Investigation of Pultrusion Die Dynamics using a Novel Rotating Core Method

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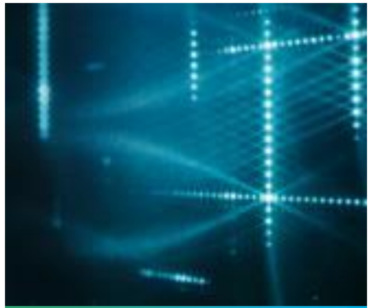

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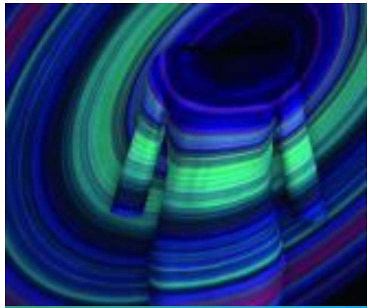
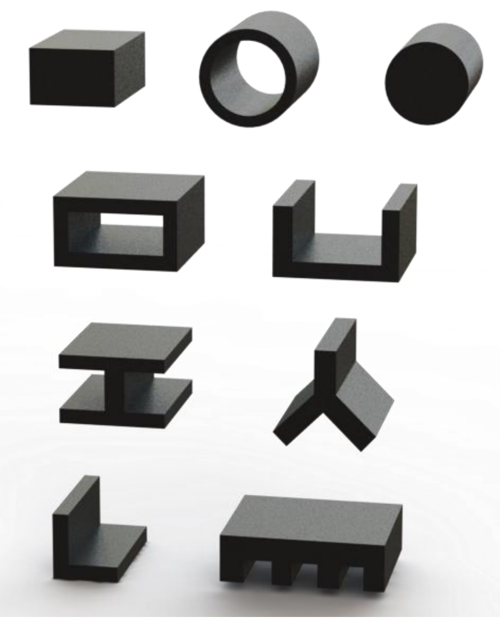


Textile 4.0

Outline

1. Background and motivation
2. State-of-the-art methodologies
3. Novel rotating core method
4. Parametric investigations
5. Validation of rotating core method
6. Summary

Composites for high performance applications



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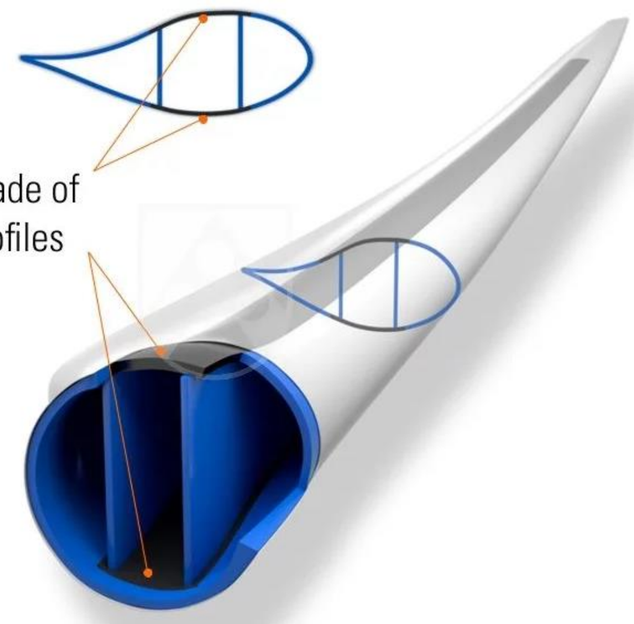
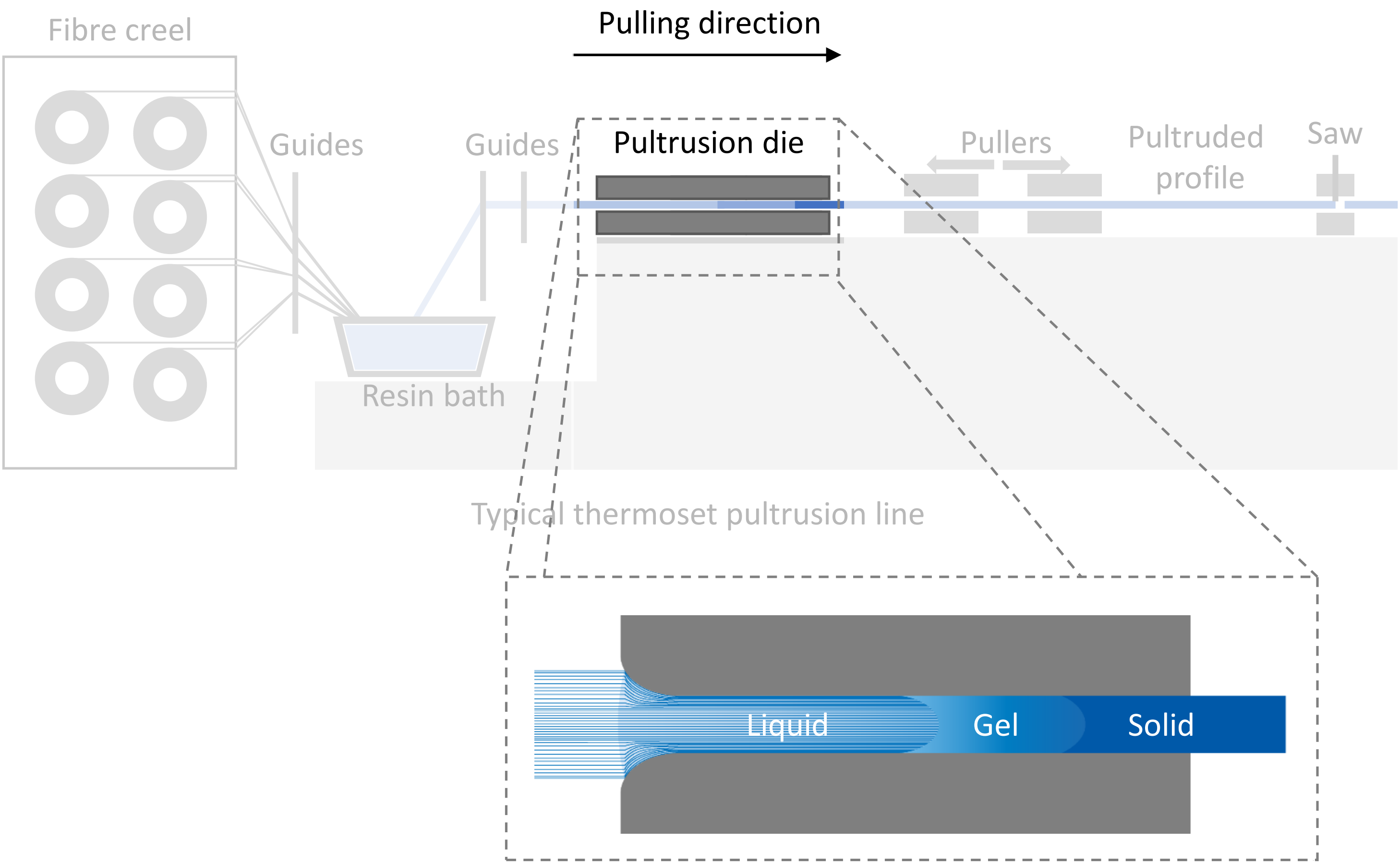
2



[1] 5M s.r.o https://www.5m.cz/en/products/kompozitni-profily [Accessed: 30.11.2020]
[2] Röchling SE & Co. KG https://www.roechling-industrial.com/industries/renewable-energies/wind-energy/materials-for-wind-turbine-blades/spar-caps-for-wind-turbines [Accessed: 30.11.2020]

