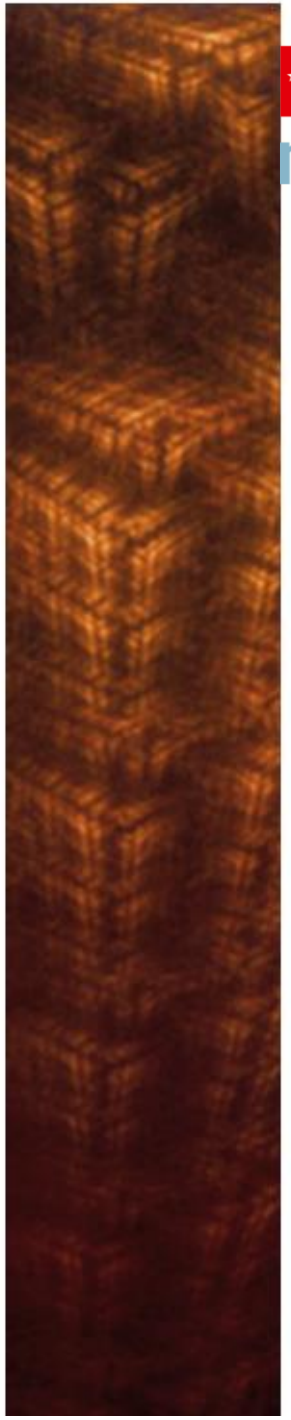

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International Conference on Composite Materials
ICCM 23

An Analytical Model For Interlaminar Friction Prediction In Prepreg Composite

D. Mocerino, D. Aveiga, C. Gonzalez

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EXCELENCIA MARÍA DE MAEZTU

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

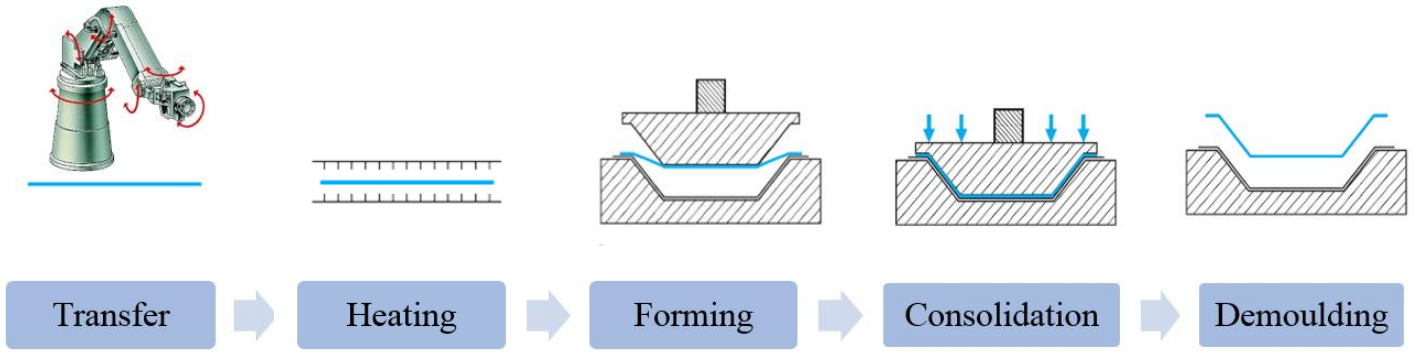
Diciembre 2019 – Diciembre 2023

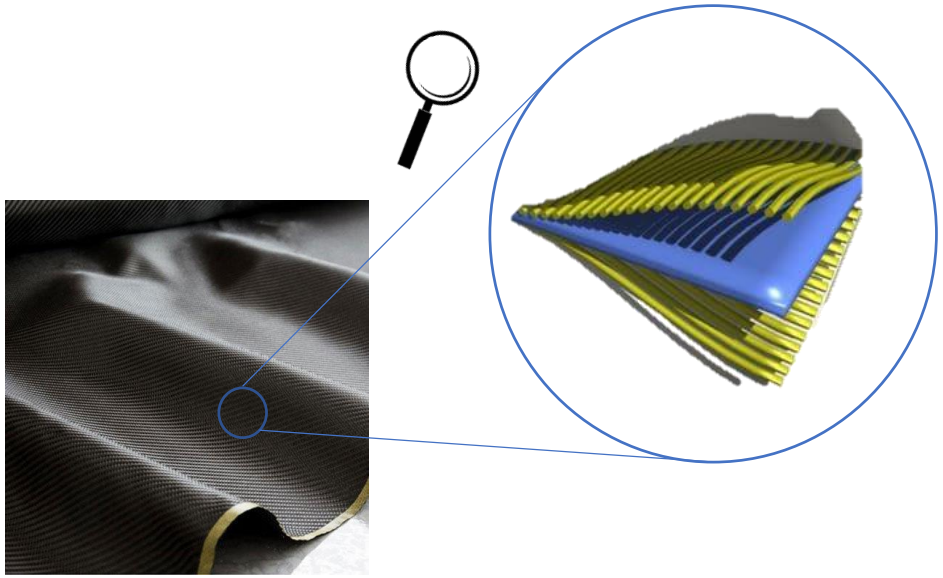
Comunidad de Madrid

Outline

- Thermoforming, defects and friction
- Pull-out Test and Tests Results
- Interlaminar Contact Surface Examination
- Analytical Model ad Lubrication Theory
- Results
- Conclusion

