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Embedding Fiber Optic Sensors in SS316 Wrought Products Through Confined Rolling

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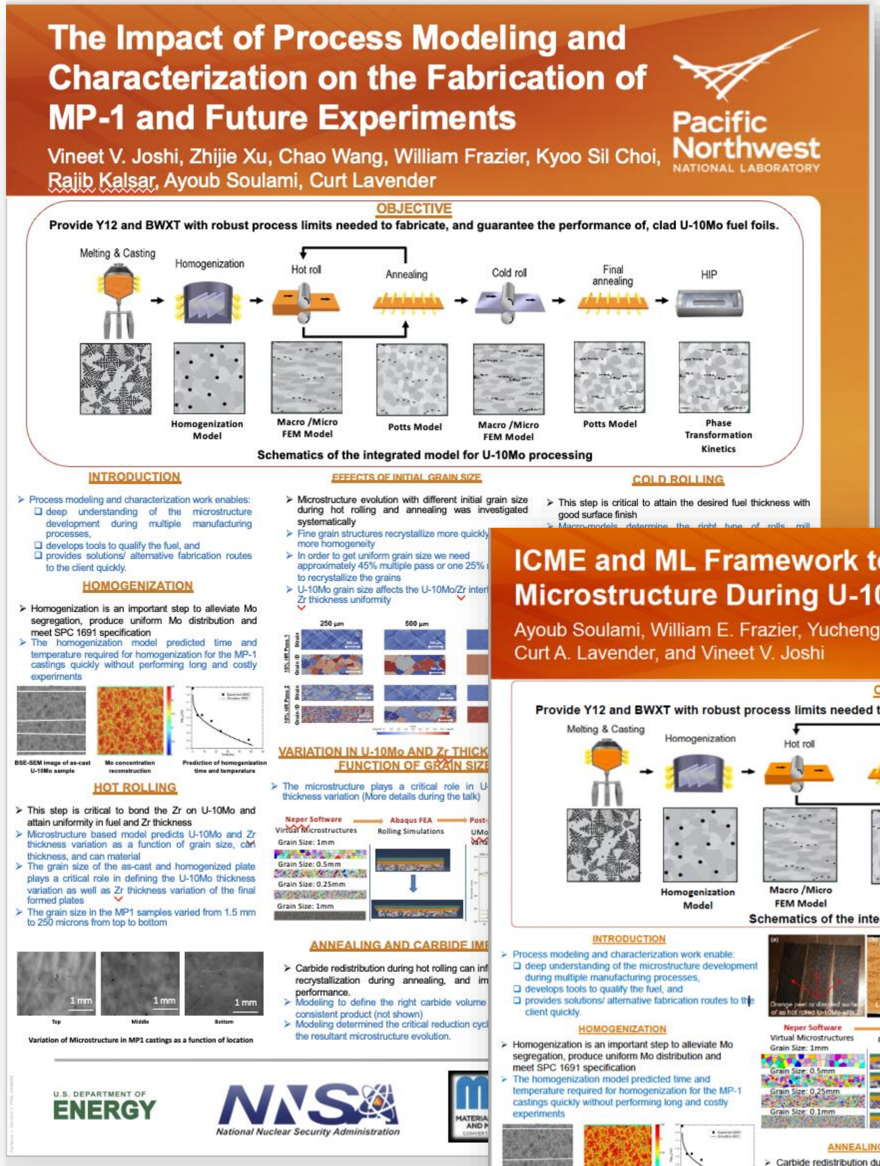
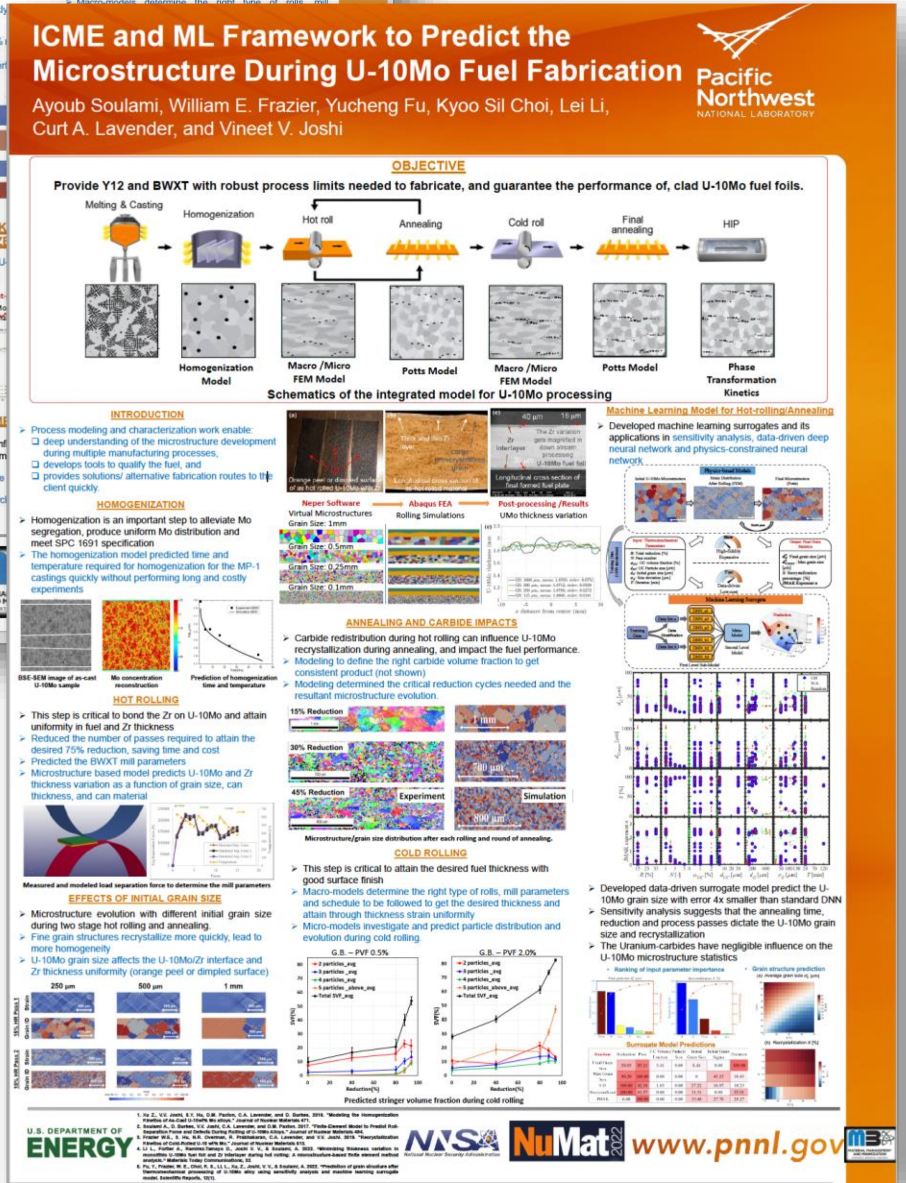
U.S. DEPARTMENT OF ENERGY BATTELLE

Outline

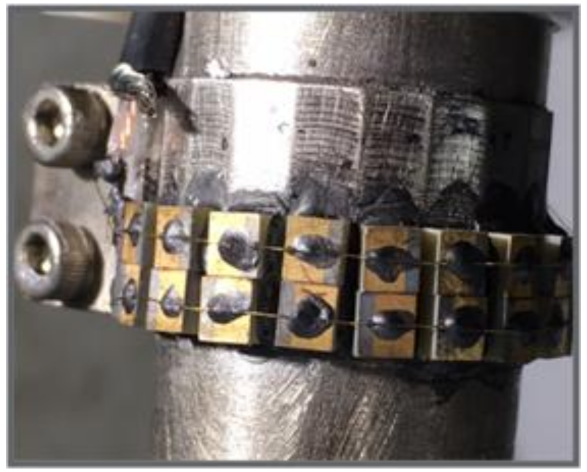
- Current State of the Art
  - Why Wrought Products
- 3 Approaches: Concept of Confined Rolling
- Performance Tests
- Approach 1:
  - Analytical Equations
  - Modeling
  - Experiments
- Approach 2:
  - Analytical Equations
  - Modeling
  - Experiments
- Expanding it to other known geometries and Shapes
- Conclusions



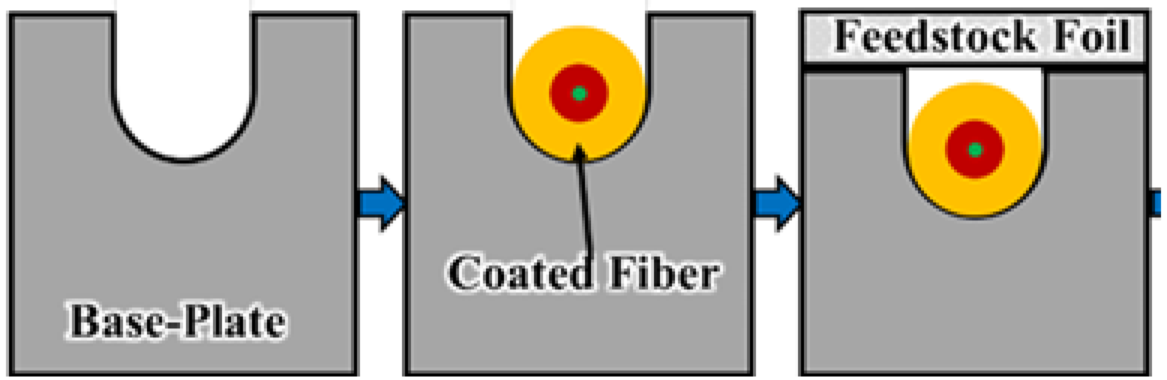


Current State of the Art and Concepts

Embedding sensors in wrought products has always been desired for a wide range of applications, especially, in harsh conditions and to detect off normal events.



Welding



Additive Manufacturing

- Sensors are glued/joined on external surfaces
- Drilling holes and embedding sensors and welding plates
- Embedding sensors in metal additive components

- ➢ Limited applications in harsh environments, looses integrity
- ➢ Component looses structural integrity and welded structure is not suitable in harsh environments
- ➢ Component has as-cast microstructure

❖ Wrought products are heavily used in nuclear and harsh environments

References

1. Functional fiber-optic sensors embedded in stainless steel components using ultrasonic additive manufacturing for distributed temperature and strain measurements, Additive Manufacturing 52 (2022) 102681.
2. Embedding sensors using selective laser melting for self-cognitive metal Parts, Additive Manufacturing 33 (2020) 101151.

Current State of the Art and Concepts: Materials and Processes Evaluated

Ultrasonic additive manufacturing (UAM)

Materials studied (Fiber coating):

- Al3003 (Al/Cu coated)
- Al6061 (Plastic coated)
- Al1100 (Bare single mode)
- **SS304 (Au coated)**
- **SS410 (No fiber)**
- 4130 steel (No fiber)

Direct Energy Deposition (DED)

Materials studied (Fiber coating):

- Inconel 718 (Cr/Ni/Cu coated)
- Tin alloys (Cu/Ni coated)

Selective laser melting (SLM)

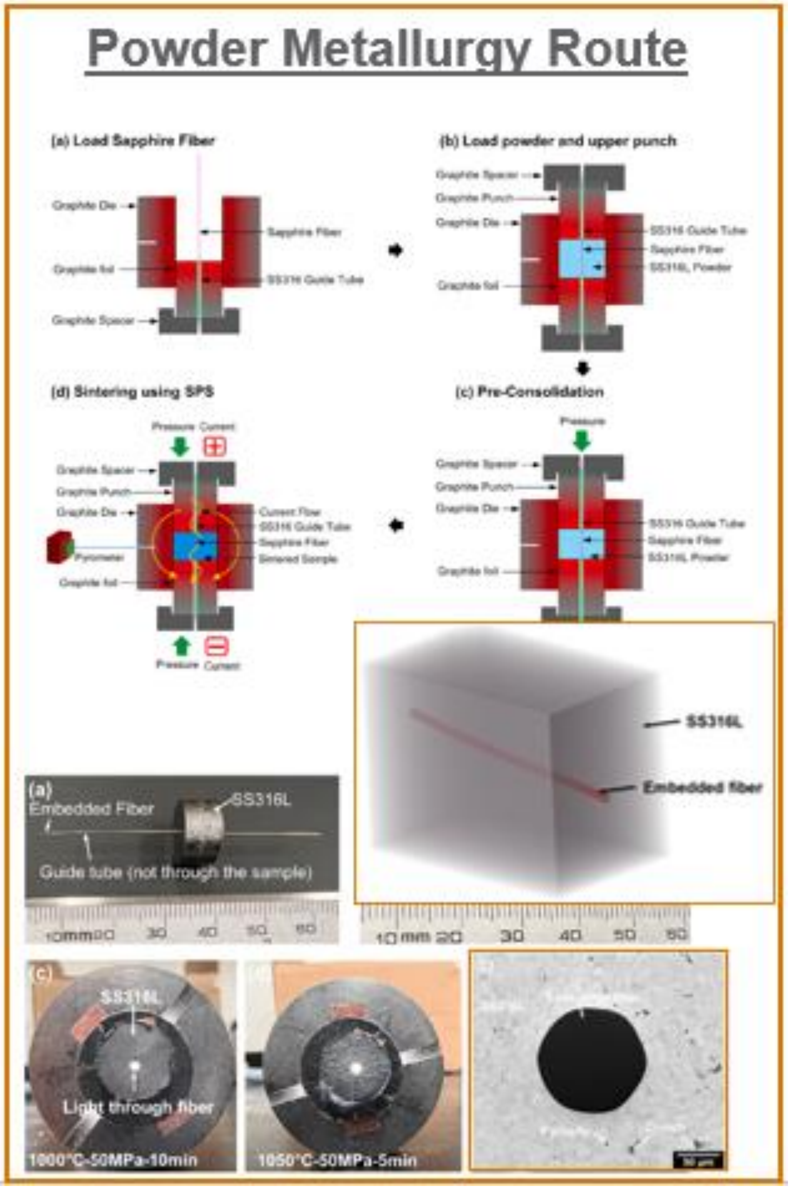
Materials studied (Fiber coating):

- **SS316 (Ni coated)**

Tungsten inert gas(TIG)

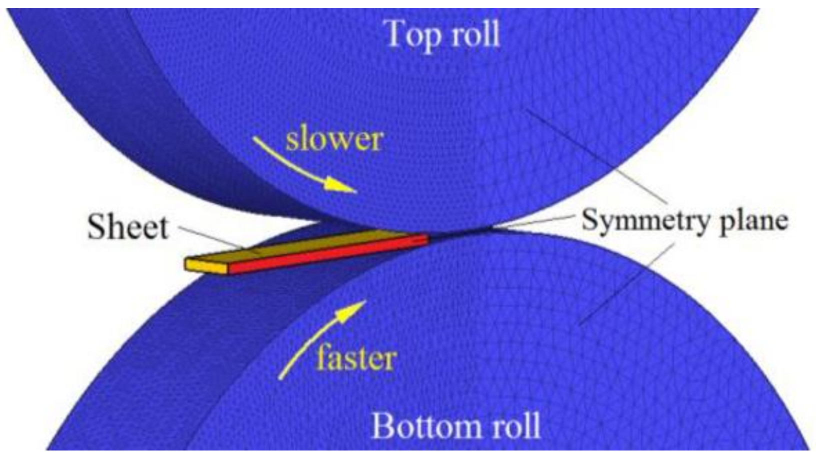
Materials studied (Fiber coating):

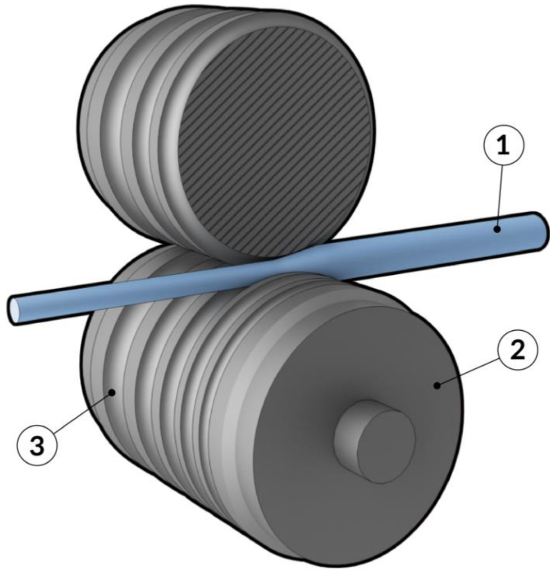
- Tin alloys (Cu/Ni coated)



Integrating fiber optic sensors into metallic components for sensing in harsh environments, Optics & Laser Technology, 170 (2024), 110188.

