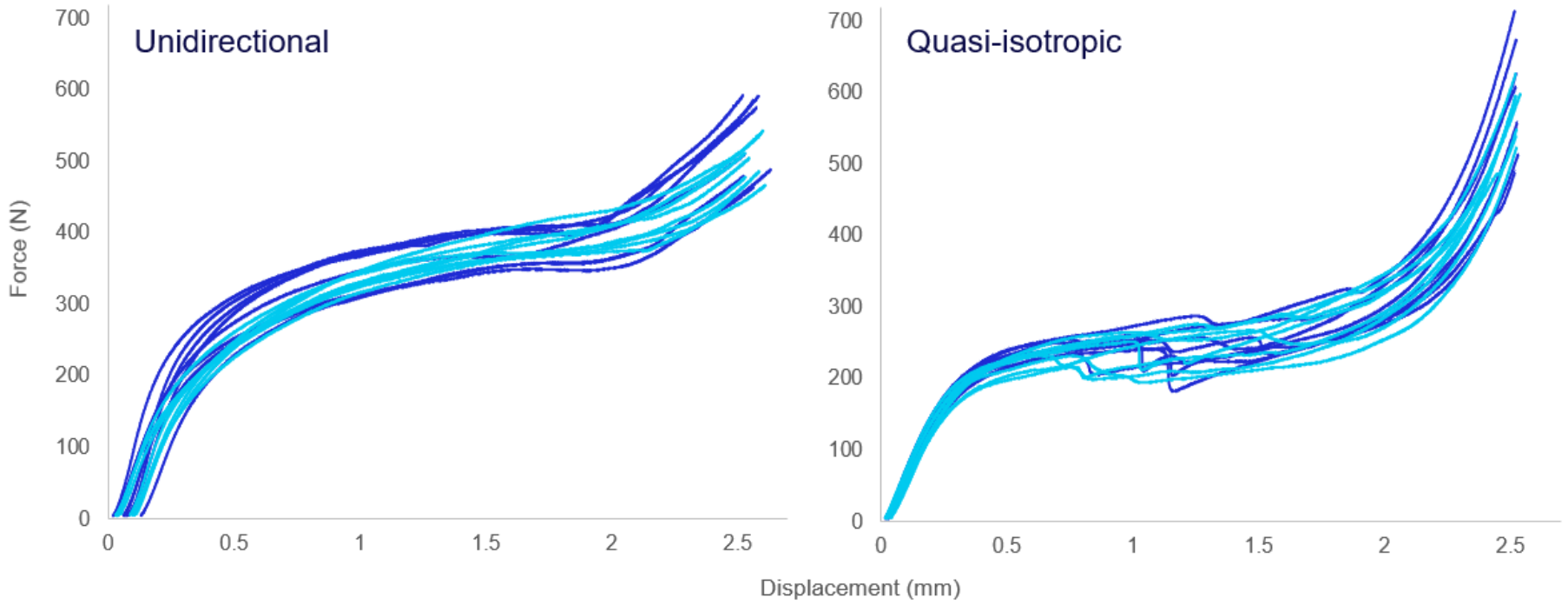
- Invalid failures for unidirectional – 0° specimens, outer matrix layer on coupon slipping in grip relative to reinforcement
  - Changing to hydraulic grips saw no improvement in UTS or modulus values

