The formation of fiber waviness during thermoplastic composite processing

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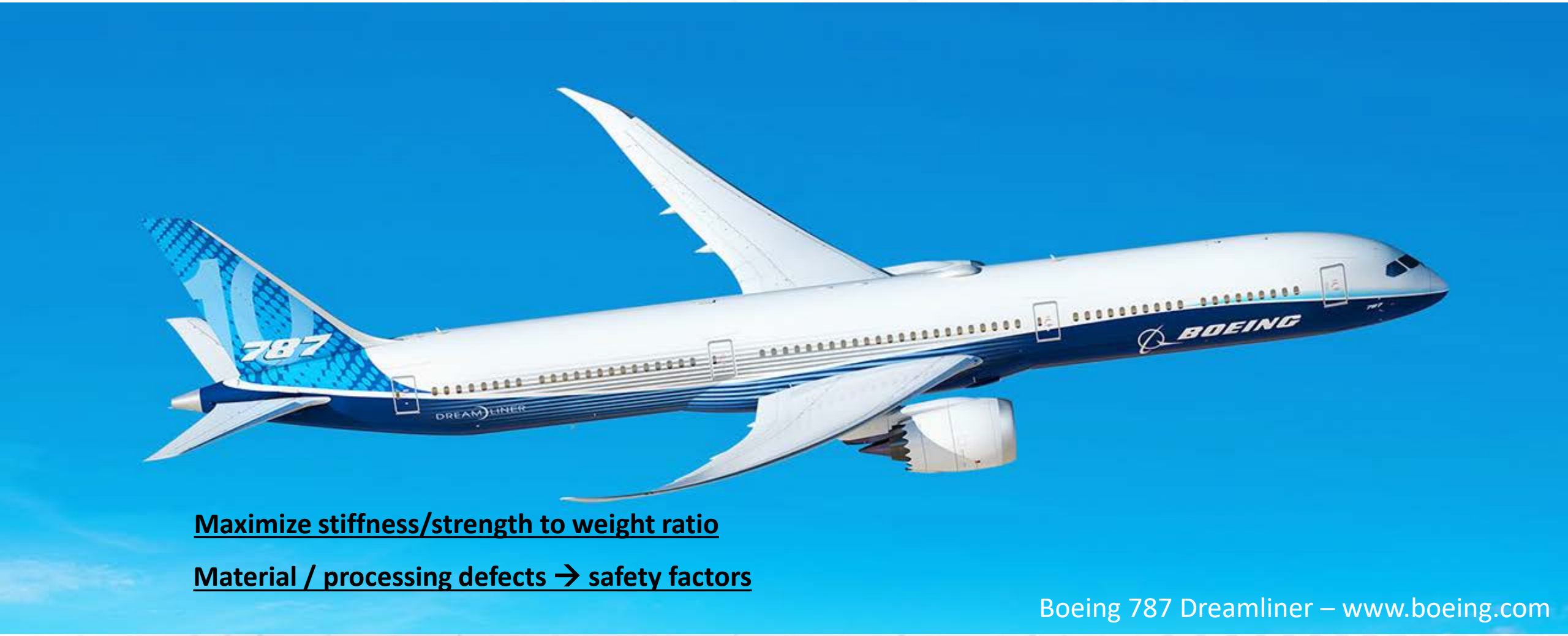
Lightweight design



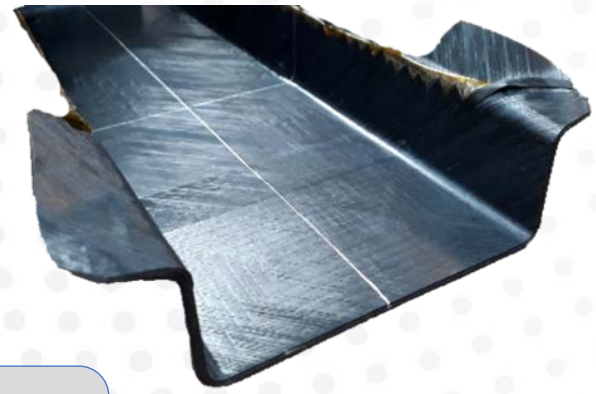
Maximize stiffness/strength to weight ratio

Material / processing defects → safety factors

Boeing 787 Dreamliner – www.boeing.com

Thermoplastic composite part manufacturing

Production



TPRC: Formation of defects

Nonconformity, out-of-tolerance

TPRC: Effects of defects

Inspection / scrap (€€)

Thermoplastic composite part manufacturing

Material constituents

Fibers, matrix

- Polymer chemistry
- Damaged fibers
- …

Intermediate material

Weaving, impregnation

- Matrix distribution
- Fiber misalignment
- Areal density
- …

Part production

Consolidation, Forming

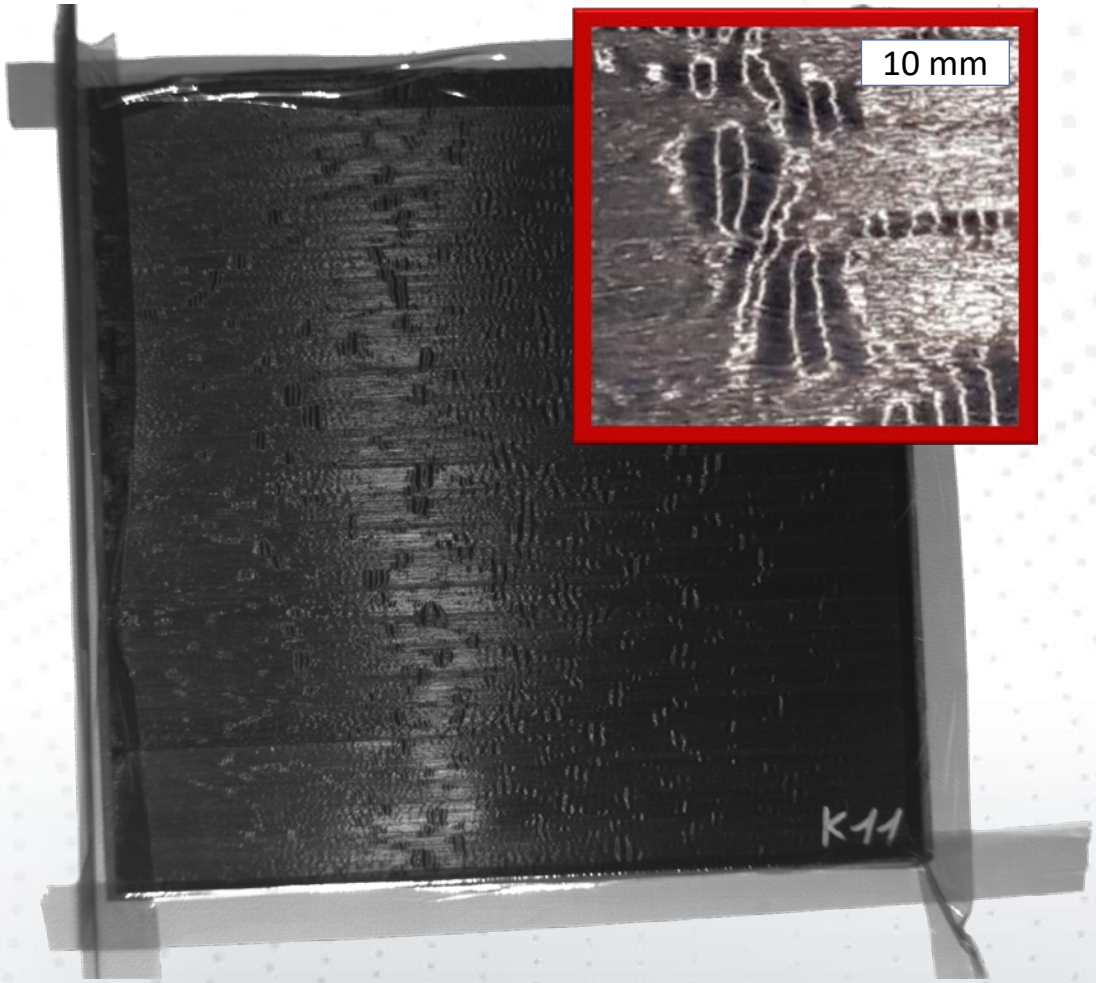
- Voids
- Waviness
- Wrinkles
- Delamination
- …

