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NUMERICAL INVESTIGATION OF THE CONTINUOUS FIBER GLASS DRAWING PROCESS

Q. Chouffart and V. E. Terrapon
Multiphysics and Turbulent Flow Computation Research Group
University of Liège, Belgium

Université de Liège

P. Simon
3B The fibreglass company – Binani Group, Belgium

Binani 3B the fibreglass company
BRAJ BINANI GROUP

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Outline

- **Motivation**
- Physical model
- Numerical investigation
- Conclusion & future work

Motivation & objectives

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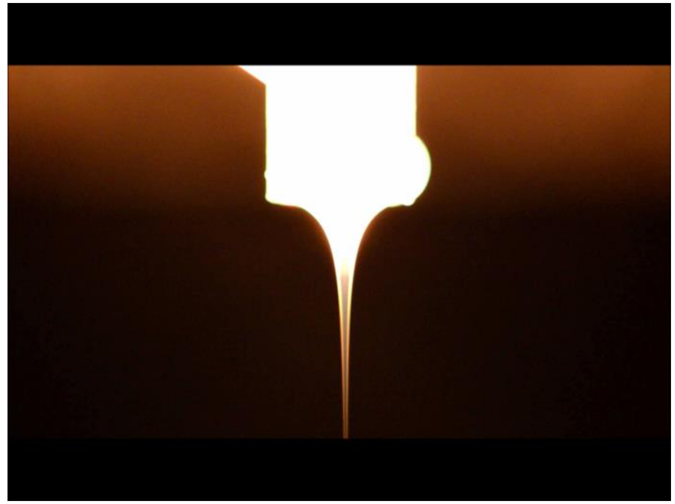
Main challenge of the process: **fiber breakage**

- **Shut down** of forming position
- Unrecyclable glass **waste**
- **Barrier** to optimization



Overall goal:
→ Understand the **fiber breaking**

Step 1 Physical modeling of forming glass

Step 2 Characterization of breaking mechanisms

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Fiberglass drawing process

General steps

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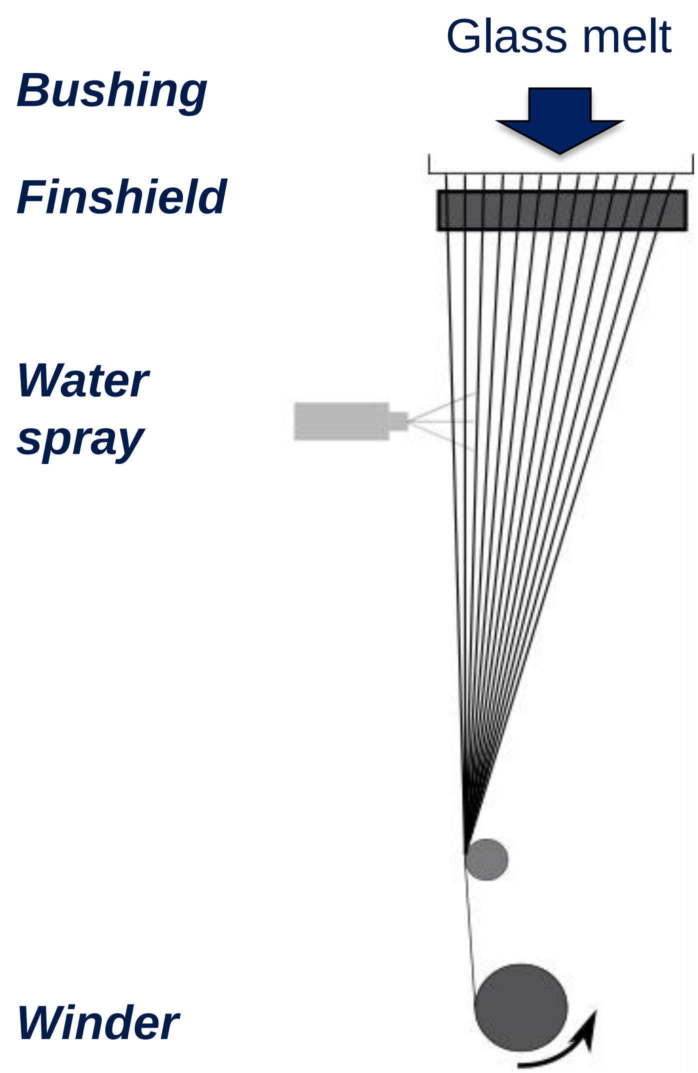

Four main steps

- Flow of glass melt through > 1000 holes

T ~ 1300°C

- Cooling by fins and water spray
- Coating
- Drawing by a winder

(20 m/s → ~10 µm fibers diameter)