Thermoforming Manufacturing *



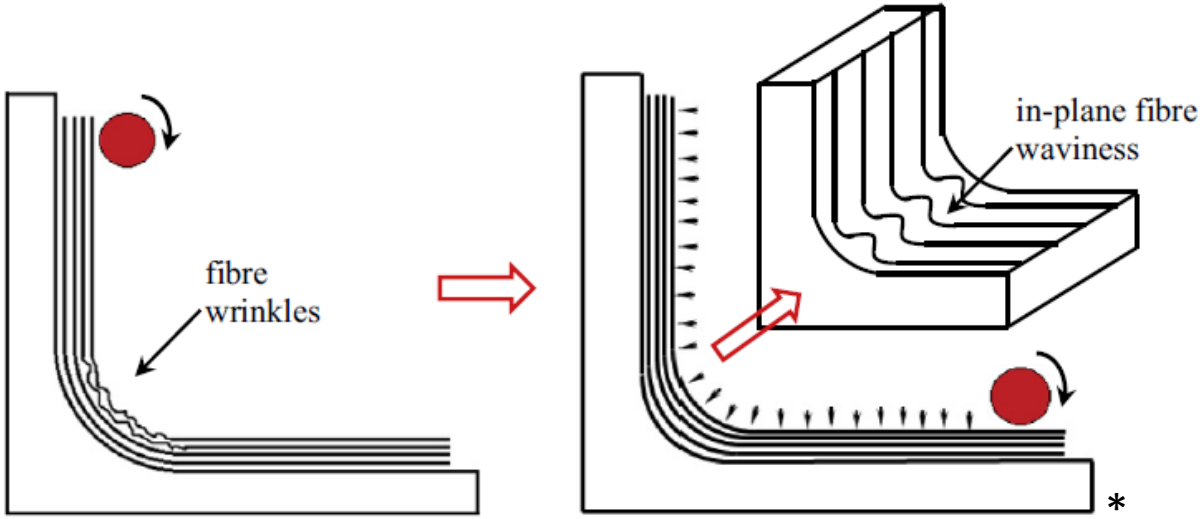


AS4/8552 PREPREG COMPOSITE

- Solid and viscous behaviour
- Temperature sensitivity

*Guzman-Maldonado, E., Hamila, N., Naouar, N., Moulin, G., & Boisse, P. (2016). Simulation of thermoplastic prepreg thermoforming based on a visco-hyperelastic model and a thermal homogenization. *Materials and Design*, *93* (January 2016).


TEMPERATURE
PRESSURE
VELOCITY
WRINKLES
FRICTION
BENDING
F



- In the process of thermoforming, it can be observed that individual lamina within a given laminate undergoes varying degrees of deformation.
- Frictional resistance exists between the layers.
- Stress concentrations may arise due to the incapacity of certain areas of the lamina to undergo deformation.
- The formation of wrinkles occurs in areas where the primary stress is compressive.
- Following the application of a distributed pressure, the initial visible appearance is the occurrence of out-of-plane fibre waviness, followed by the formation of in-plane wrinkles.

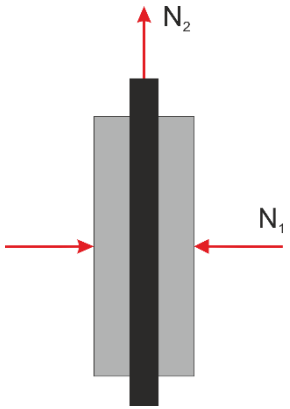
*K. Ç inar, N. Ersoy, Effect of fibre wrinkling to the spring-in behaviour of L-shaped com-posite materials, Composites Part A: Applied Science and Manufacturing 69 (October)(2015) 105–114.

Interlaminar Shear Characterisation

Friction Test:

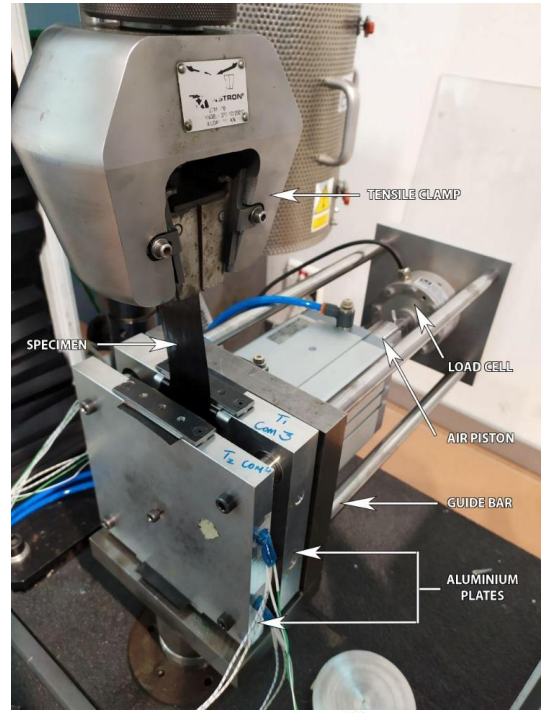
Variables

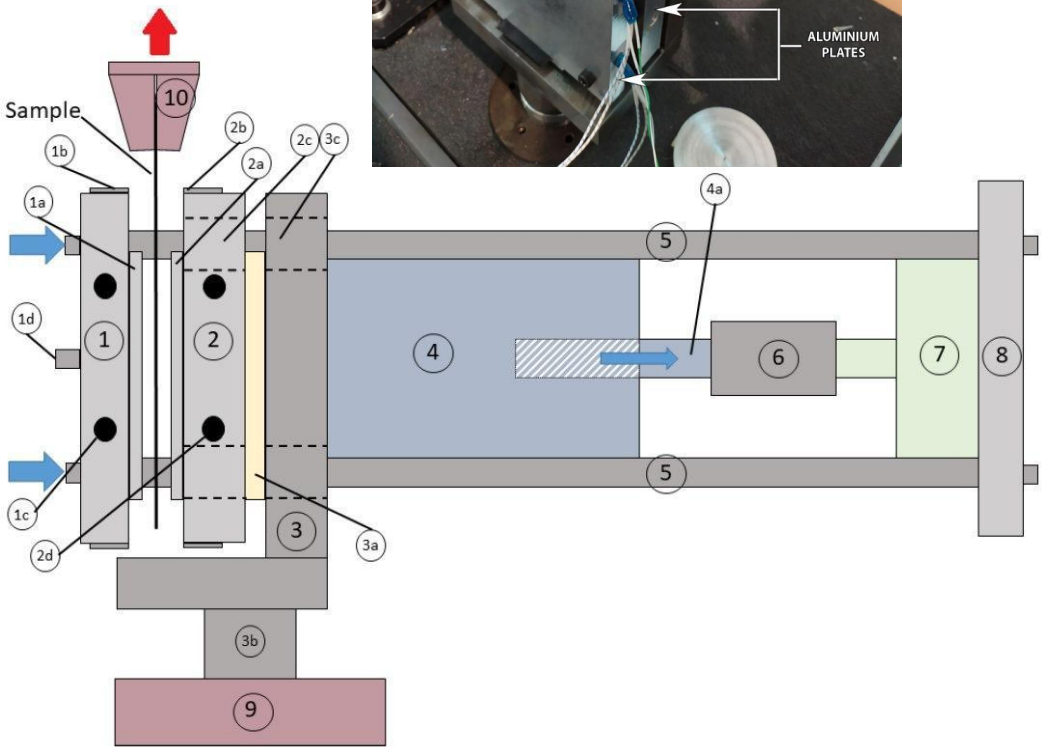
Temperature (°C)	40, 60
Pressure (bar)	0.5, 1, 2
Velocity (mm/min)	1, 3, 5, 10