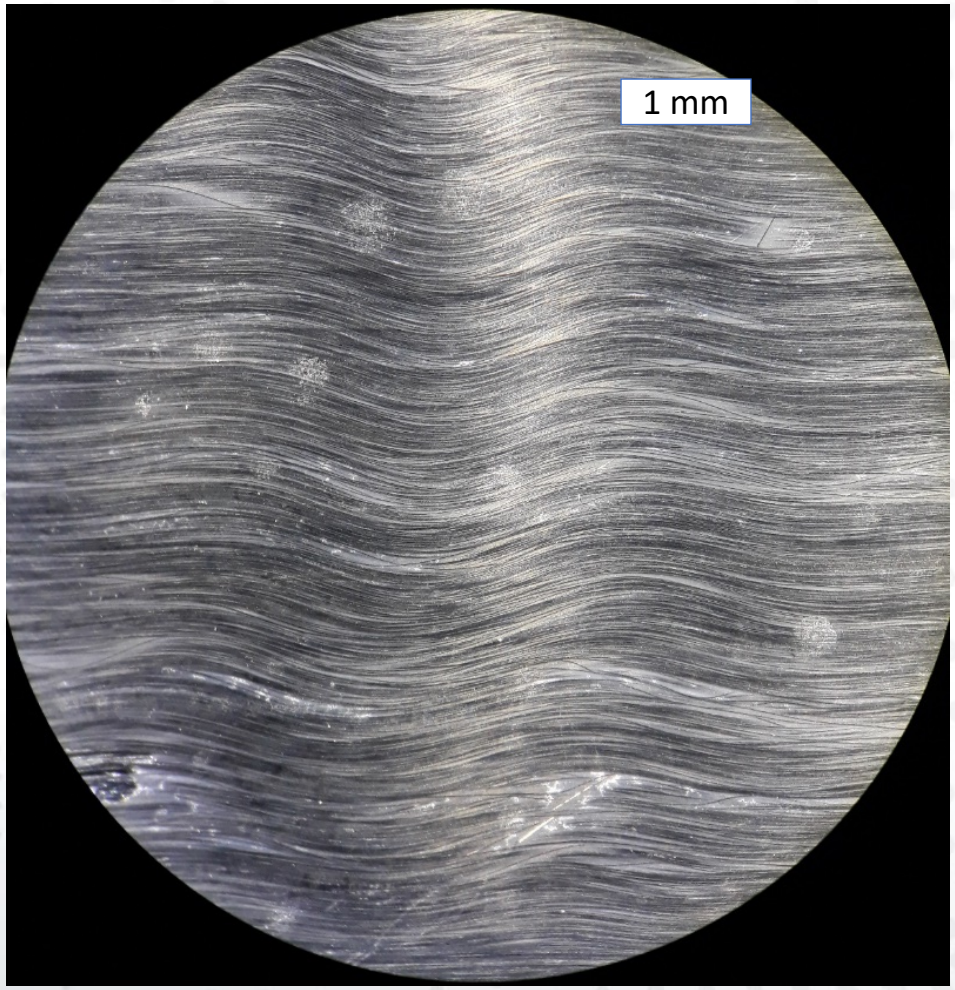
Assembly

Joining, drilling

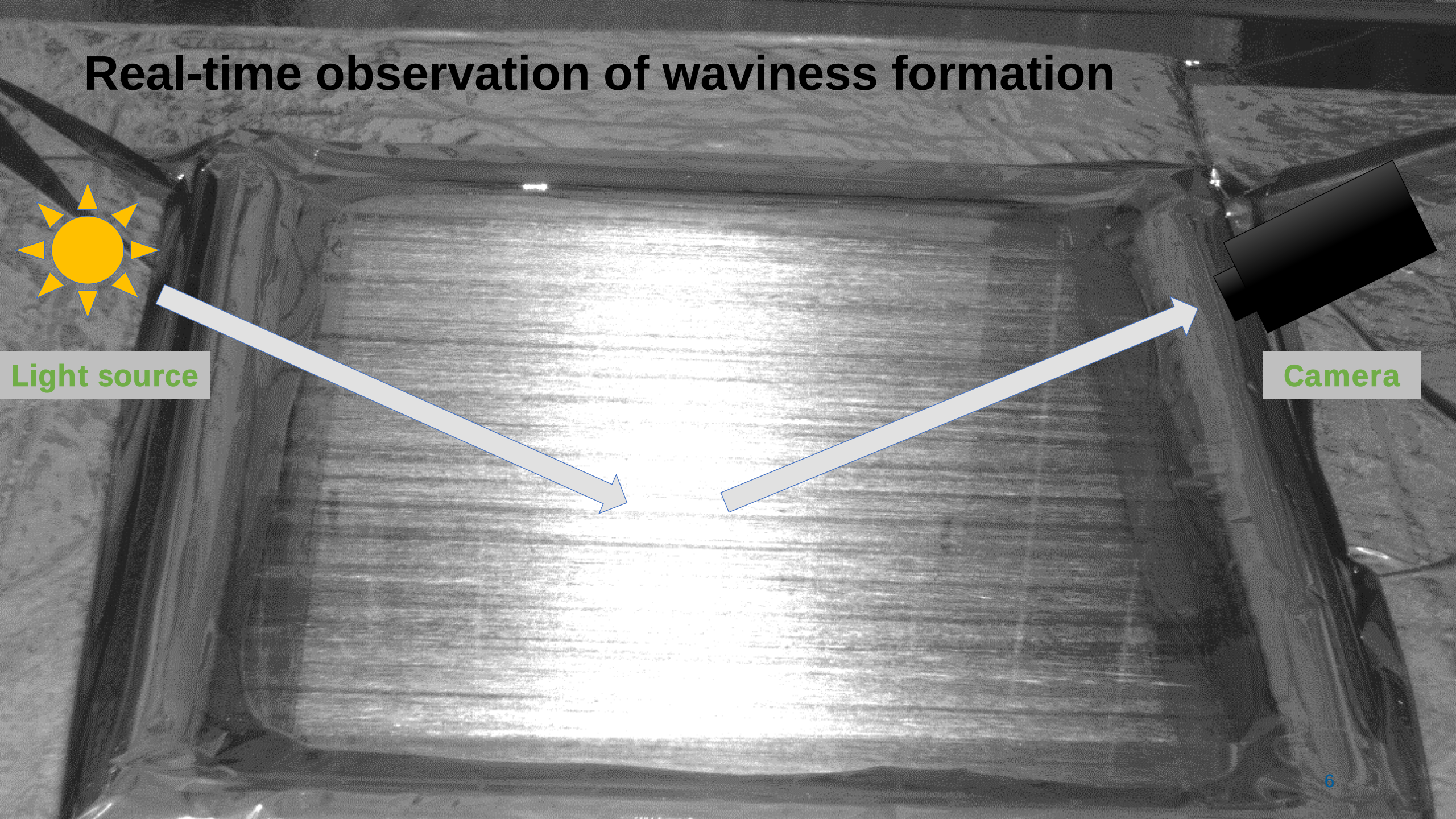
- Fiber breakage
- Edge damage
- Delamination
- …

Example of in-plane fiber waviness



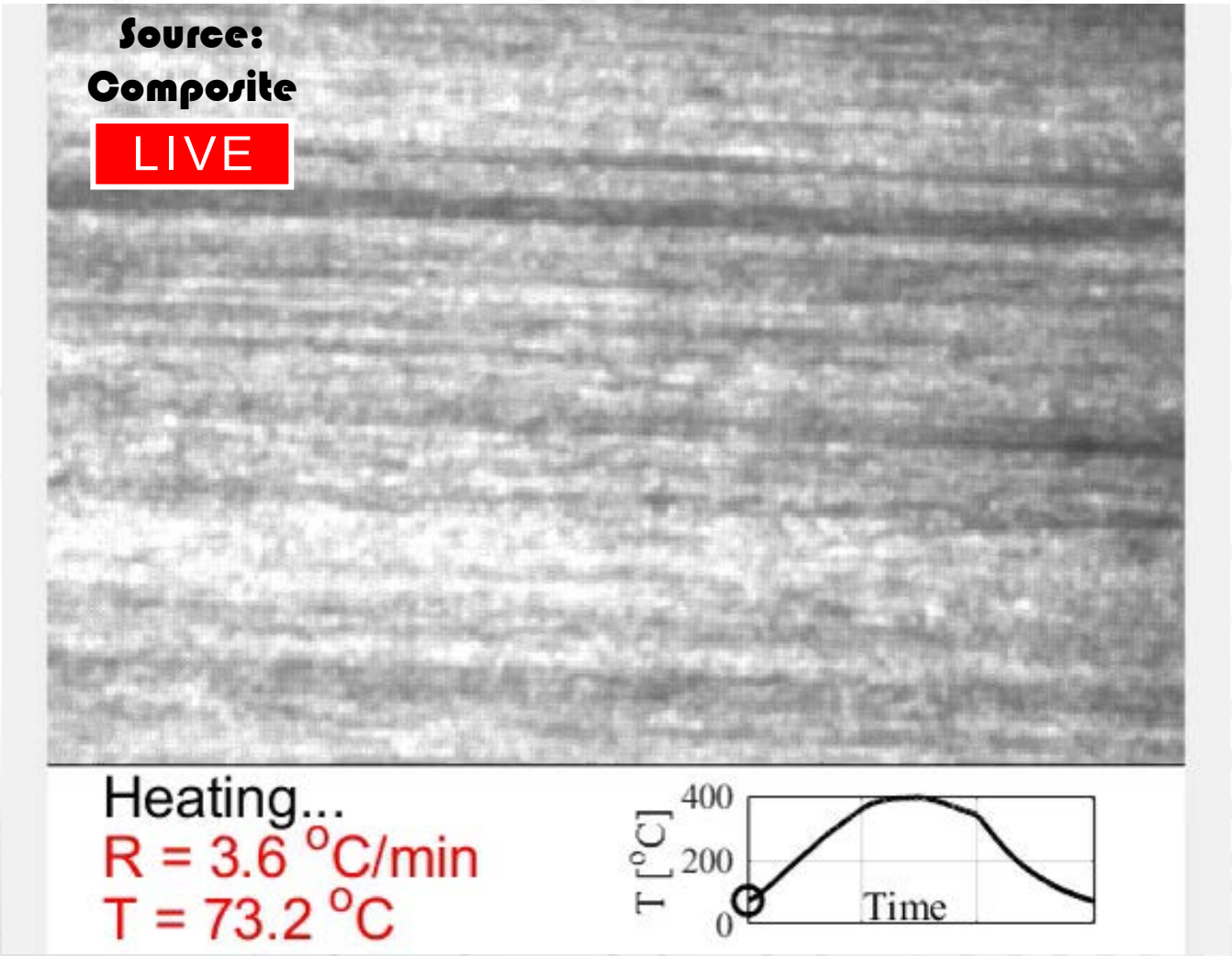


Real-time observation of waviness formation



Real-time observation of waviness formation

- Heating
  - Melting point: reflectivity changes
- Cooling
  - Waviness forms
  - Crystallization (reflectivity change)
  - Waviness formation stops
- Formation between $T_{\max}$ and T_{cryst}



Underlying mechanisms for waviness formation

- During consolidation of laminates, waviness forms:
  - During cooling
  - Between the processing temperature and the crystallization temperature (for semi-crystalline TPCs)

- Tool-ply interaction
  - Thermal expansion?
  - Friction?