Pultrusion process



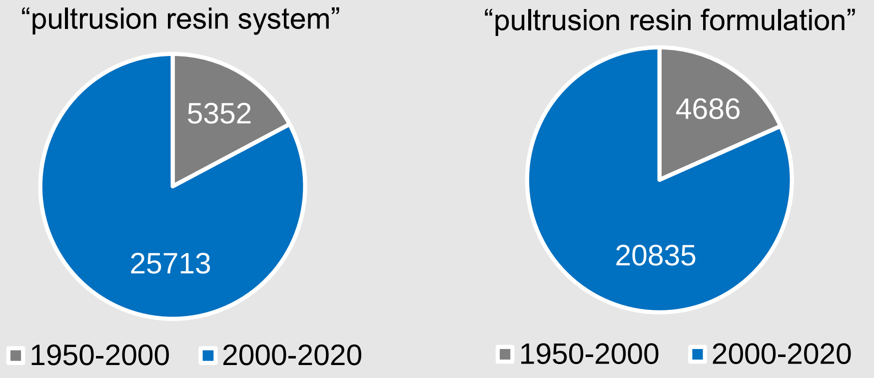
"Heart of pultrusion"

Influencing parameters

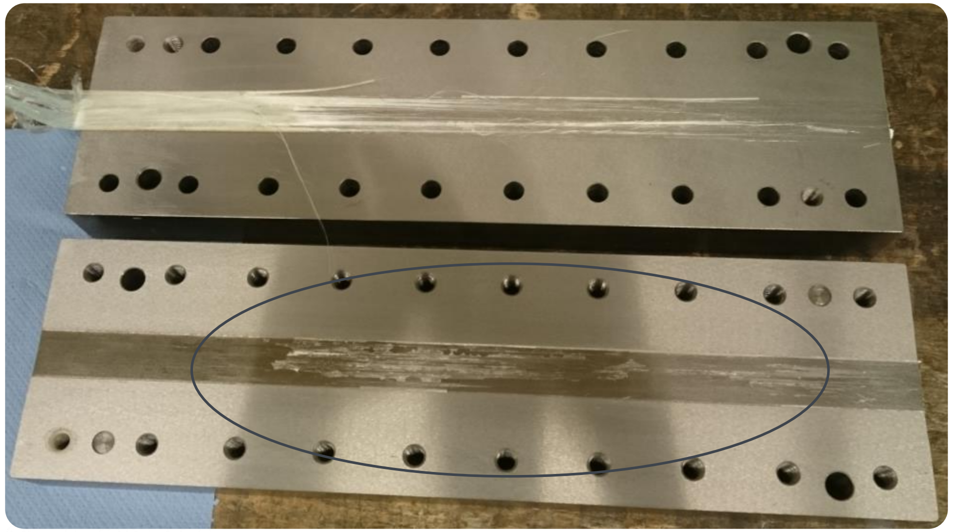
Material
- Reinforcement type
- Fibre volume fraction
- Matrix system
- Functional additives
- Process additives

Process
- Temperature profile
- Pulling speed
- Profile geometry

Motivation



*Google patent search [Status:01.12.2020]



Incompatible parameter selection:

- Under cured profile or degraded matrix
- Mould sticking and fouling
- Tensile failure of profile → uneconomical

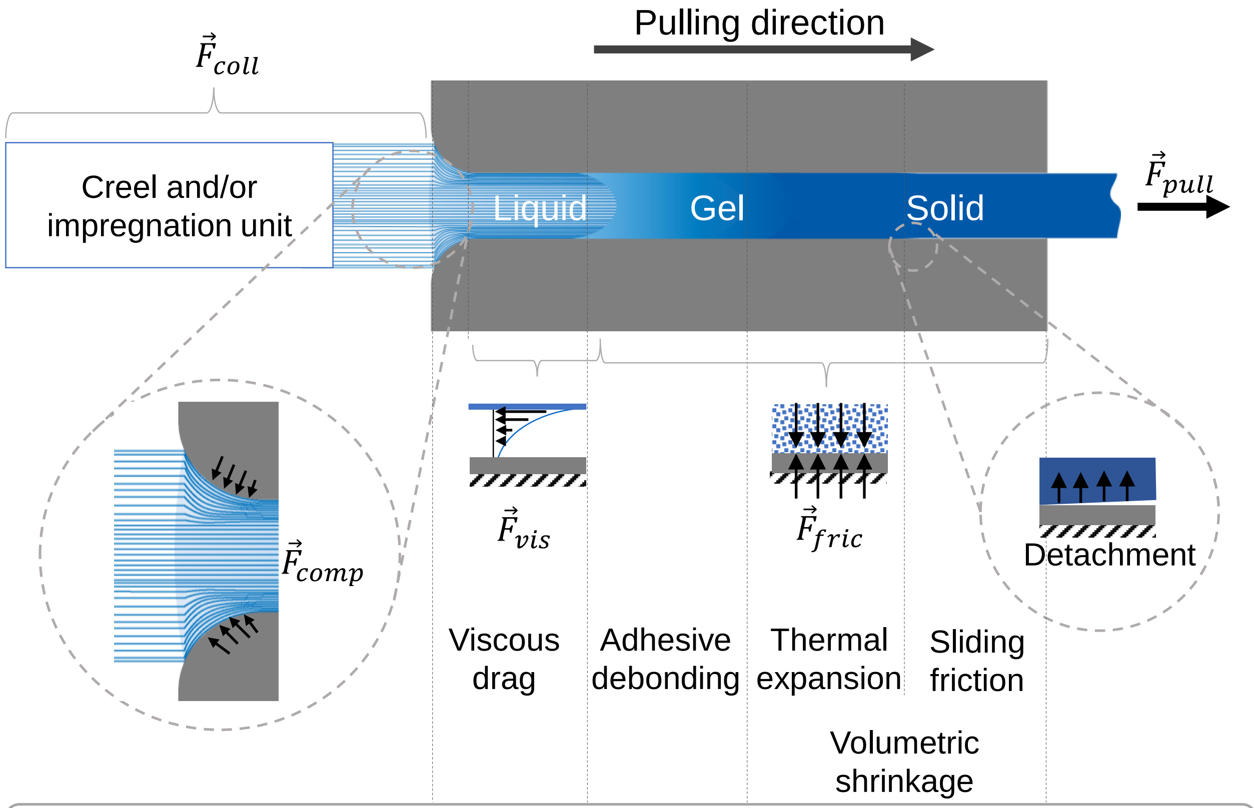
Extensive pultrusion trials required for:

- Process parameter determination
- Material selection (e.g. Internal Mould Release)
- Die (tool/mould) design

Understanding die dynamics is vital

No standardised investigative methods available

Die dynamics in pultrusion



$$\vec{F}_{pull} = \vec{F}_{coll} + \vec{F}_{comp} + \vec{F}_{vis} + \vec{F}_{fric}$$

<u>Pulling force</u>

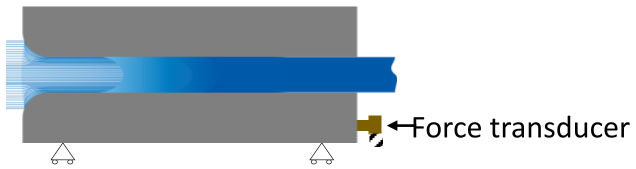
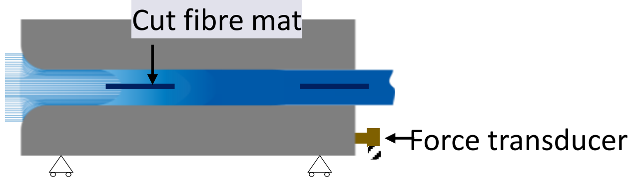
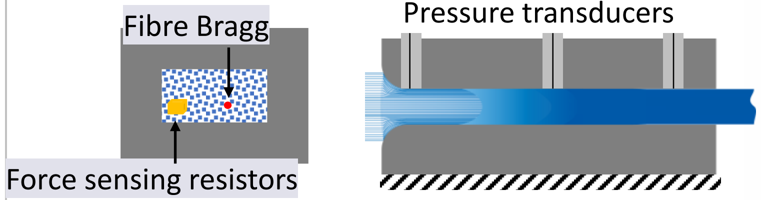
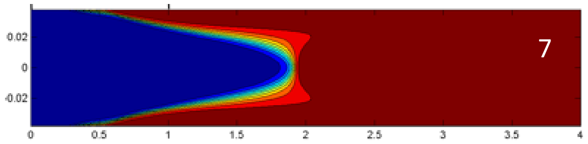
a measure of die dynamics