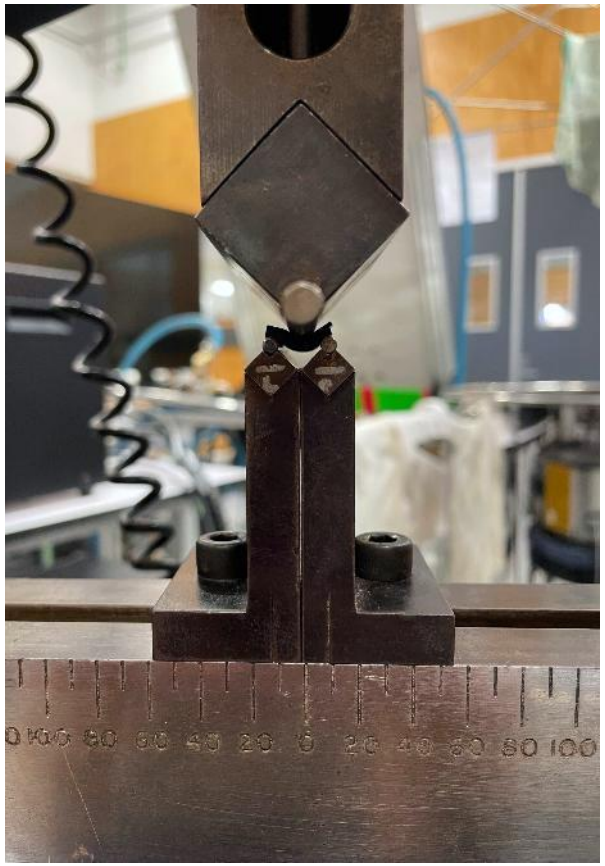


Characterisation – Short beam strength (SBS)

- Unidirectional specimens exhibited invalid inelastic deformation failure
- Multimode failure observed for some quasi-isotropic specimens

- Negligible difference between performance of untreated fibre and plasma-treated fibre specimens = **plasma surface treatment of fibres alone cannot overcome dominance of polymer phase separation effects**





Untreated fibres
Plasma-treated fibres

Characterisation – Microscopy

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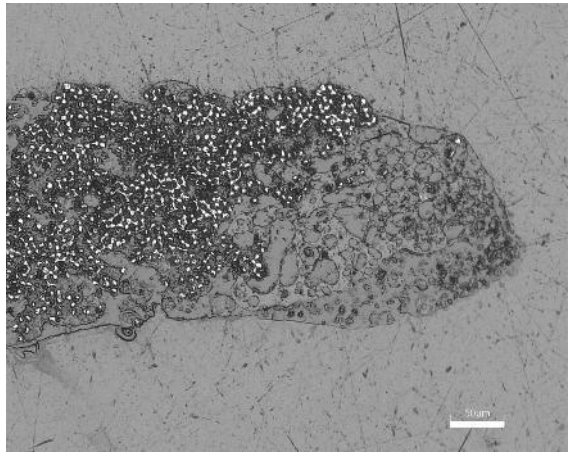
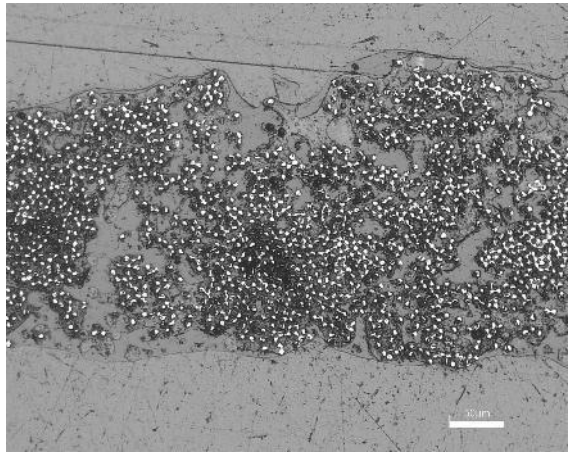
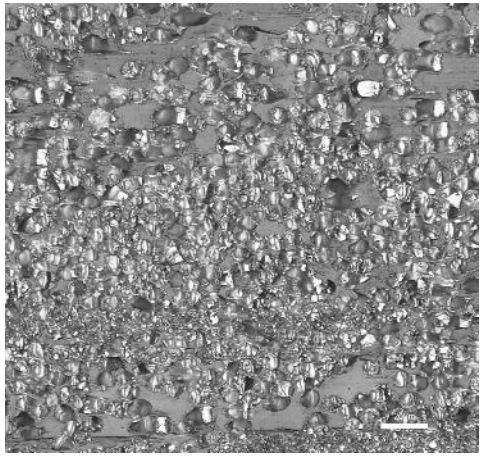
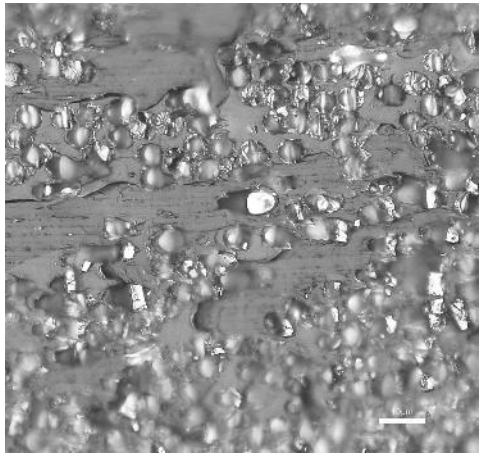
Wet grinding & polishing