Big Challenge with Embedding Sensors in Wrought Products



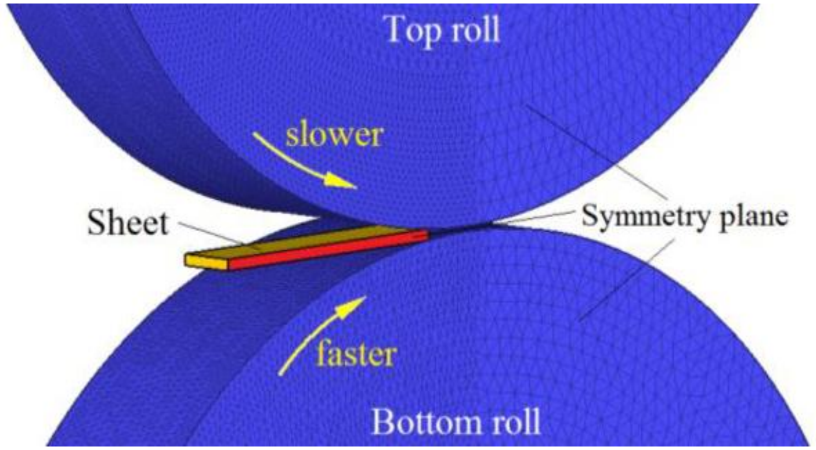


- Conventional processes such as rolling, forging, extrusion and pilgering introduce large plastic deformation and stresses
- These products are cheaper and faster to make
- Known technologies and products properties are well understood

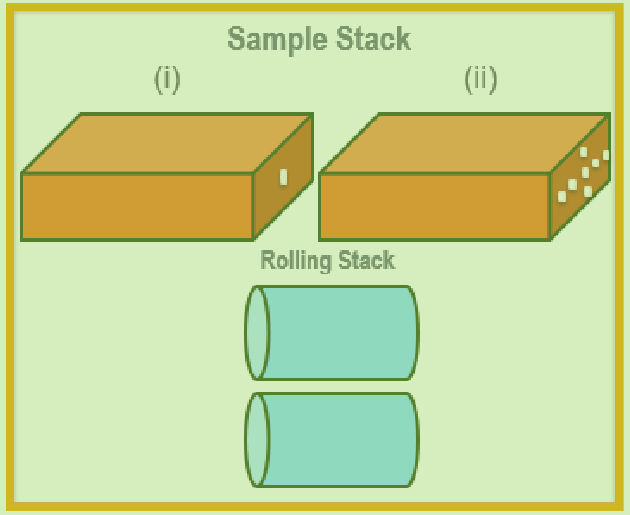
Preserving the structural integrity of the sensor

Systematically understanding the nature of stress and manipulating the deformation mechanism we can place/ embedded sensors in wrought products

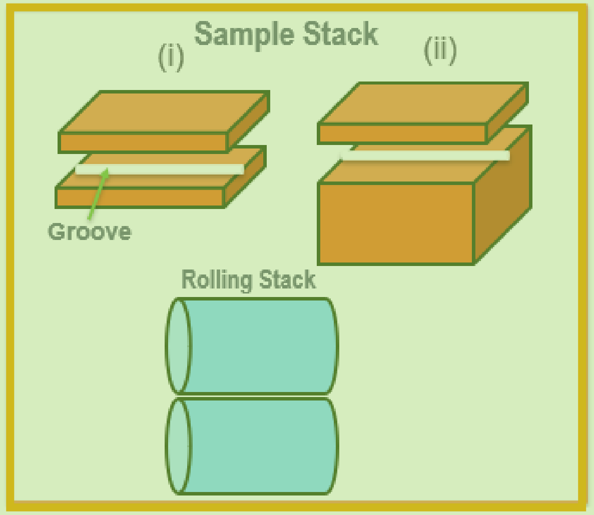
Solution To Embed Sensors in Wrought Products: Concept of Confined Rolling



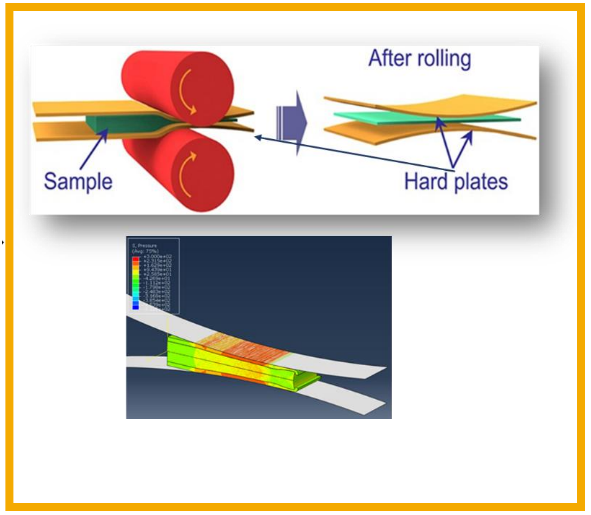
Approach 1



Approach 2



Approach 3



The concept of hot confined rolling is to embed the sensor and minimize stresses at the center of the sheet to minimize stresses at the sensor location

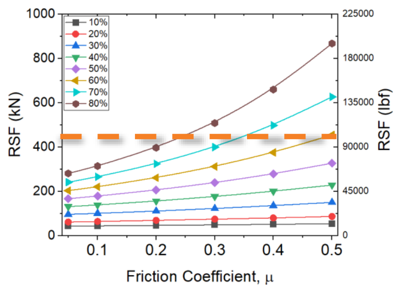
The connections and Wires can be connected initially during the rolling process

Approach: *Minimize the Number of Experiments*

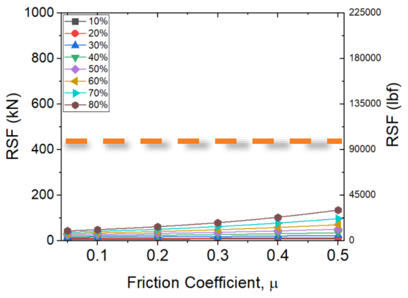
Analytical Calculation

- Roll separation force

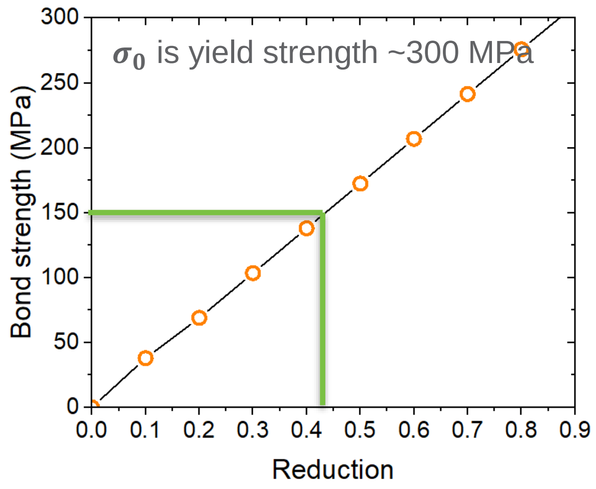
RSF @RT



RSF@1000°C



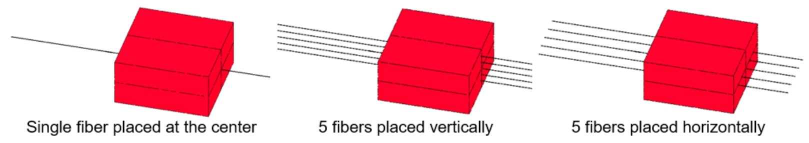
- Roll bonding criteria



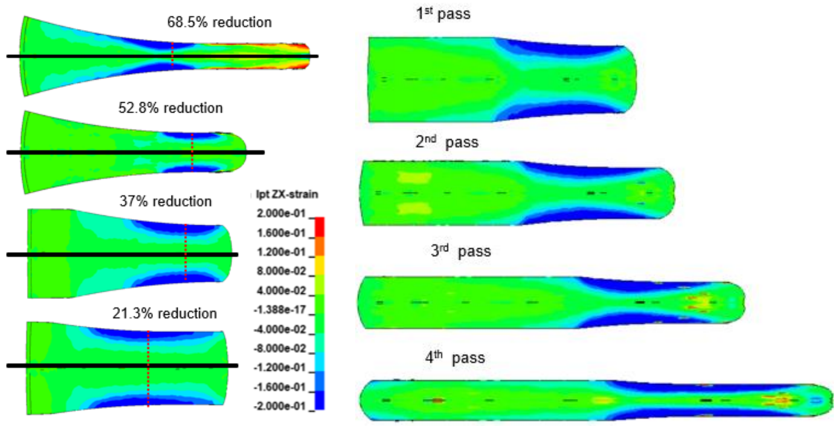
~43% reduction needed to have bond strength of ~ $\frac{1}{2}\sigma_0$

FEM Modeling

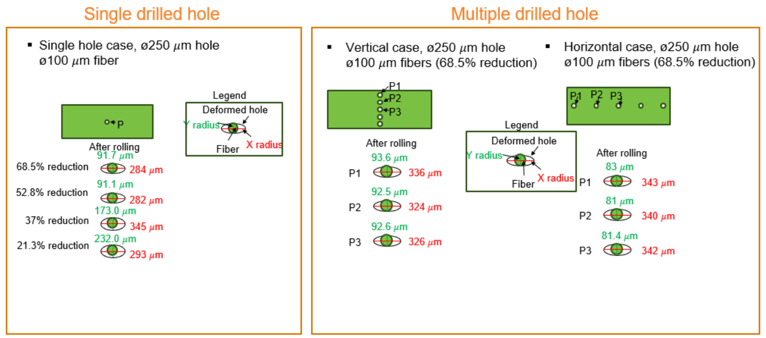
- Fiber location



- Single vs Multi pass strain

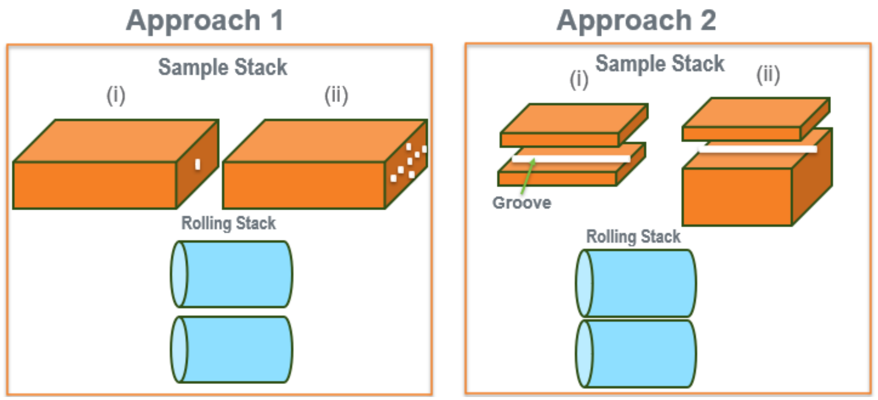


- Channel collapse

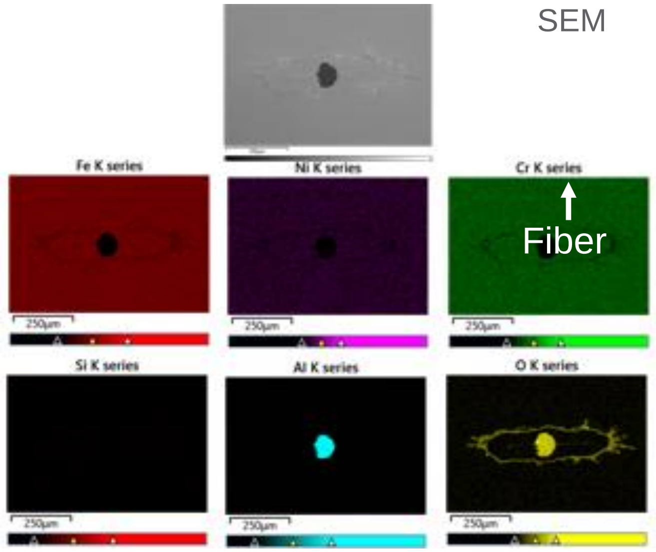


Experimental

- Rolling configuration



- Microstructure (Approach 1)



Testing – Post Fabrication

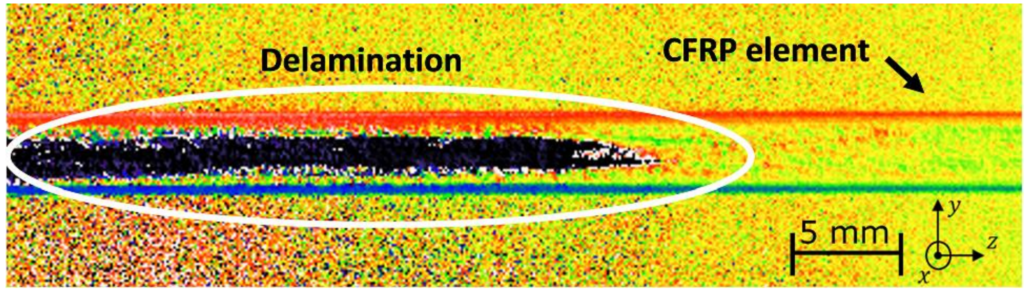
(1) NDE Testing: Ultrasonic test

- Continuity of fibers after rolling
- Detect processing defects, such as voids, debonding, delamination etc.

(2) Optical testing: Wavelength attenuation/ amplitude of laser signal, dB

- Continuity of the optical fibers
- Performance of the fibers at elevated temperature and strain

NDE: Carbon fiber composites



1. Journal of Nondestructive Evaluation (2019) 38:23.

Optical fiber performance evaluation

Measurement schematic

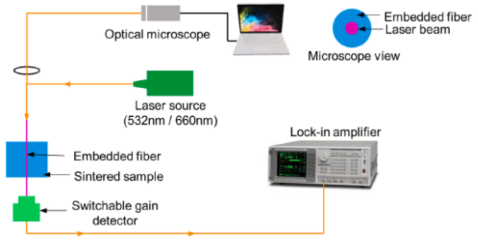


Fig. 3. Optical attenuation measurement of optical fibers post-integration.

Temperature measurement

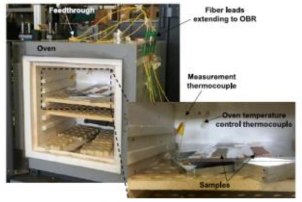
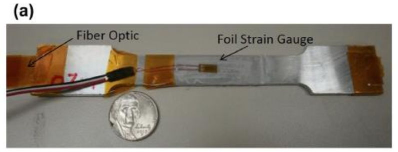
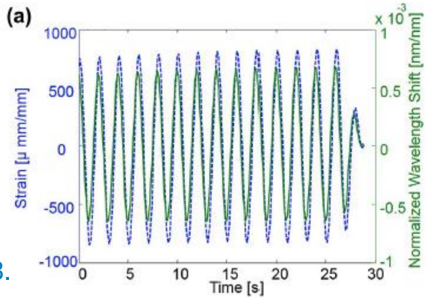


Figure 2. Experimental setup for high-temperature testing of embedded fibers. Fibers were passed out of the furnace through an insulated feedthrough for connection to the OBR. A measurement thermocouple was placed near the sample to monitor the temperature.

Strain measurement





1. Optics & Laser Technology 170 (2024) 110188.
2. JOM, Vol. 70, No. 3, 2018.
3. Smart Mater. Struct. 28 (2019) 055012 (12pp).
4. Sensors 2020, 20, 360.

Analytical Calculations: *Defining the Sample Size and Roll Separation Force*

Roll separation force

$$F = wL_pP_a$$

$$P_a = \frac{h}{\mu L_p}\left[\exp\left(\frac{\mu L_p}{h}\right)-1\right]\sigma_0$$

Projected length of the arc of contact:

$$\boldsymbol{L_p = [R(h_0 - h_f) - \frac{(h_0 - h_f)^2}{4}]^{1/2}}$$

$$\boldsymbol{\approx [R(h_0 - h_f)]^{\frac{1}{2}} \approx \sqrt{R\Delta h}}$$

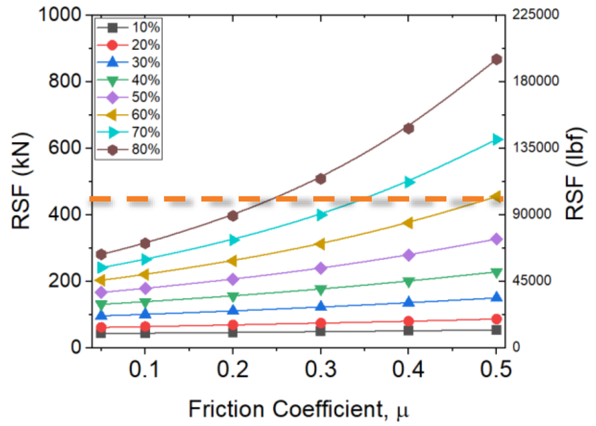
Flow stress (Johnson-cook equation):

$$\sigma_0 = [A + B\varepsilon^n]\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$$