Pre-die
- Reinforcement tension
- Guide element friction
- Impregnation unit friction

Within the die
- Compaction
- Viscous drag
- Thermal expansion
- Adhesion
- Friction

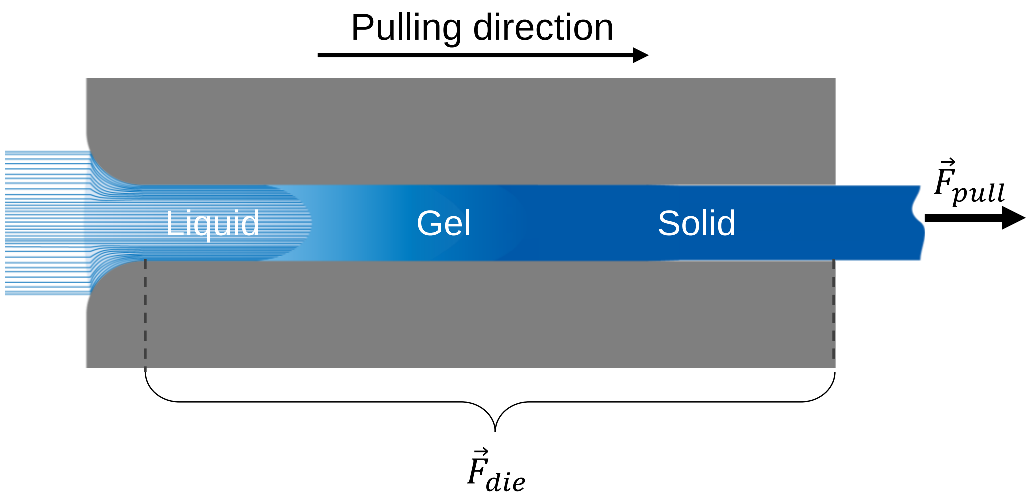
H.L.J. Price, Curing and Flow of Thermosetting Resins for Composite Material Pultrusion, Old Dominion University, 1979.

State-of-the-art methods to quantify the resistive forces

	Method	Schematic representation	Issues
Experimental methods	I On-die force measurement [1]		▪ Do not quantify the individual components of the total force
	II Mat tracer [2]		▪ Susceptible to errors caused by increased (local) reinforcement volume
	III In-die measurement techniques [3-5]		▪ Sophisticated, cost intensive and needs mathematical interpolation
	IV Numerical modelling [6]		▪ Demands vast experimental data ▪ No full-scale validation methods available

[1] D. Srinivasagupta et al, Compos. Part A Appl. Sci. Manuf. 34 (2003) 835–846.
[2] S. Li et al, J. Compos. Mater. 37 (2003) 163–189
[3] D. Sharma, T.A. McCarty, J.A. Roux, J.G. Vaughan, Polym. Compos. 19 (1998) 180–192.
[4] J. Fanucci et al, Int. SAMPE Symp. Exhib. 35 Th, Anaheim, CA, 1990: pp. 1205–1219
[5] A.L. Kalamkarov et al, Compos. Part B Eng. 30 (1999) 167–175.
[6] A.A. Safonov, P. Carlone, I. Akhatov, Compos. Struct. 184 (2018) 153–177.
[7] https://www.datadvance.net/assets/files/media/news/2016/pultrusion-3.gif [Accessed: 27.01.2020]

Research question



F_{die} → Forces that arise in the straight segment within the pultrusion die

$$\vec{F}_{pull} = \vec{F}_{coll} + \vec{F}_{comp} + \vec{F}_{vis} + \vec{F}_{fric}$$

How to quantify the forces that arise along the length of a pultrusion die and hence quantify the die dynamics of a pultrusion process?

Research gaps to be addressed:

- Comprehensive and continuous force data
- Effectiveness of additives (e.g. IMR)
- Pre-determine process variables

Approach

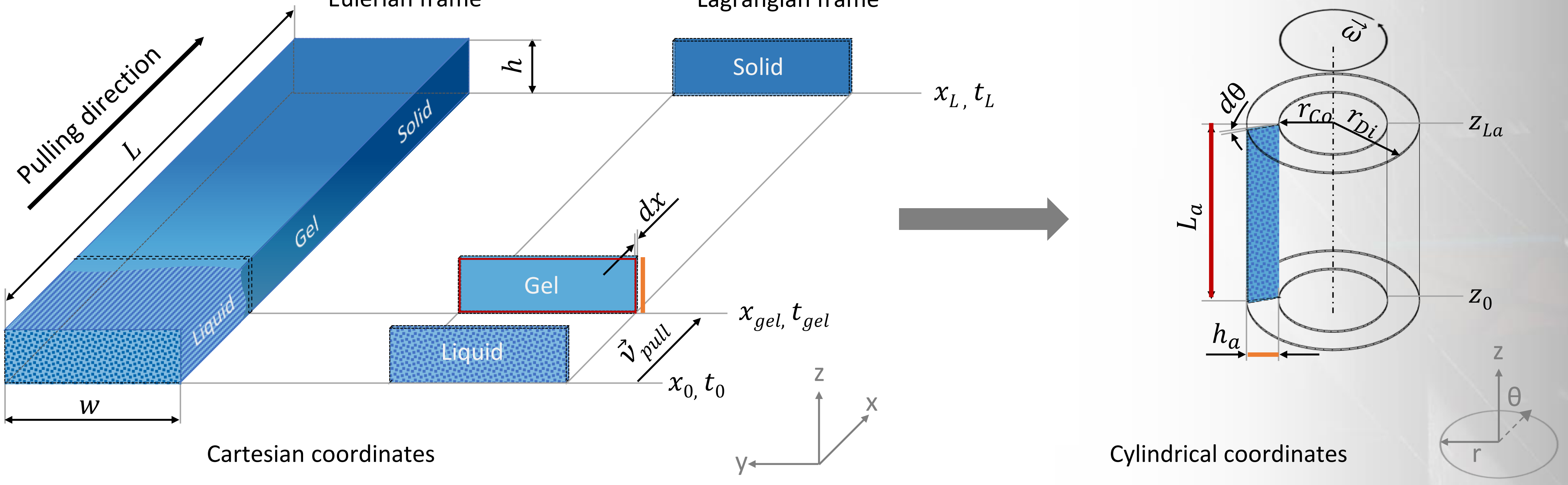
Rotating core method development → Parametric investigations

↓ ↓

Rotating core method validation using pultrusion ← Die dynamics model development

