Extrusion Deposition Additive Manufacturing (EDAM) of carbon fiber reinforced composite parts and tools for particle detector mechanics

Purdue University – Composites Manufacturing & Simulation Center

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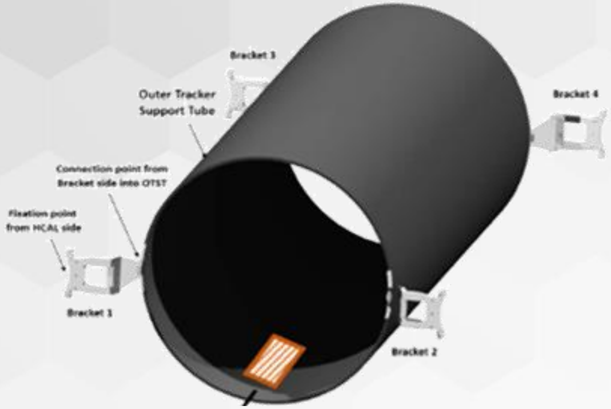
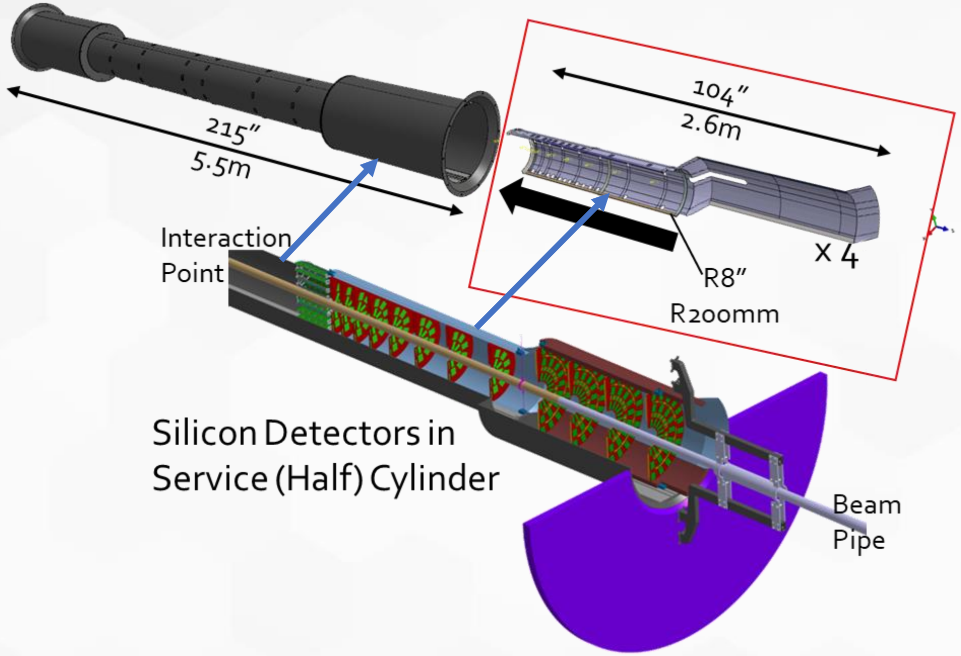
June 10, 2022

On behalf of CMS

Partially supported by NSF

What structures are we involved with?