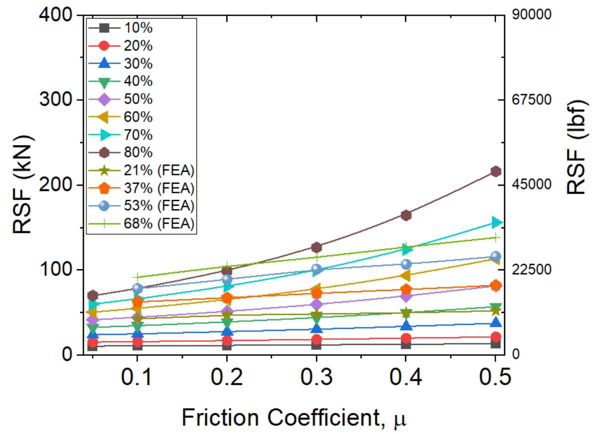
Johnson-cook parameters: SS316

A	B	C	m	n
305	1161	0.01	0.517	0.61

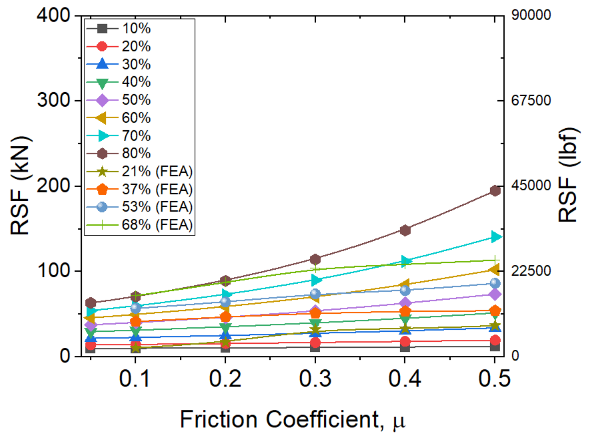
RSF @RT



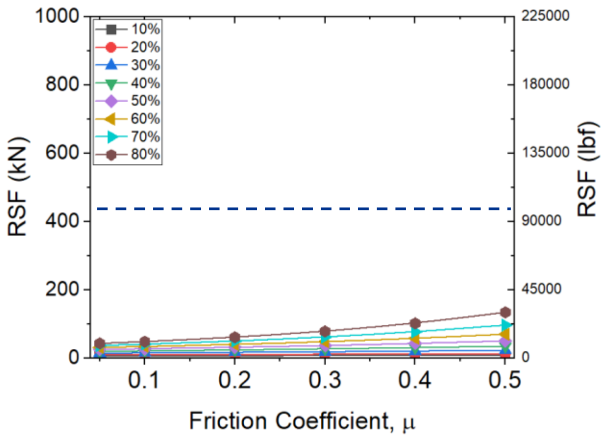
RSF@800°C



RSF@850°C



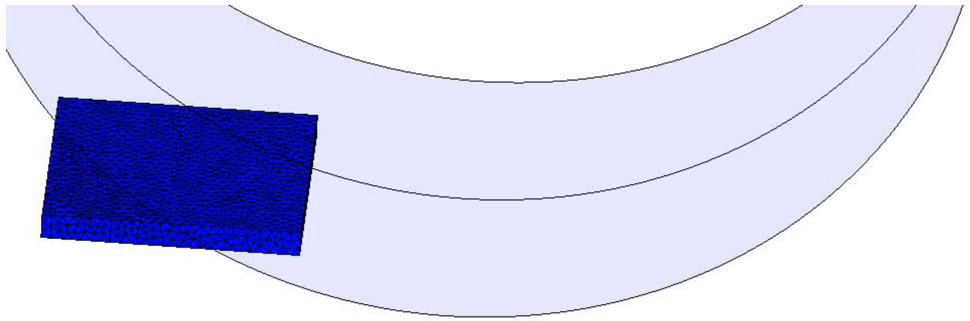
RSF@1000°C

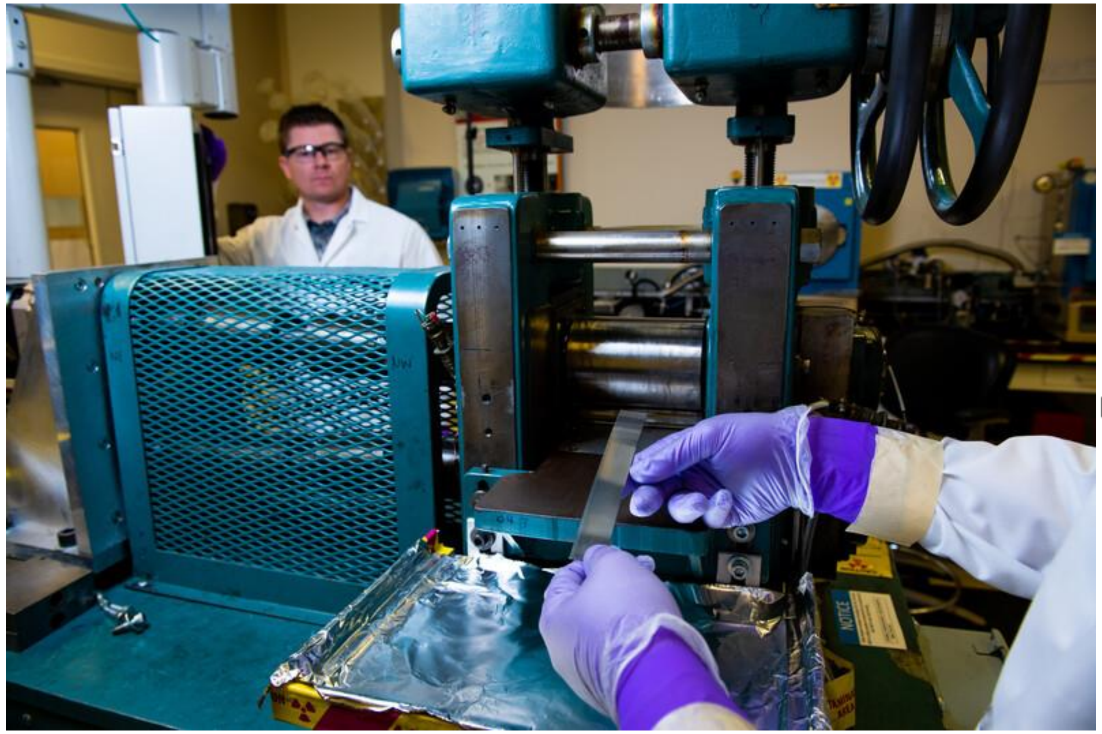


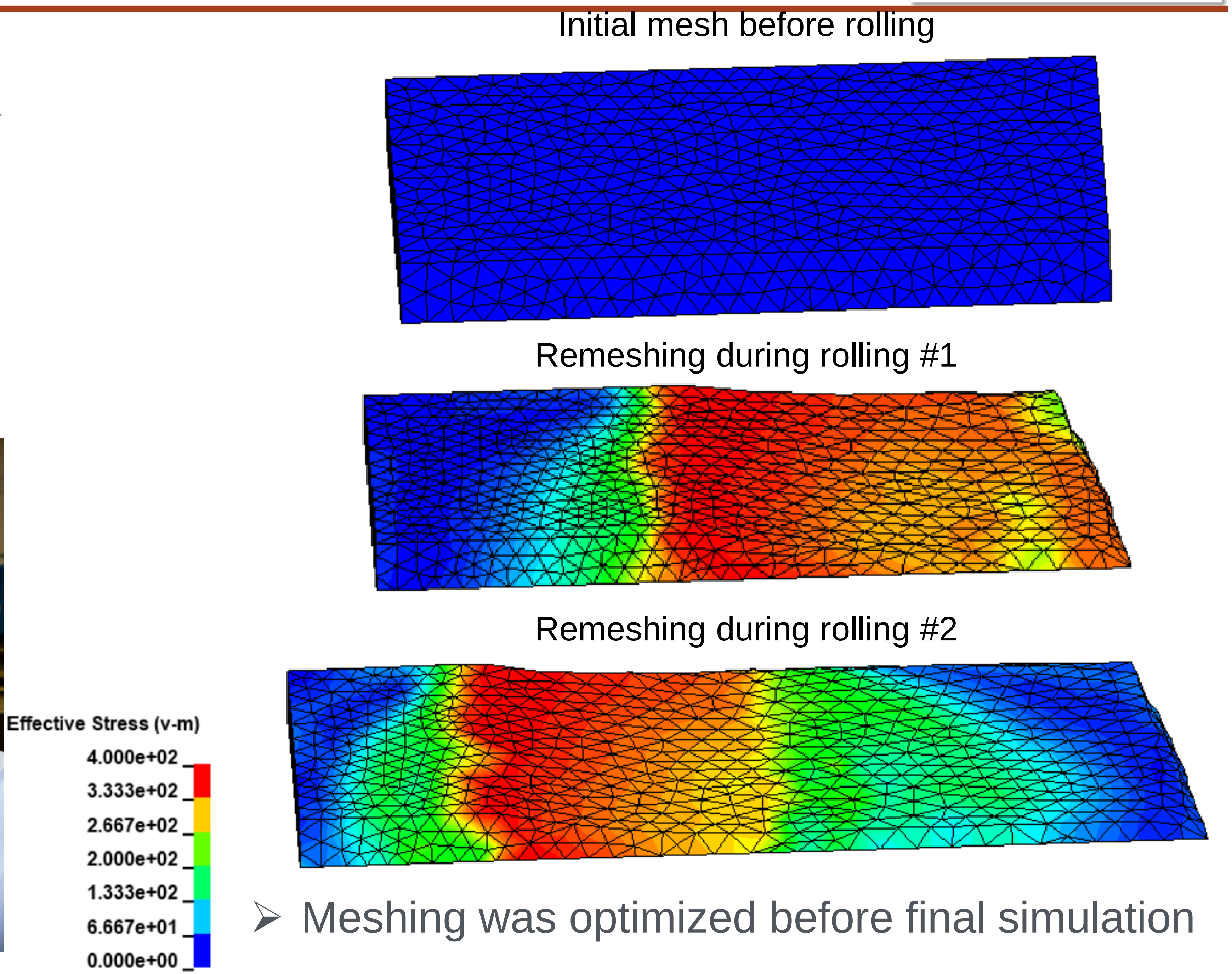
1. https://www.sciencedirect.com/topics/engineering/roll-separating-force.
2. https://www.sciencedirect.com/science/article/pii/S2214785322006319.
3. Chandrasekaran, H., M'Saoubi, R., Chazal, H. "Modelling of mate-rial flow stress in chip formation process from orthogonal milling and split Hopkinson bar test", Machining Science and Technology, 9(1), pp. 131–145, 2005.

Simulation Capability:
Hot Rolling FEM Model

- Rolling with adaptive meshing





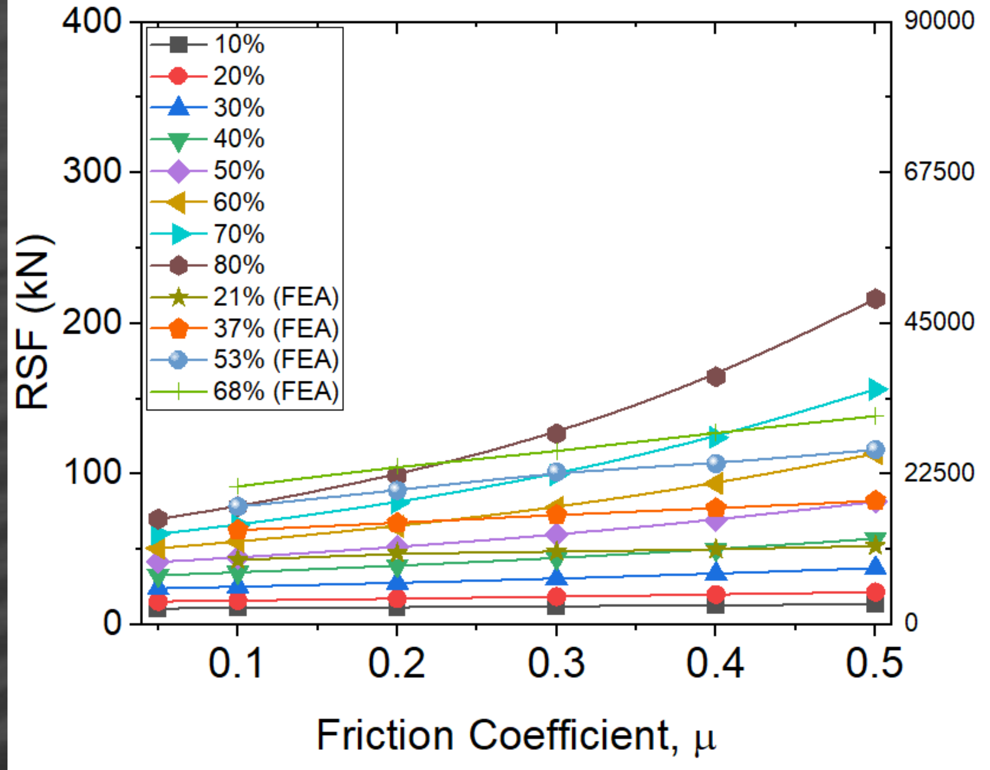


➢ Meshing was optimized before final simulation

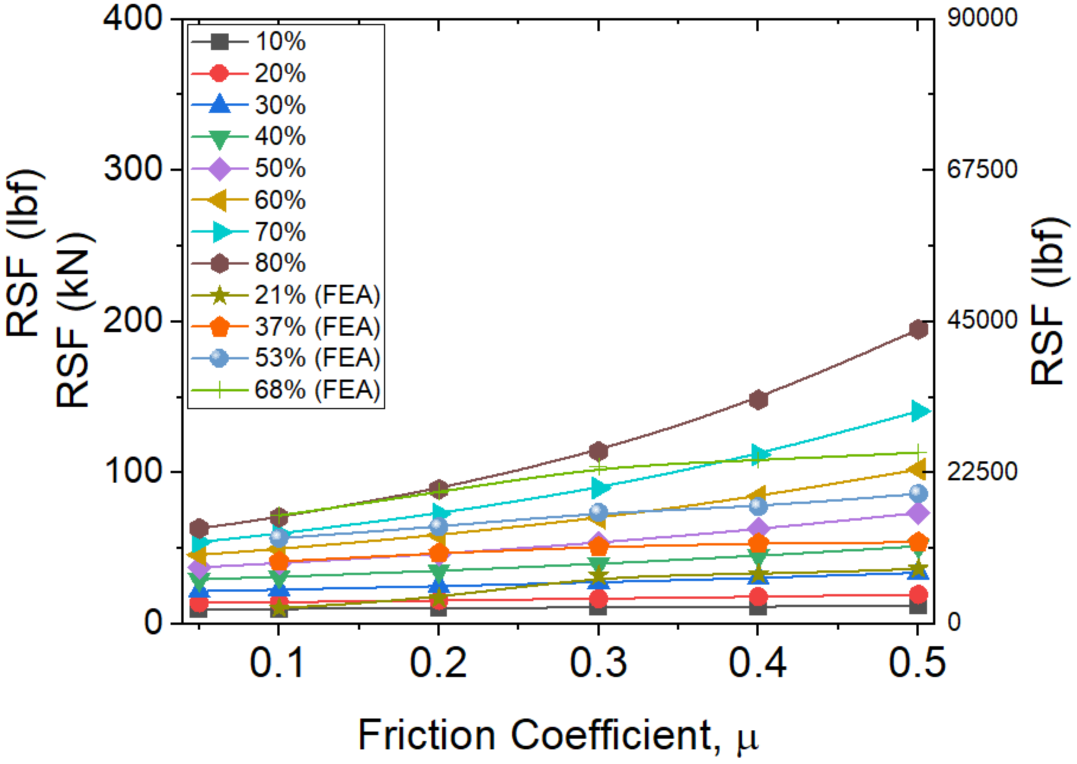
Model Validation

Roll Separation Force: Analytical vs. FEM vs. Exp

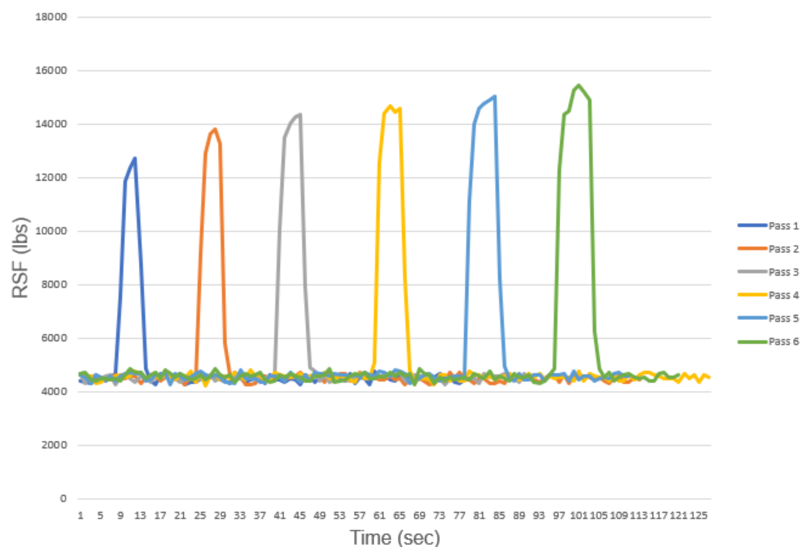
RSF@800°C



RSF@850°C



Exp RSF@800°C



- Roll Dia: 4’’; Plate Width: 0.5’’; h_0: 6.35 mm
- The analytically calculated and FEM modeled roll separation force (RSF) values are very comparable

Finite Element Method Model Setup for Hot Rolling of Wrought Product with Fiber Embedded

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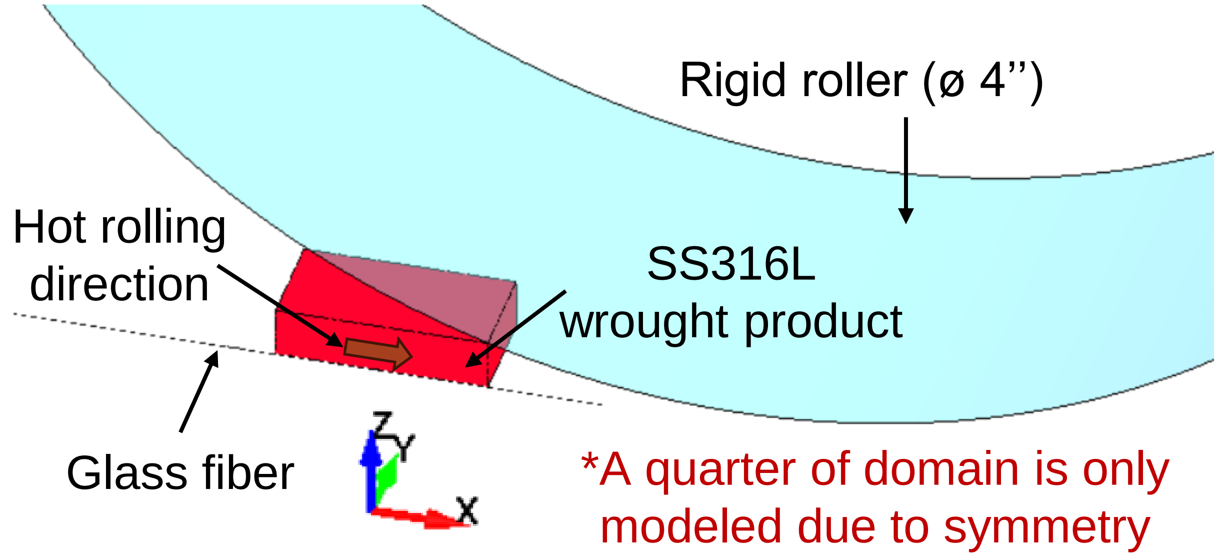
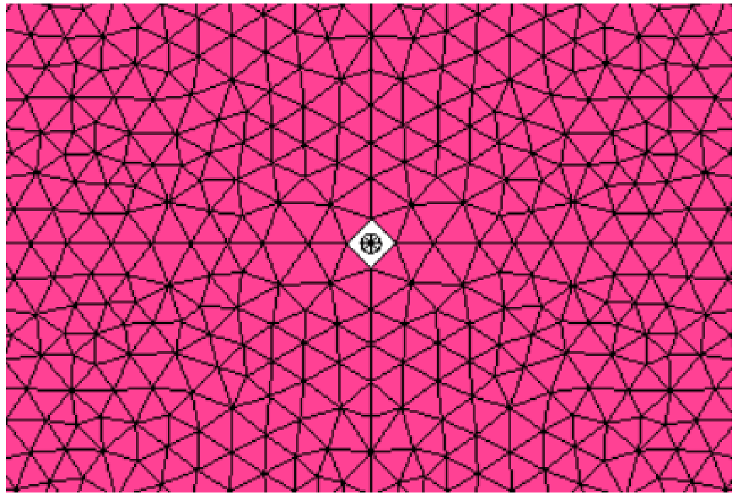
- Finite element method (FEM) model setup

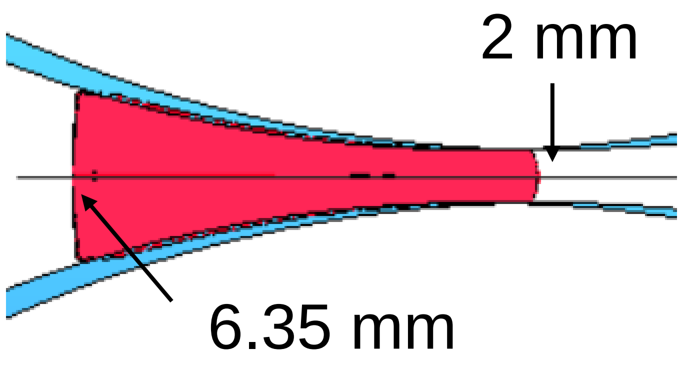


*A quarter of domain is only modeled due to symmetry

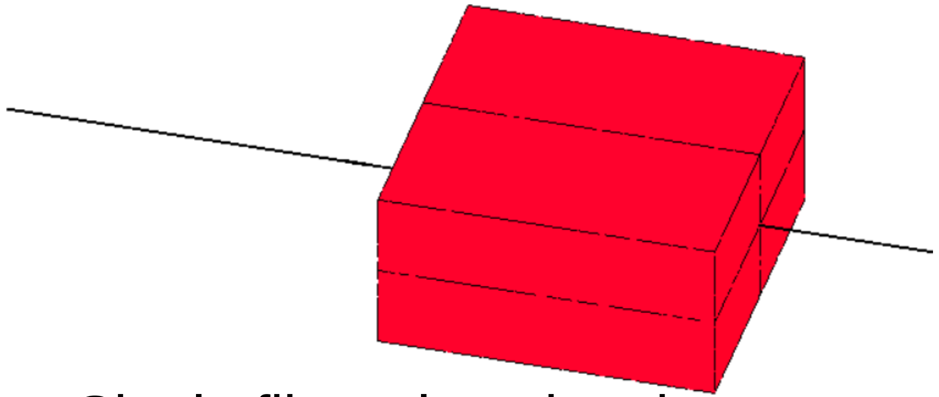
- ø250 μm drilled hole to hold a ø100 μm fiber