Novel rotating core method

Transformation of linear system to rotational system

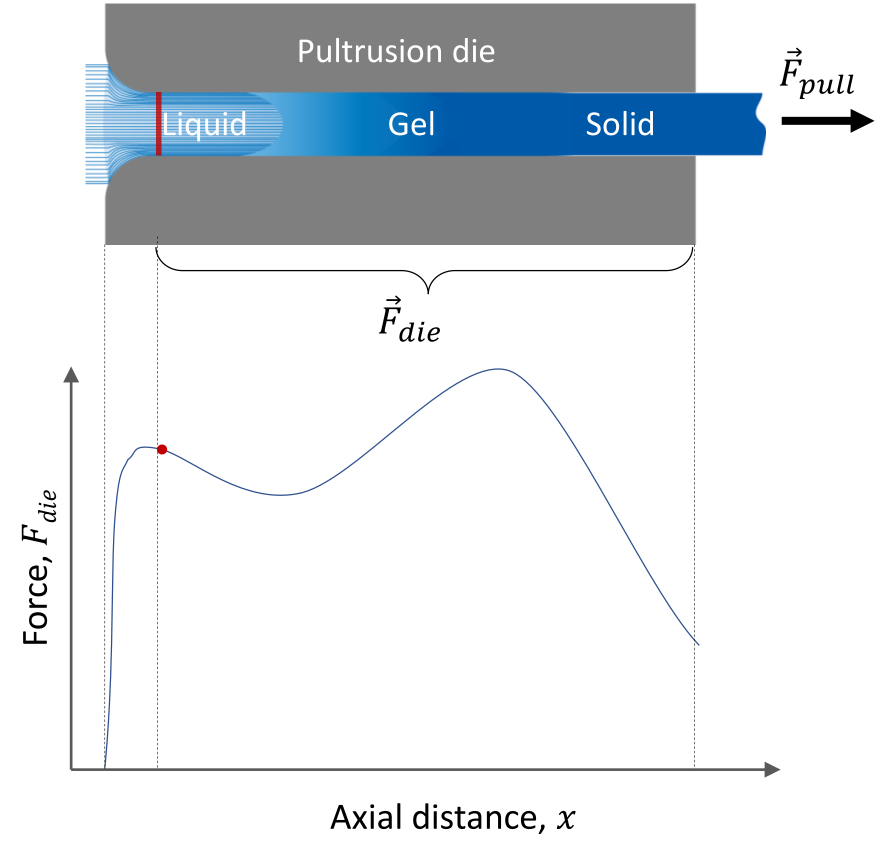


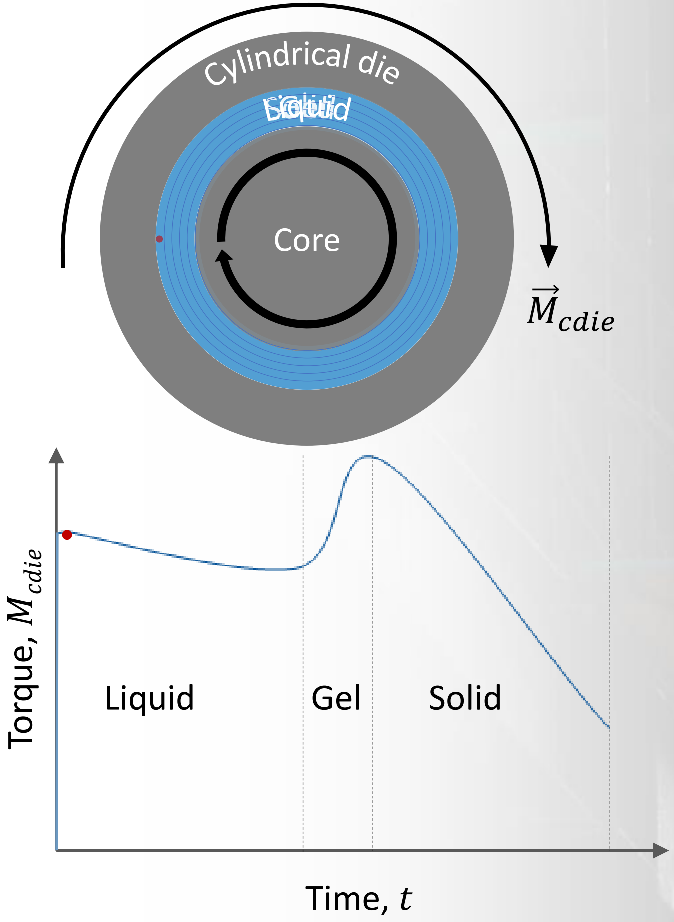
Cartesian coordinates

Cylindrical coordinates

Patent - DE102018127540

Novel rotating core method





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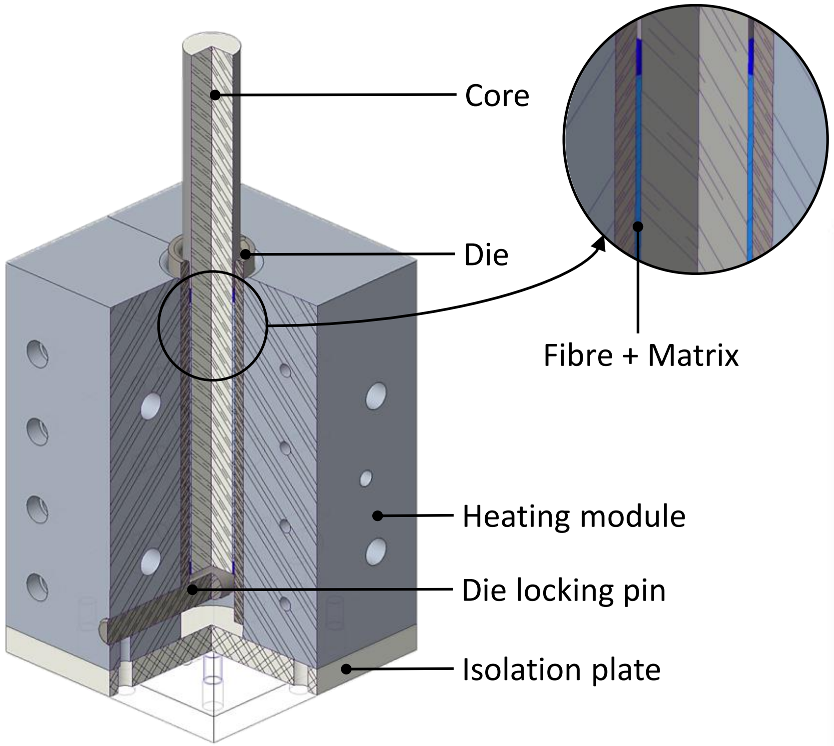
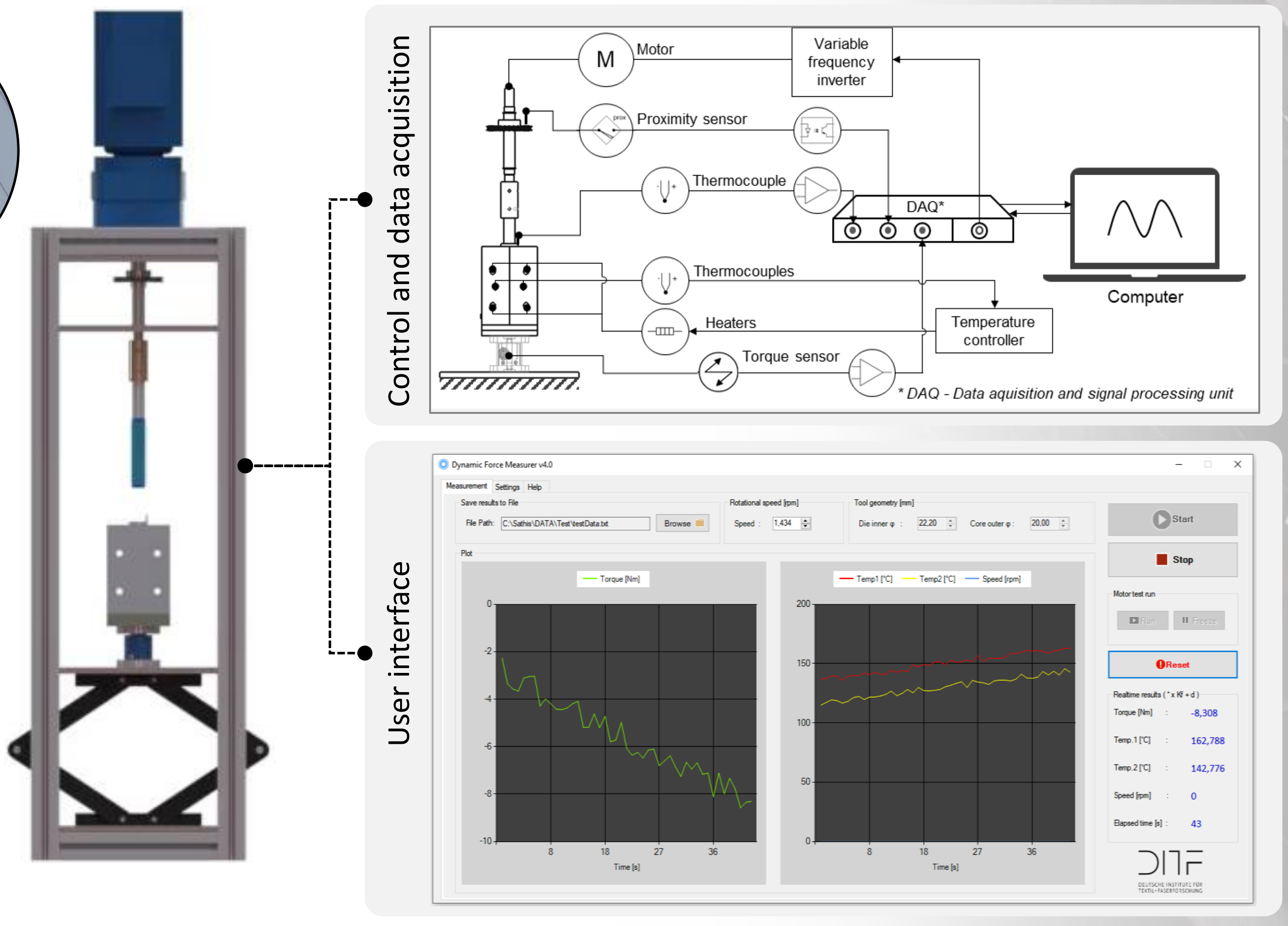
Die Dynamics Simulator (DDS)