Calculations

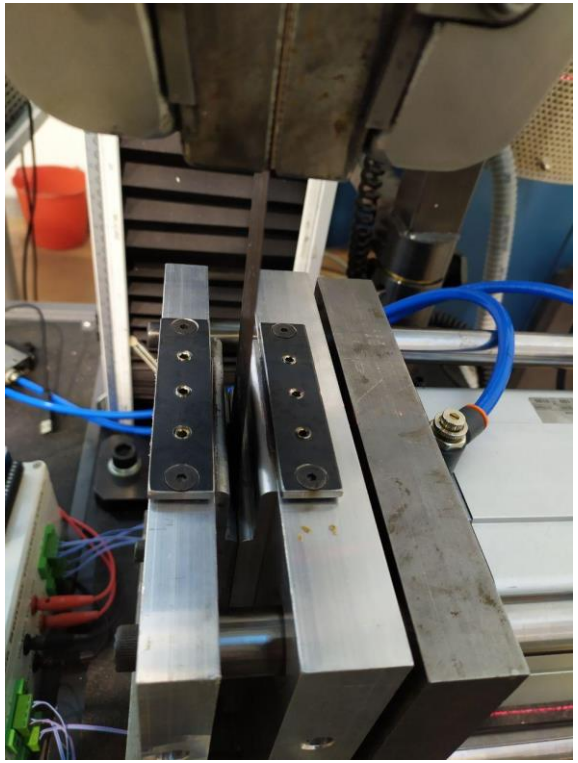
$$\mu = \frac{N_2}{2N_1}$$



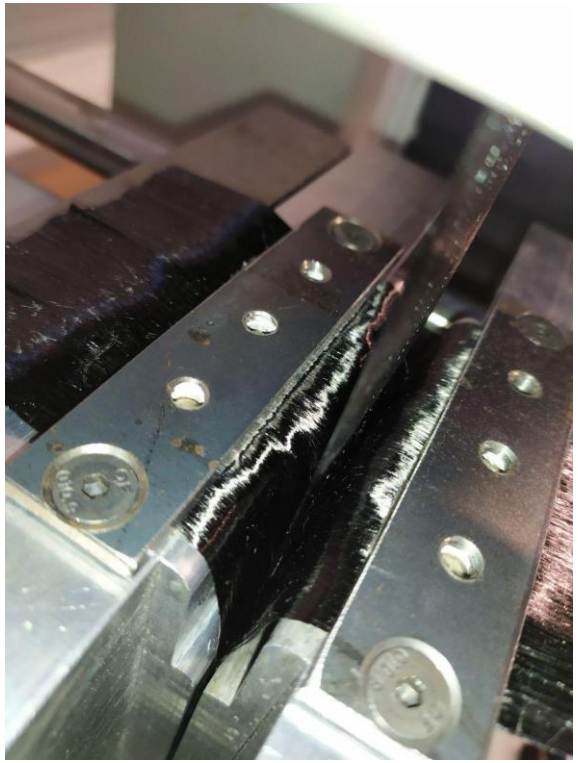


Interlaminar Shear Characterisation

Friction Test: Is there a difference between ply-ply friction and ply-tool friction?