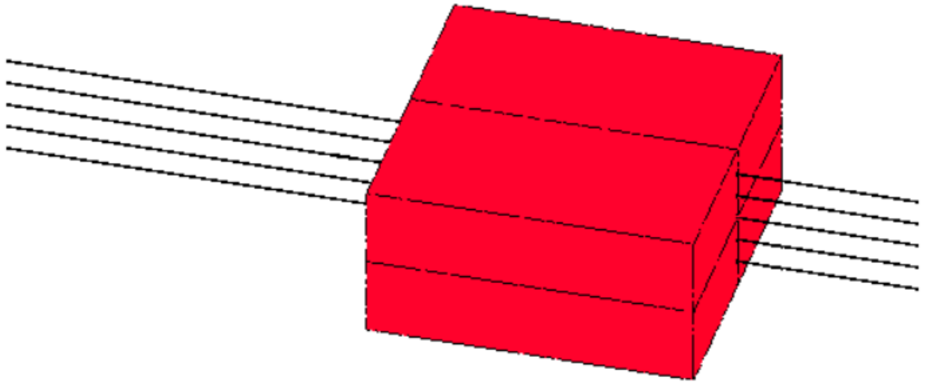
- Baseline reduction rate: 68.5%



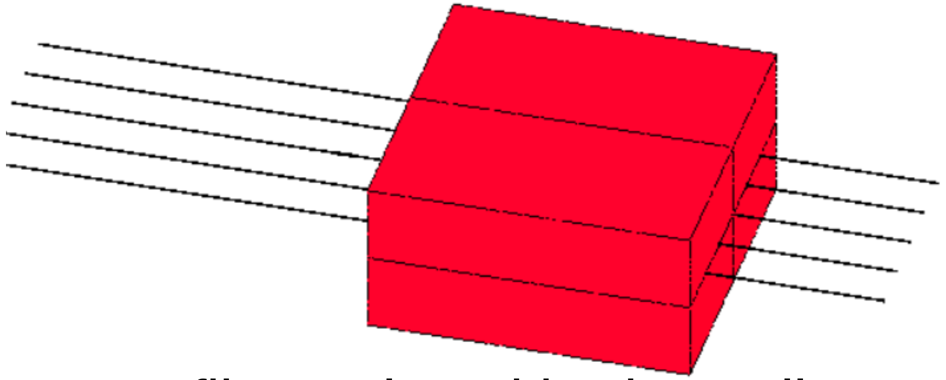
- Fiber embedding cases with wrought product sized in 0.5’’ x 0.5’’ x 6.35 mm



Single fiber placed at the center



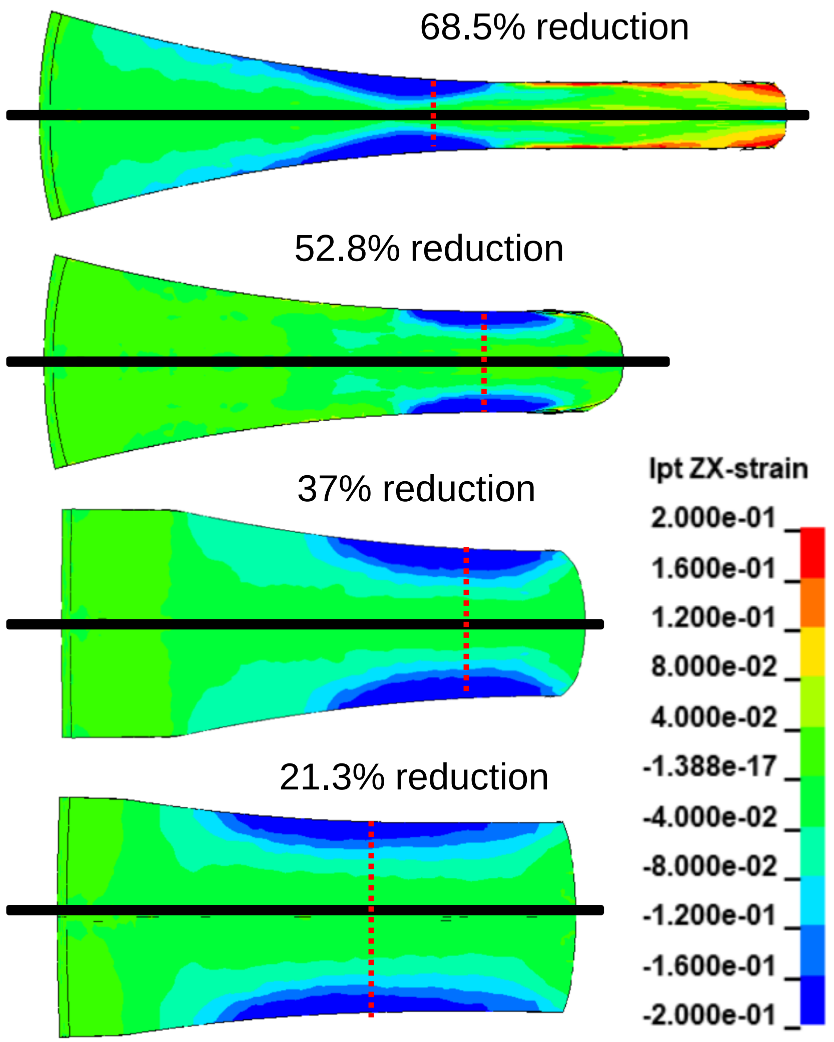
5 fibers placed vertically



5 fibers placed horizontally

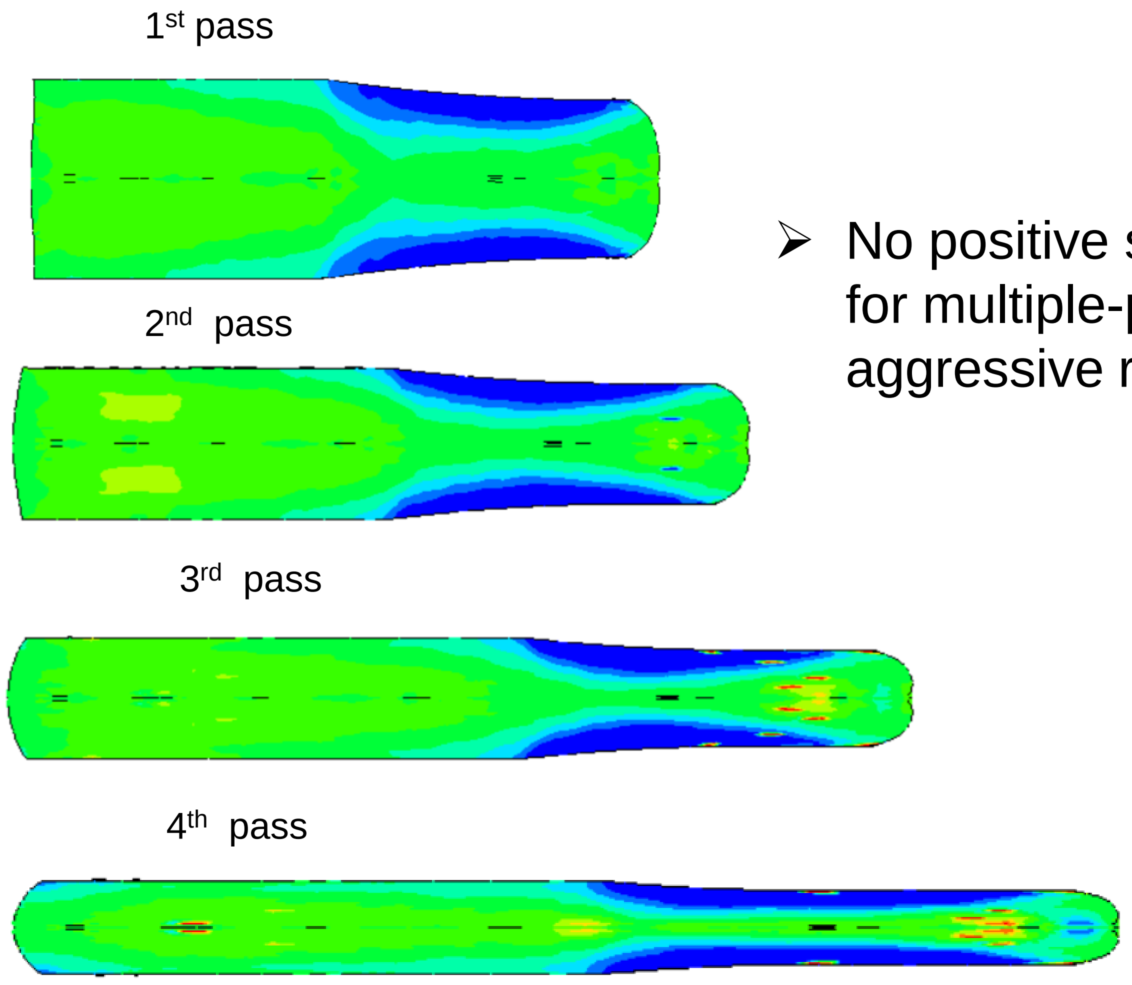
Through Thickness Shear Strain: Single vs Multi pass

- Single pass with different reductions



➢ Rolled at 850°C

- Multiple passes with 21% reductions

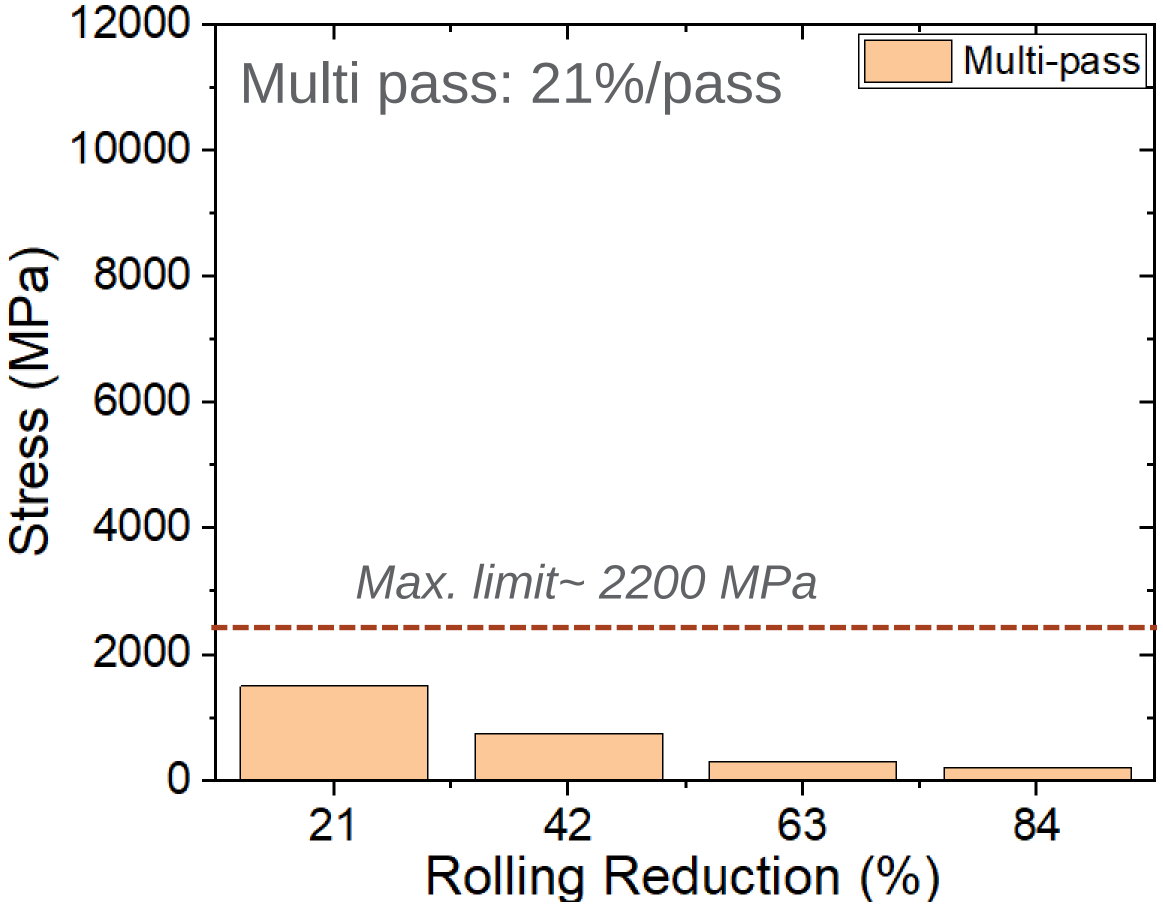


➢ No positive shear strain is obtained for multiple-pass case due to less aggressive reduction for each pass

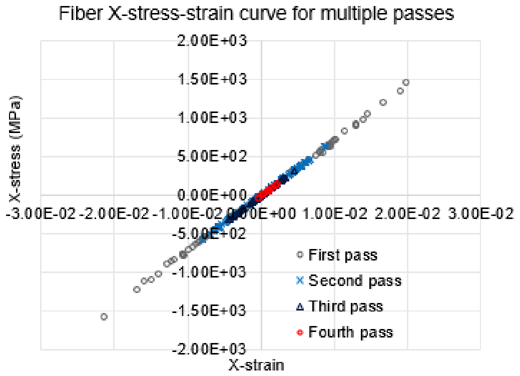
Fiber experienced stressed: Single vs. Multi-pass Rolling

- Sapphire fibers undergone maximum stress during rolling (Single vs Multi pass)

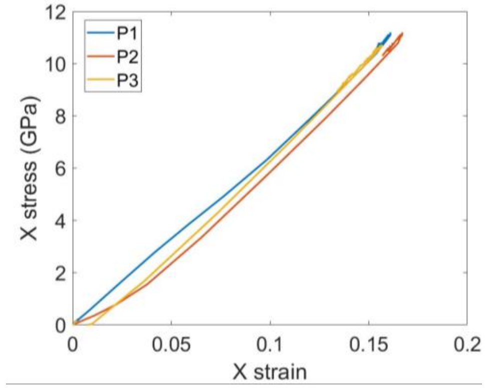
Multi pass Rolling



Multi pass 21%/ pass



Single pass 53% reduction



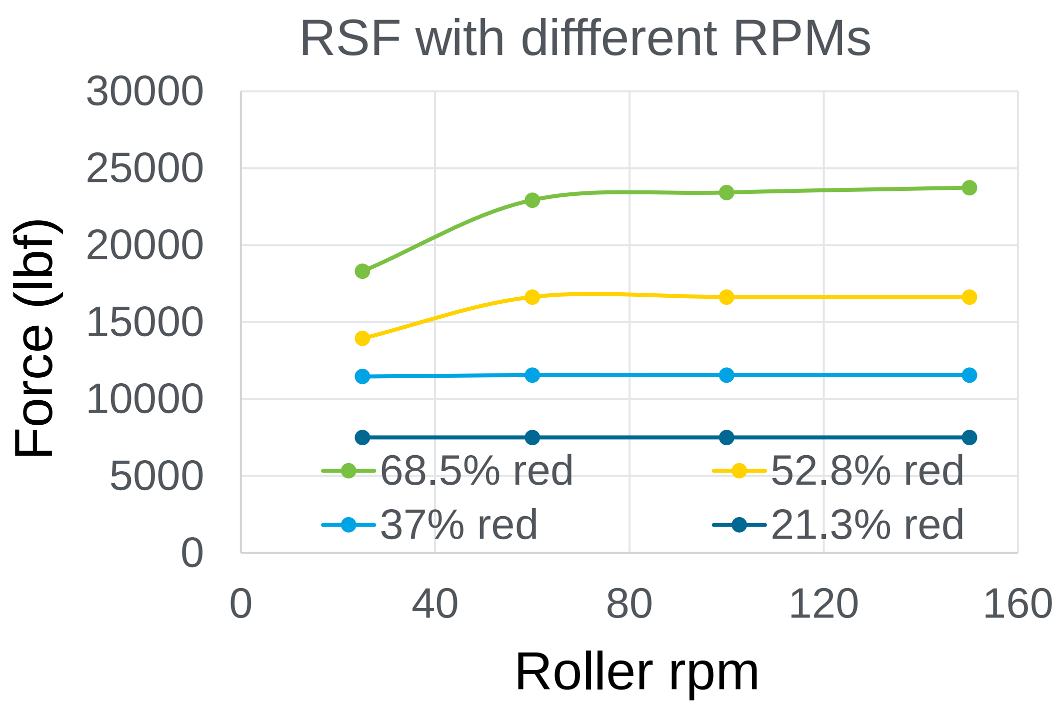
Sapphire (α-Al_2O_3): http://www.micromaterialsinc.com

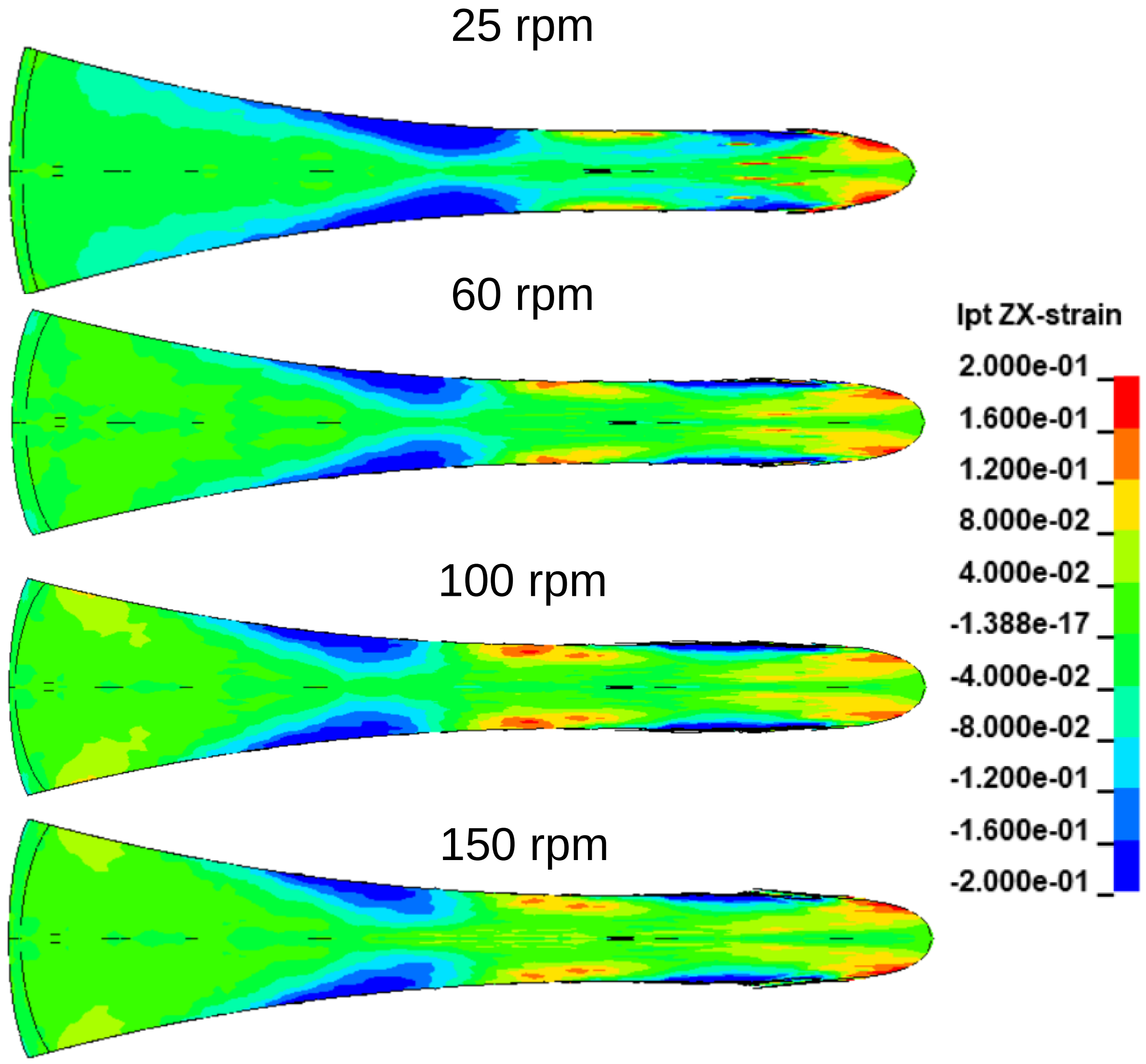
- Tensile strength: 2200 MPa

- Multi-pass rolling less aggressive and adopted for initial trials
- Dividing the reduction into multiple passes can significantly reduce the stress in the fiber.