Die-Core assembly



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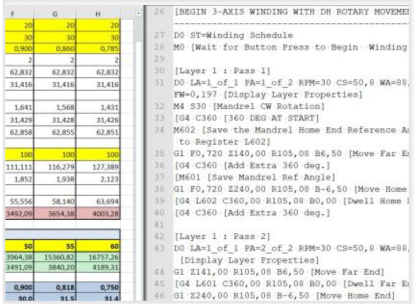
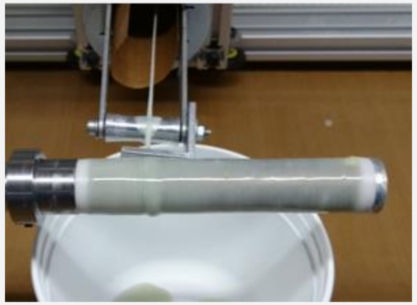
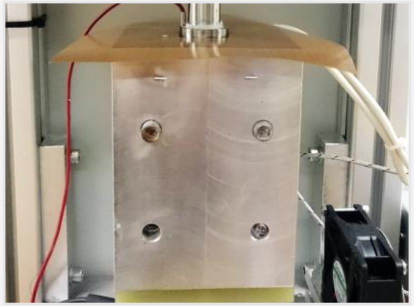
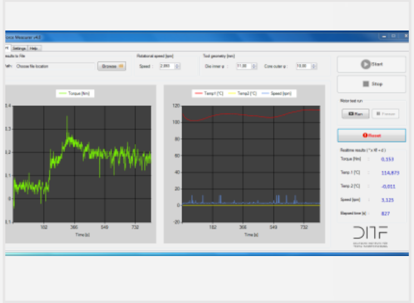
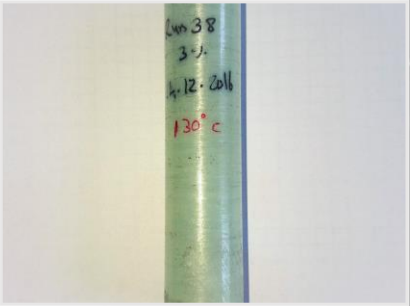
Measurement process steps











Winding preparation

- Fibre volume fraction
- Resin formulation

Filament winding

- Roving tension
- Winding angle

Torque measurement preparation

- Die temperature
- Rotational speed

Torque Measurement

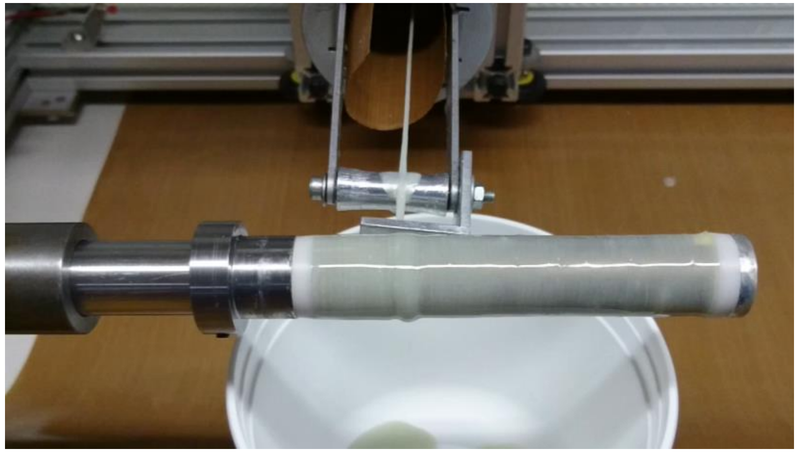
- Measurement of torque, temperature and speed

Post-measurement

- Subjective inferences
- Through-thickness flow
- Resin layer thickness
- Torque evolution
- Die dynamics

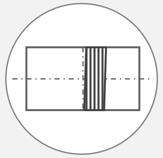
Patent - DE102018127540

Filament winding parameters



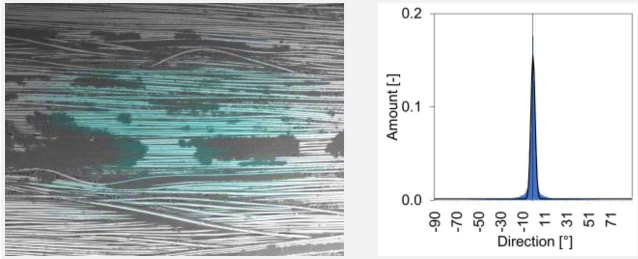
Reinforcement architecture

- Fibre orientation
- Fibre distribution

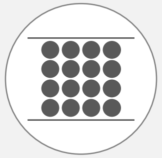


Fibre orientation

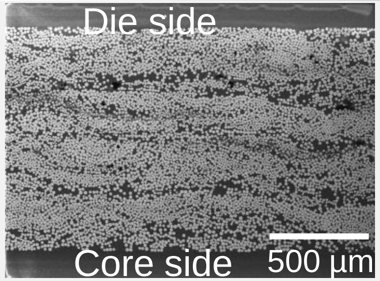
1 N winding tension



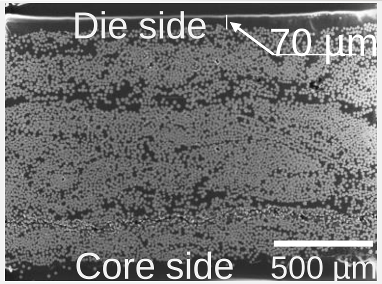
1.8 N winding tension



Fibre distribution



ϕ_{fa} = **0.61**, h_a = 1 mm



ϕ_{fa} = **0.56**, h_a = 1 mm

Parametric investigations on DDS

Process	Geometry	Material
Die temperature (T) Rotational velocity (V)	Die radius (R) Annular gap (H)	Fibre volume fraction (FV) IMR concentration (IMR)

T [°C]	V [mm min^{-1}]	R [mm]	H [mm]	FV [-]	IMR [phr]
120	100	11	1	0.56	0.5
140	200	5.5	2	0.61	1.5
	300				3.0