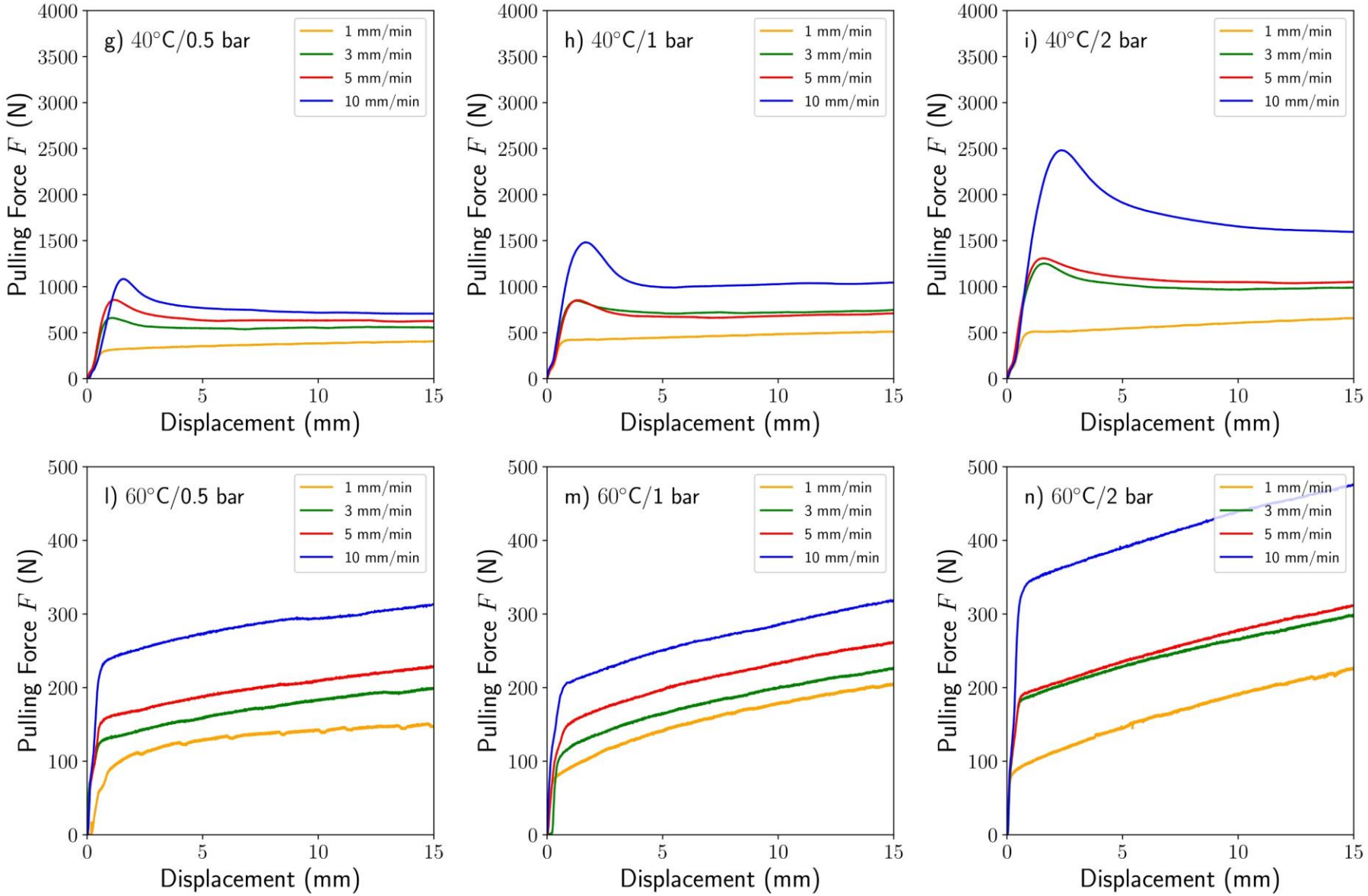


Ply-Tool

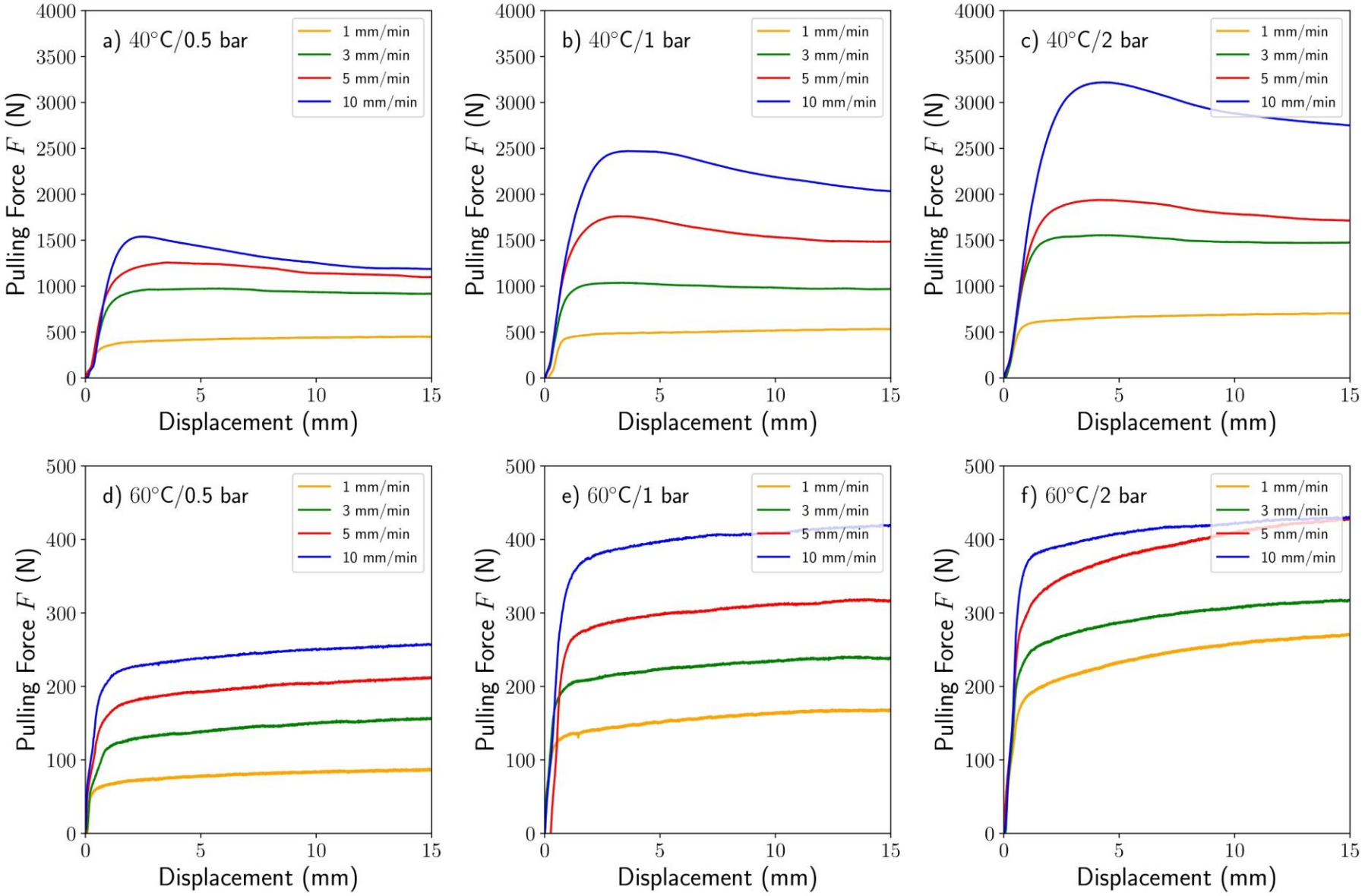


Ply-Ply

PLY-TOOL

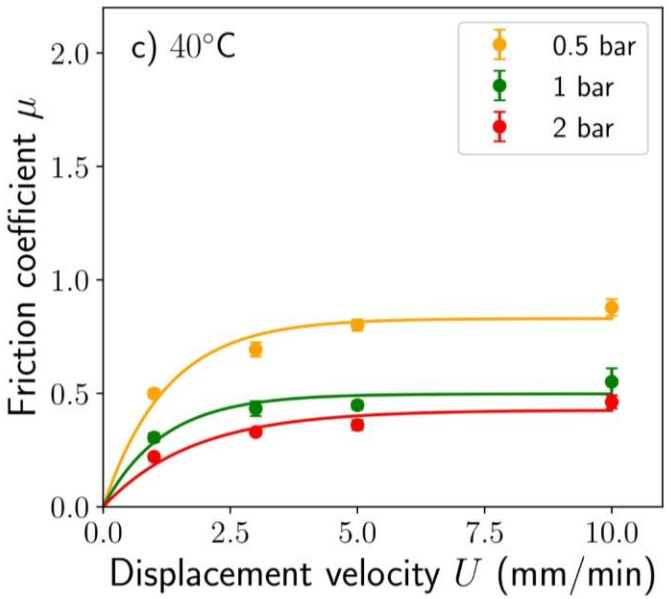

g) 40°C/0.5 bar
h) 40°C/1 bar
i) 40°C/2 bar
l) 60°C/0.5 bar
m) 60°C/1 bar
n) 60°C/2 bar
1 mm/min
3 mm/min
5 mm/min
10 mm/min
Pulling Force F (N)
Displacement (mm)