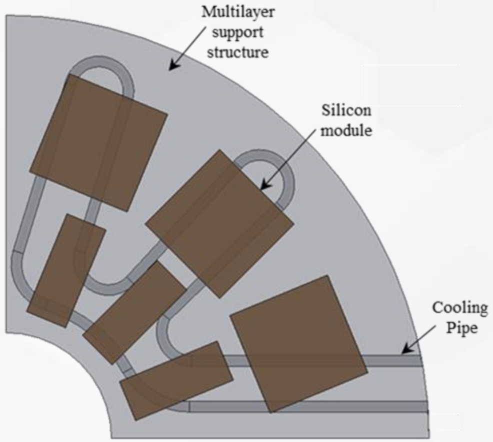
HL-LHC CMS Upgrade

Large Support Structures –

1. Boundary Tracker Support Tube (BTST)
2. Inner Tracker Support Tube (ITST)
3. Inner Tracker Service Cylinder

Small Structures –

1. Detector dees multilayer support structure
2. Flat plate stock for Silicon Modules backing / cooling plates

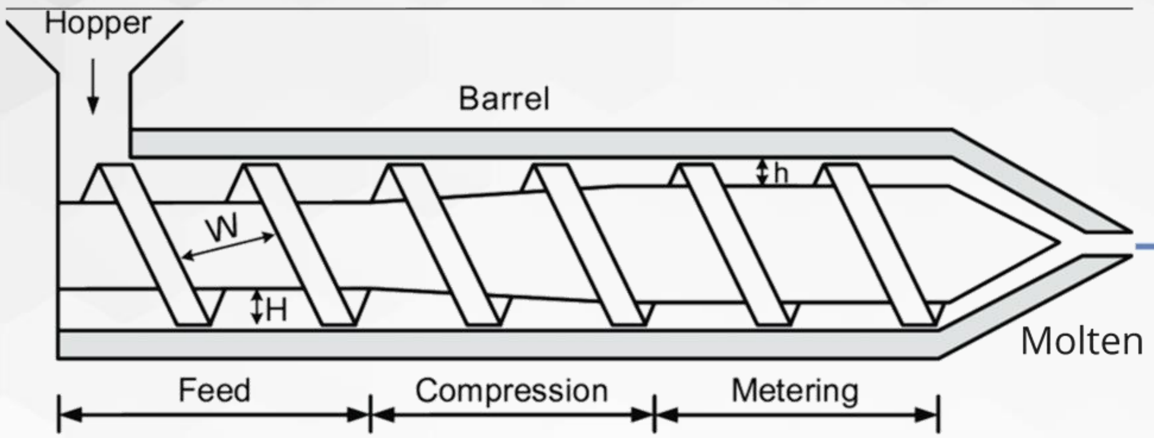


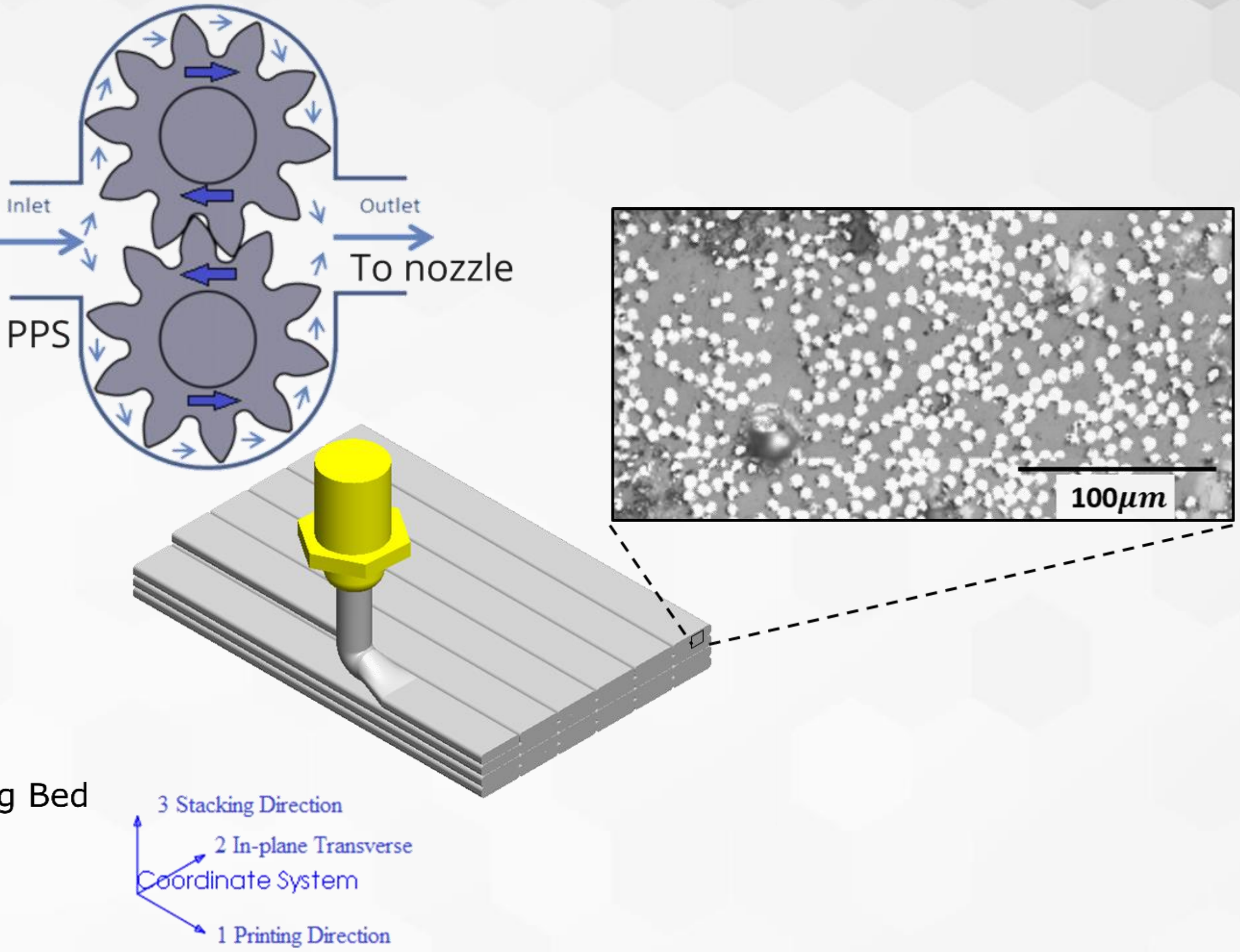
Overview

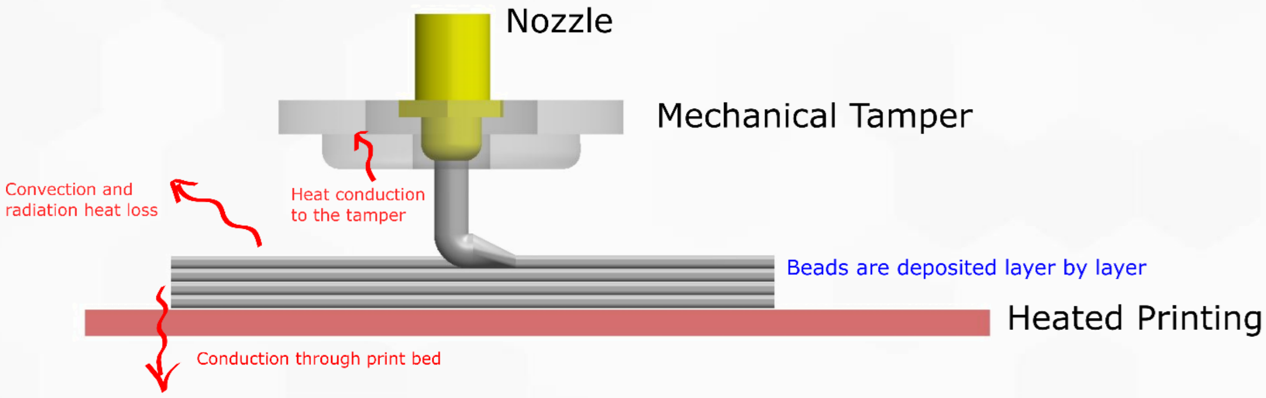
- Introduction to EDAM
- Material selection and testing for EDAM
    - Radiation testing for degradation
    - Characterization methods and results
    - Material characterization for printing and process performance simulations
- Additive3D printing and process performance simulations
- Case studies
    - Bonding and machining tools for CMS
    - Pre-preg layup tools
    - ITST Inner Track Rails

What is Extrusion Deposition Additive Manufacturing

Feed Stock - Polyphenylene sulfide (PPS)

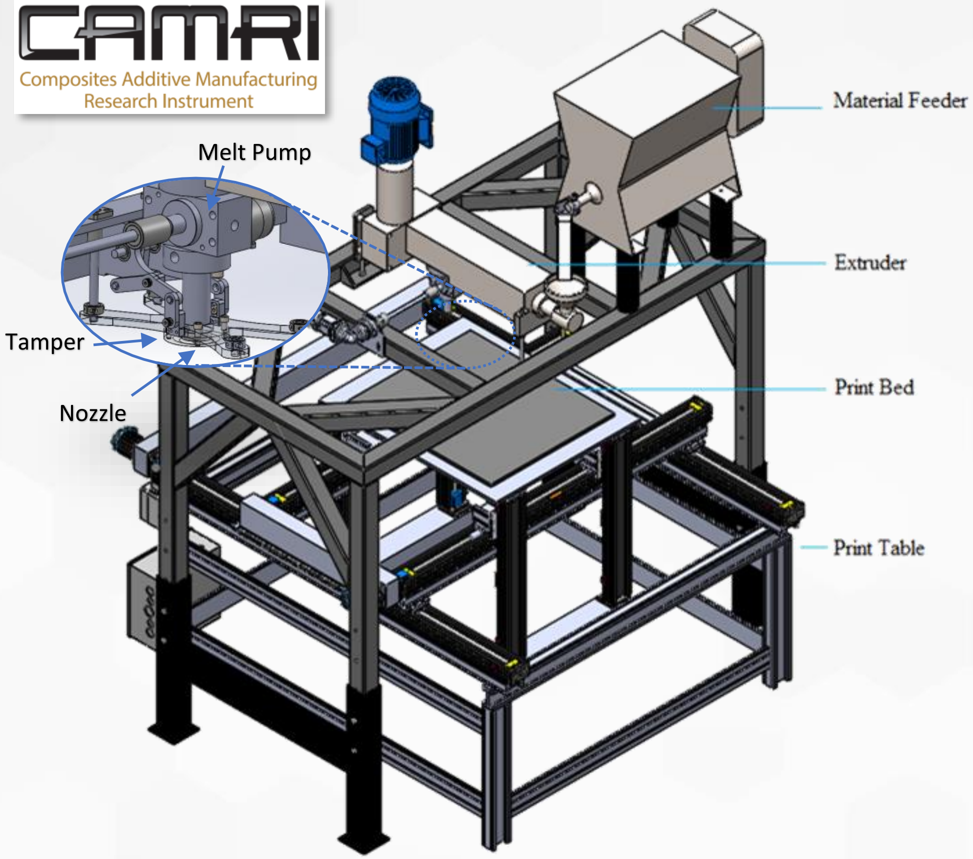






EDAM Process – Heat Transfer Schematic

Extrusion Deposition Additive Manufacturing



- Composite Additive Manufacturing Research Instrument (CAMRI) at Purdue
- Fixed single screw extruder configuration
- Numeric controlled print bed
- Printing highly filled thermoplastics
- Characterization/validation tool
- 20 x 20 x 10 inch print volume (0.5 x 0.5 x 0.25 meter)