Characterization of fiber waviness

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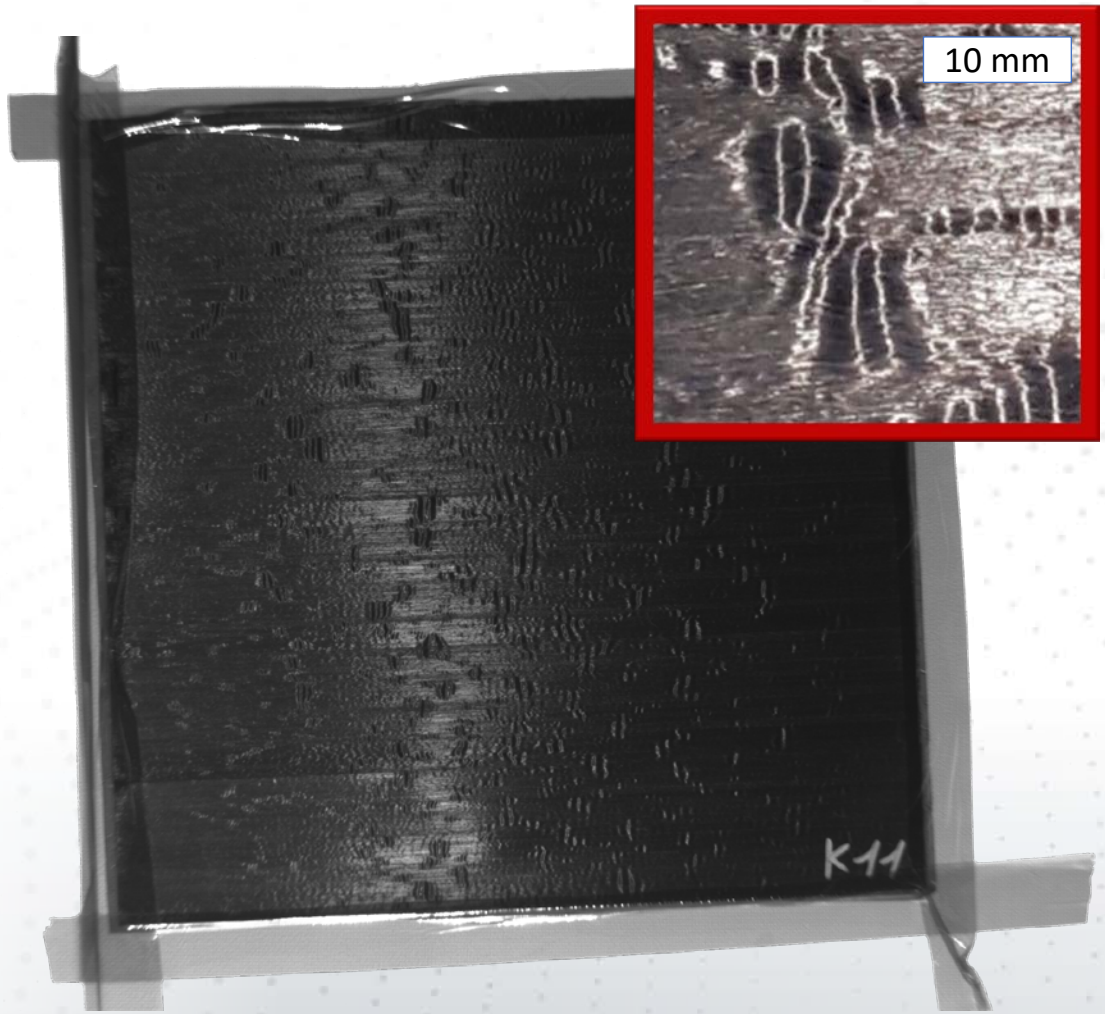
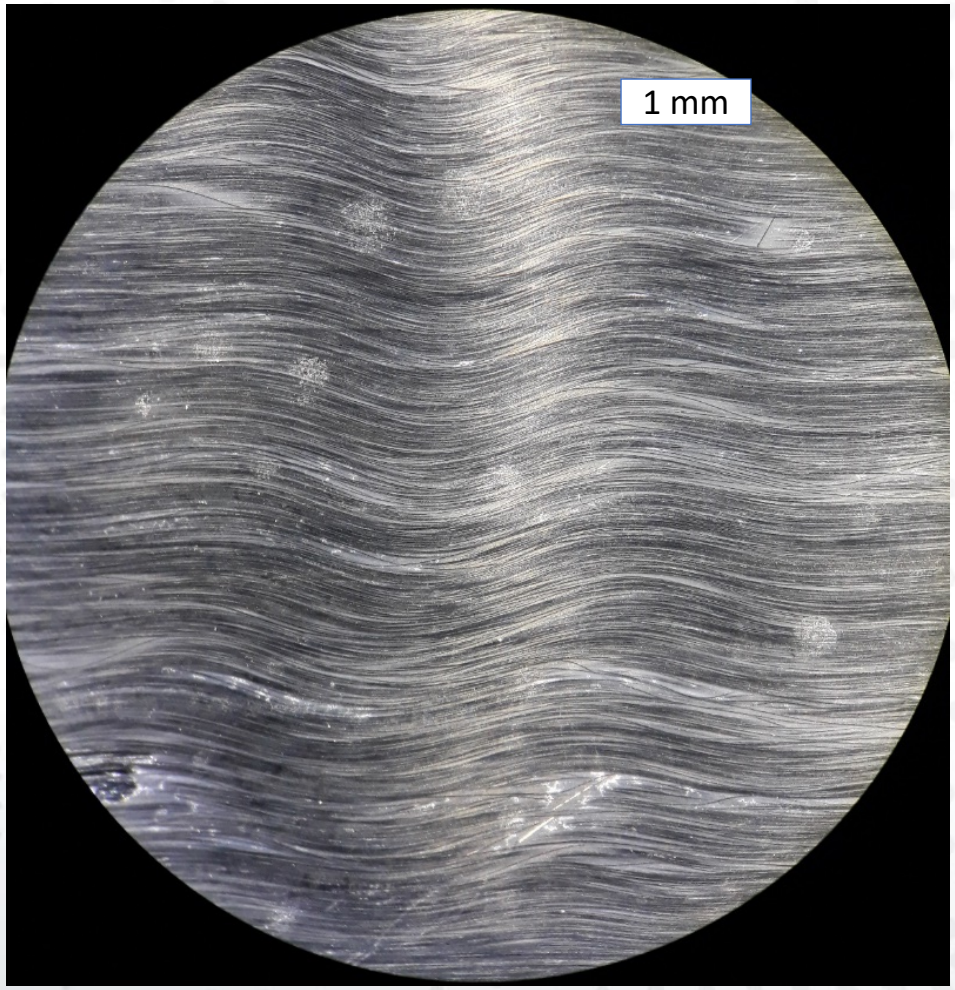
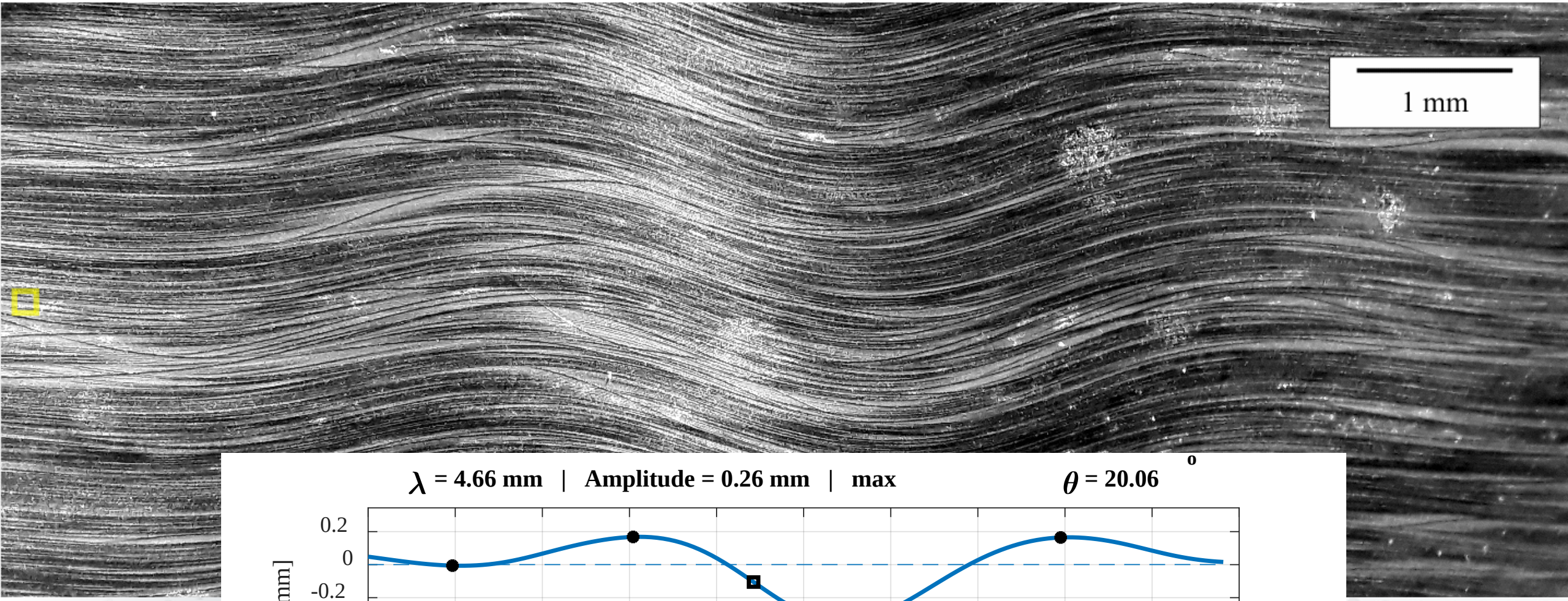