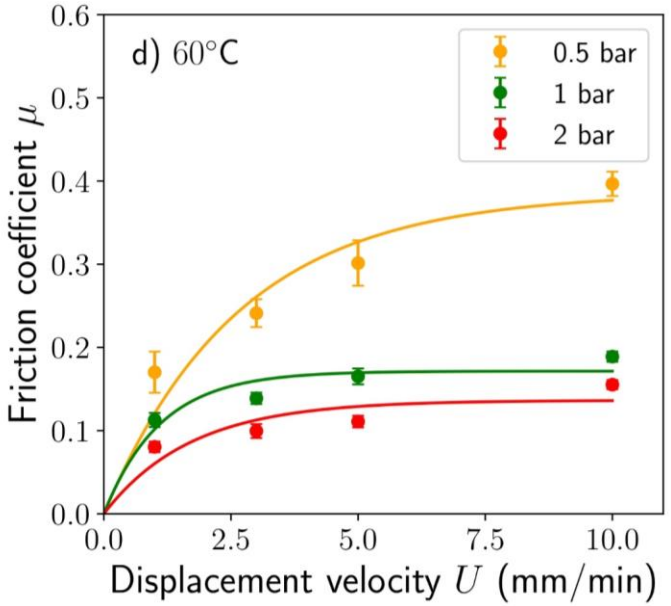
PLY-PLY


a) 40°C/0.5 bar
b) 40°C/1 bar
c) 40°C/2 bar
d) 60°C/0.5 bar
e) 60°C/1 bar
f) 60°C/2 bar
1 mm/min
3 mm/min
5 mm/min
10 mm/min
Pulling Force F (N)
Displacement (mm)

PLY-TOOL

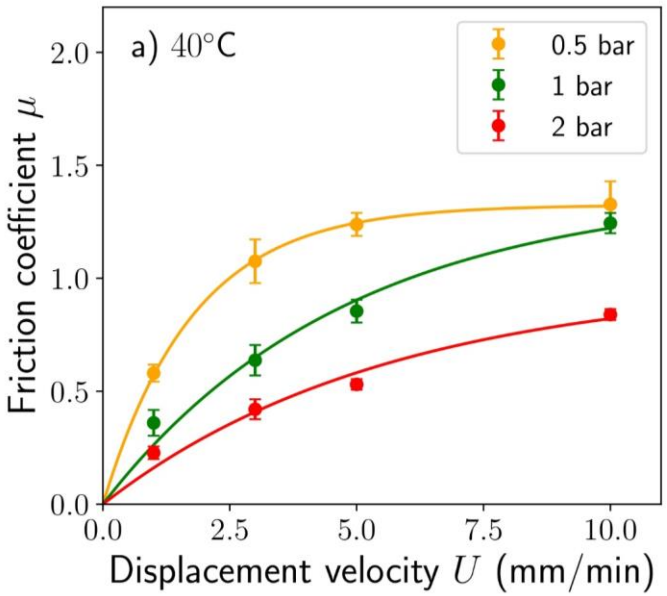
Clamping Pressure (bar)	Pulling velocity (mm/min)	Friction coefficients at 40°C Ply-Tool	Friction coefficients at 60°C Ply-Tool
0.5	1	0.47± 0.02	0.17± 0.03
	3	0.68± 0.02	0.23± 0.02
	5	0.78± 0.02	0.28± 0.008
	10	0.86± 0.04	0.39± 0.01
1	1	0.30±0.02	0.10±0.008
	3	0.42±0.04	0.13±0.007
	5	0.44±0.02	0.15±0.008
	10	0.55±0.06	0.18±0.005
2	1	0.21±0.006	0.07±0.007
	3	0.33±0.01	0.09±0.007
	5	0.35±0.02	0.19±0.008
	10	0.47±0.02	0.14±0.005

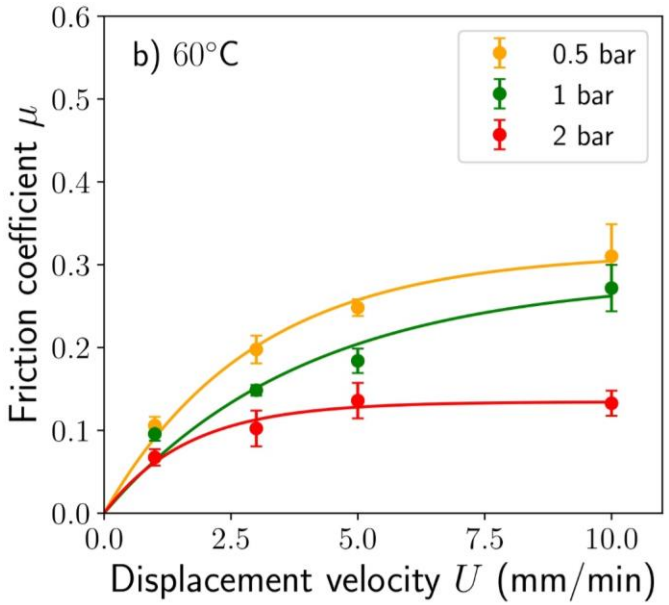




PLY-PLY

Clamping Pressure (bar)	Pulling velocity (mm/min)	Friction coefficients at 40°C Ply-Ply	Friction coefficients at 60°C Ply-Ply
0.5	1	0.59± 0.03	0.1± 0.004
	3	1.08± 0.03	0.19± 0.01
	5	1.23± 0.03	0.25± 0.005
	10	1.31± 0.07	0.3± 0.03
1	1	0.33±0.007	0.09±0.007
	3	0.67±0.04	0.15±0.001
	5	0.85±0.04	0.19±0.009
	10	1.27±0.03	0.26±0.02
2	1	0.23±0.03	0.06±0.003
	3	0.41±0.04	0.09±0.008
	5	0.54±0.01	0.13±0.01
	10	0.85±0.02	0.14±0.01