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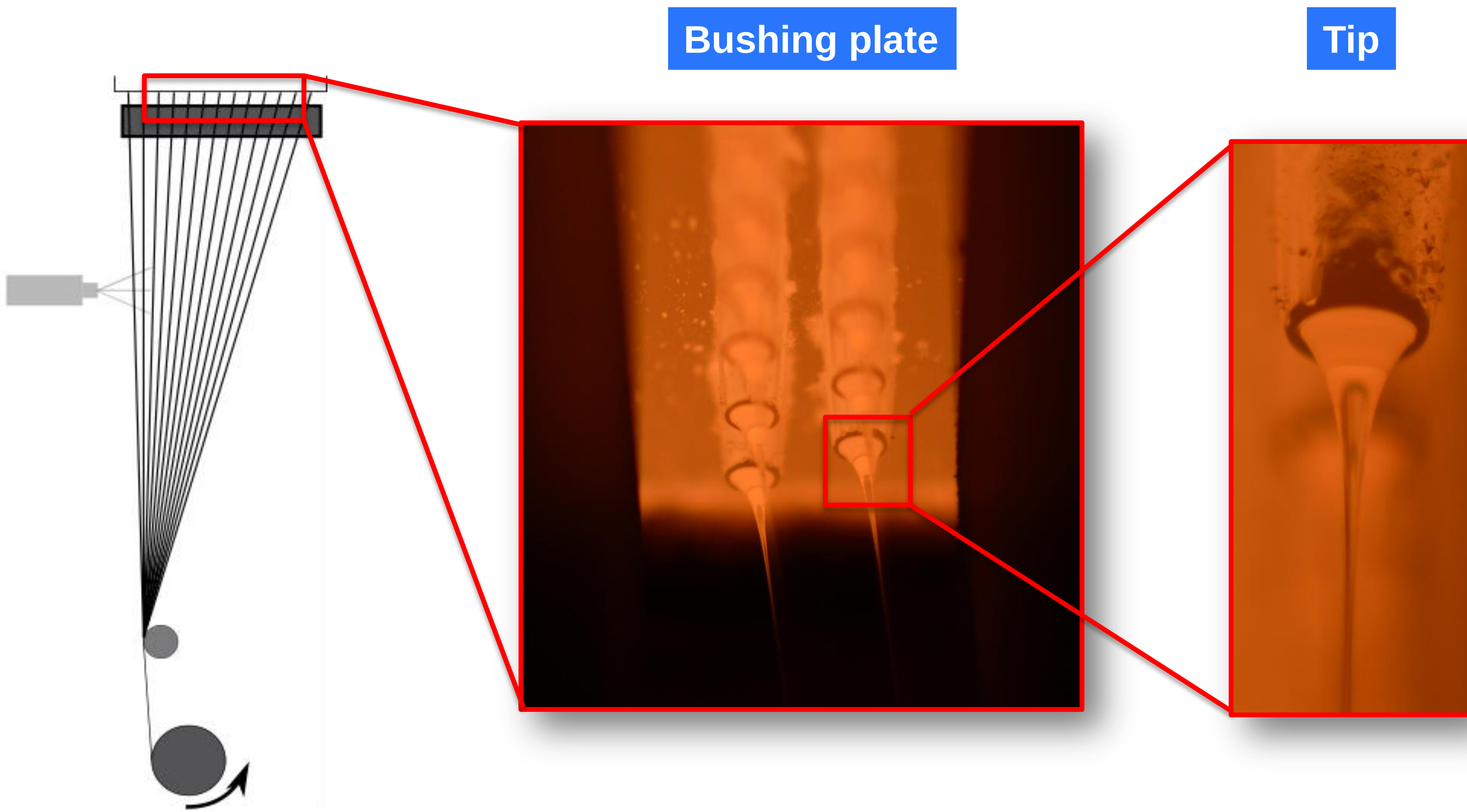
Fiberglass drawing process
Bushing plate & tips



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Physics of the forming of a single fiber

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Glass state

Rheology ↔ **Heat transfer**

Coupling

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Physics of the forming of a single fiber

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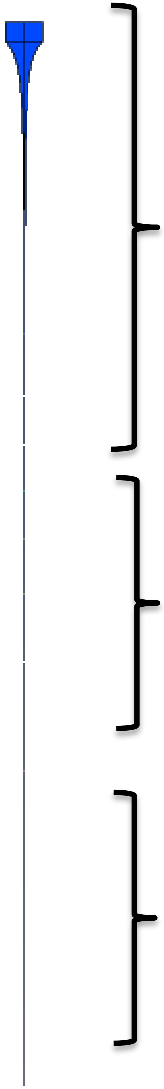
Glass state	Rheology	Heat transfer
Glass melt $T > T_g$	Newtonian viscous flow	Inside the fiber: ***Conduction & Radiation*** Around the fiber: ***Convection & Radiation***
Glass transition $T \approx T_g$	Viscoelastic flow	Inside the fiber: ***Conduction*** Around the fiber: ***Convection***
Glassy state $T < T_g$	Elastic solid	Inside the fiber: ***Conduction*** Around the fiber: ***Convection***

Physics of the forming of a single fiber



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Physical model

Governing equations

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Mass conservation:

$$\frac{D\rho}{Dt} = 0$$

Momentum conservation:

$$\frac{D(\rho \boldsymbol{v})}{Dt} = \nabla . \boldsymbol{\sigma} + f$$

Energy conservation:

$$\frac{D(\rho C_p T)}{Dt} = \sigma : \nabla \boldsymbol{v} - \nabla . (\boldsymbol{q}_{cond} + \boldsymbol{q}_{rad})$$

Assumption: Internal radiation → neglected

Physical model
Governing equations

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Newtonian flow:
$\sigma = -p\mathbf{I} + 2\eta\mathbf{D}$

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$$\sigma = -p\mathbf{I} + 2\boldsymbol{\eta}\mathbf{D}$$

coupled through viscosity

Fulcher law
$$\eta = 10^{-A + \frac{B}{T - T_0}}$$
(η = dynamic viscosity)