Strain Rate Sensitivity Study

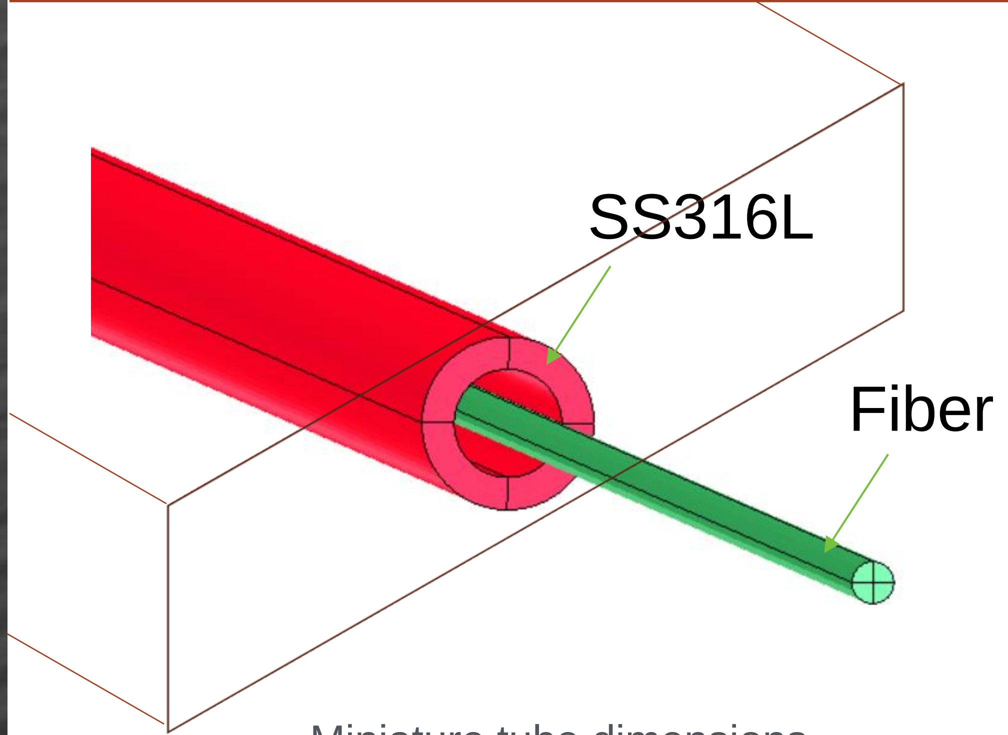
- Rolling results with different rpms
  - 25, 60, 100, 150 rpms
  - 21.3%, 37%, 52.8%, 68.5% reductions
  - 850 °C temperature



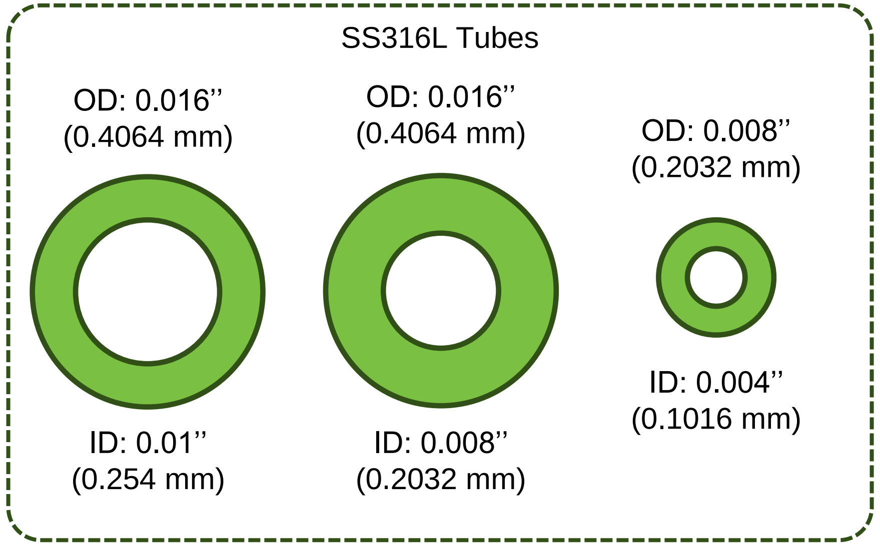


- When reduction rate is high, slower rpm can significantly reduce the RSF.
- RSF and shear strain are lower with slow rpm, and converge to certain values with increasing RPM
- RSF tends to be constant for low reduction rate

Developing Model with Guided Tube:
For better adherence of fibers and matrix

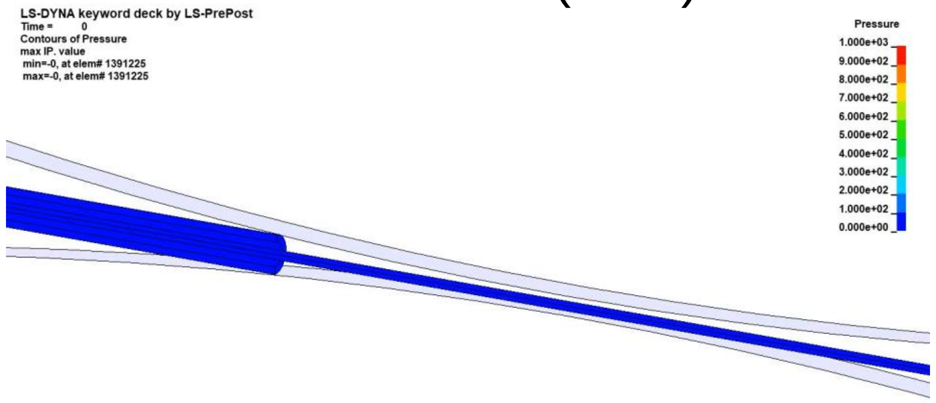


Miniature tube dimensions

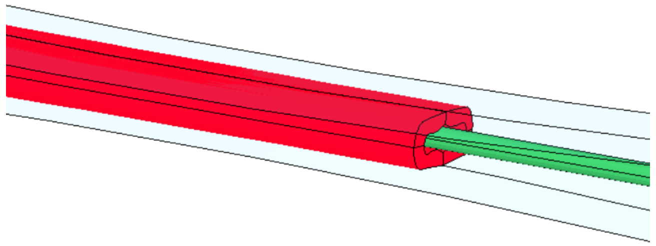


50% reduction

Pressure (MPa)



Deformed tube

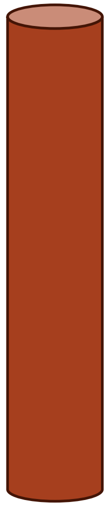


Insertion of 316 tube along with fiber in 316 matrix is beneficial for bonding and reduces stress

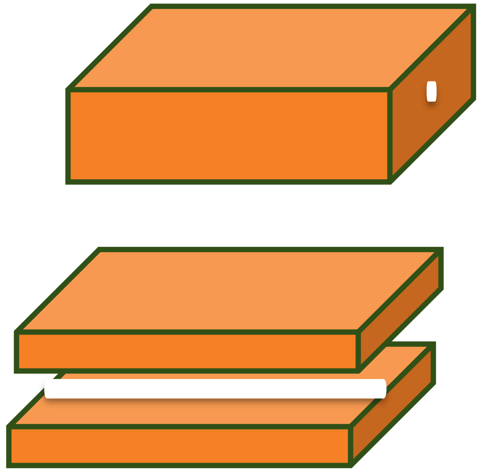
Approach 1: Fiber Assembly

Fiber Assembly I

Bare fiber

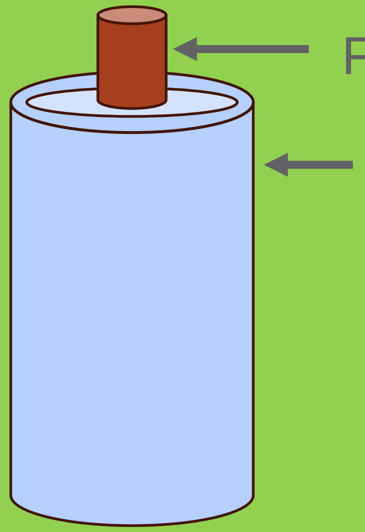


Rolling plate assembly

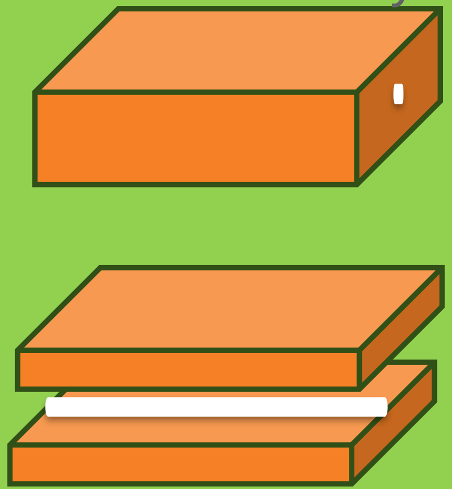


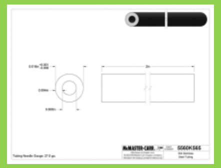
Fiber Assembly II

Fiber inserted into miniature tube



Rolling plate assembly



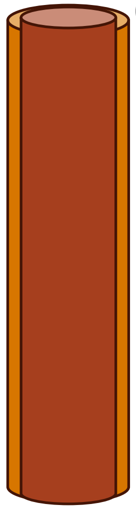


Tube outer dia: 0.4 mm

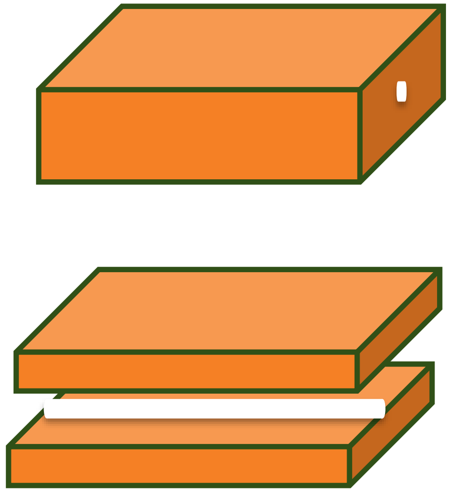
Inner dia: 0.25 mm

Fiber Assembly III

Fiber coated with copper/aluminum



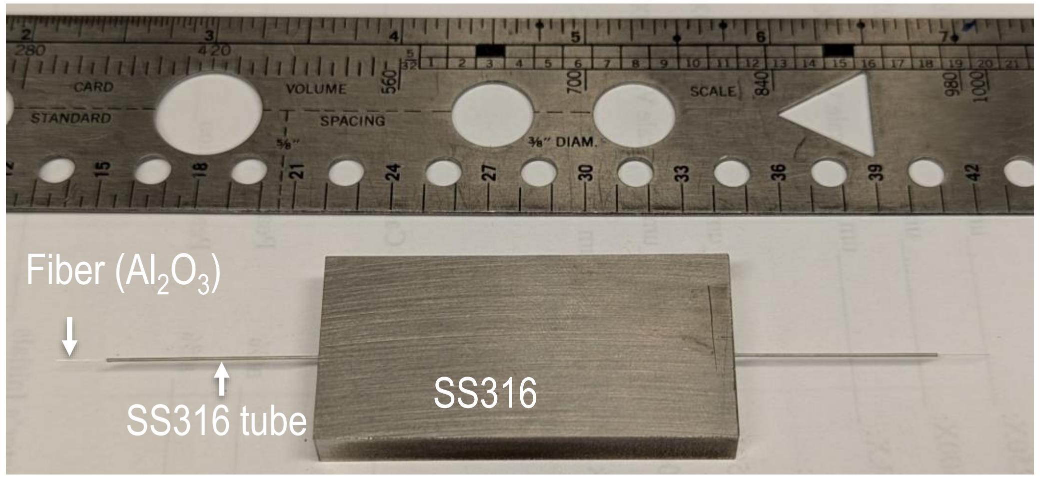
Rolling plate assembly



Approach 1
Multi-pass Rolling: Up to 20% Rolled
(6.2 mm to 5.0 mm)

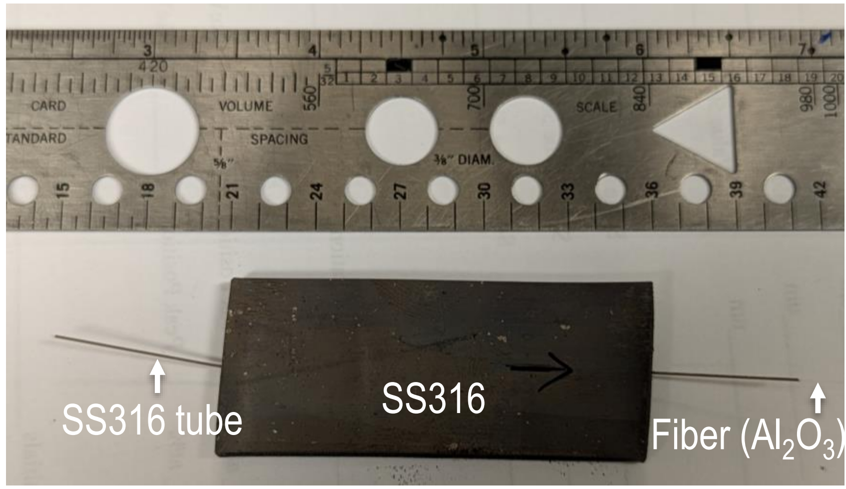
Embedded fiber:
- Rolling temperature: 900°C
- 5 min soaking time
- Total reduction: 19.35% (10%/pass)

Starting assembly



10% Rolled

20% Rolled

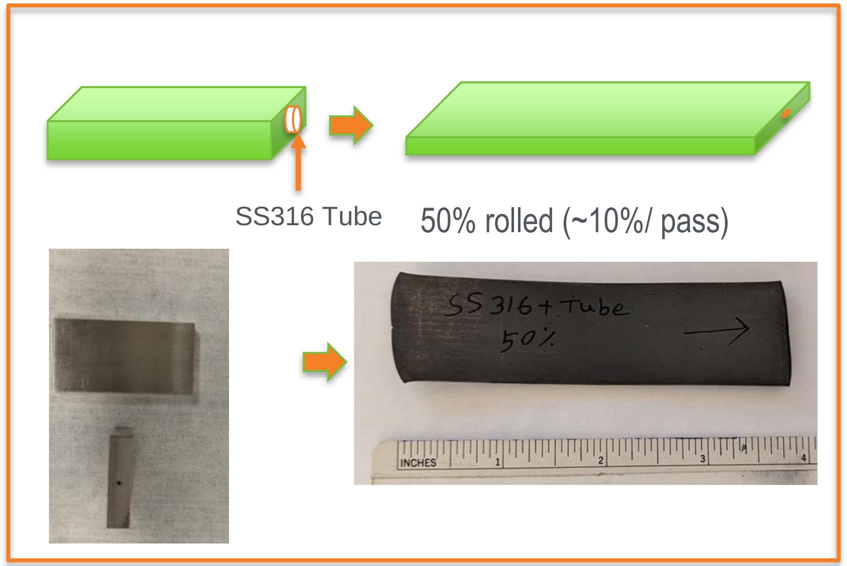


Fiber intact and visible after 20% reduction

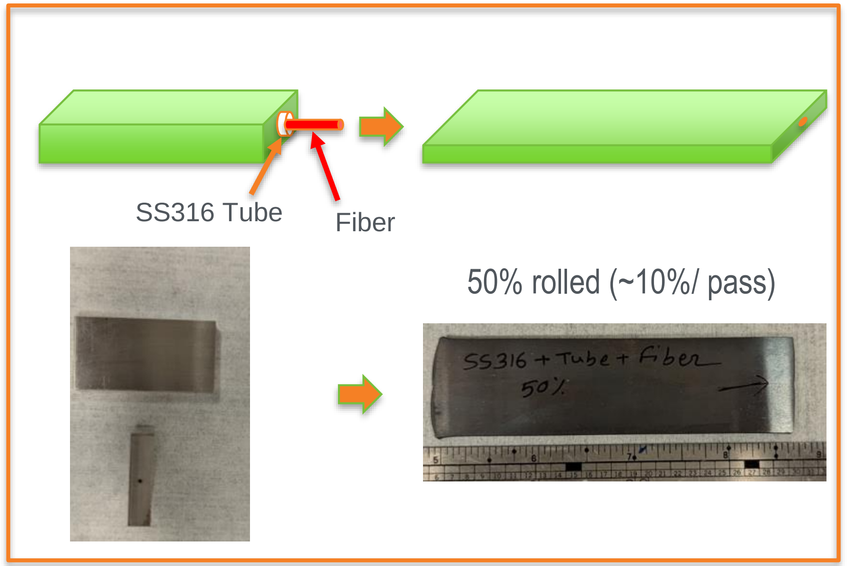
Approach 1
Multi-pass Rolling: Up to 50% Rolled
(6.2 mm to 3.1 mm)

#	Dimension	Multi pass reduction (%)	Temp (°C)	Soaking (min)	Drilled hole/Fiber	Observations
1	2"x1" (6.2 mm thick)	~50	800	15	w/o channel (Dummy plate)	Rolled, defects free
2	2"x1" (6.2 mm thick)	~50	800	15	w/ channel (0.5 mm dia) + Tube	Rolled, defects free
3	2"x1" (6.2 mm thick)	~50	800	15	w/ channel (0.5 mm dia) + Tube + long Fiber	Rolled, defects free
4	2"x1" (6.2 mm thick)	~50	800	15	w/ channel (0.5 mm dia) + long Tube + long Fiber	Rolled, defects free