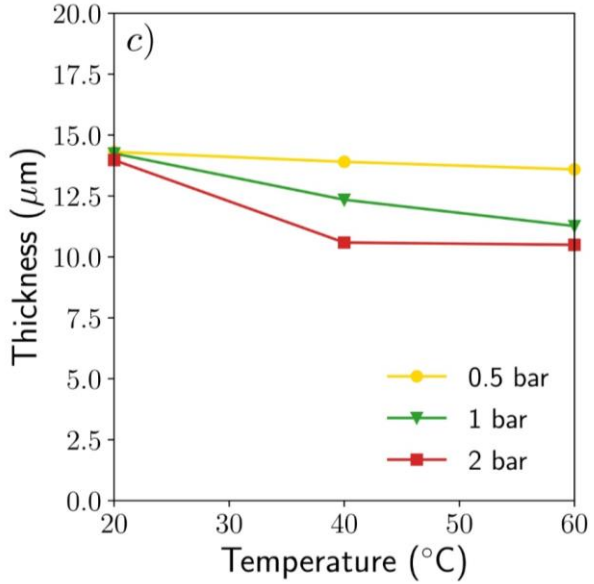


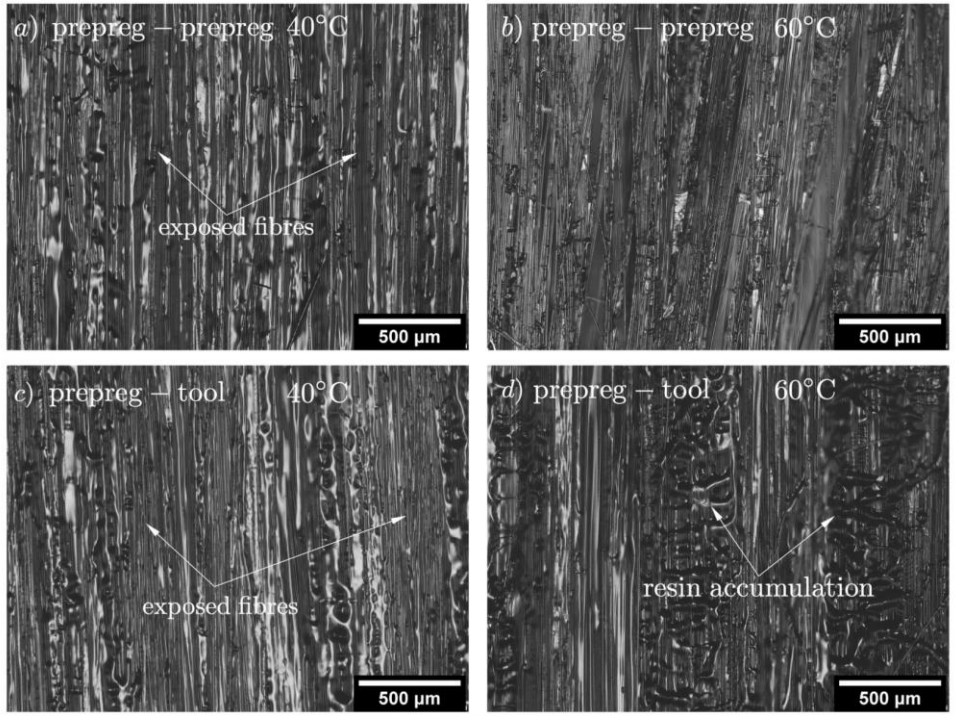


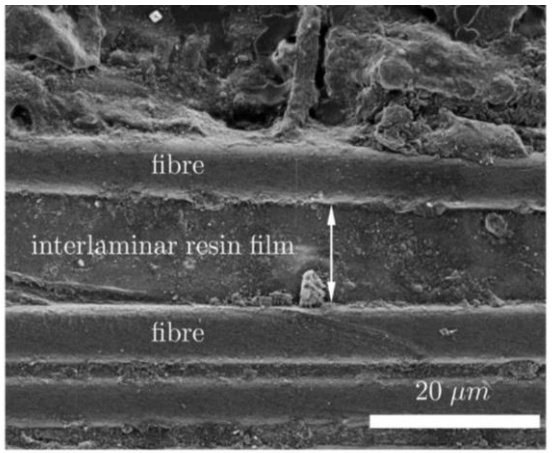
Roughness & Resin Layer

Composite Friction Surface

Contact type	40°C	60°C
Prepreg-prepreg	3.22± 0.23	3.17± 0.66
Prepreg-tool	3.93± 0.46	3.10± 0.12