Feed Stock - Polyphenylene sulfide (PPS)

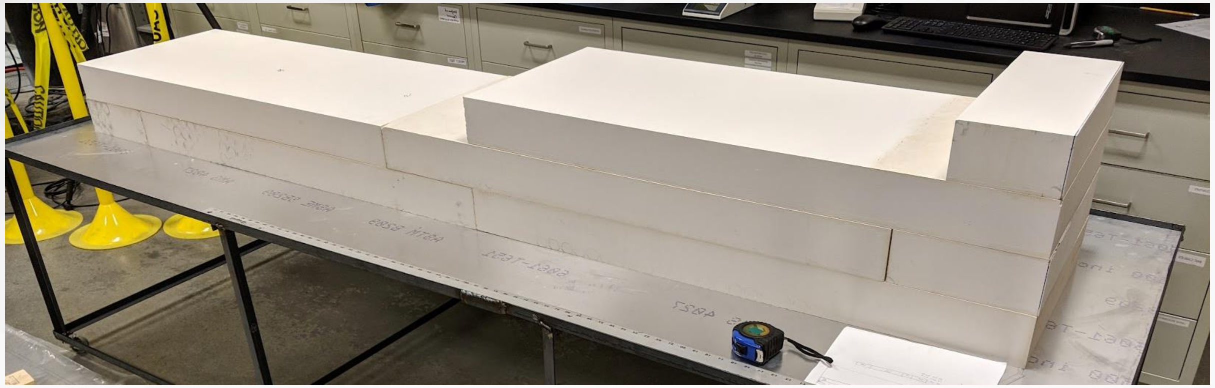
Thermwood LSAM Research Laboratory at Purdue

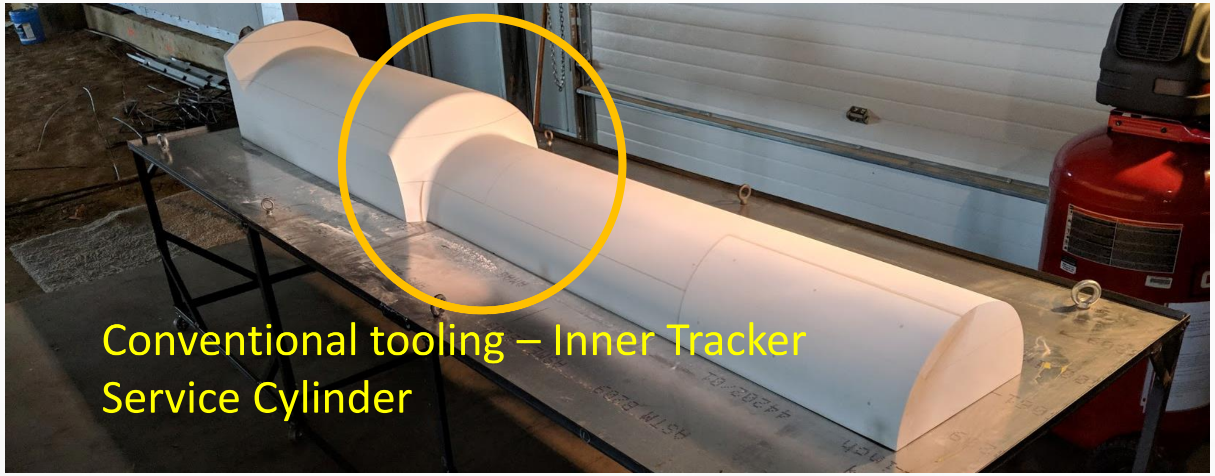
LSAM ADDITIVE PRINTER (10'X5')

- 5 x 10 x 4 feet (1.5m x 3m x 1.2m) print volume
- Print rates up to 200 pounds (90 kg) per hour
- The system has been modified to enable print temperatures of 450°C
- 5 axis LSAT – CNC milling machine

Need for simulations and 3D printing for CMS project

1. Large tooling and trimming fixtures needed for assembly, trimming and composite layup





Conventional tooling – Inner Tracker Service Cylinder

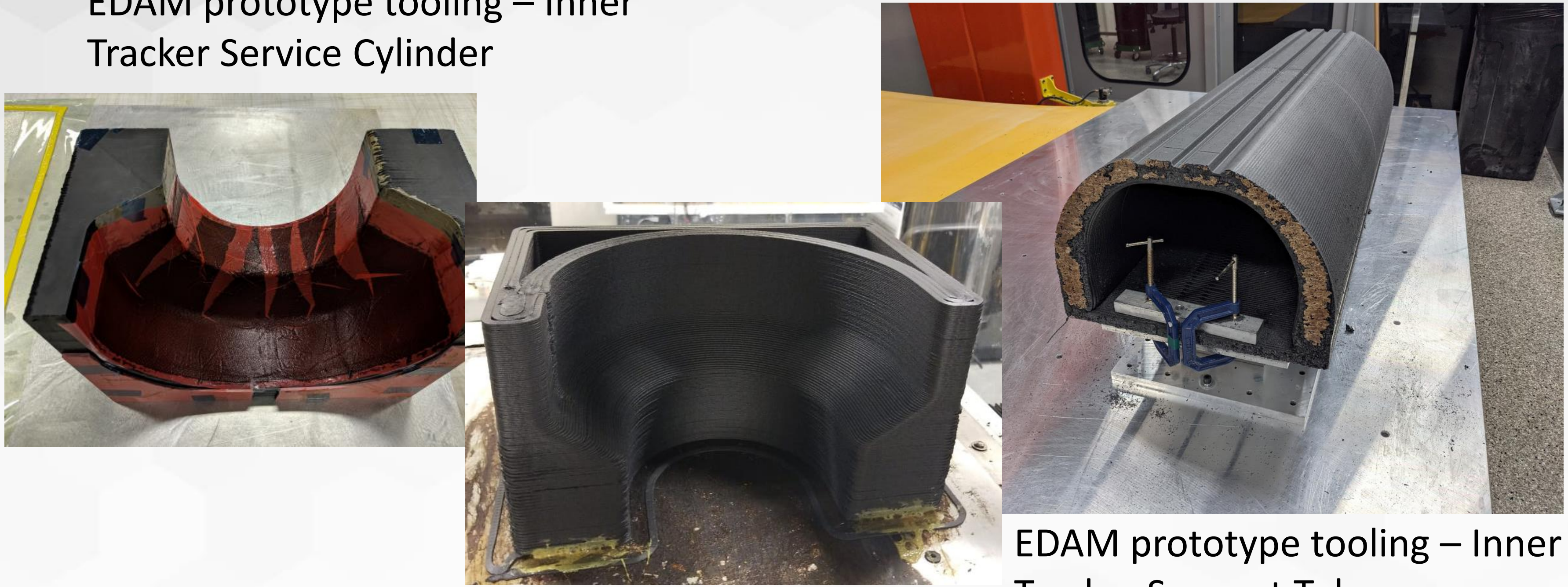
Conventional tooling – Inner Tracker Support Tube

Conventional tooling-

- Heavy
- Lead to higher material loss in CNC machining
- Need to use rectangular blocks to make complex shapes as needed by the CMS project
- Better precision than 3D printed tooling for high temperature cure layup tools

Need for simulations and 3D printing for CMS project

EDAM prototype tooling – Inner Tracker Service Cylinder



EDAM prototype tooling – Inner Tracker Support Tube

Finished tool surface coated with mold release

Layup and vacuum bagging

Conventional tooling-

- Lighter to handle
- Minimal material loss in CNC machining
- complex shaped can be directly printed as needed by the CMS project
- Lower precision than conventional tooling for layup tools – but still within the required tolerance on service cylinder / ITST (?)