Characterization of fiber waviness



Tool-ply interaction

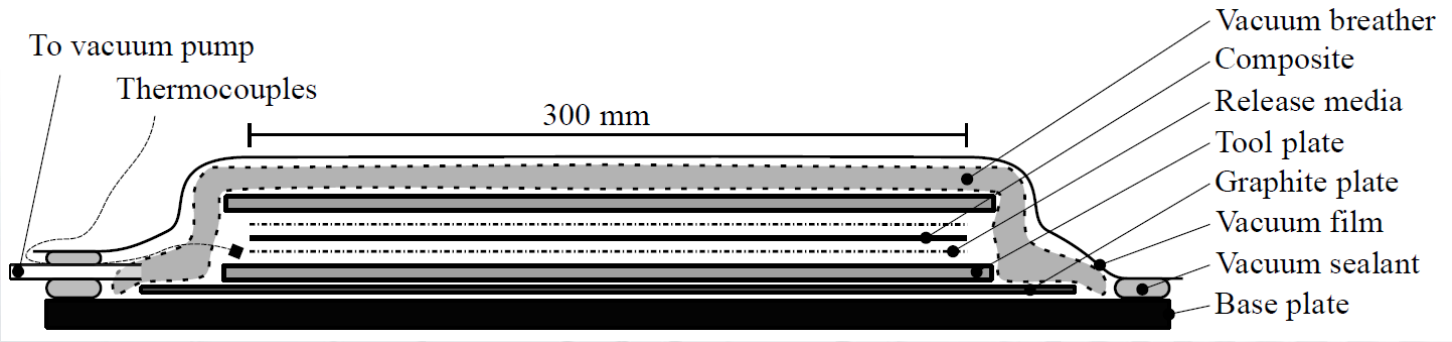
Processing variables

Flat laminate consolidation

- ✓ Waviness formation interval identified ($T_{max} - T_{cryst}$)
- ✓ Characterization method available

- ➢ Tool plate material
  - Role of tool coefficient of thermal expansion
- ➢ Release media
  - Role of tool-ply friction
- ➢ Consolidation temperature
  - Role of thermal strain
- ➢ Laminate size

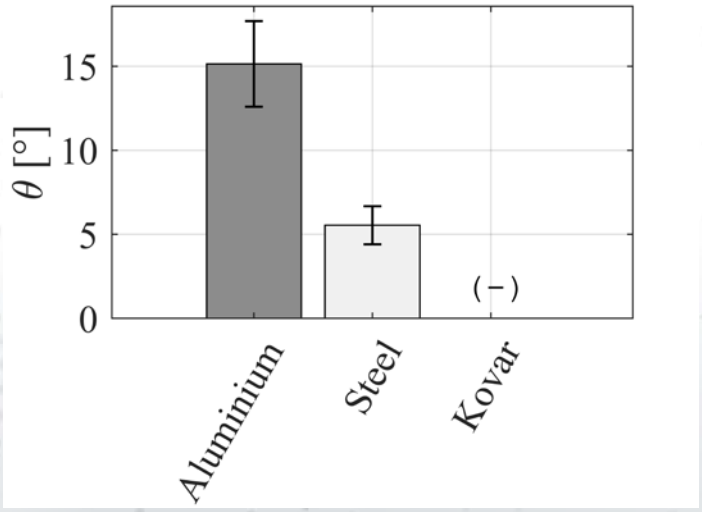
300 mm x 300 mm single ply
1 bar vacuum bag
385 °C