Assumption: Internal radiation → neglected

Physical model
Boundary conditions

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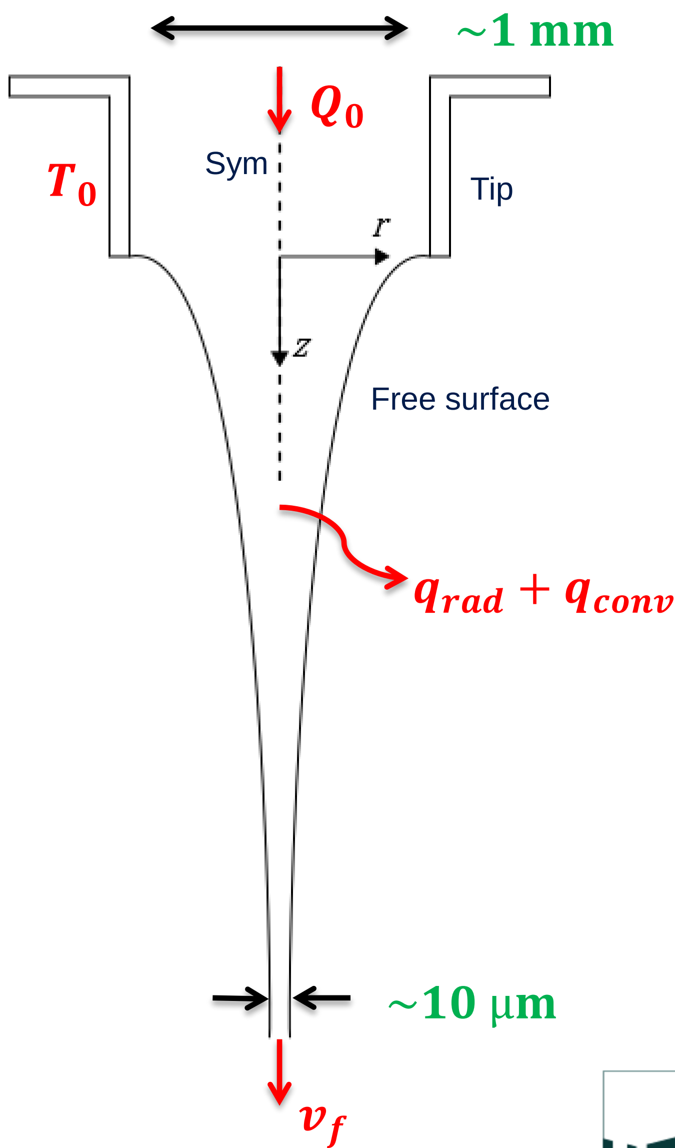
- **At tip**:
  - *Volumetric flow rate (Poiseuille law)*
  - T_0 *constant*
- **At surface**:
  - *Free surface conditions & surface tension*
  - $q = \varepsilon\sigma(T^4 - T_{ext}^4(z)) + h(z)\big(T - T_{ext}(z)\big)$

Radiation **Convection**

- **At outlet**: *Drawing velocity*



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Solution of the physical model

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Physical Model

1D
Elongational model

Analytic and ODE solved with the *Finite Difference Method*

- ***Improve convergence***
- ***Less accurate***
- ***Global information***

2D
Axisymmetric model

Solved with the *Finite Element Method*

- ***More accurate***
- ***Local information***

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Numerical investigation

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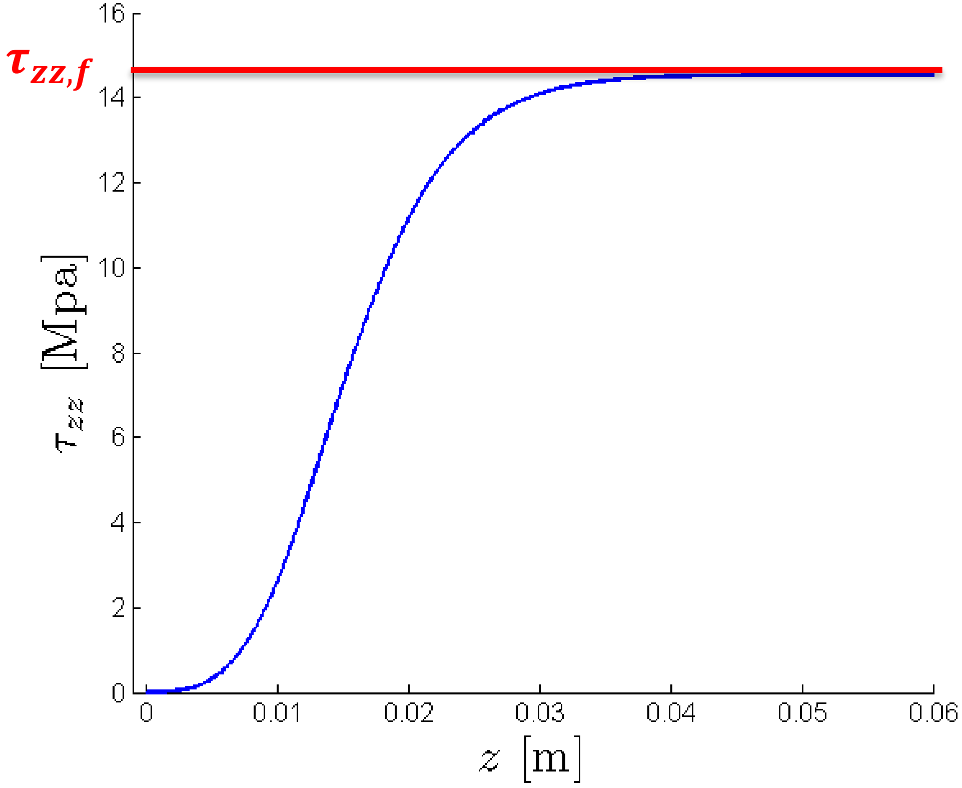
3. Axial stress



$$\tau_{zz,f} = \frac{3}{\varphi_g} v_f \ln\left(\frac{v_f}{v_0}\right)$$

Stress depends on:

- **Diameter ratio**
- **Drawing velocity**
- **Fiber cooling**

Stress is a good indicator of the robustness

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Numerical investigation

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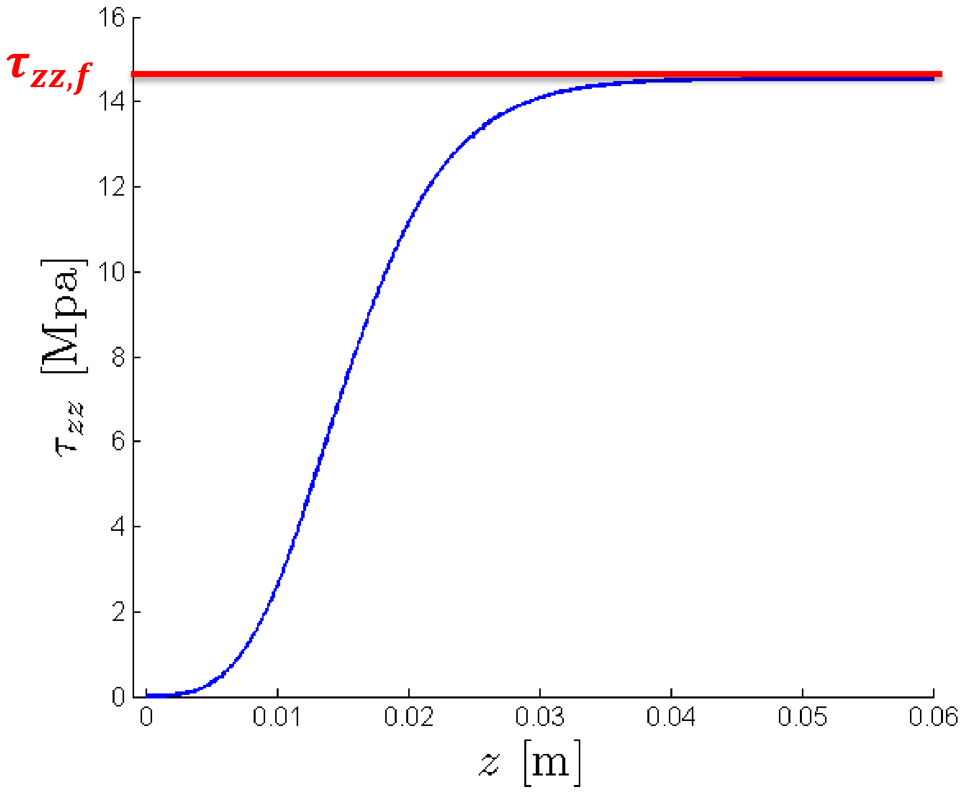
3. Axial stress



Key questions

- What are the **key process parameters** controlling the stress?
- How can the operating window be adjusted in order to reduce the stress?

Stress is a good indicator of the robustness

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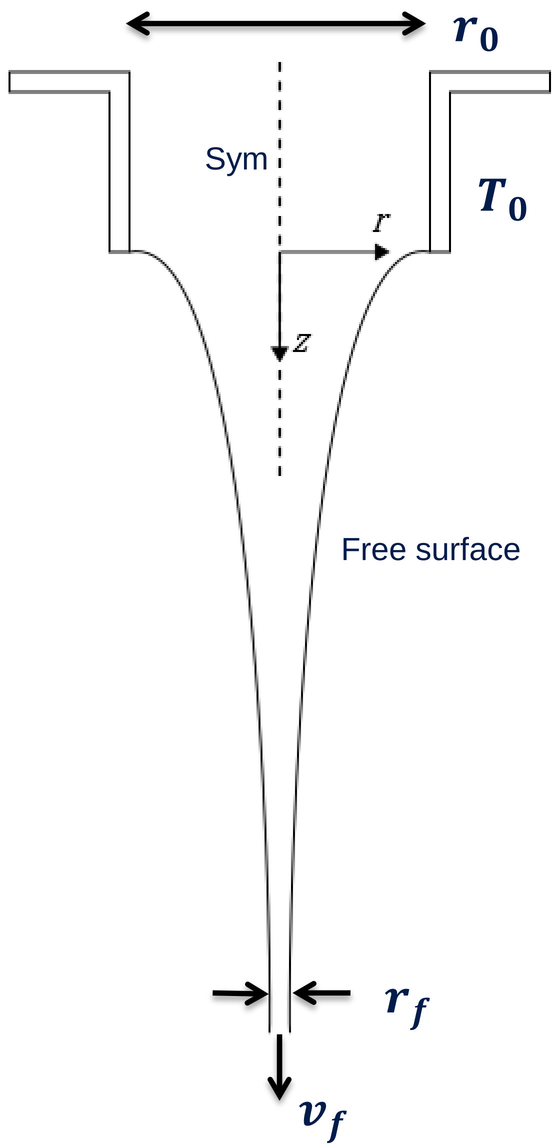
The control process parameters:

- **Tip temperature T_0** impacting φ_g and v_0
- **Tip radius r_0** impacting v_0
- **Drawing velocity v_f**
- **Glass height above the bushing plate** impacting v_0

How is the stress affected by these parameters?