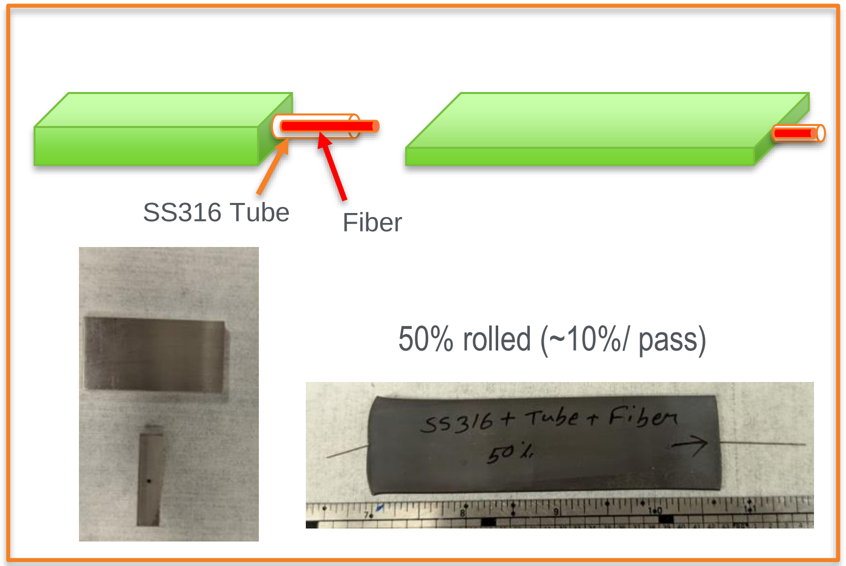
Bare Steel + SS316 Tube



Bare Steel + SS316 Tube + long Fiber



Bare Steel + long SS316 Tube + long Fiber

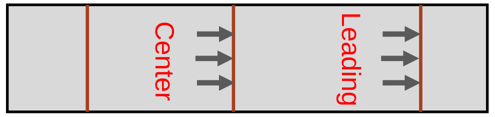


Fiber intact and adjusted to the length

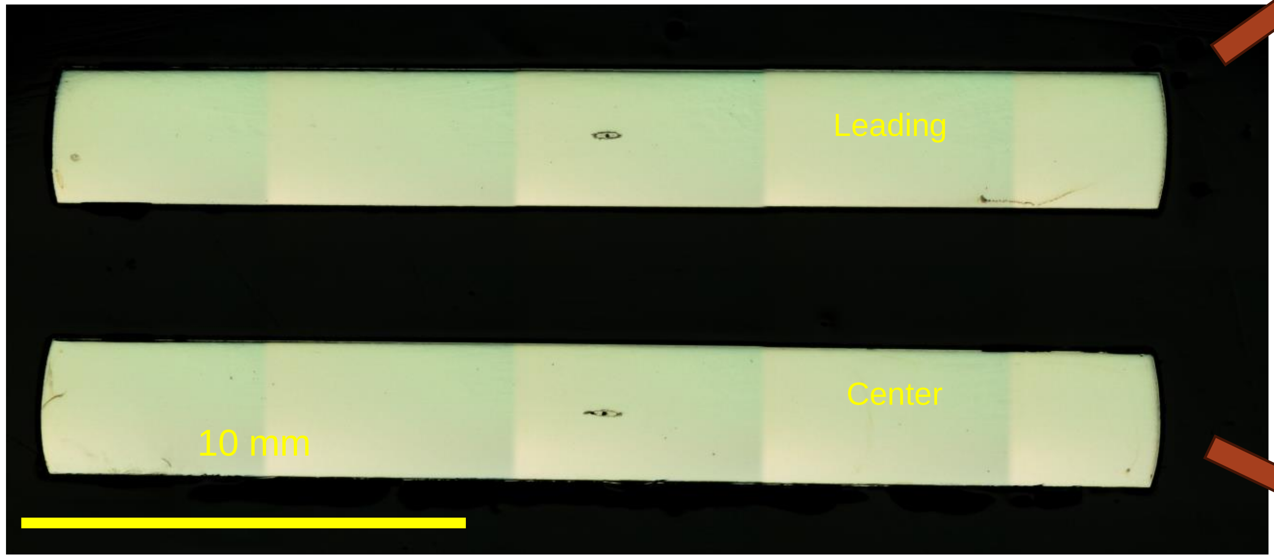
Approach 1: Cross-Sectional Microscopy: SEM Analysis

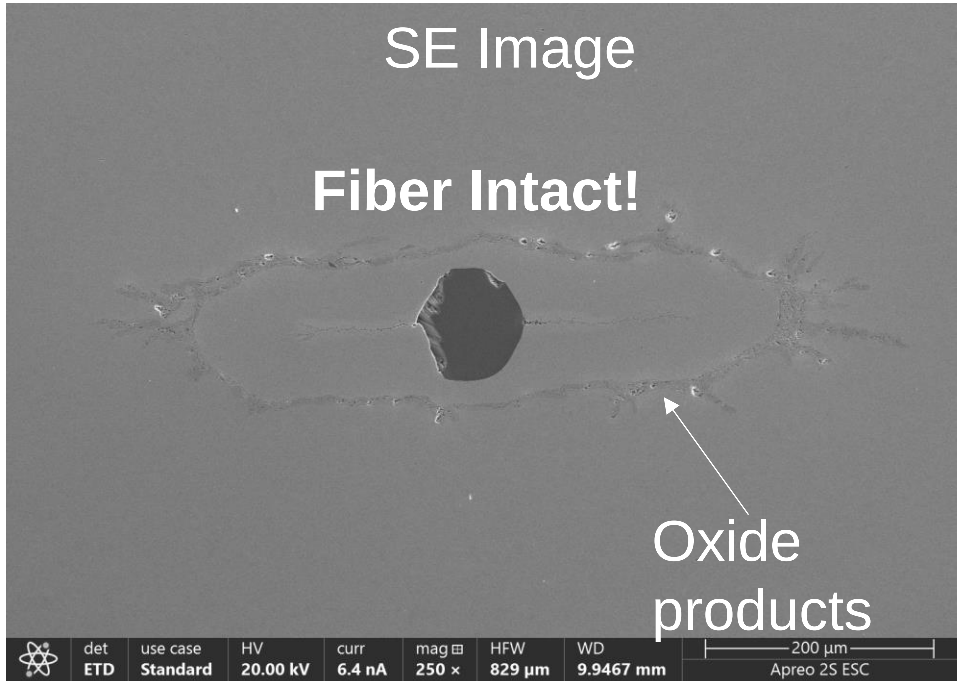
SS316 + long Tube+ long Fiber (800°C, ~50%)

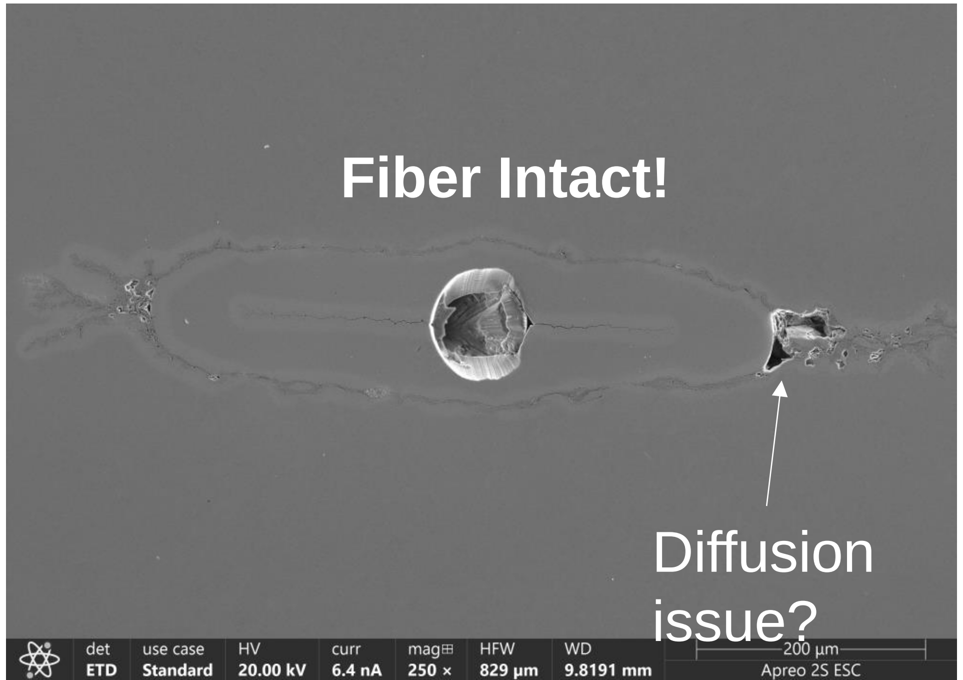
Rolling direction →



Cross section view





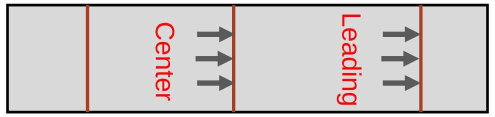


Fiber intact and adjusted to the length

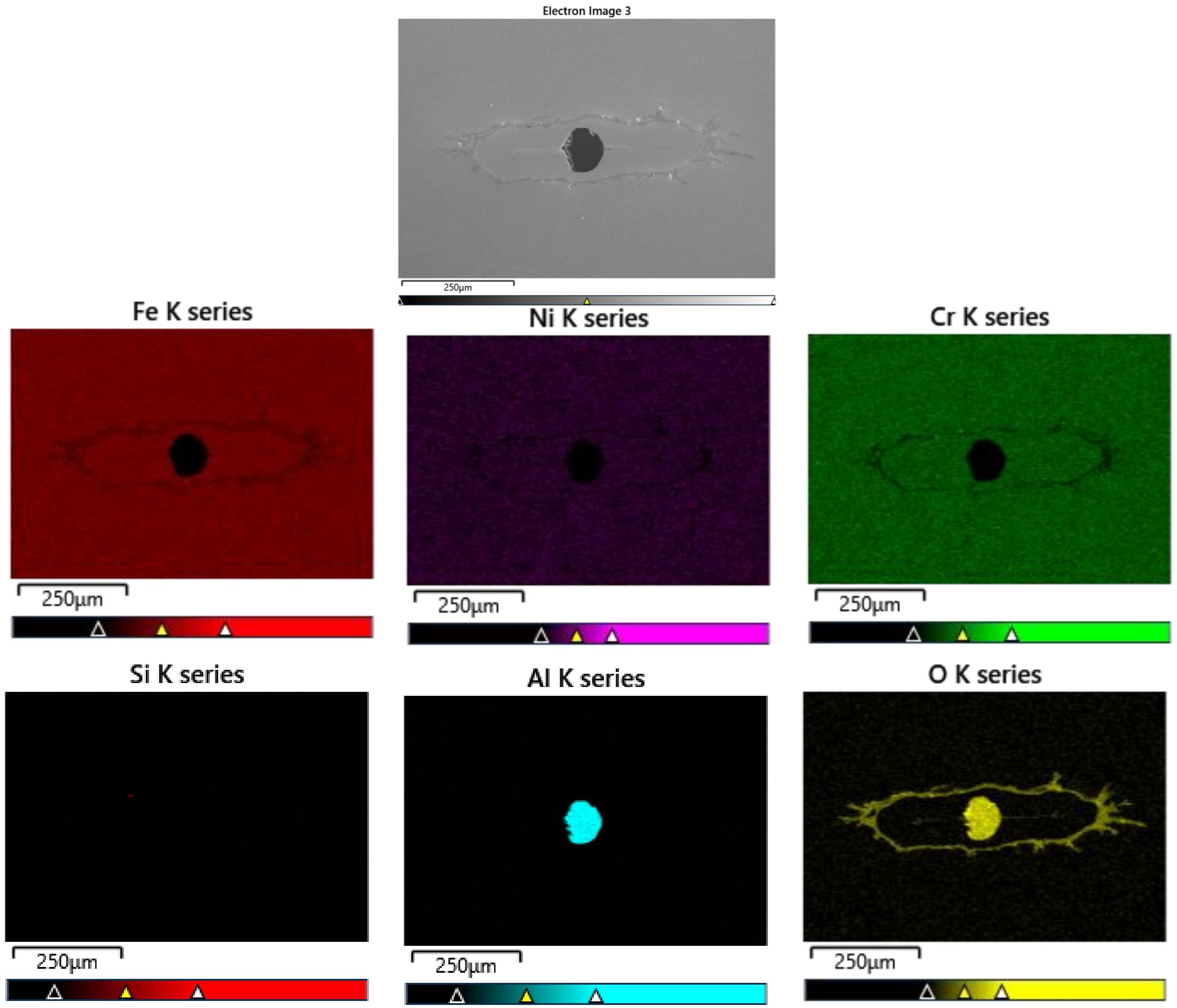
Cross-Sectional Microscopy: EDS
Oxide layer can be addressed by cleaning process and covers

SS316 + long Tube+ long Fiber (800°C, ~50%)

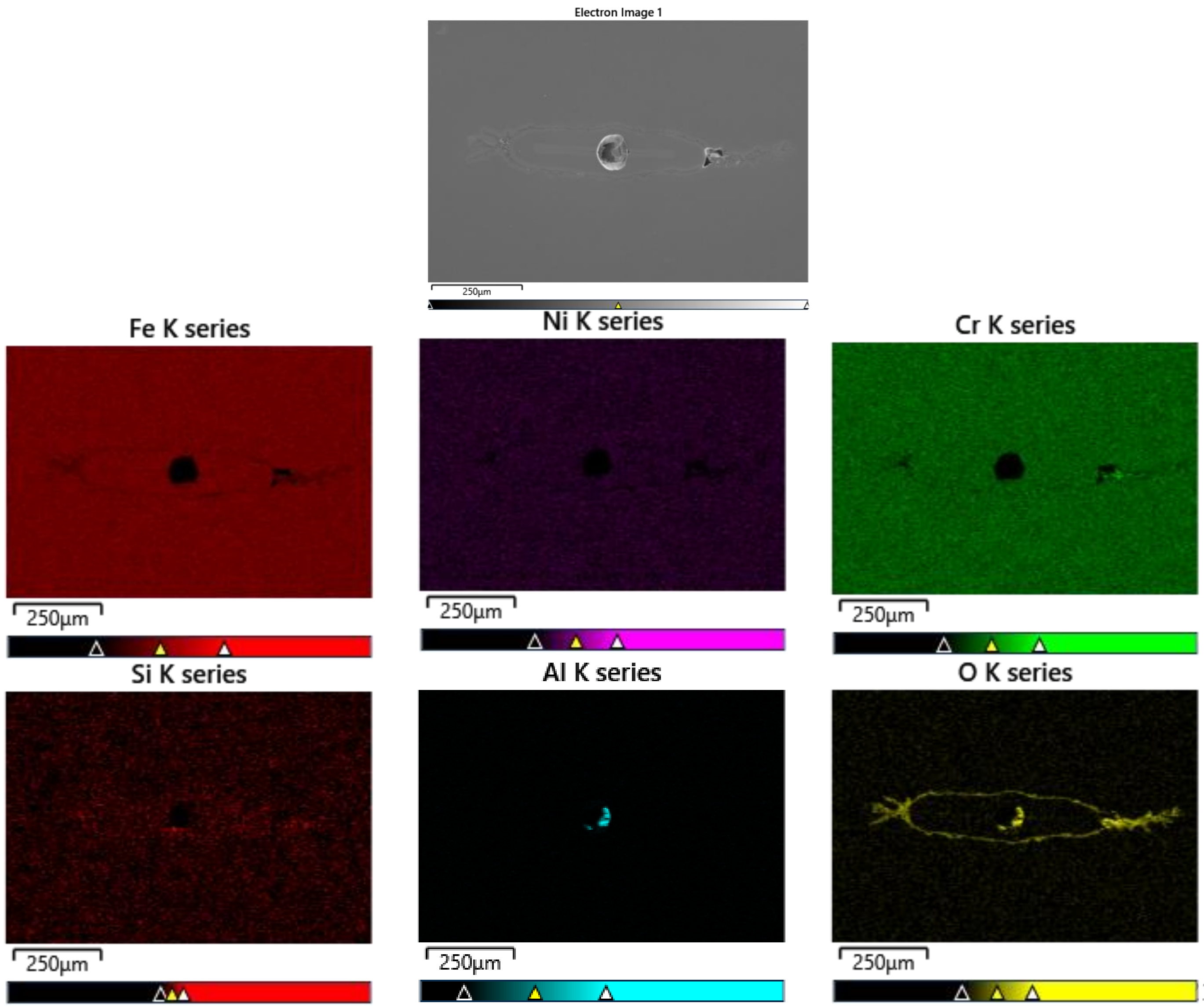
Rolling direction



Leading



Center

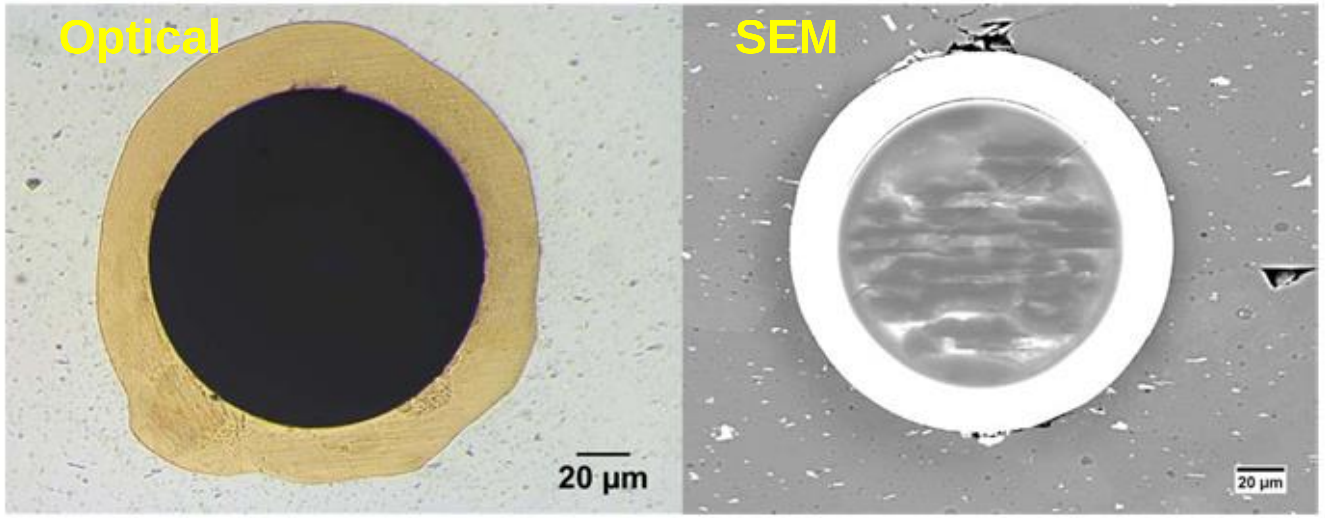


Approach 1: Summary of Results

Performed targeted and successful experiments by utilizing modeling

- Roll separating force for hot rolling of wrought product with embedded fibers is systematically studied with various temperatures and friction coefficients.
- The stress-strain distributions in wrought product and fiber have been investigated with fibers embedded at different locations of the wrought product.
- Deformation of pre-drilled holes with vertical and horizontal orientations is studied with rolling reduction up to ~70% at rolling temperature of 850°C.
- The through thickness shear strain map is studied with various reduction ratios.
- Demonstrated and validated the models
- Successfully showcased that we can embed sensor using the first approach
- Performance evaluation is underway

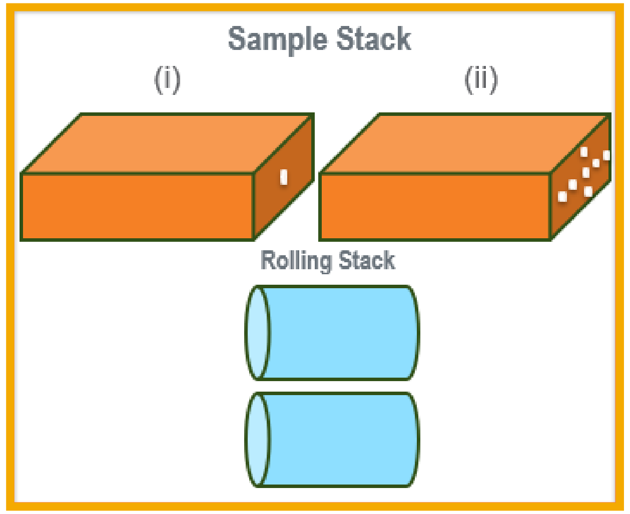
Embedded fibers with copper coatings



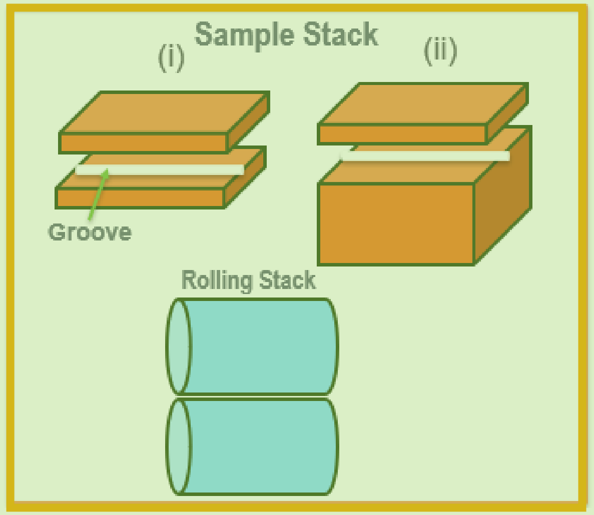
Christian M Petrie, Niyanth Sridharan, Mohan Subramanian, Adam Hehr, Mark Norfolk and John Sheridan, Embedded metallized optical fibers for high temperature applications, Smart Mater. Struct., 28 (2019) 055012.