IDEAL FOR ASSEMBLY AND CNC TRIMMING FIXTURES

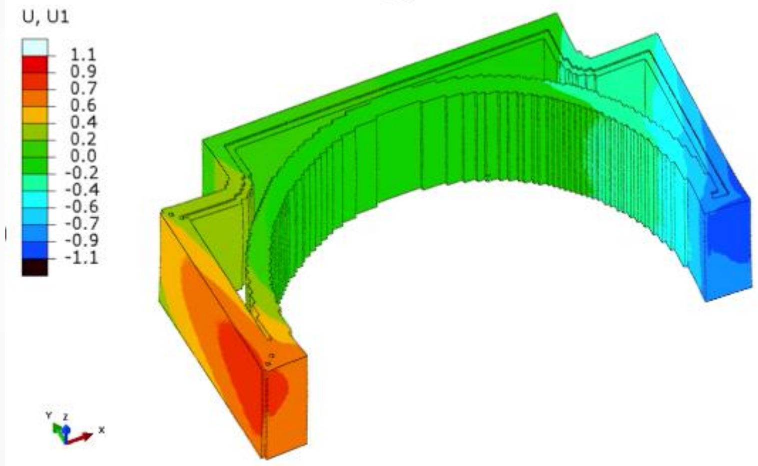
Need for simulations and 3D printing for CMS project

2. Material cost and machining time (Tooling comparison provided for Inner Tracker tool)

		Conventional Tooling	**PPS + CF material for high temperature CF pre-preg cure (EDAM)**	**ABS + CF material for tooling and assembly at room temp (EDAM)**
1.	Cost per unit weight	$ 8.5/lb ($18.7/kg) – sold as blocks of size (1000x500x100mm)	$ 28/lb ($61.7/kg)	$ 15/lb ($33/kg)
2.	Cost of material needed for the ITST tool	$ 2550 (tooling block + adhesive + surface treatment)	$ 2800	$ 1500
3.	Time needed for final tool	~ 50 working hours	~ 60 working hours (15 simulation + 15 design iterations + 30 EDAM and CNC)	~ 30 working hours
4.	Total weight	~ 184 lbs (83.5 kg)	~ 100 lbs (45 kg)	~ 100 lbs (45 kg)

Need for simulations and 3D printing for CMS project

3. Precisions / tolerances needed for CMS parts we need to understand how the shape change happens
    - Aspect ratios and shapes – ITST track – long and thin parts lead to high process induced warpage – hence we need to predict it and compensate for this shape change



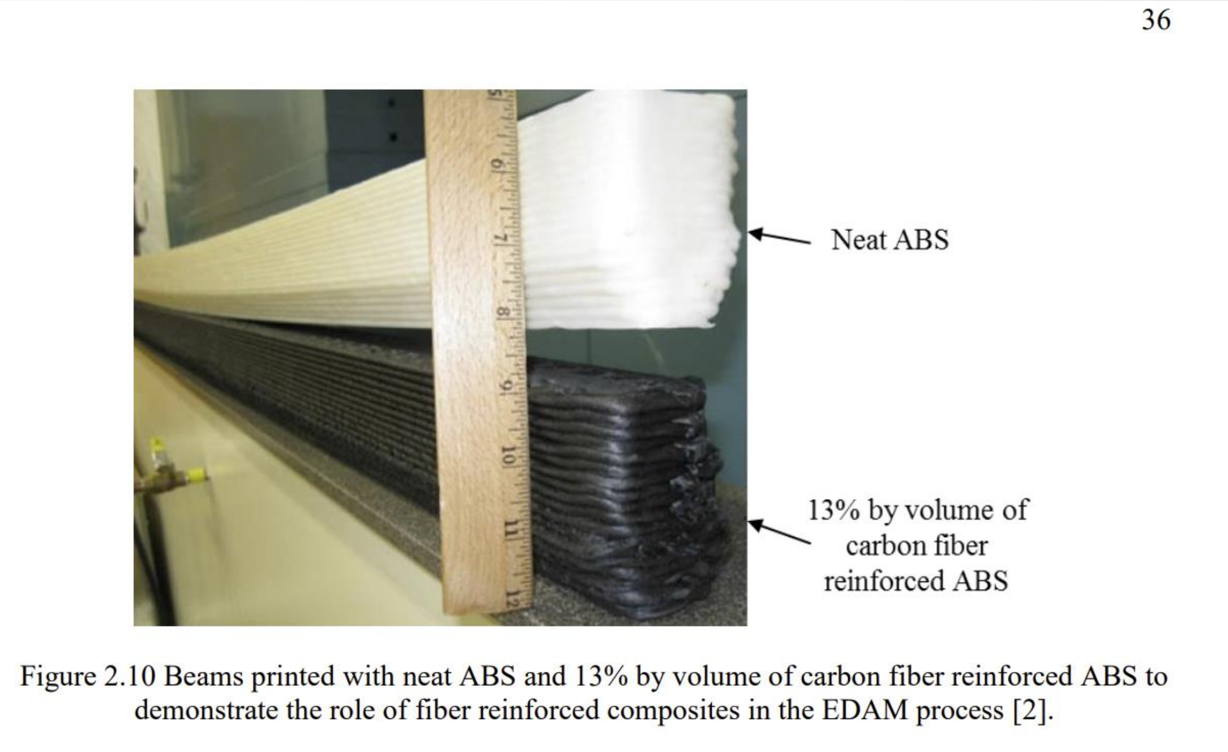

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Figure 2.10 Beams printed with neat ABS and 13% by volume of carbon fiber reinforced ABS to demonstrate the role of fiber reinforced composites in the EDAM process [2].

Material Characterization

Radiation Resistance

Effect of radiation on –

- Thermal Conductivity
- Elastic modulus
- Poisson’s ratio
- Coefficient of thermal expansion (CTE)

Heat Transfer

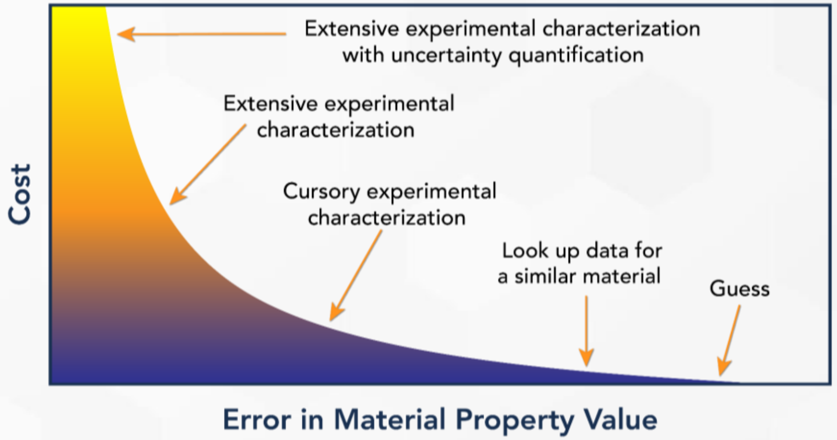
- Thermal Conductivity
- Specific Heat
- Emissivity
- Performance at sub-zero temperatures