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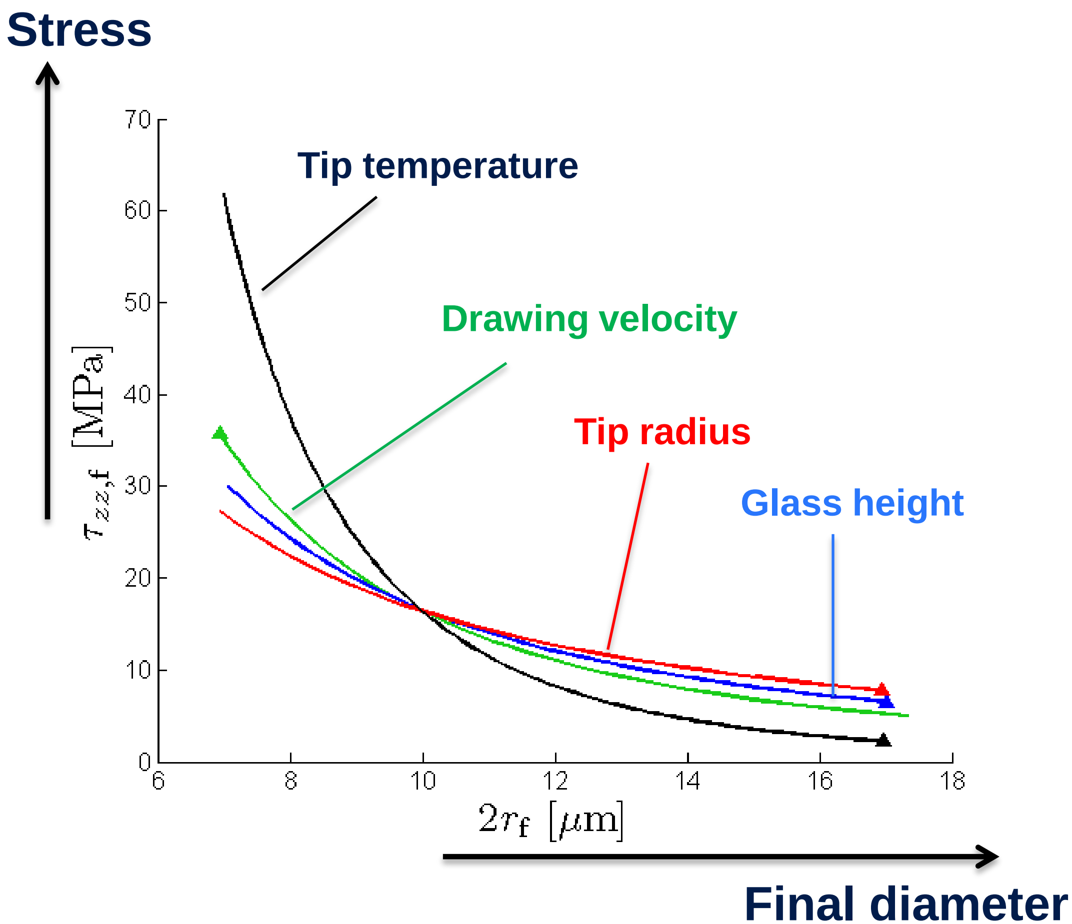
4. Stress sensitivity due to the variation of the control parameters

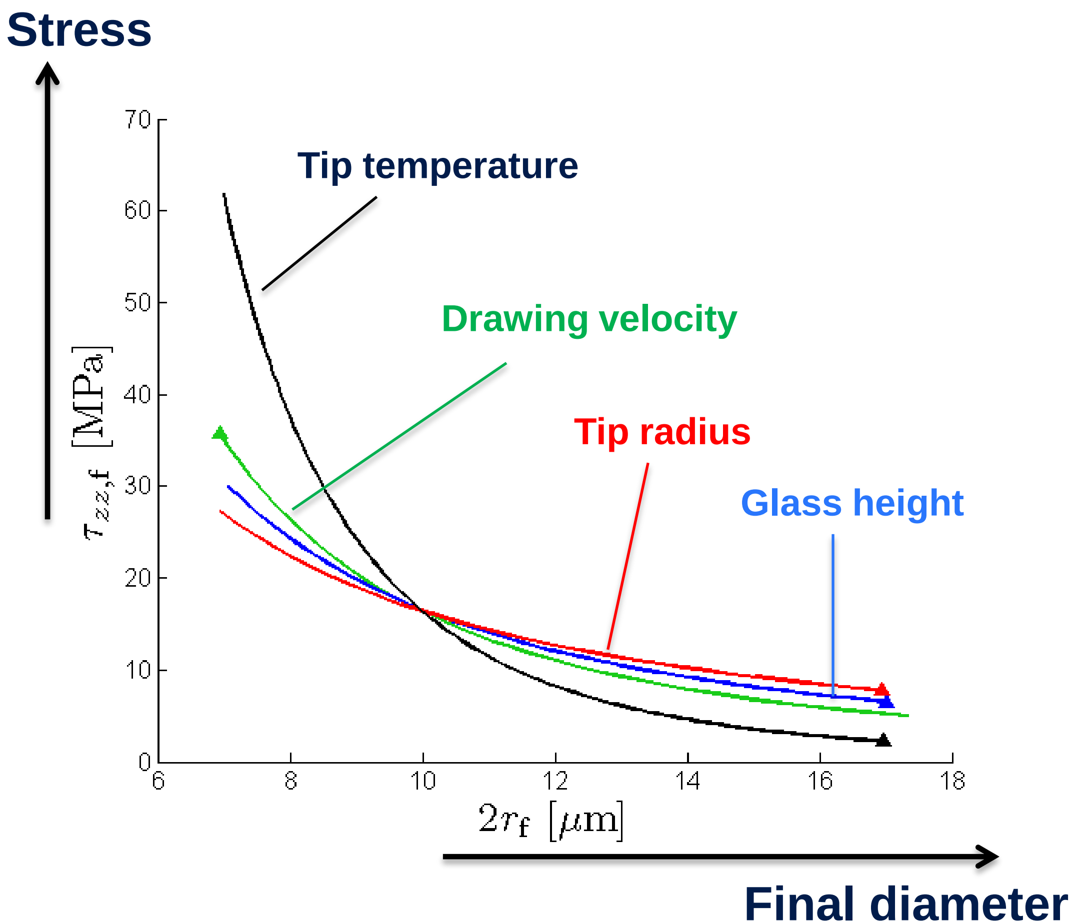


Sensitivity study

- Each parameter is varied independently, while keeping the others constant
- Range of variation is set to have the final radius between 7 and 17 µm