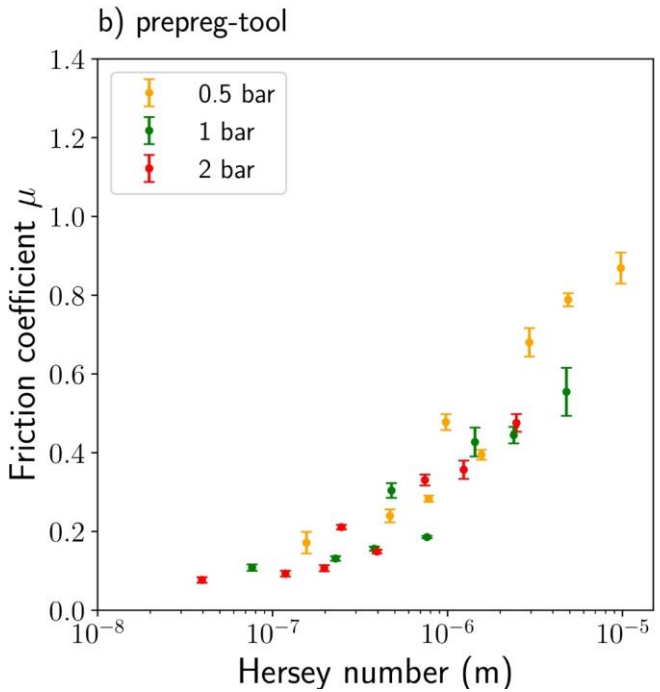


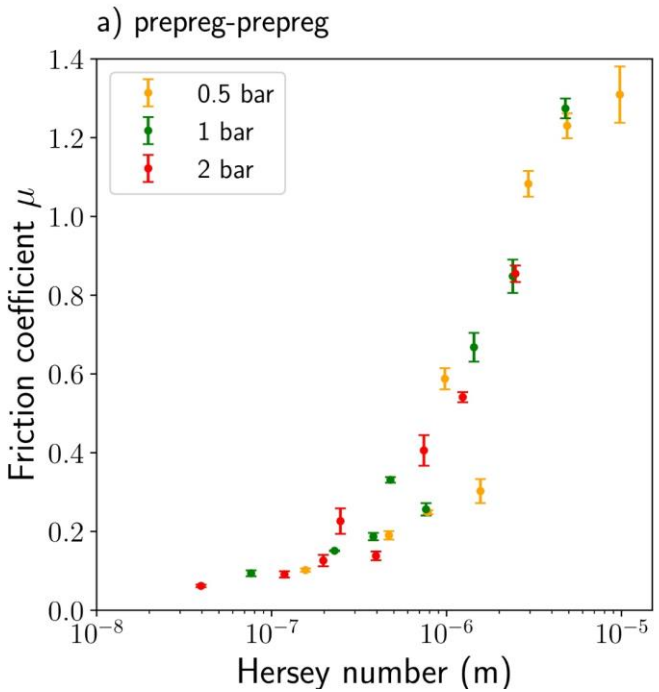
$$H = \frac{\eta \dot{U}}{P}$$

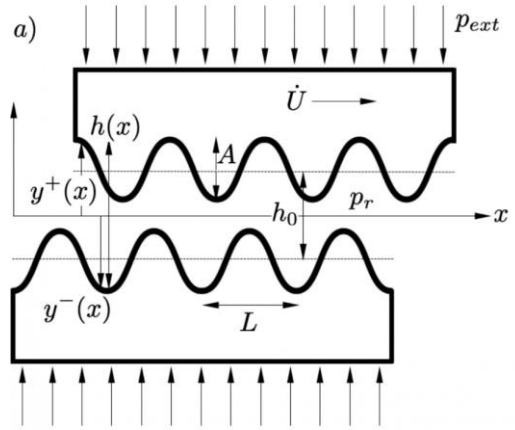
H = Hersey Number
η = Viscosity (Pa.s)
$\dot{U}$ = Velocity (s^{-1})
P = Pressure (Pa)

$$\eta(T) = Ae^{\frac{-B}{RT}}$$

$A = 2.06548437 \times 10^{-9}$
$B = 7.9498278 \times 10^{4}$
R = Gas constant
T = Temperature (K)







$$y^+(x) = \frac{h_0}{2} + A\cos\left(\frac{2\pi x}{L}\right)$$

$$y^-(x) = -\frac{h_0}{2} - A\cos\left(\frac{2\pi x}{L} + \delta\right)$$

$$h(x) = h_0 + 2A_0\cos\delta\cos\left(\frac{2\pi x}{L} + \delta\right)$$

Estimated with optical images

Estimated with roughness

L = wavelength

A = wave amplitude

$\frac{h}{2}$ = half of total thickness of resin layer

$$\tau_r(\hat{x}) = \eta\frac{\dot{U}}{2} + \frac{h}{2}\frac{\partial p_r}{\partial \hat{x}}$$

$$\frac{\partial}{\partial \hat{x}}\left(\frac{h^3}{\eta}\frac{\partial p_r}{\partial \hat{x}}\right) = 6\dot{U}\frac{\partial h}{\partial \hat{x}}$$

$$\mu = \frac{\bar{\tau}_r}{\bar{p}_r}$$

Used Material AS4/8552

L≈64μm

A≈3.5μm

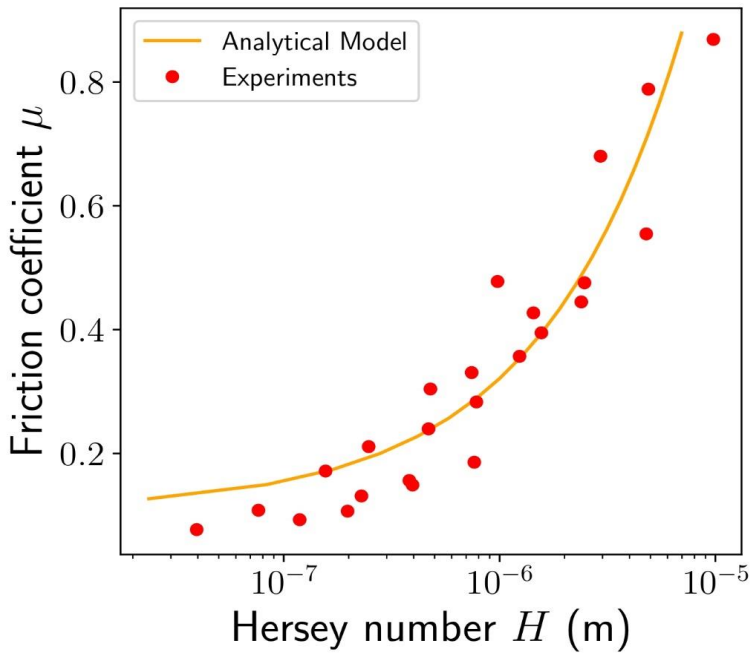
h_0 = [3 – 15μm]

Friction Prediction

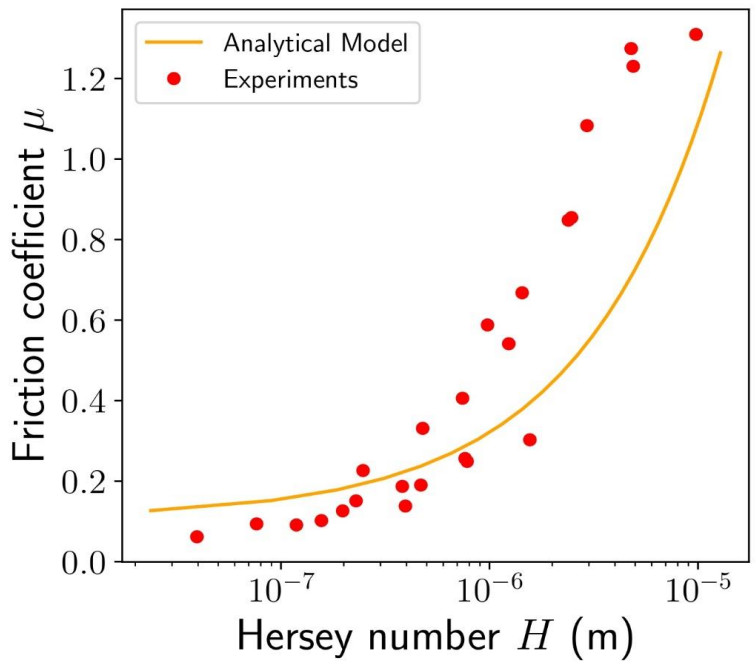
Used Material AS4/8552

L≈64µm
A≈3.5µm
h_0 = [3 – 15µm]