Thermo-mechanics

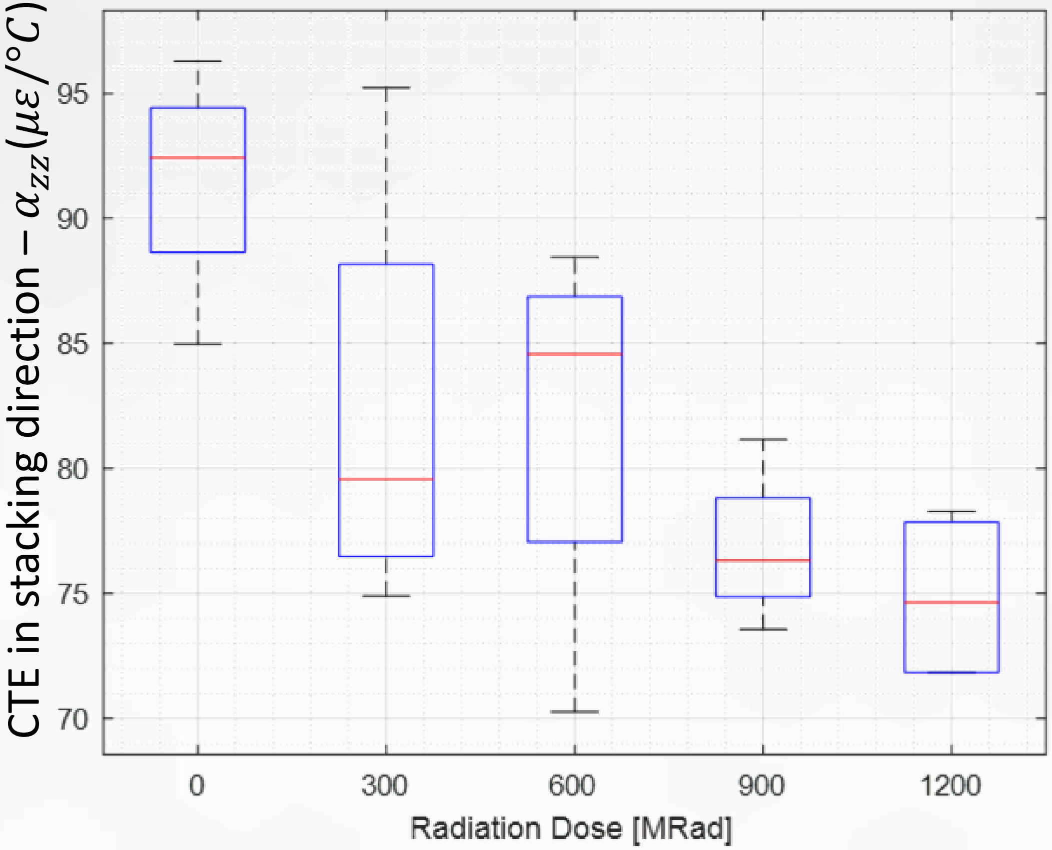
- Crystallization / Melting
- Coefficients of Thermal Expansion
- Bonding

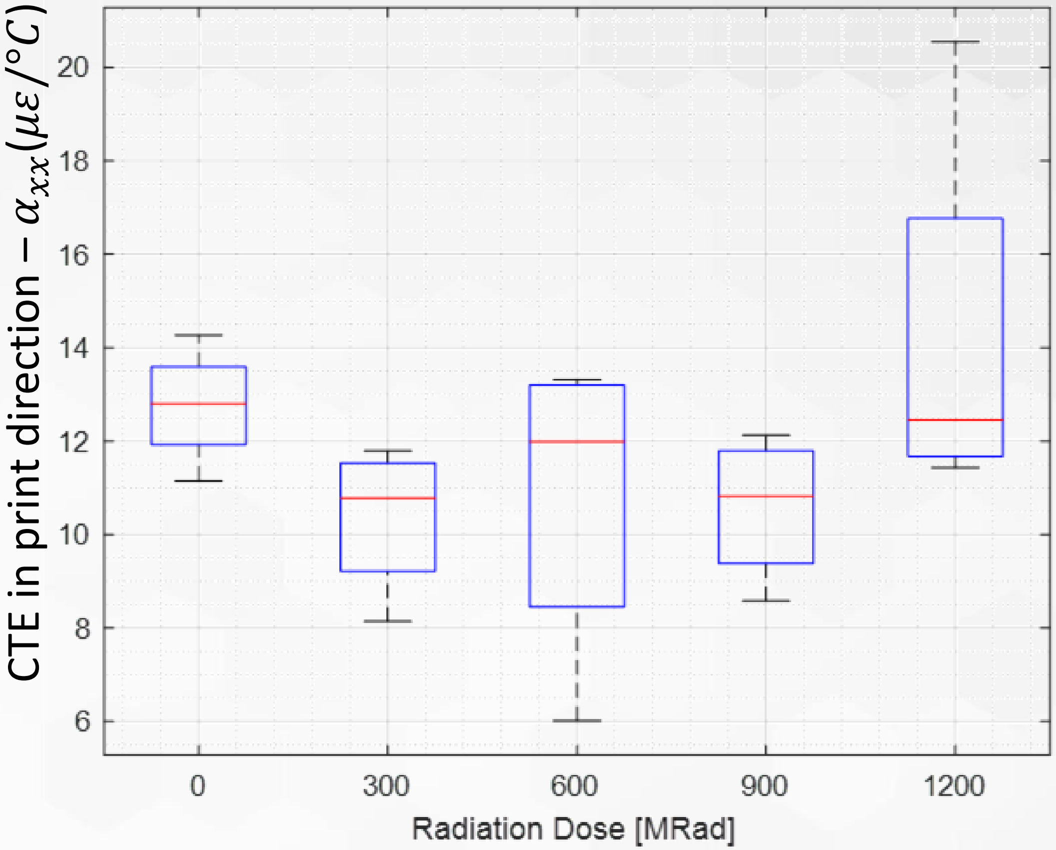
Viscoelasticity

- Prony Series model



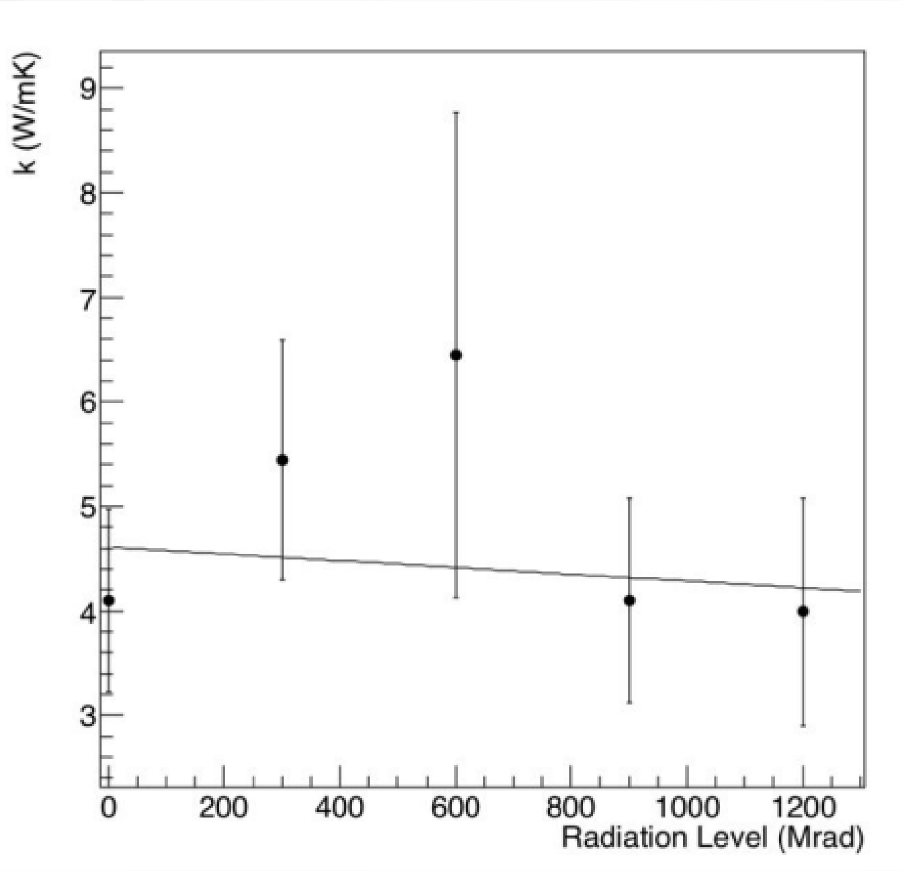
CTE results – ThermaTech PPS – no significant degradation as f (rad-dose)