- **Stress increases** when the **diameter decreases**
- **Glass height** and **tip radius** have almost the **same effect**
- **Tip temperature** is the most **critical** parameter

4. Stress sensitivity due to the variation of the control parameters



- **Decrease in temperature** leads to a large **stress increase**
- The **opposite** is observed when the **temperature increases**

Numerical investigation

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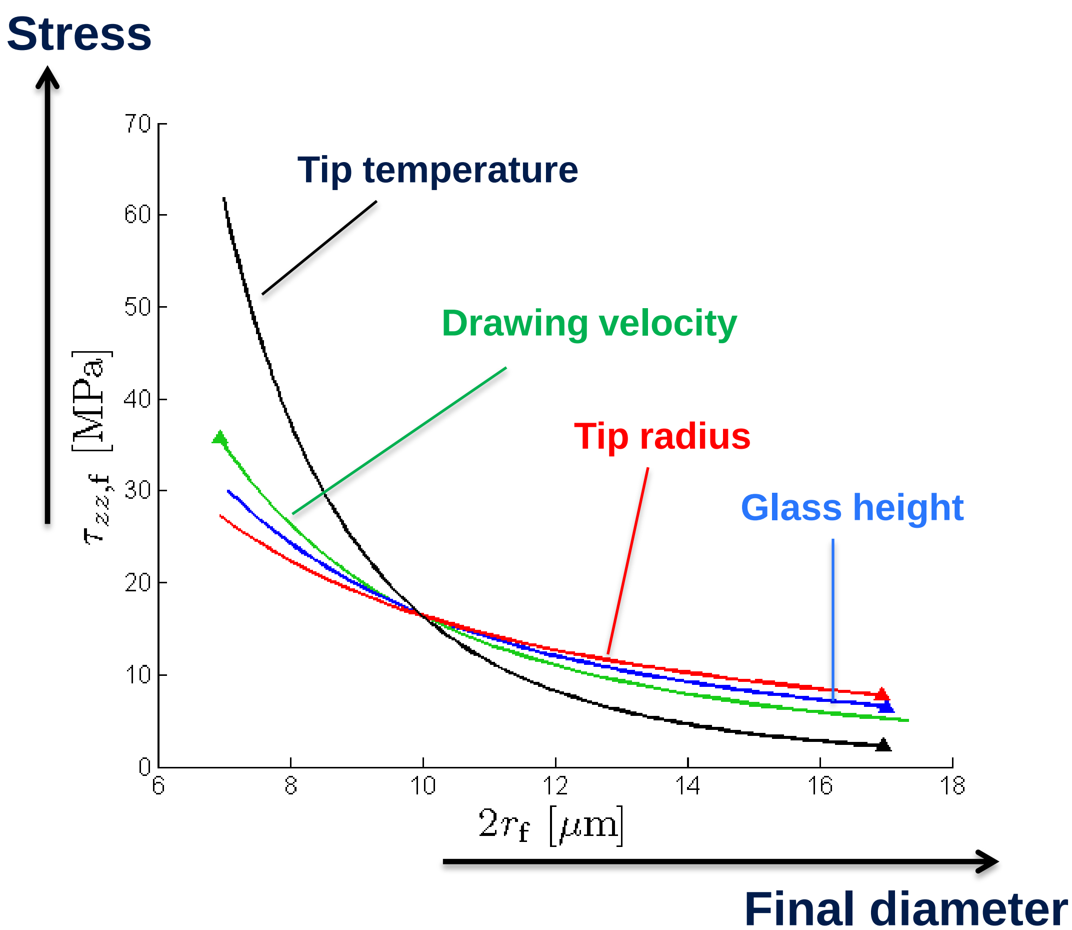

- **Decrease temperature** leads to a large **stress increase**
- The **opposite** is observed when the **temperature increases**

Given a **target radius**, what are the **velocity** and **temperature** leading to a lower stress?