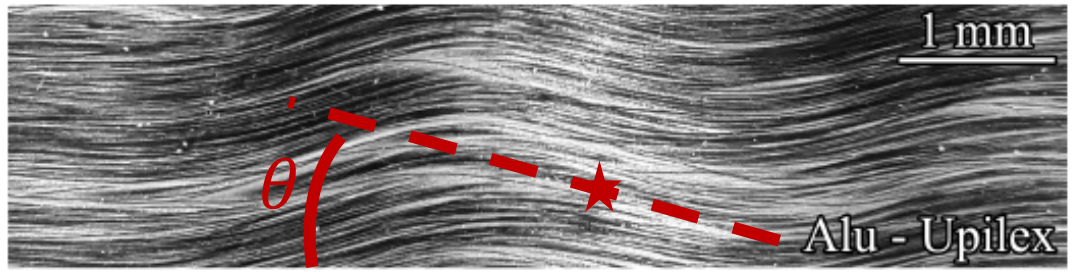


Tool plate material

High CTE -> High misalignment angle

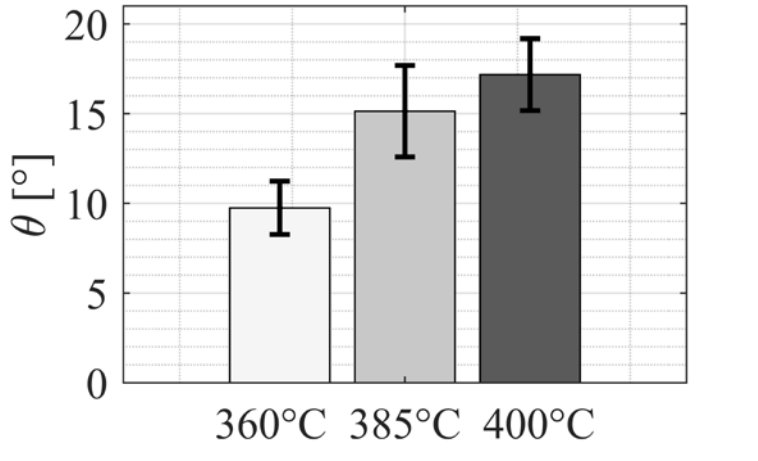
Tool plate material	Thermal expansion @ 20 ℃ $[10^{-6}\ \mathrm{K}^{-1}]$	Thermal expansion @ 300-400 ℃ $[10^{-6}\ \mathrm{K}^{-1}]$
Aluminium (1050)	22	28.9
Steel (AISI 430)	11	12.6
Kovar	5	5





Consolidation Temperature

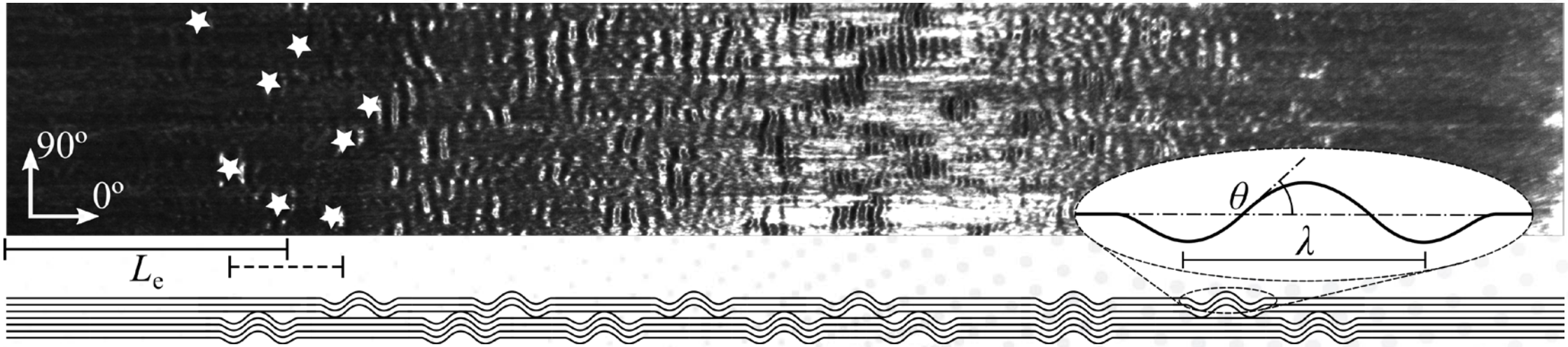
Parameters
Aluminium tool plates
Upilex 25S release film
300 mm x 300 mm single ply