Thermal conductivity – ThermaTech PPS – no significant degradation as f(rad-dose)

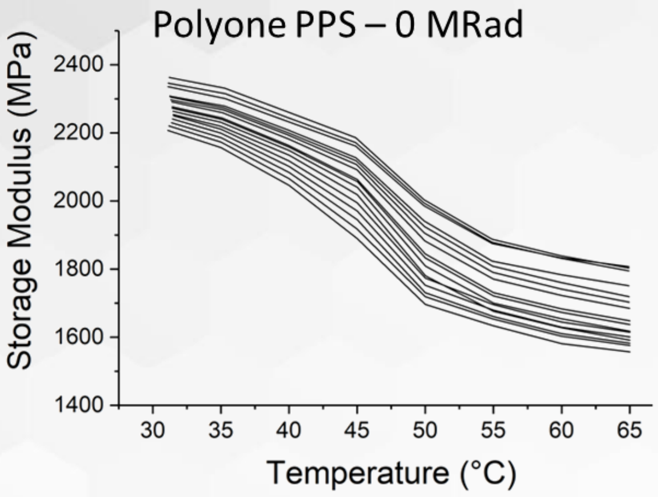
Thermal conductivity results from Ryan

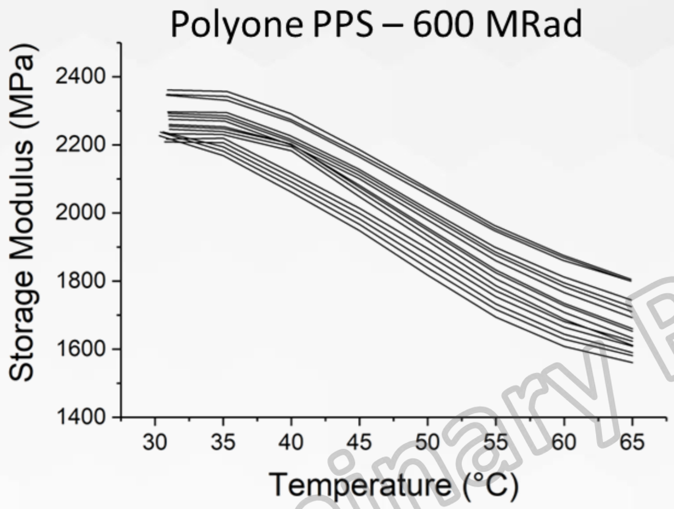


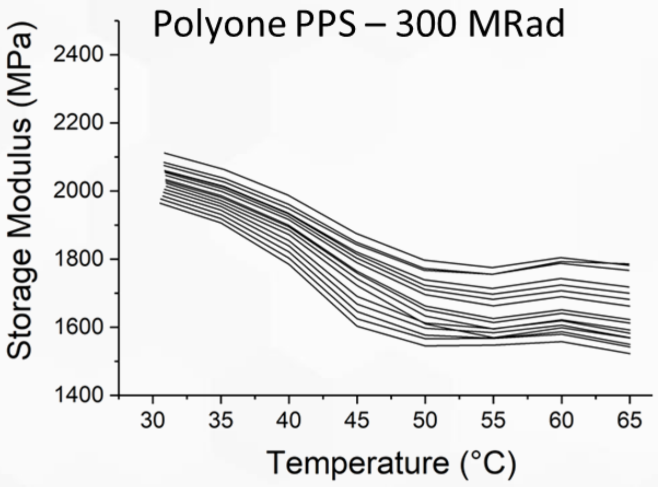
- https://indico.cern.ch/event/1065348/
- https://www.physics.purdue.edu/cmsfpix/ThermalMeasurements/

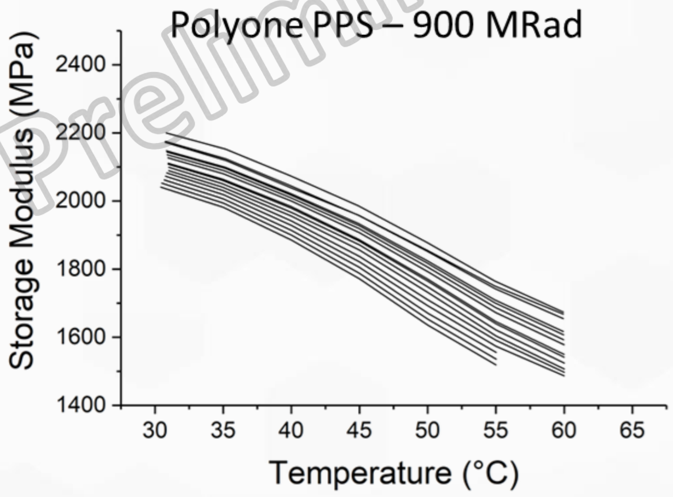
This material has thermal conductivity at 4 W/mK in stacking direction and about 13W/mK in print direction, so really useful in Dees where thermal pathway needed between coolant tube to portcards / sensor assembly

Preliminary DMA results for storage modulus

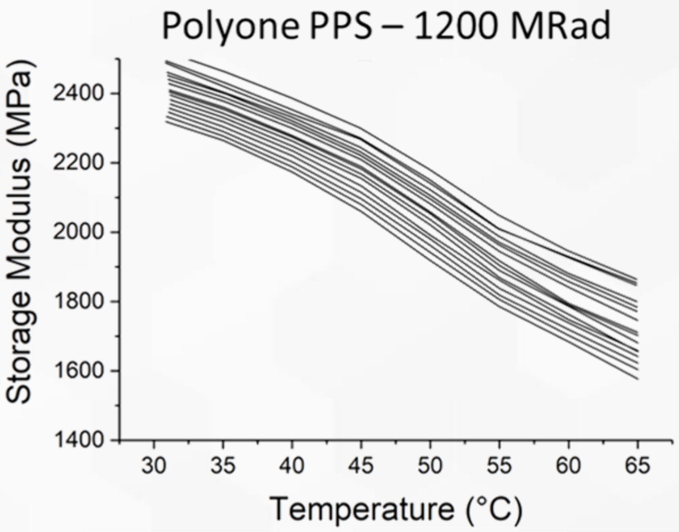








- No significant change in modulus reported !!
- Storage modulus is analogous to elastic modulus for linear elastic loading