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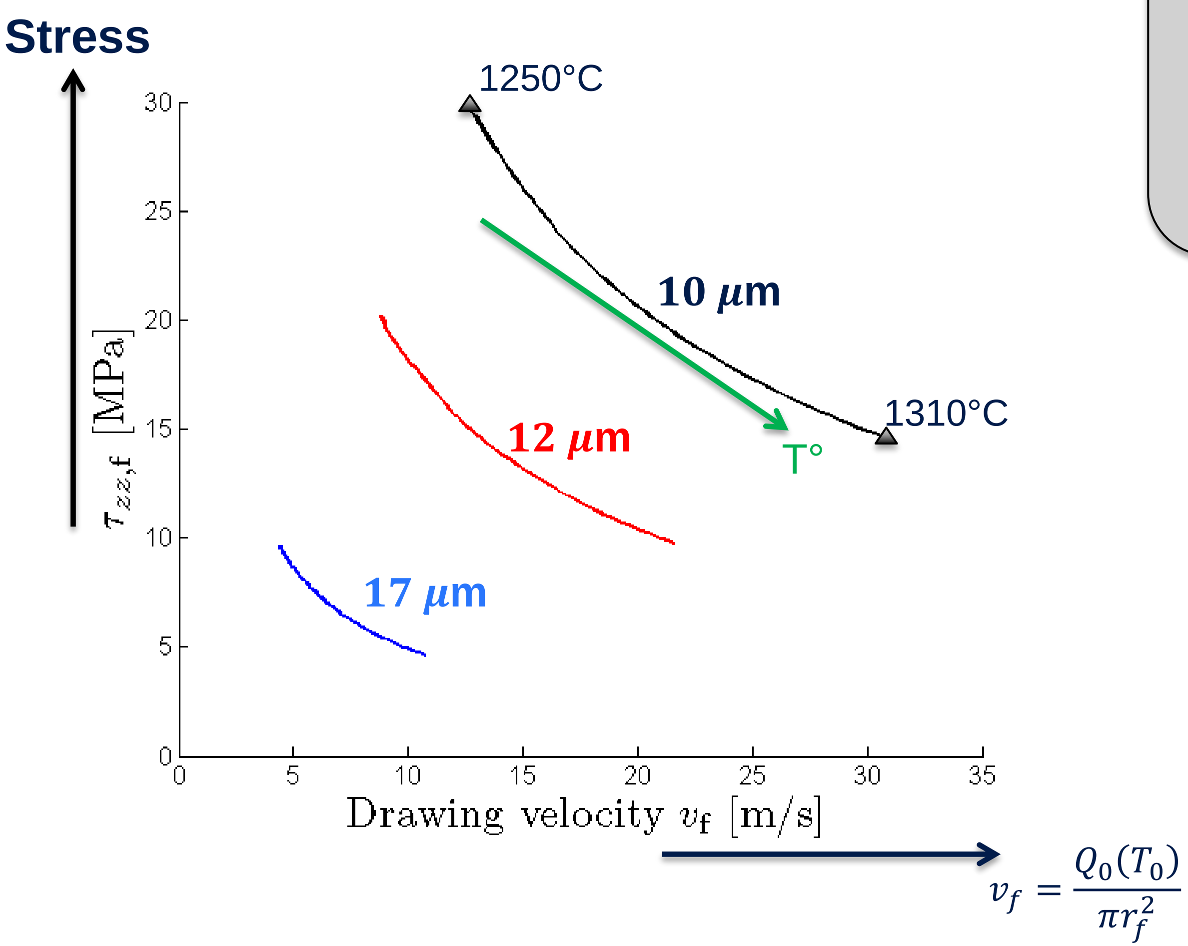
5. What is the optimal choice for the velocity and the temperature?



Drawing velocity

$$Q_0(T_0) = \pi r_f^2 v_f$$

$$\rightarrow \quad v_f = \frac{1}{\pi r_f^2} Q_0(T_0)$$

- **Smaller radius amplifies the impact of the temperature on the stress**
- **Increasing the tip temperature decreases the stress, even if the drawing velocity increases**

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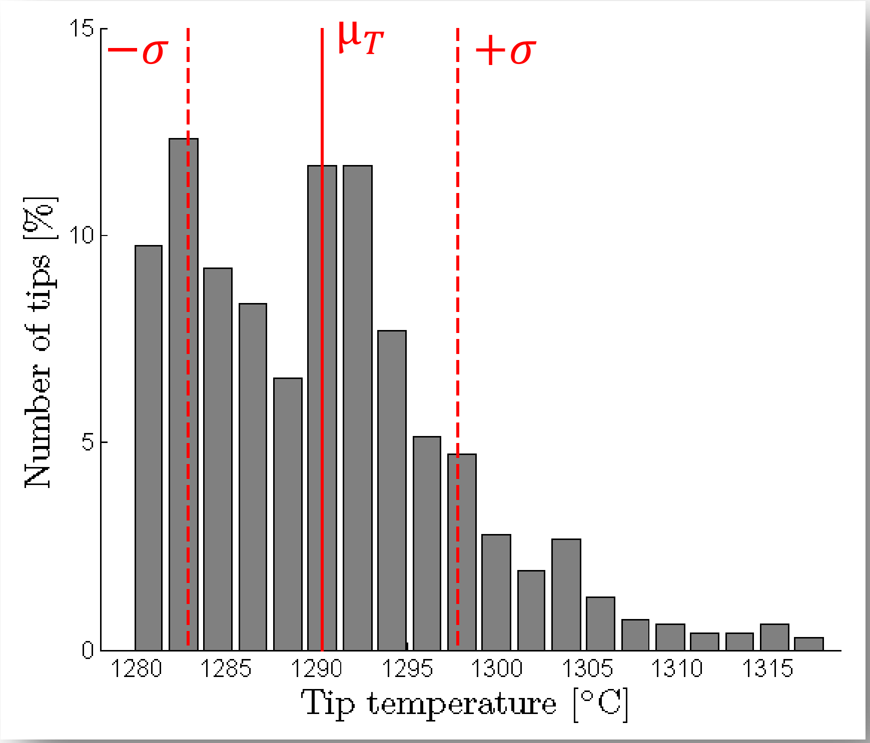
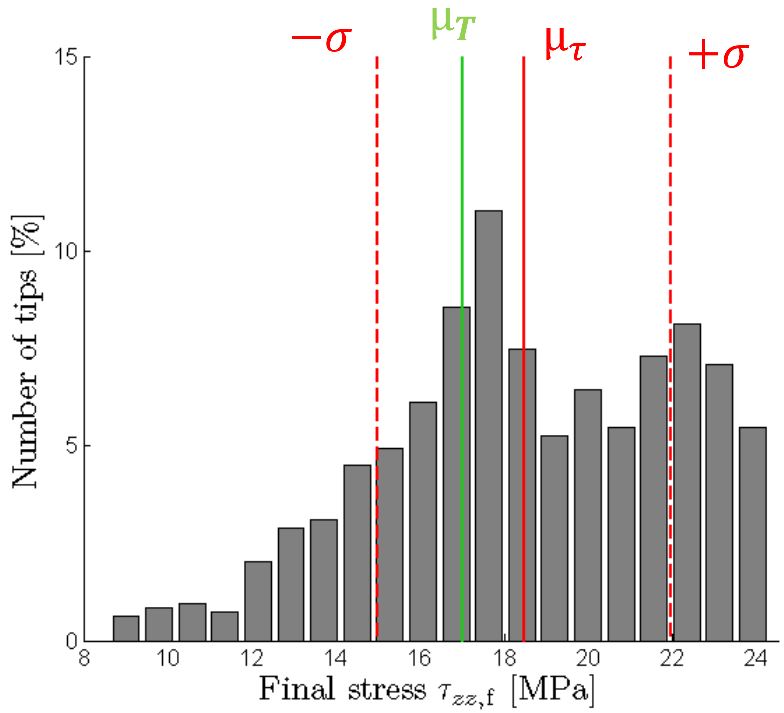
Bushing: problem statement