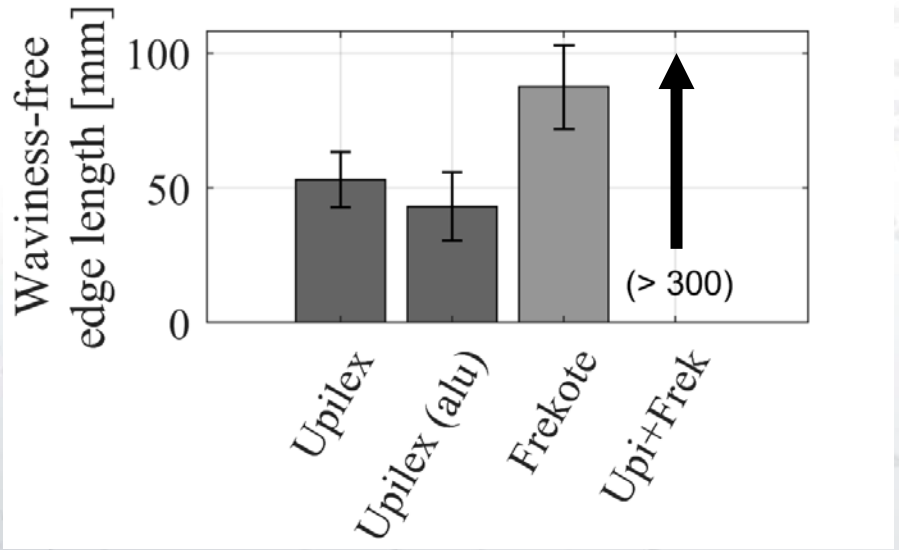


High consolidation temperature -> High misalignment angle

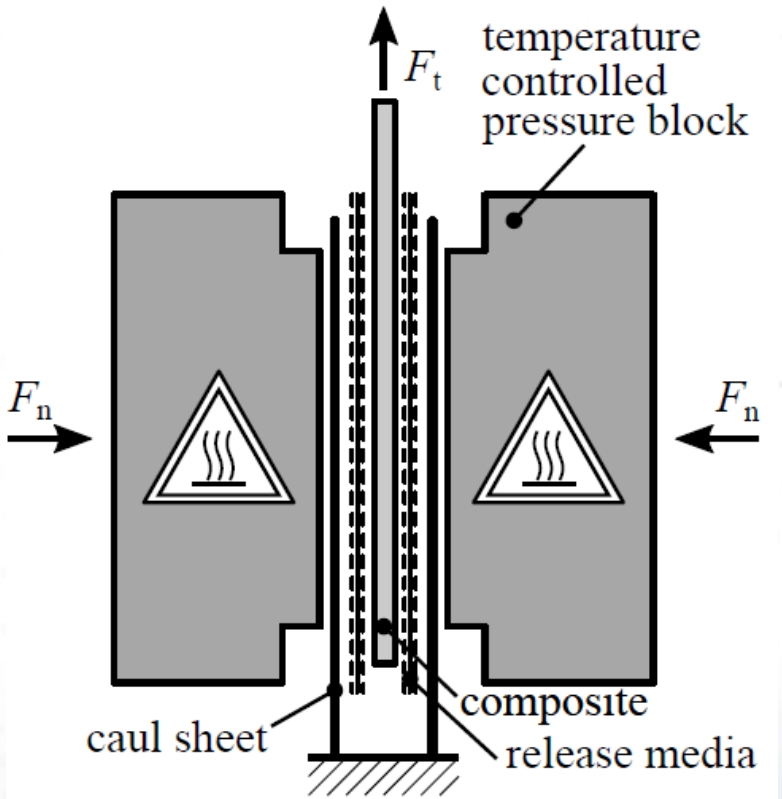
Release media

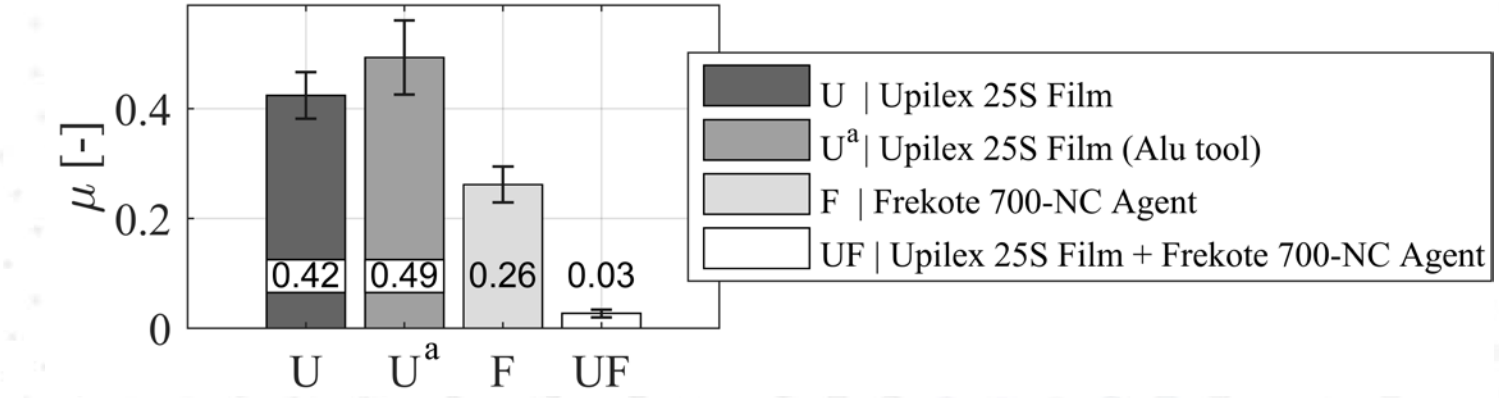
Waviness-free edge length

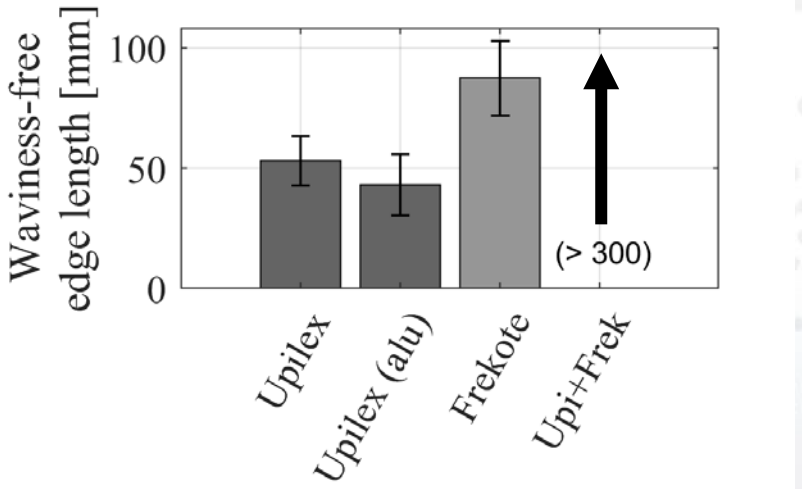




Tool-ply friction



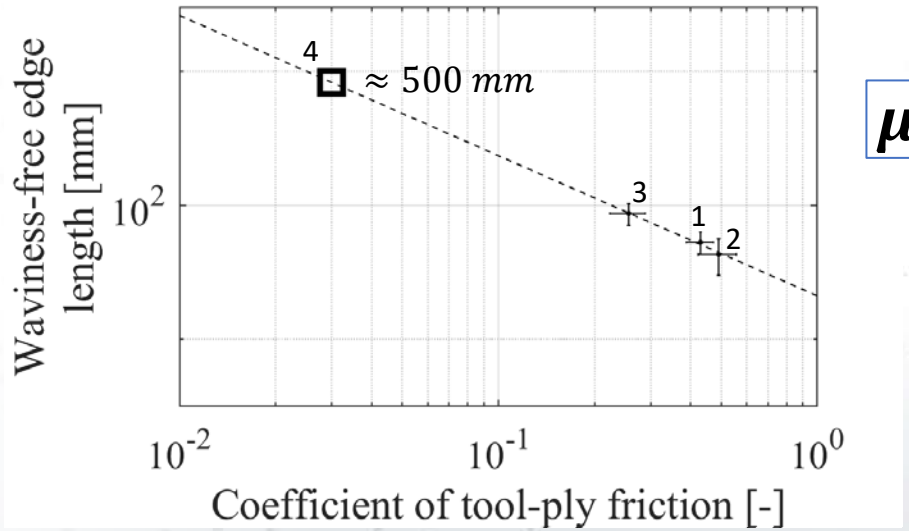




Low CoF → High waviness-free edge length

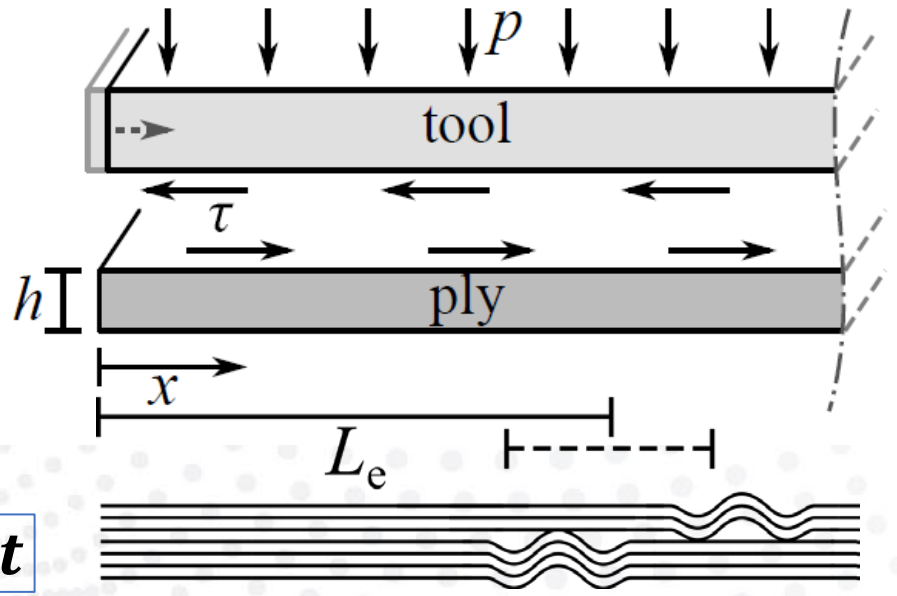
Modeling

Experiment #	Tool plates	Release combination	μ [-]	L_e [mm]
1	Steel	Release film	0.42 (0.043)	53 (10)
2	Aluminium	Release film	0.49 (0.067)	43 (13)
3	Steel	Release agent	0.26 (0.033)	87 (16)
4	Steel	Release film + agent	0.03 (0.007)	>300

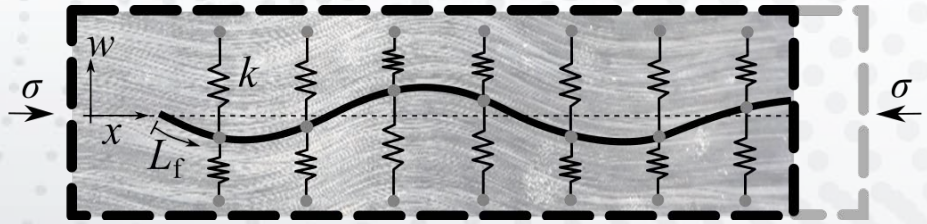


$$\mu \cdot L_e = constant$$

$$L_e = \frac{h\sigma_{crit}}{2\mu p}$$



$$\sigma_{\text{crit}} = \frac{2}{h}\int_0^{L_e} \mu p \, dx \approx \sigma_{\text{crit}} = \frac{2\mu p L_e}{h}$$