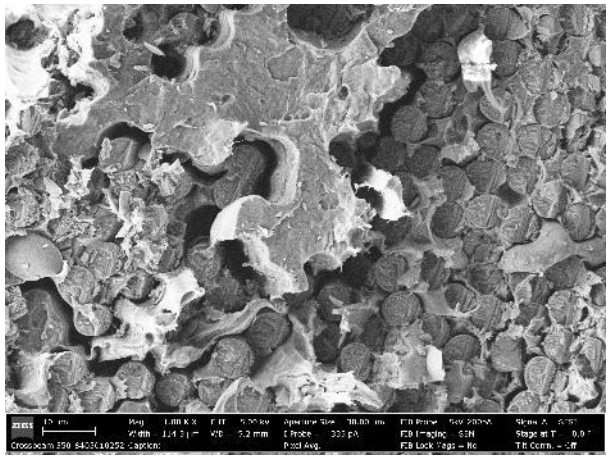


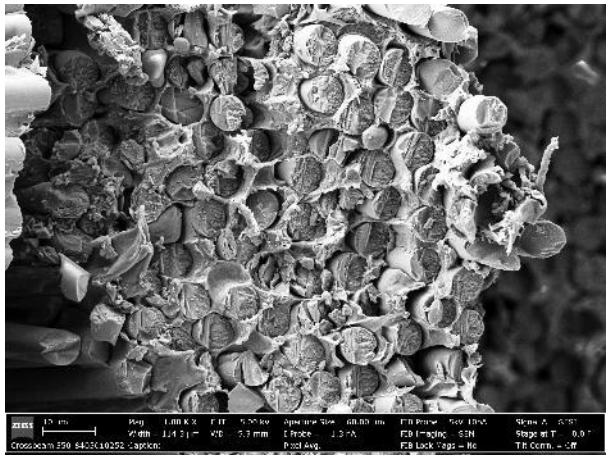
Microtome cutting

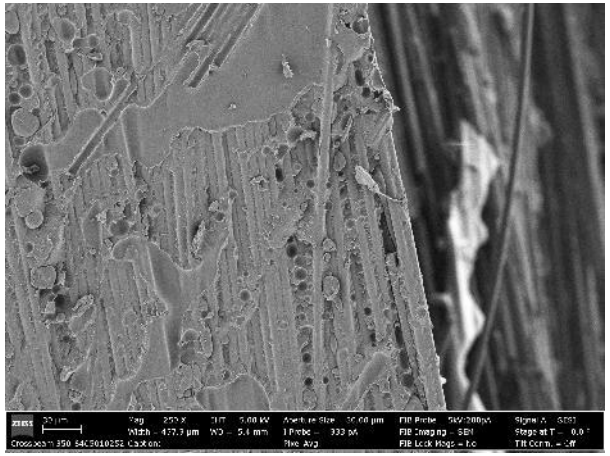




Cryofracture SEM







Conclusions and future outlook

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Conclusions

- Tapes containing primarily PA6 benefited from the carbon fibre surface **O/C ratio increase of 36%** via plasma treatment**.**
- **Mechanical performance enhancement in small scale manufacturing**
  - pCF/PA6 short beam strength up 45.2%
  - pCF/PA6/PP (50:50 wt.%) short beam strength up 89.8%
- pCF/PA6/PP (50:50 wt.%) **tapes successfully laid up by ATL**, and subsequently **thermoformed into a demonstrator part**.
- Mechanical/quality characterisation of plates continues, and lack of SBS enhancement by plasma treatment being explored.

Future outlook

- Further development of composites using recycled blends, and expansion of blend matrix types.
- Deeper studies of tape layup and welding, and laminate formability.

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ACKNOWLEDGEMENTS

This work is supported by the Ministry of Business, Innovation and Employment endeavour program ID: UOAX2212 ‘Shaping a circular market system for plastics in New Zealand’ and by the New Zealand Synchrotron Group Capability Development grant. M. Pitto and O. Gordon have been funded by the University of Auckland Doctoral Scholarships.

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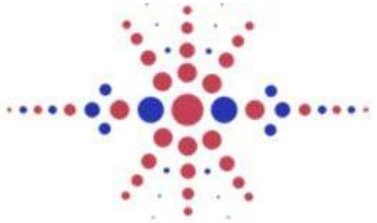

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