6. Temperature inhomogeneity on a 6000 tips bushing plate

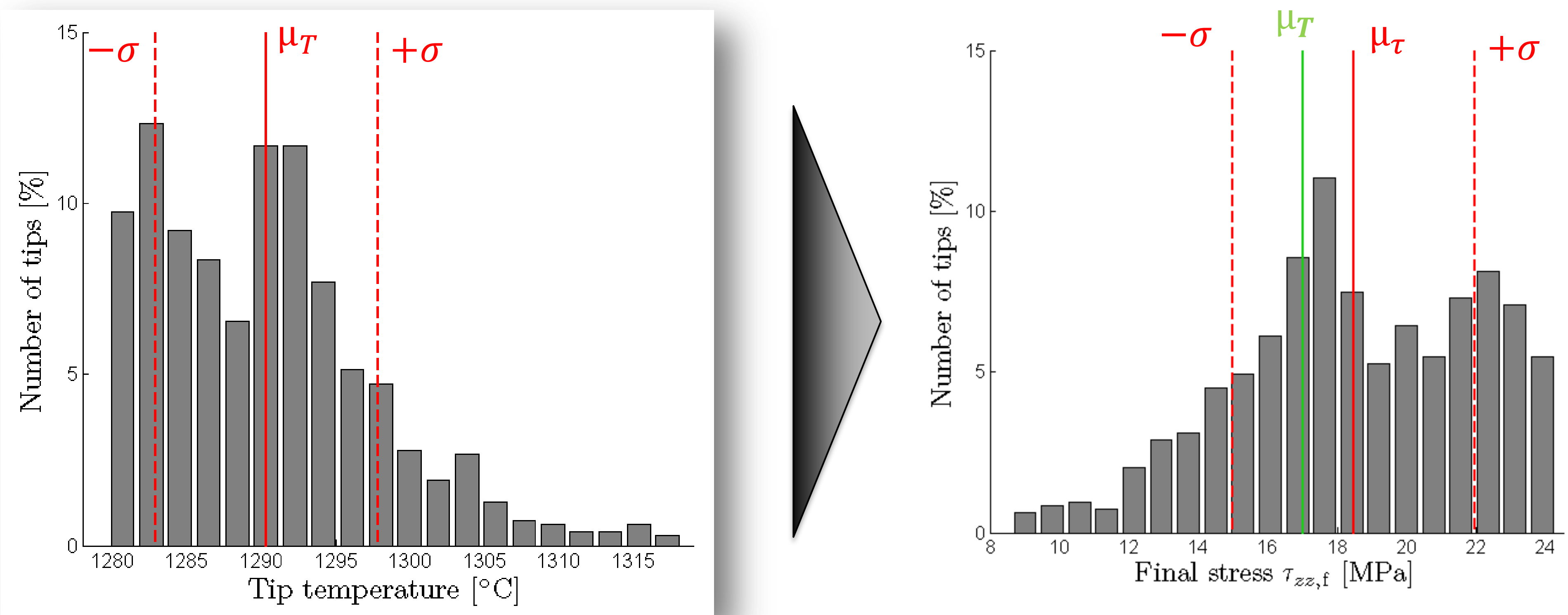




- **Temperature inhomogeneity** leads to a **distribution of fiber radius**
- And leads to a **large variation in stress**
- **Mean stress** is **larger** than the stress corresponding to the **mean temperature**

Bushing: problem statement

6. Temperature inhomogeneity on a 6000 tips bushing plate



→ Heat pattern on the bushing plate is critical

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Conclusion & further work

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Conclusion

- **Physical model** of single fiber drawing has been developed
- **Numerical solutions** help to **understand the process**
- **Fiber** forming is strongly affected by the **temperature at the tip**
- **Stress** is a good indicator to understand the **robustness** of the process
- **Temperature inhomogeneity** across the bushing plate leads to a **large distribution** of stress

Further work

- Add a **radiation model** for the heat transfer inside the glass
- Investigate the **glass transition** region
- Link the **breaking rate** with the stress

Acknowledgements

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