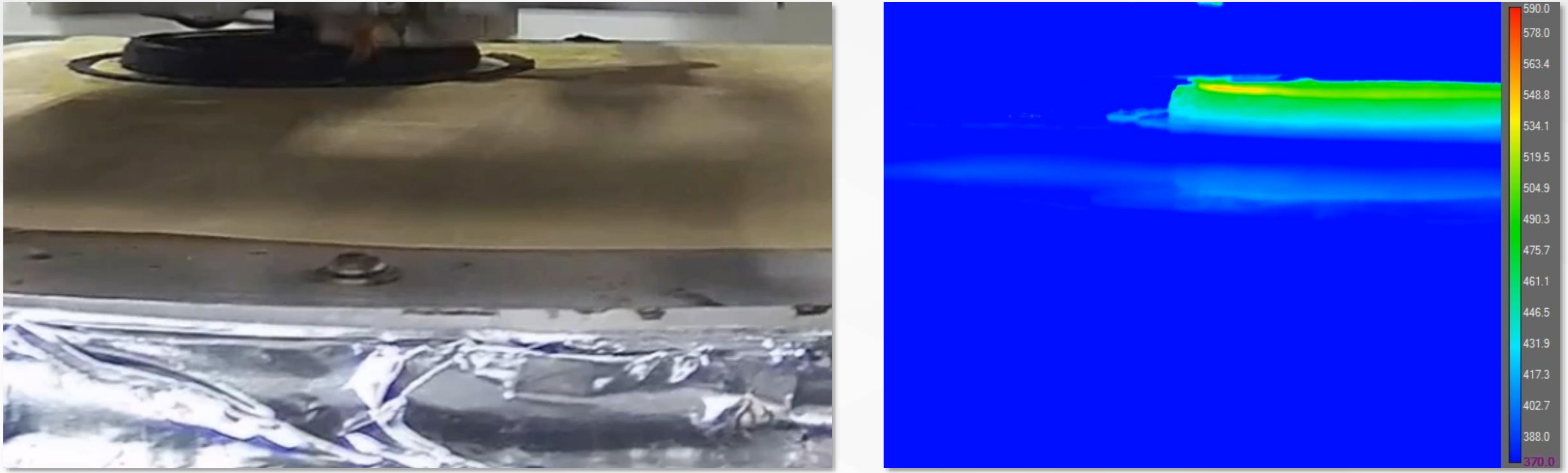


Additive3D printing and process performance simulations

On behalf of

Partially supported by

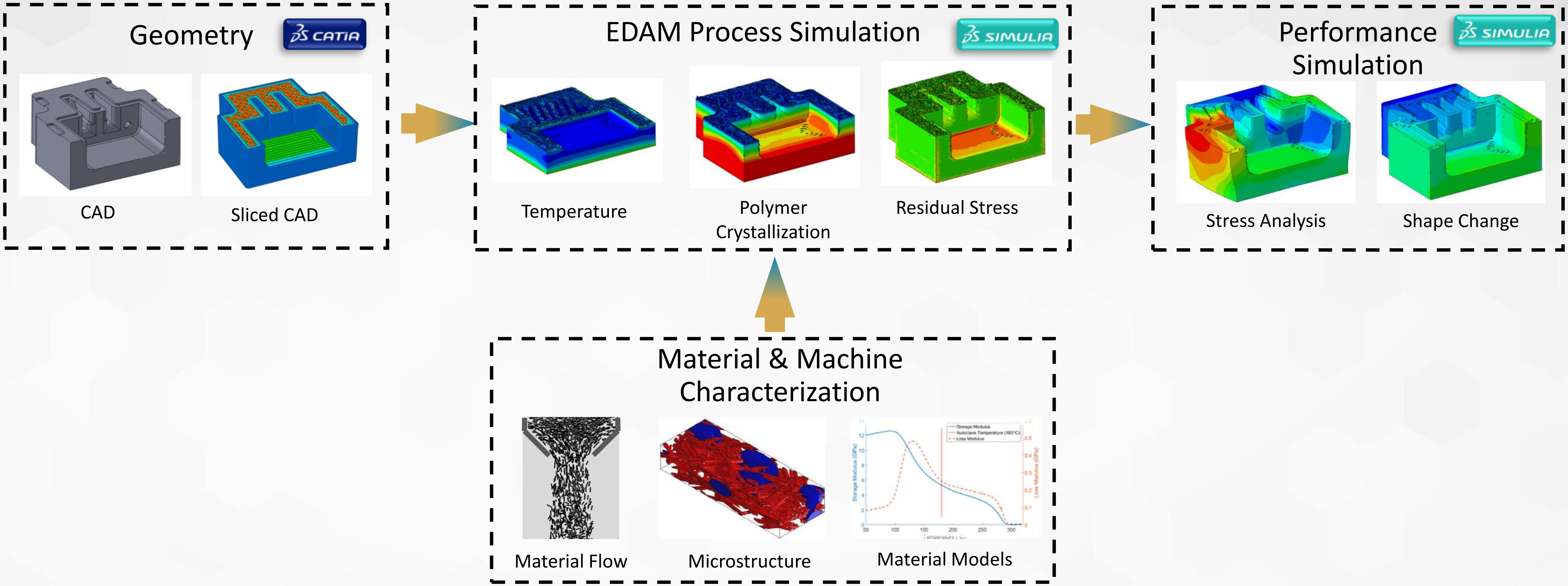
CAMRI – Process Monitoring



Video 10X

LSAM Printing Process

ADDITIVE3D Workflow



Geometry

CAD

Sliced CAD

EDAM Process Simulation

Temperature

Polymer Crystallization

Residual Stress

Performance Simulation

Stress Analysis

Shape Change

Material & Machine Characterization

Material Flow

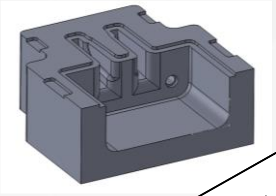
Microstructure

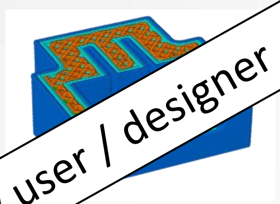
Material Models

ADDITIVE3D Workflow

Geometry

CATIA

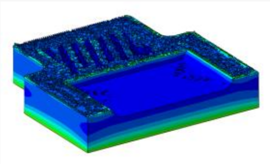

CAD

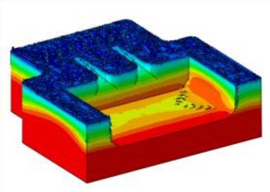

Sliced CAD

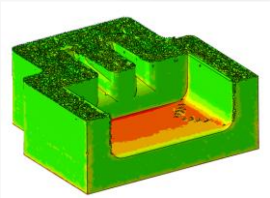
Provided by user / designer

EDAM Process Simulation

SIMULIA

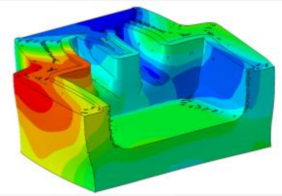

Temperature

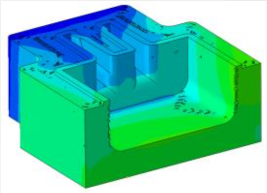

Polymer Crystallization


Residual Stress

Performance Simulation

SIMULIA

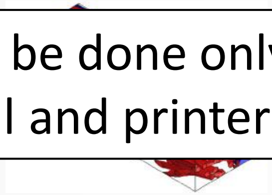

Stress Analysis

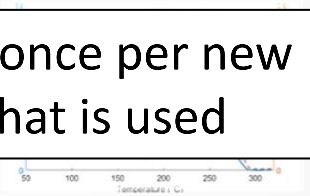

Shape Change

Material & Machine Characterization

Needed to be done only once per new material and printer that is used

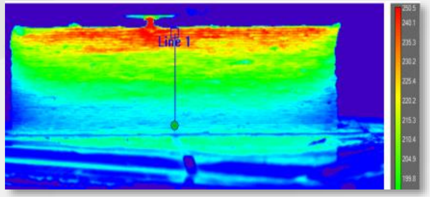

Material Flow


Microstructure

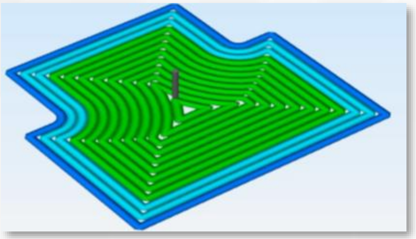


Material Models

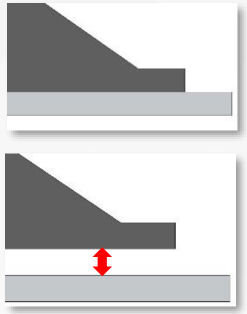
EDAM System Characterization



Heat Losses

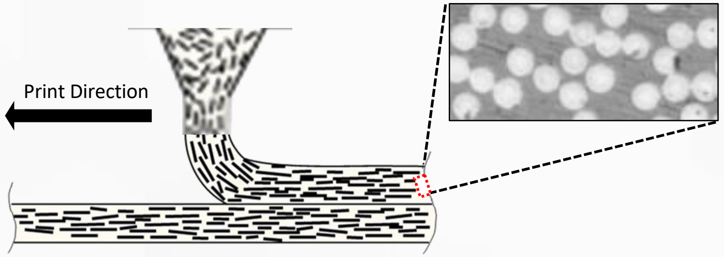