Unidirectional roving

E-glass fibres

Fineness: 600 tex

Epoxy system

EPIKOTE™ MGS® LR285

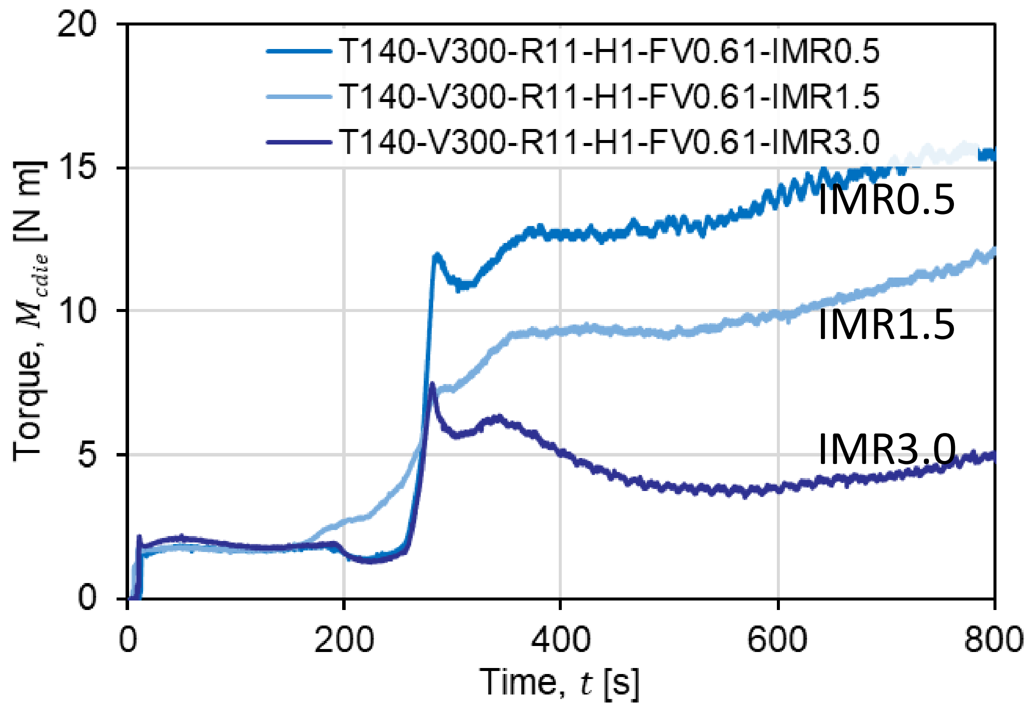
EPIKURE™ MGS® LH286

Internal Mould Release

PAT® IMR System

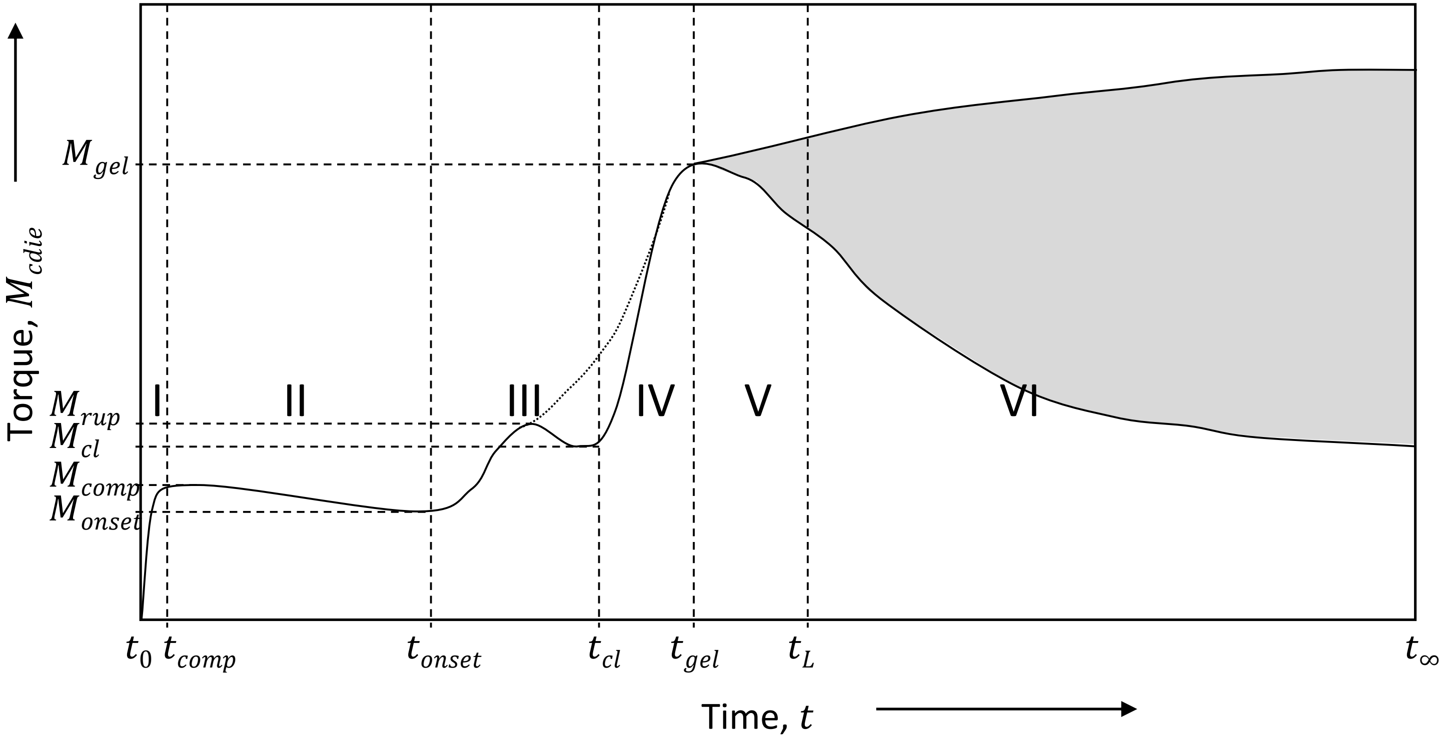
Effect of Internal mould release on torque

IMR concentration



Die dynamics model

Parametric investigations + Rheokinetics of the resin formulation



Zone I:
Compaction

Zone II:
Viscosity reduction

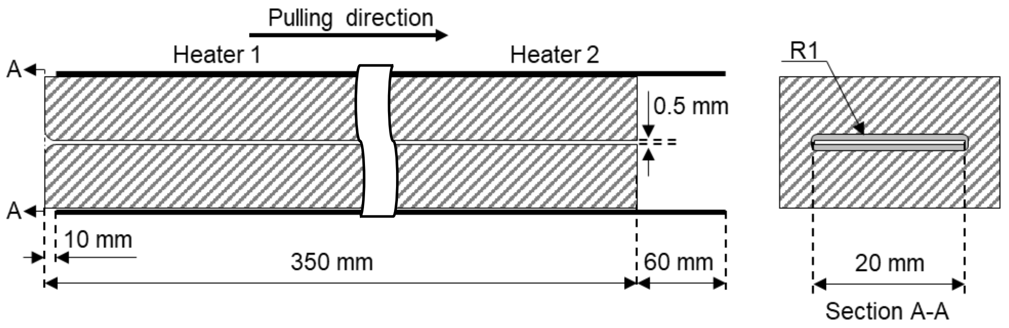
Zone III:
Curing onset, Stable/Unstable network

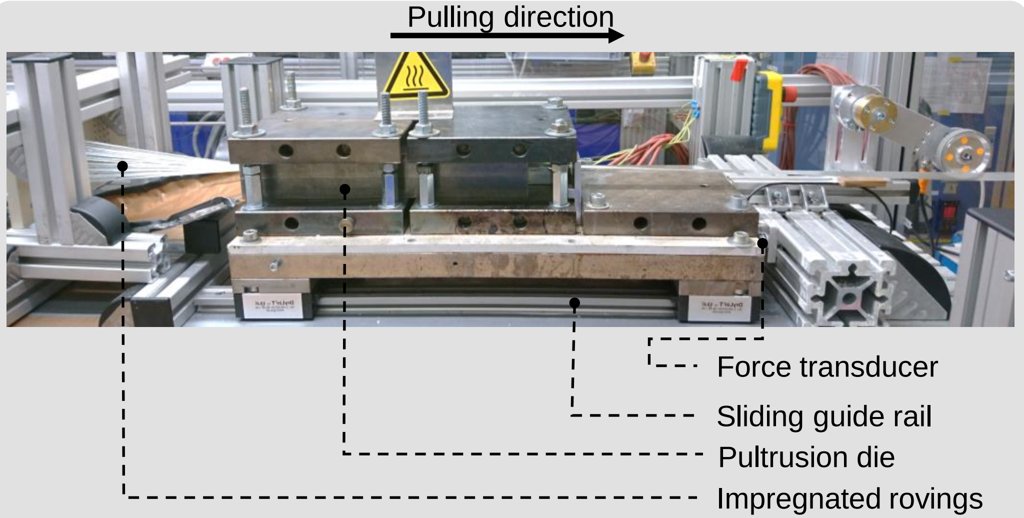
Zone IV:
Gelation, Thermal expansion, Adhesion → IMR effectiveness