Approach 2: Diffusion Bonding of Two Plates with Rolls

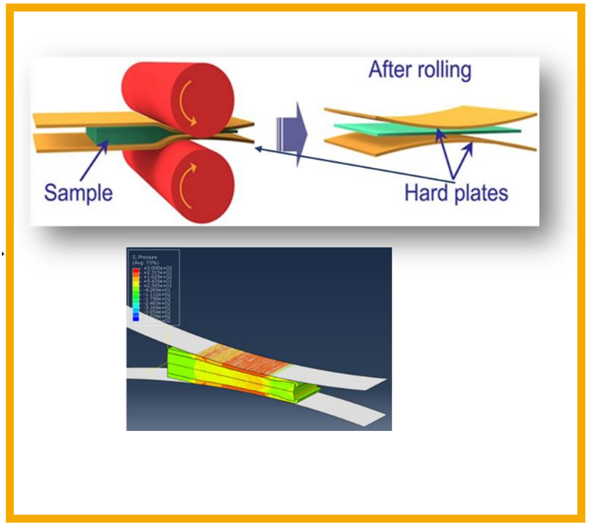
Approach 1



Approach 2



Approach 3



The concept of hot confined rolling to embed the sensor and minimize stresses at the center of the sheet to minimize stresses at the sensor location

The connections and Wires can be connected initially during the rolling process

Modelling of bonding: Contact Algorithm Method

➢ Zhang-Bay model

To estimate the bond strength, two maximum limits must be applied, as discussed by Bay et al.

$$(\frac{\sigma_B}{\sigma_0})_{max1} = \frac{2}{\sqrt{3}}Y = \frac{2}{\sqrt{3}}r$$

OR, $(\sigma_B)_{max1} = \sigma_0 \frac{2}{\sqrt{3}}Y$ σ_0 is yield strength

$$(\frac{\sigma_B}{\sigma_0})_{max2} = 1$$

In fact, σ_B shows the bond strength in normal direction of the interface. The bond strength in tangential direction can be described as:

$$\tau_B = \frac{\sigma_B}{\sigma_0}\frac{C}{\sqrt{3}}[B - \frac{2}{\sqrt{3}}ln(1-r)]^n$$

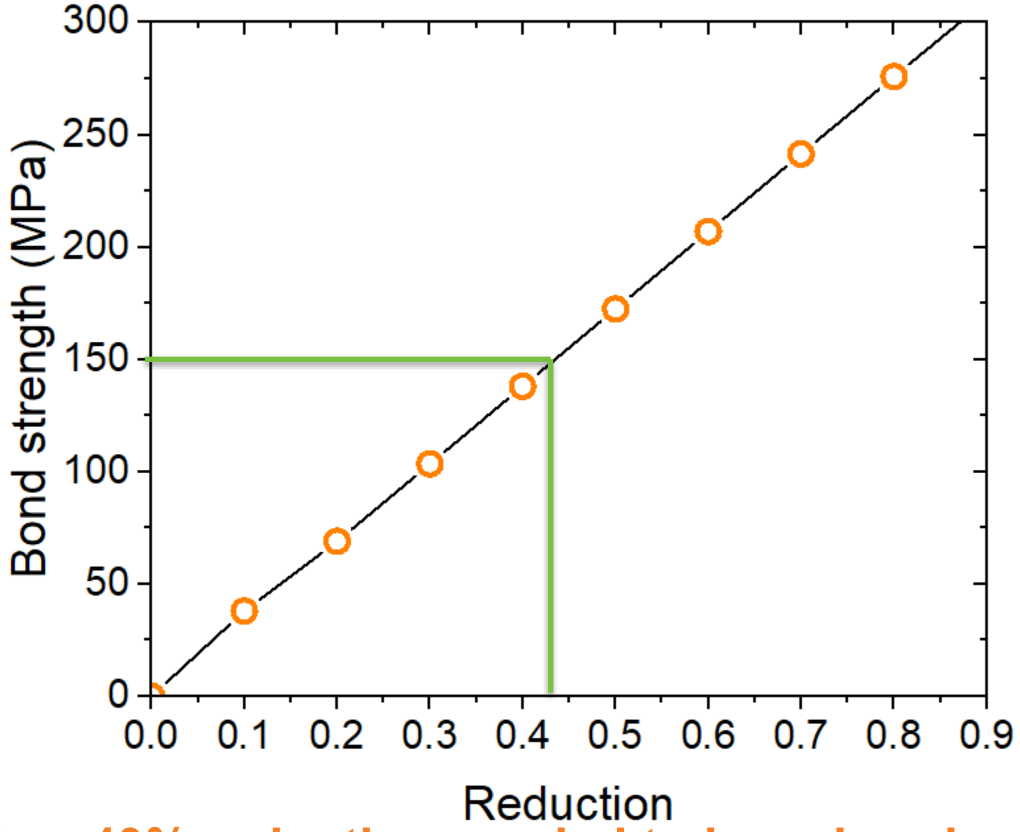
➢ **Bond strength depends on reduction (%) and pressure**

Where, C, B and n are the material parameters of swift hardening law.

Swift hardening law:

$$\sigma = k(\varepsilon_0 + \varepsilon^p)^n$$

σ_0 is yield strength ~300 MPa



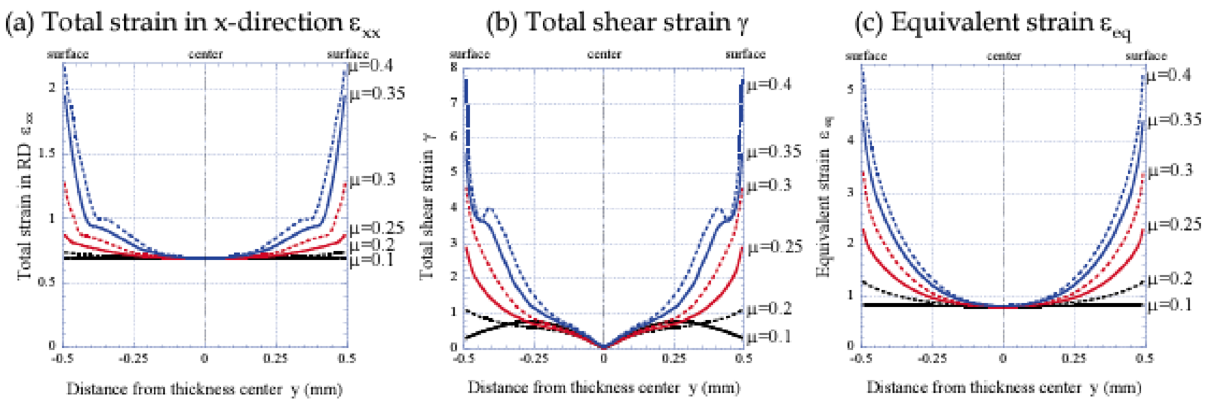
➢ **~43% reduction needed to have bond strength of ~ $\frac{1}{2}\sigma_0$**

Recent advances and trends in roll bonding process and bonding model: A review, Chinese Journal of Aeronautics, Volume 36, Issue 4, April 2023, Pages 36-74.

Through Thickness Strain:

Find a suitable location

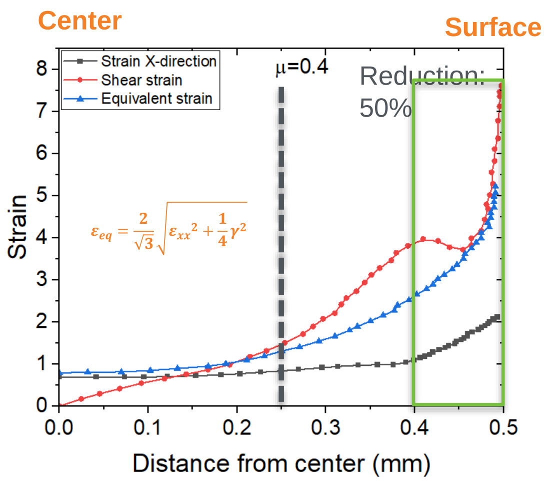
Equivalent *strain distribution*



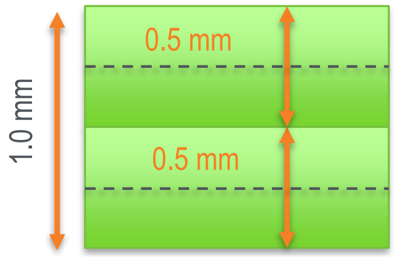
- ➢ Strain gradient increases with friction coefficient, μ

Reference:
I. Tadanobu, National Institute for Materials Science, Japan.

Equivalent *strain distribution*

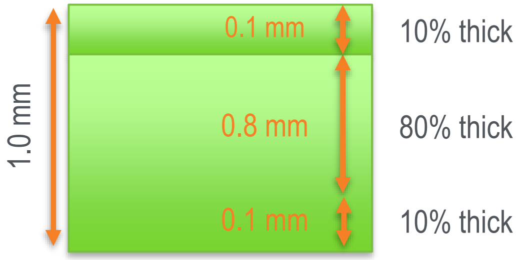


Case- I



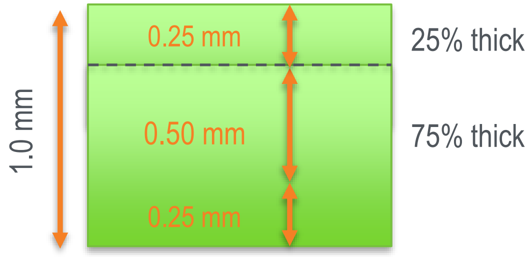
Shear strain, γ=0

Case- II



Shear strain, γ=max

Case- III

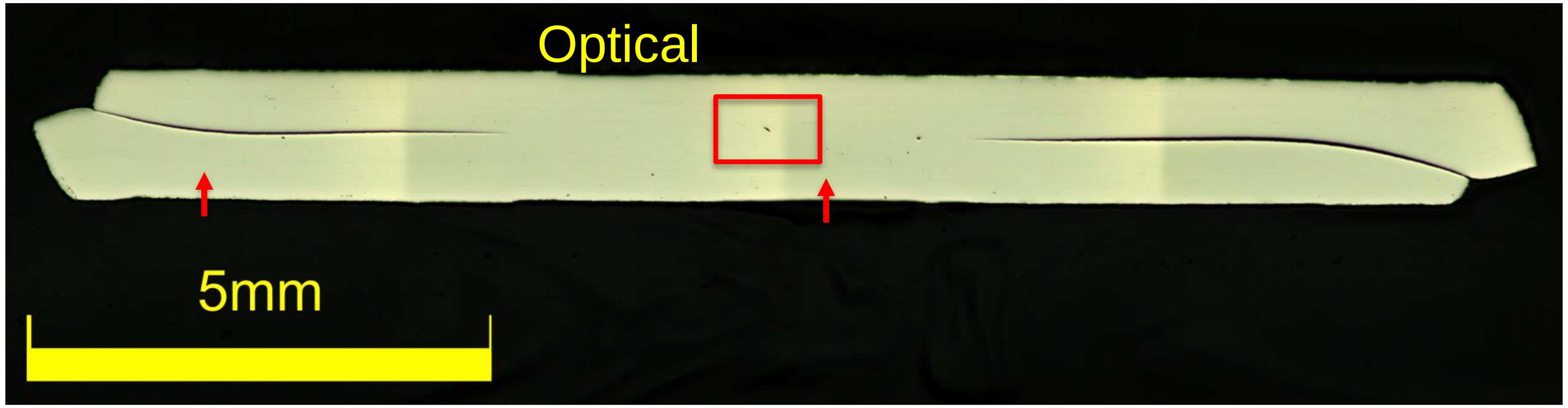


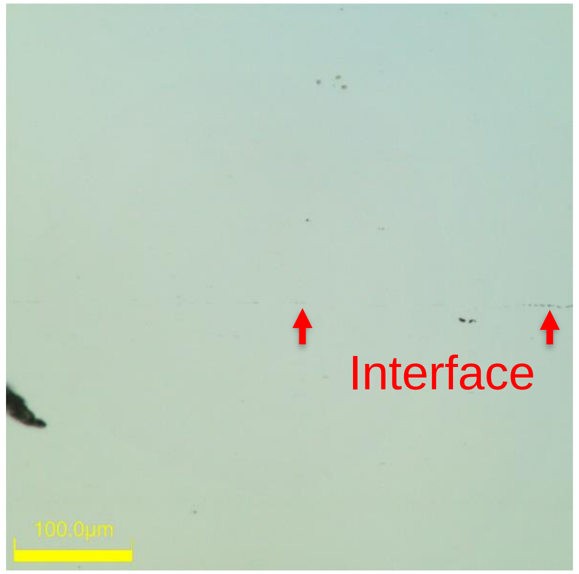
Shear strain, γ=moderate

- ➢ Understanding shear strain distribution, center experience zero shear and surface maximum
- ➢ Avoid high shear zone to minimize fiber damage
- ➢ Fibers were placed at center

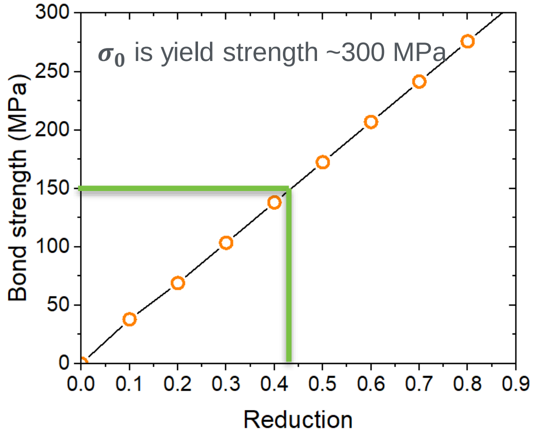
Cross-Sectional Microstructure (3 mm to 1.6 mm)

#	Dimension	Single pass reduction (%)	Temp (°C)	Soaking (min)	Grooved/Fiber	Observation
3	1”x0.5” (1.5 + 1.5 mm thick)	~45	900	15	w/o groove	Bonded





Analytical calculation

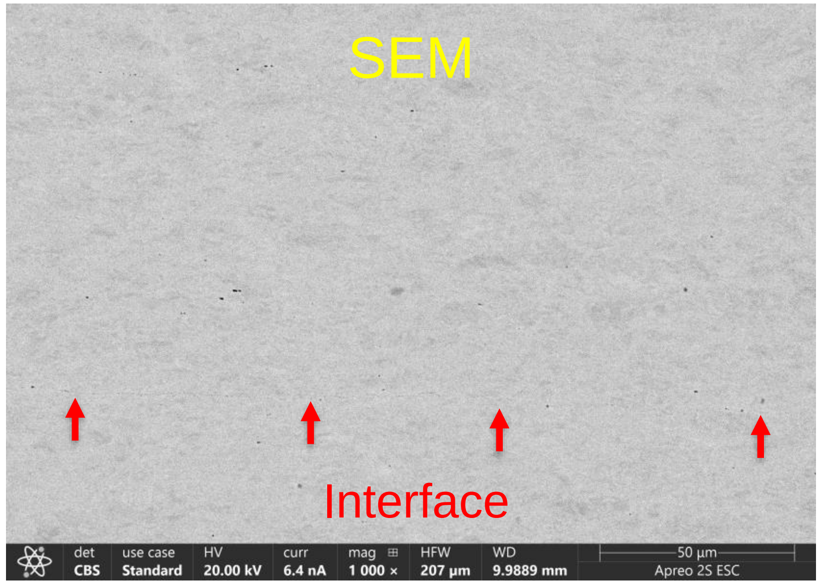


- ~43% reduction needed to have bond strength of ~ $\frac{1}{2}\sigma_0$

$$\left(\frac{\sigma_B}{\sigma_0}\right)_{max1} = \frac{2}{\sqrt{3}} Y = \frac{2}{\sqrt{3}} r$$

$$(\sigma_B)_{max1} = \sigma_0 \frac{2}{\sqrt{3}} Y$$

σ_0 is yield strength

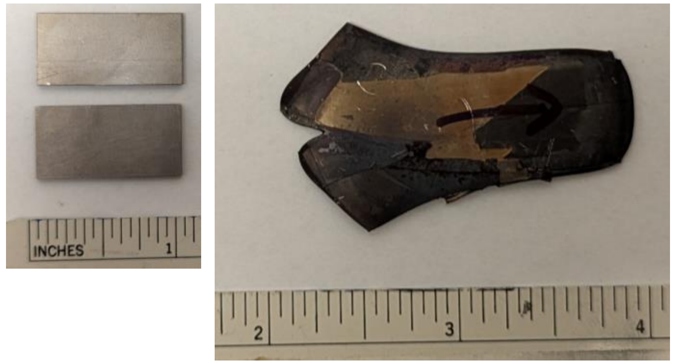


- Center part is bonded well
- Very thin bond line was observed

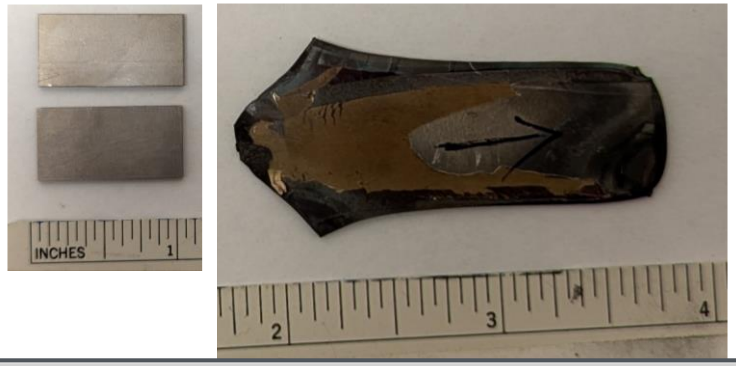
Approach 2
Roll Bonding: ~62% Reduction
(3.0 mm to 1.6 mm)