Conclusion

Observations

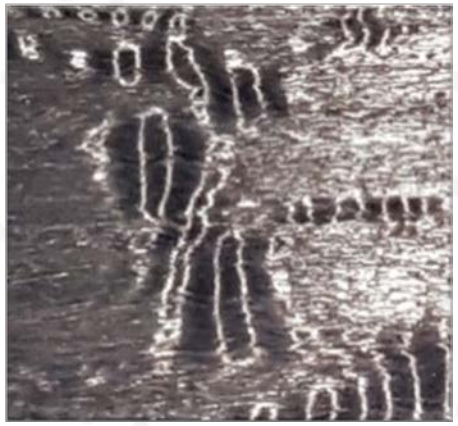
High consolidation temperature -> High misalignment angle

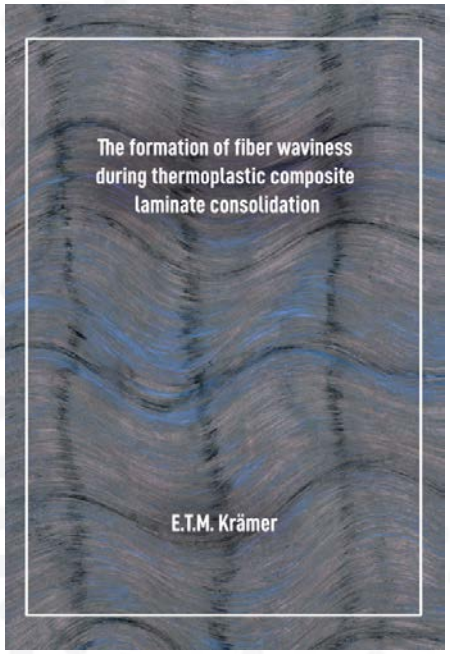
High CTE -> High misalignment angle

Low CoF → High waviness-free edge length

During consolidation of laminates

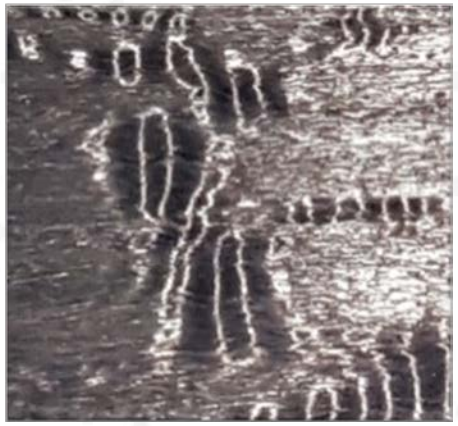
- Waviness forms during cooling
- Waviness forms between T_{max} and T_{cryst} for semi-crystalline TPCs
- Tool-ply friction is a key parameter

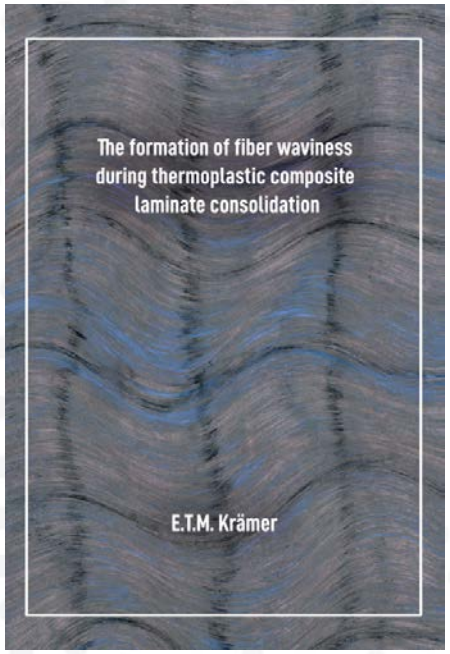




Conclusion

Manufacturing guidelines





- Low consolidation temperature
  - Limited by proper ply bonding
- Low tool CTE
  - Requires investment
- Low CoF
  - Possible with release film + agent
  - Limited to single curved parts
  - More research into surface treatments for high temperatures ($\approx 400°C$)