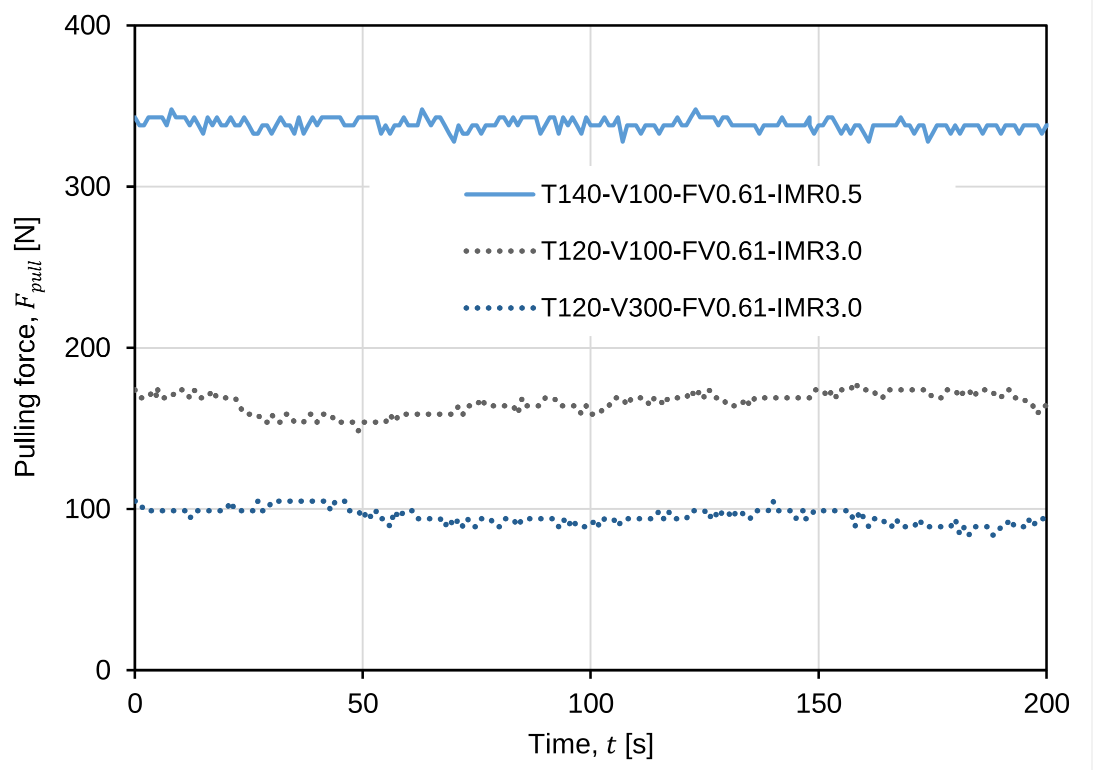
Zone V:
Seperation or Mould sticking

Zone VI:
Friction

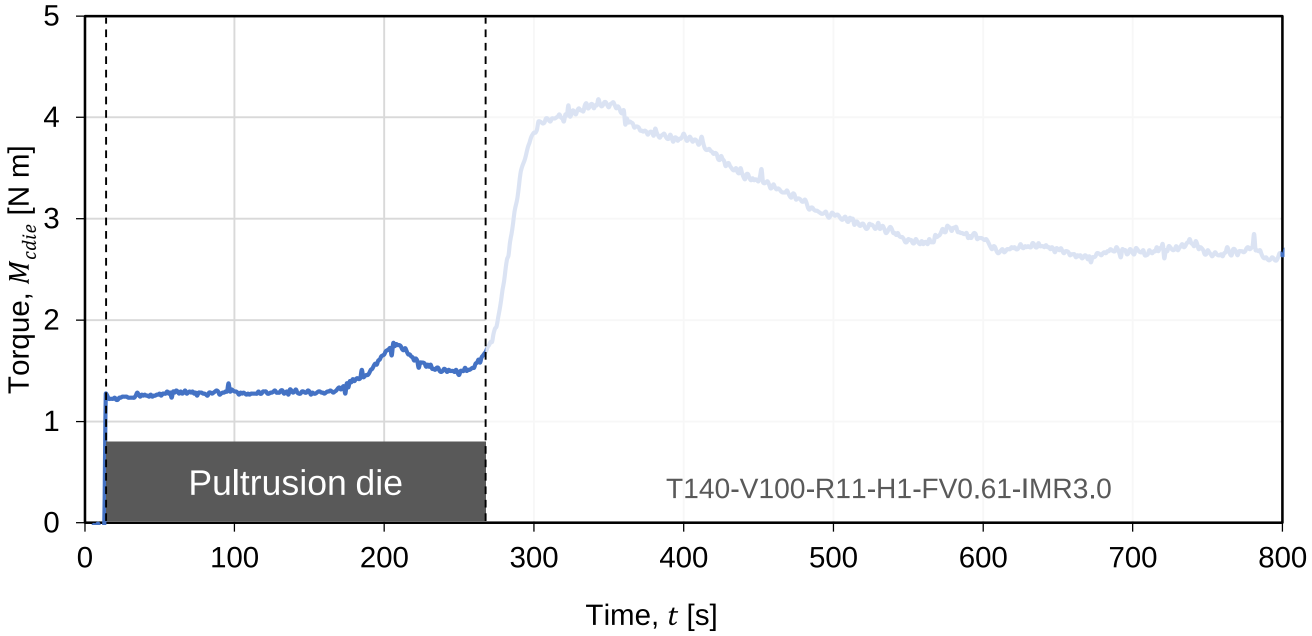
Pulling force measurement







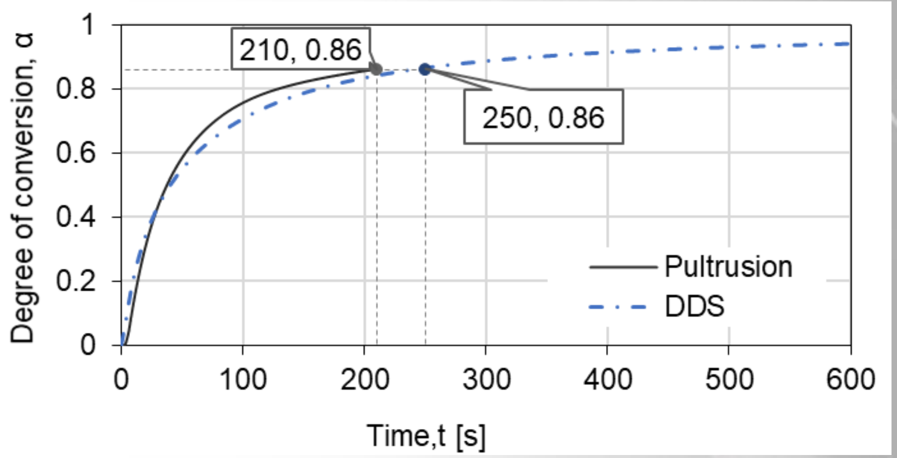
Calculation of pulling force equivalence from torque