#	Dimension	Single pass reduction (%)	Temp (°C)	Soaking (min)	Grooved/Fiber	Observations
1	1"x0.5" (1.5 + 1.5 mm thick)	~62	900	5	w/o groove	Bonded, split observed at trailing
2	1"x0.5" (1.5 + 1.5 mm thick)	~62	900	5	w/o groove	Bonded
3	1"x0.5" (1.5 + 1.5 mm thick)	~62	900	5	w/ groove + Tube	Bonded

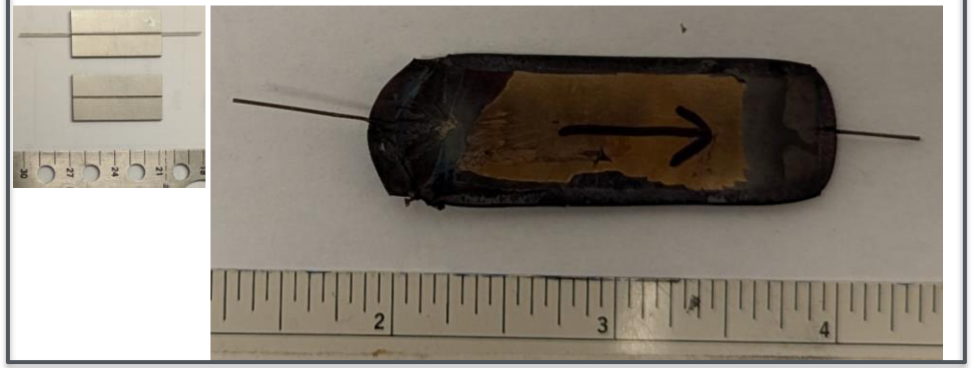
#1



#2

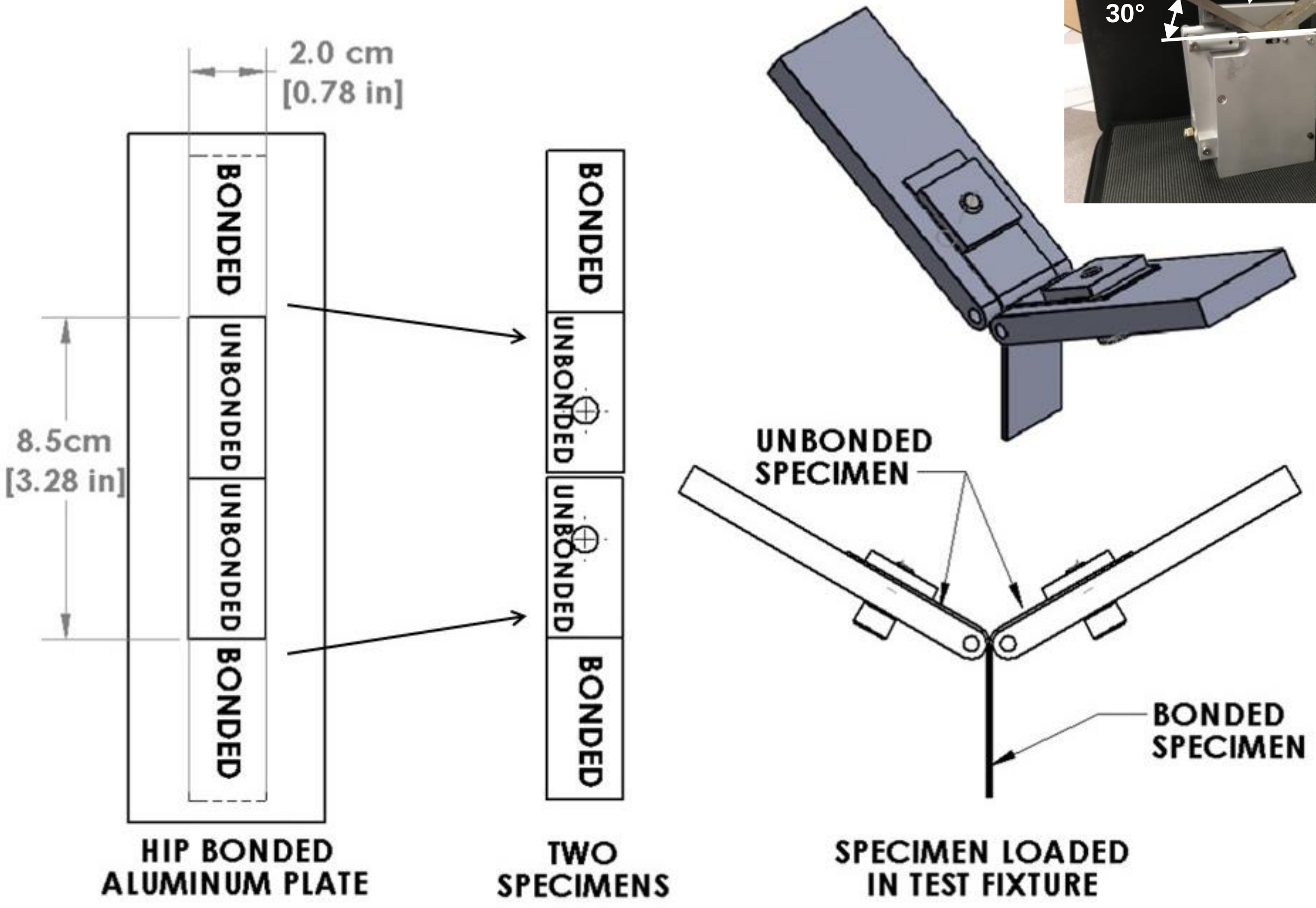


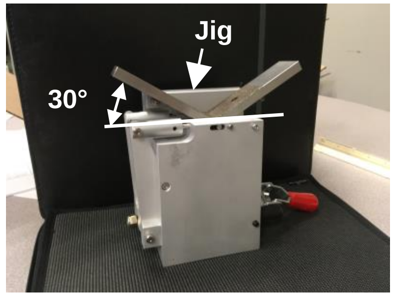
#3



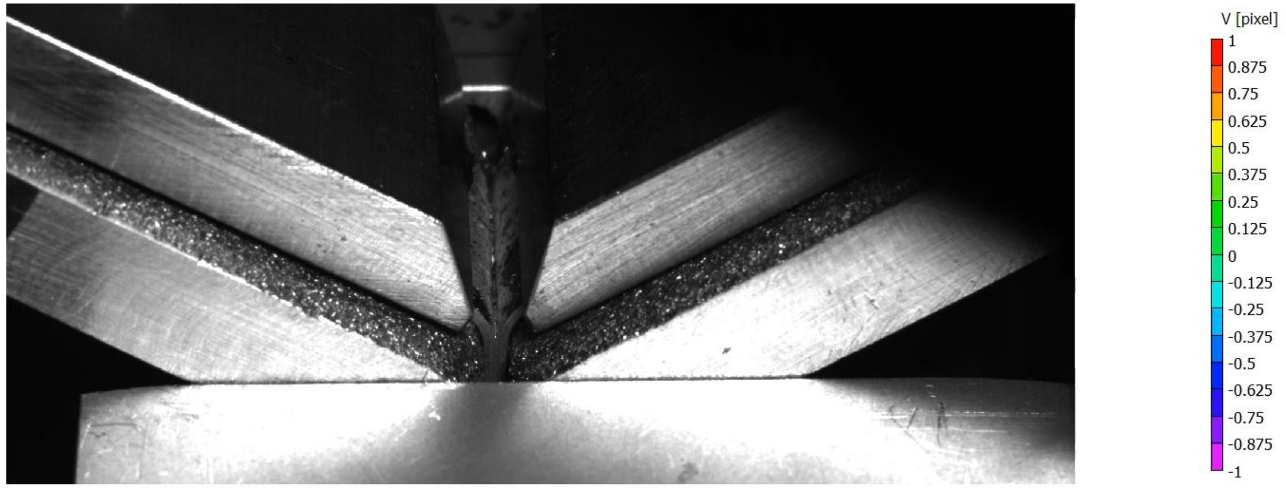
Bond Strength Evaluation- PNNL Developed Peel Testing Method

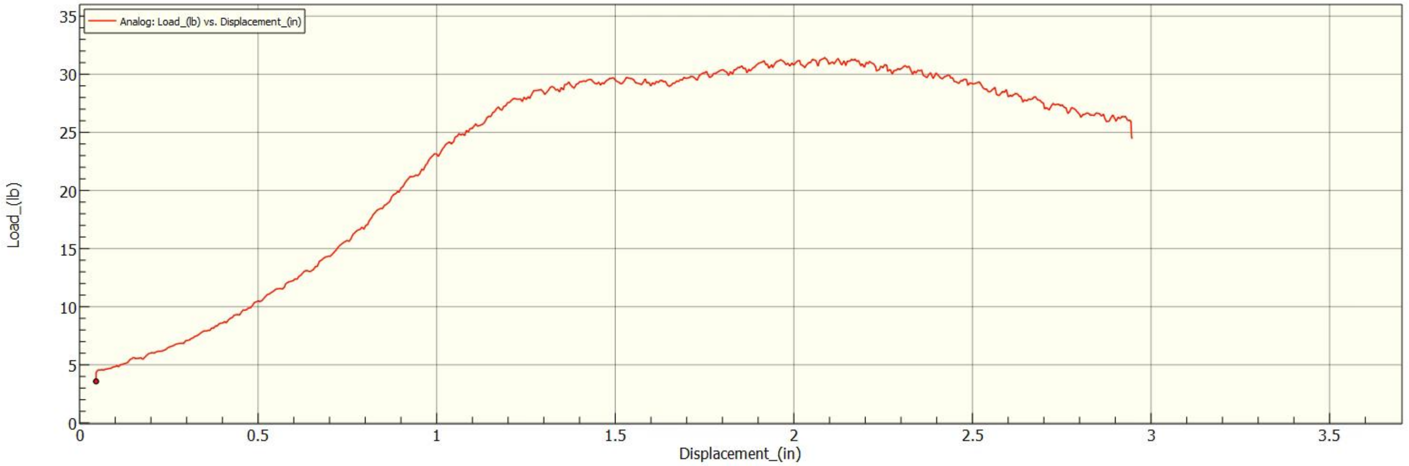
Peel specimen





Peel test





Ref.: Standard Test Method for Peel Resistance of Metal Sheets Joined by High Strength Bonds, ASTM B1021.

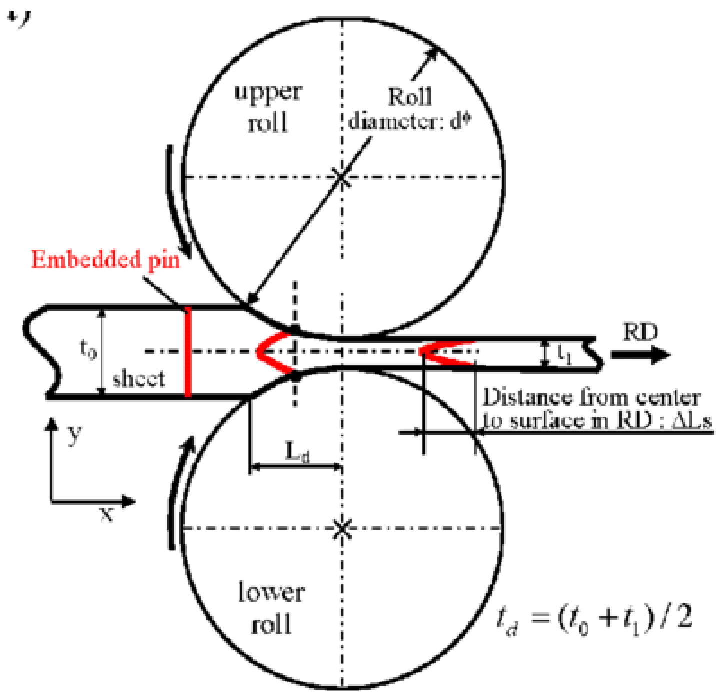
Approach 2: Summary of Results

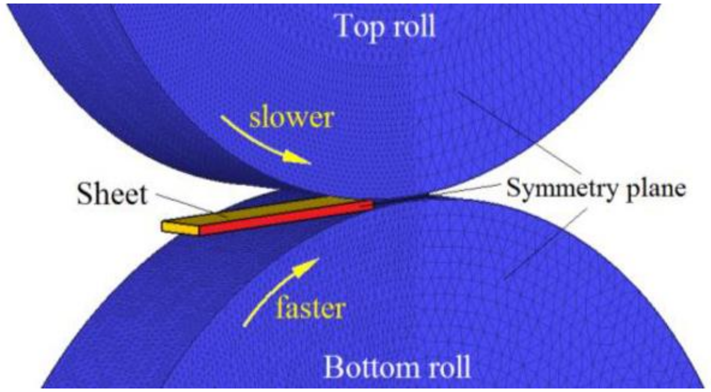
- Zhang Bay Model Predictions and calculations validated for bonding
- The stress-strain distributions in wrought product and fiber have been investigated with fibers embedded at different locations of the wrought product.
- Deformation of pre-drilled holes with vertical and horizontal orientations is studied with rolling reduction up to ~70% at rolling temperature of 850°C.
- Successfully showcased that we can embed sensor using the second approach
- Performance evaluation is underway

Rolling Sheet → Rod or Tube

Concept can be applied to other forms as well

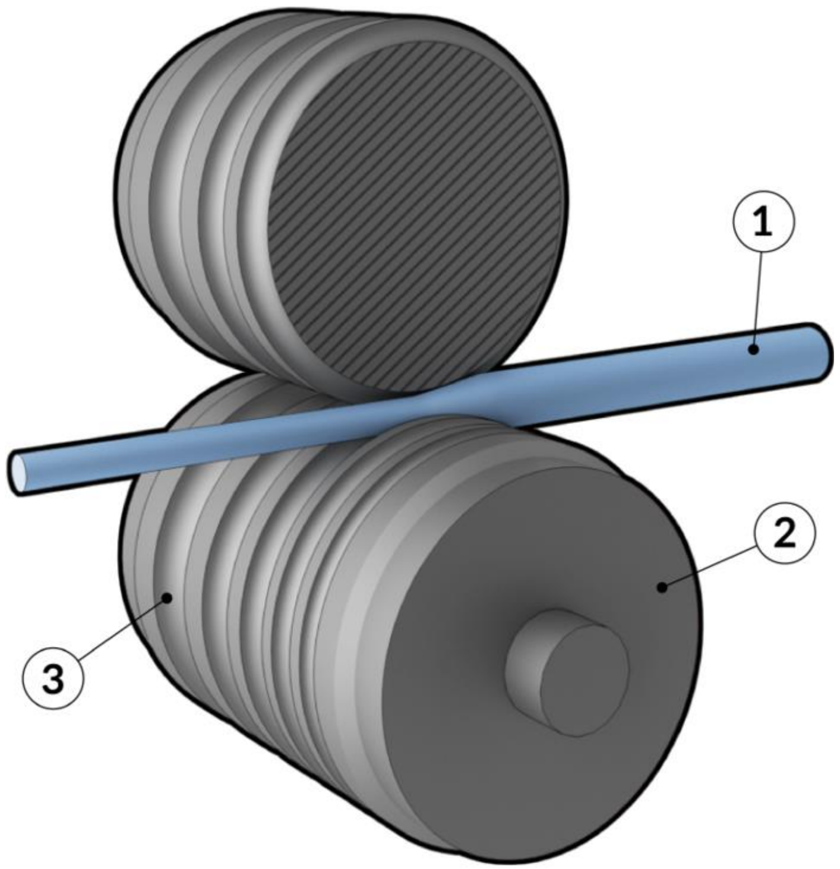
Sheet rolling





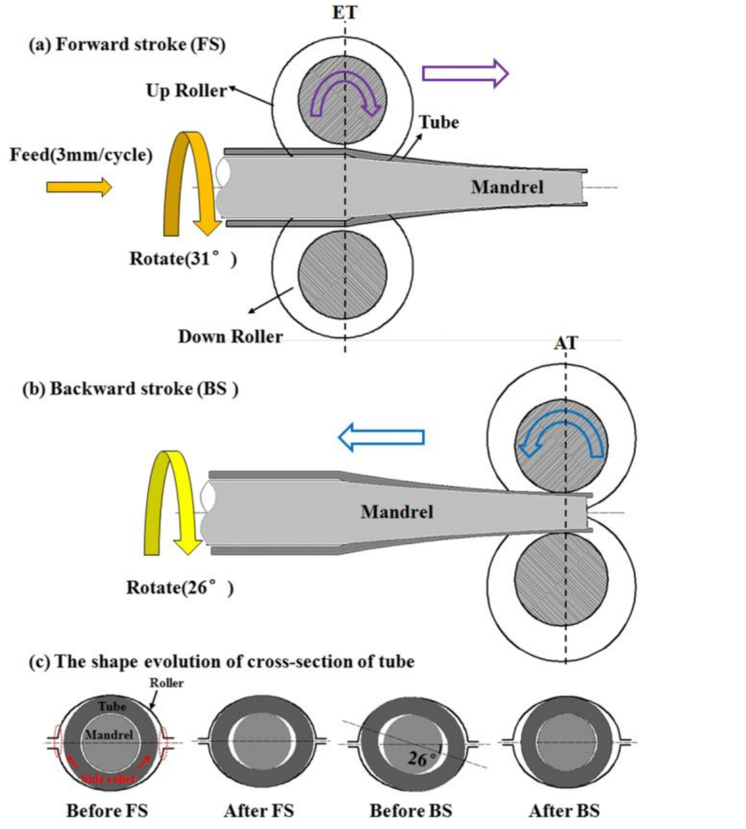
1. Metals **2020**, 10(1), 91.
2. The 12th International Conference on Numerical Methods in Industrial Forming Processes, MATEC Web Conf., 80 (2016).

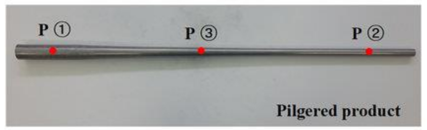
Rod rolling/ Groove rolling

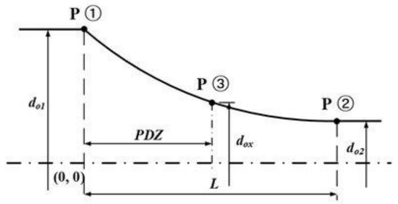


1. https://www.manufacturingguide.com/en/rod-rolling

Tube rolling/ Pilger rolling







1. International Journal of Material Forming (2021) 14:533–545.
2. Appl. Sci. 2021, 11(23), 11265.

Next Steps…

- Continue with the experimental plan- (1) Drilled hole, (2) Roll bonding, and (3) Confined rolling
- Cross sectional microscopy- Examine the interface of fiber/matrix
- Non-destructive characterizations- X-ray CT, UT for fiber continuity study

Pacific Northwest
NATIONAL LABORATORY

Thank you