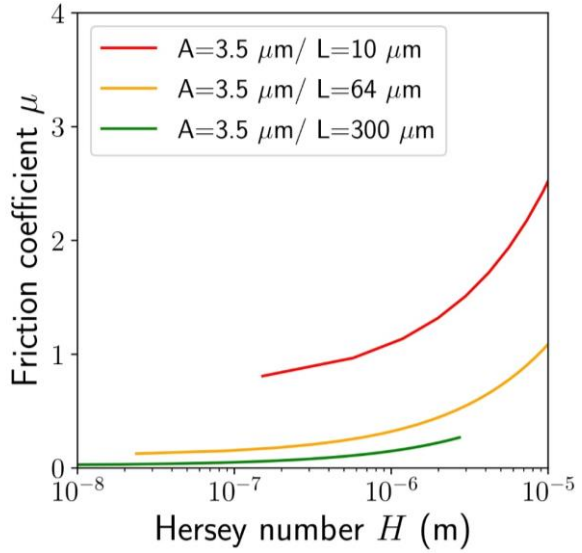
Prepreg-tool

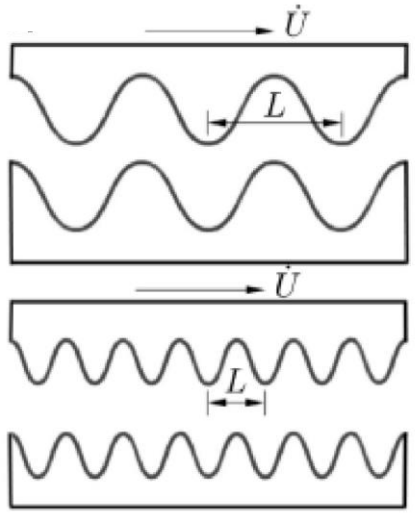


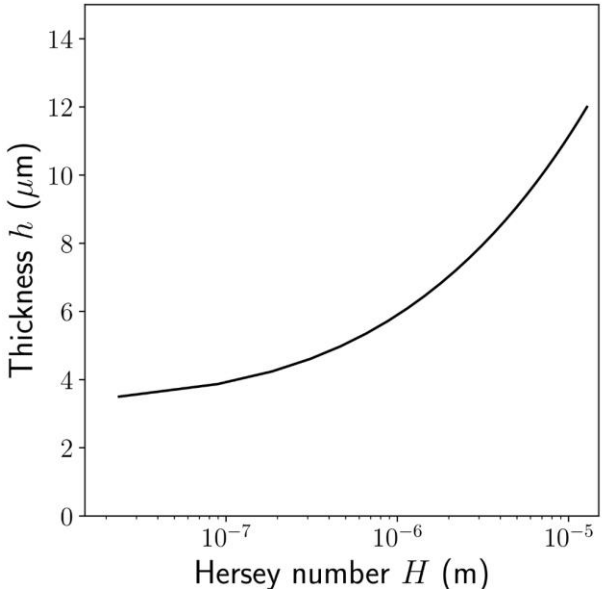
Prepreg-prepreg

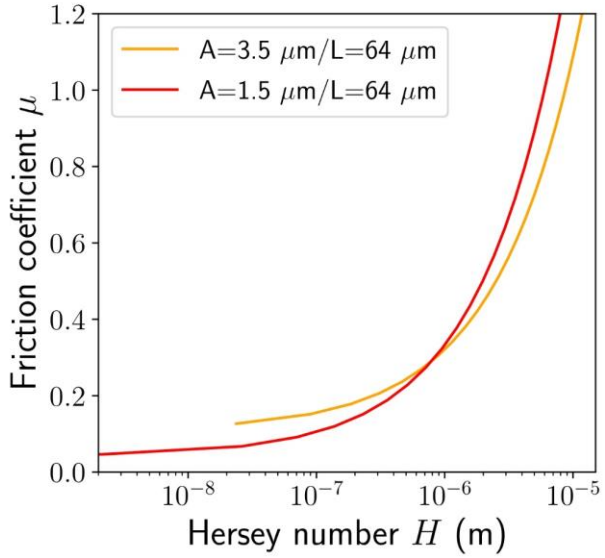


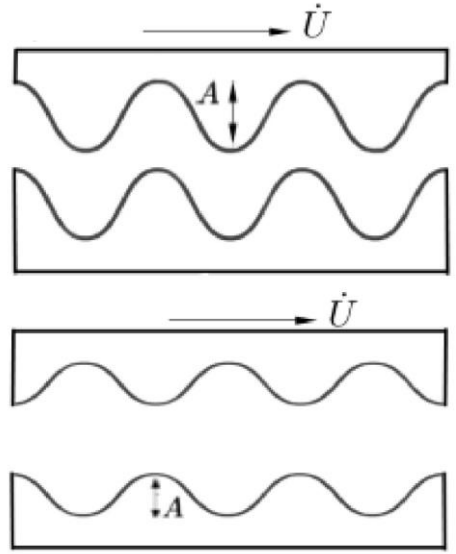
Parametric Study











- Elevated temperatures have the potential to reduce the viscosity of the resin, leading to a notable decrease in the friction coefficient by a factor of 6 to 10. When high pressure is taken into consideration, the coefficient may decrease by a factor ranging from 15 to 18 times its original value.
- In general, it was observed that the Ply-Ply configuration exhibited higher friction values due to the presence of two additional layers of adhesive prepreg. Nevertheless, the frictional resistance exhibited identical behaviour as observed in the previous scenario.
- The examination of the prepreg surface after friction has revealed certain geometric characteristics such as resin accumulations, exposed fibres, and surface roughness. The phenomenon can be represented by a sinusoidal shape characterised by a specific wavelength and roughness.
- An analytical model was formulated. Using the wavelength and amplitude of the resin accumulations on the prepreg surface as inputs, a reliable friction coefficient can be determined.
- By comparison of the model and experimental results, a minimal deviation is detected in the prepreg-prepreg interaction at higher Hershey values. The observed outcome was postulated to be a result of dry lubrication, which can be attributed to the prevailing solid-to-fluid behaviour of the resin

- Madrid Community – Project TEMACOM – Advanced manufacturing technologies for the new generation of composite materials.
- Imdea Materials Institute
- FIDAMC

Prof. Carlos González

David Aveiga

Thanks for your attention

Any questions?