$$\sum_{t=0}^{t=250} F_{cdie}$$

Die residence time → Time boundaries to consider on DDS data

- Equivalent degrees of conversion of the matrix in both DDS and Pultrusion



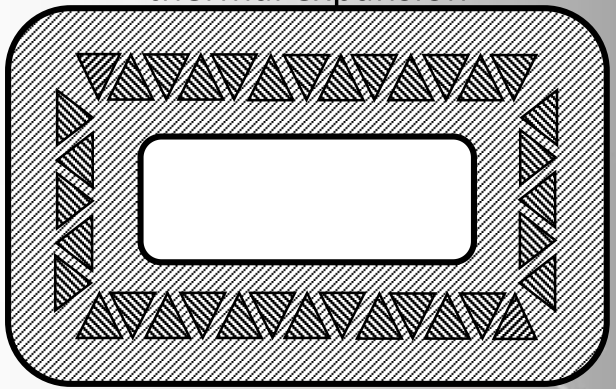
Comparison of measured forces

Sample set	Pultrusion		DDS		Mean deviation [%]
	Mean pulling force F_{pull} **[N]**	Std. Dev [N]	**Measured mean force** F_{cdie} **[N]**	Std. Dev [N]	
T140-V300-FV0.61-IMR3.0	**162.21**	4.27	**158.15**	5.31	**-2.50**
T140-V300-FV0.61-IMR0.5	**192.59**	4.72	**194.94**	6.58	**1.22**
T140-V100-FV0.61-IMR3.0	**137.38**	6.52	**134.86**	4.04	**-1.83**
T140-V100-FV0.61-IMR0.5	**335.5**	7.09	**318.12**	7.04	**-5.89**
T120-V100-FV0.61-IMR3.0	**165.23**	5.99	**152.19**	18.45	**-7.89**
T120-V300-FV0.61-IMR3.0	**97.08**	5.28	**94.18**	4.72	**-2.99**
T120-V300-FV0.61-IMR0.5	**95.49**	2.99	**86.33**	5.56	**-9.16**
T120-V300-FV0.56-IMR0.5	**85.47**	7.97	**52.7**	18.4	**-38.34**
T120-V300-FV0.56-IMR3.0	**87.11**	6.59	**39.67**	14.29	**-54.46**

Advantages of rotational core method

- Enable to create database for process optimisations
- Economically beneficial compared to full scale process
- Aids die design, tribological properties analysis of die materials
- Composite samples produced in DDS can be directly used for further testing
- Application of DDS can be extended to the batch processes such as RTM → Demoulding characteristics

Use of materials with different thermal expansion



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Summary

- Our new approach empirically simulates the pultrusion die dynamics
- Proved feasibility to quantify the individual components ($\vec{F}_{vis}$ & $\vec{F}_{fric}$) of the resistive forces in the die
- Investigated effect of process and material parameters on the resistive forces and established die dynamics model
- Successfully validated the rotating core method using pultrusion experiments

Investigation of Pultrusion Die Dynamics using a Novel Rotating Core Method

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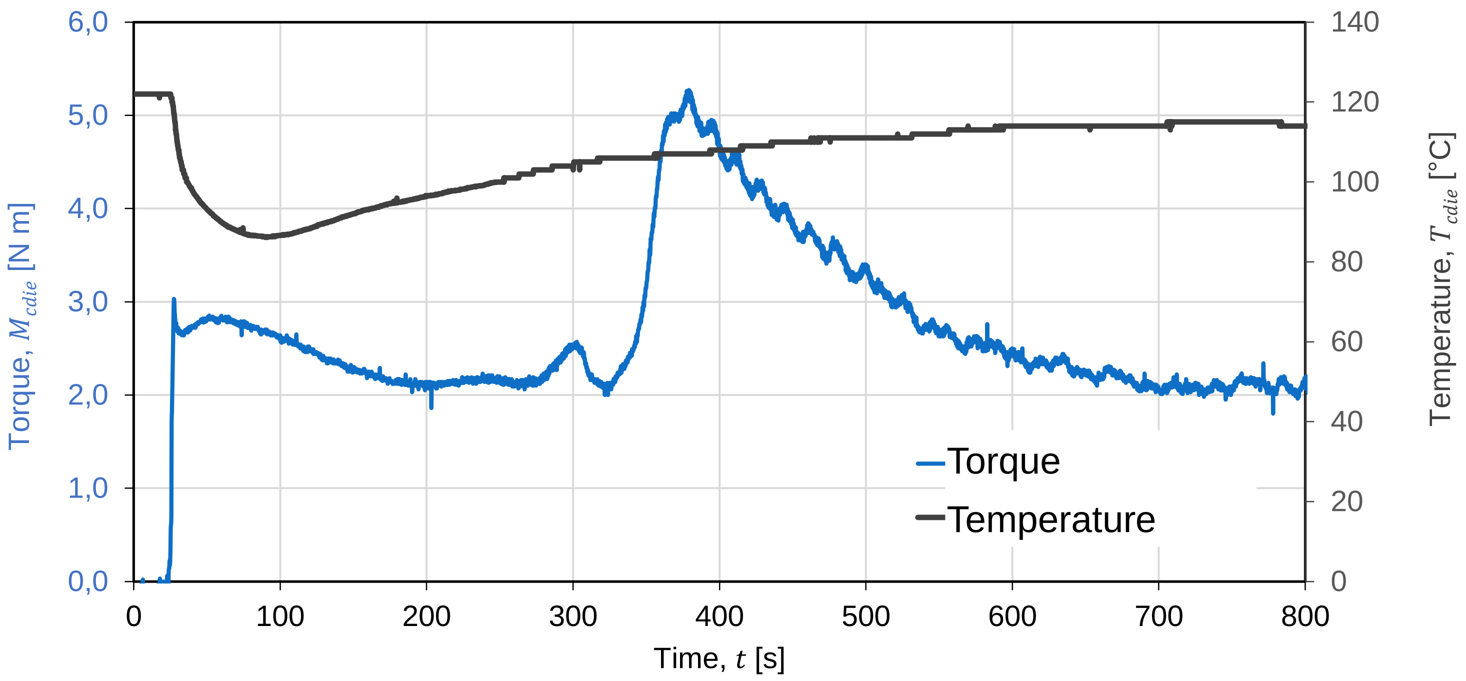
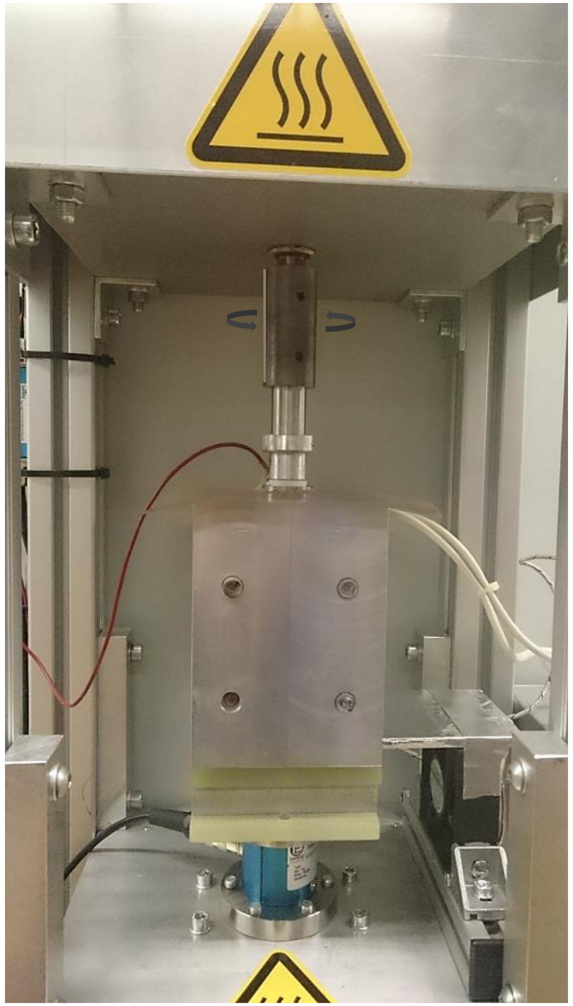
Torque measurement on DDS





Torque evolution behaviour

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% Fibre volume fraction (FV)