Bead Geometry,
Event Series



Boundary
Conditions

Process
Conditions



Deposition, Compaction

Process Controlled
Microstructure

CAMRI
Composites Additive Manufacturing
Research Instrument

LSAM
Large Scale Additive Manufacturing

CI BAAM

AM System Card

Event Series

Global and local
fiber orientations

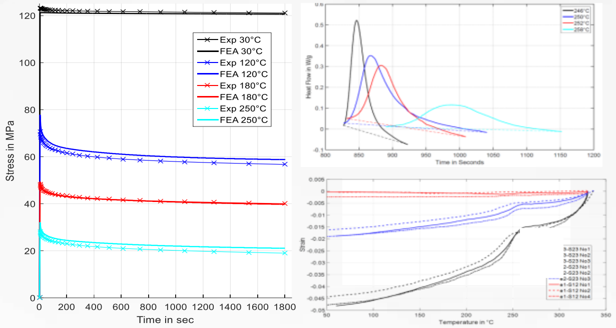
Boundary
conditions

Simulation Inputs

Material Characterization

User Input

Experimental Characterization



Experimental Data

AM System Card

CAMRI
Composites Additive Manufacturing Research Instrument

LSAM
Large Scale Additive Manufacturing

CI BAAM

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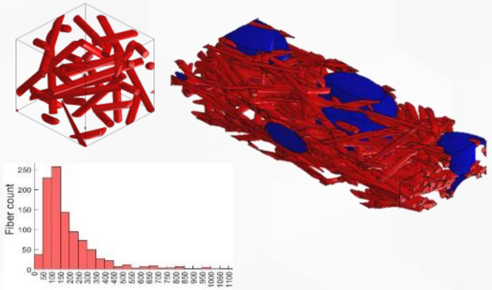
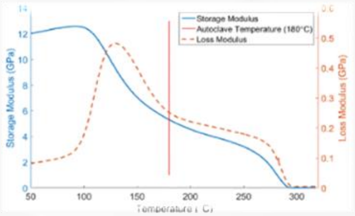
Constituent Properties,
Homogenized Properties

Bead Geometry
Local Fiber Orientation,

Material Card Generation



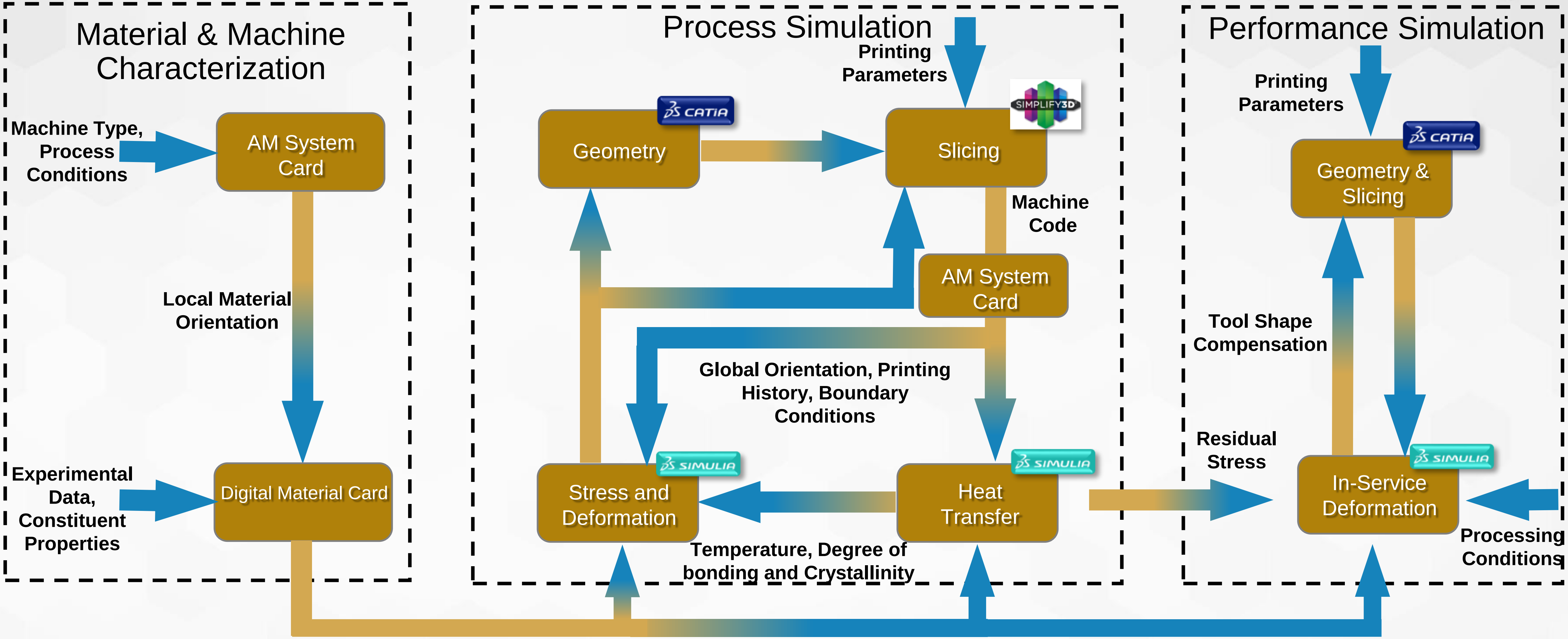
Property Prediction



Material Models

Digital Material Card

Process and Performance Simulation



Material & Machine Characterization

Machine Type, Process Conditions

AM System Card

Local Material Orientation

Experimental Data, Constituent Properties

Digital Material Card

Process Simulation

Printing Parameters

Geometry

Slicing

Machine Code

AM System Card

Global Orientation, Printing History, Boundary Conditions

Stress and Deformation

Heat Transfer

Temperature, Degree of bonding and Crystallinity

Performance Simulation

Printing Parameters

Geometry & Slicing

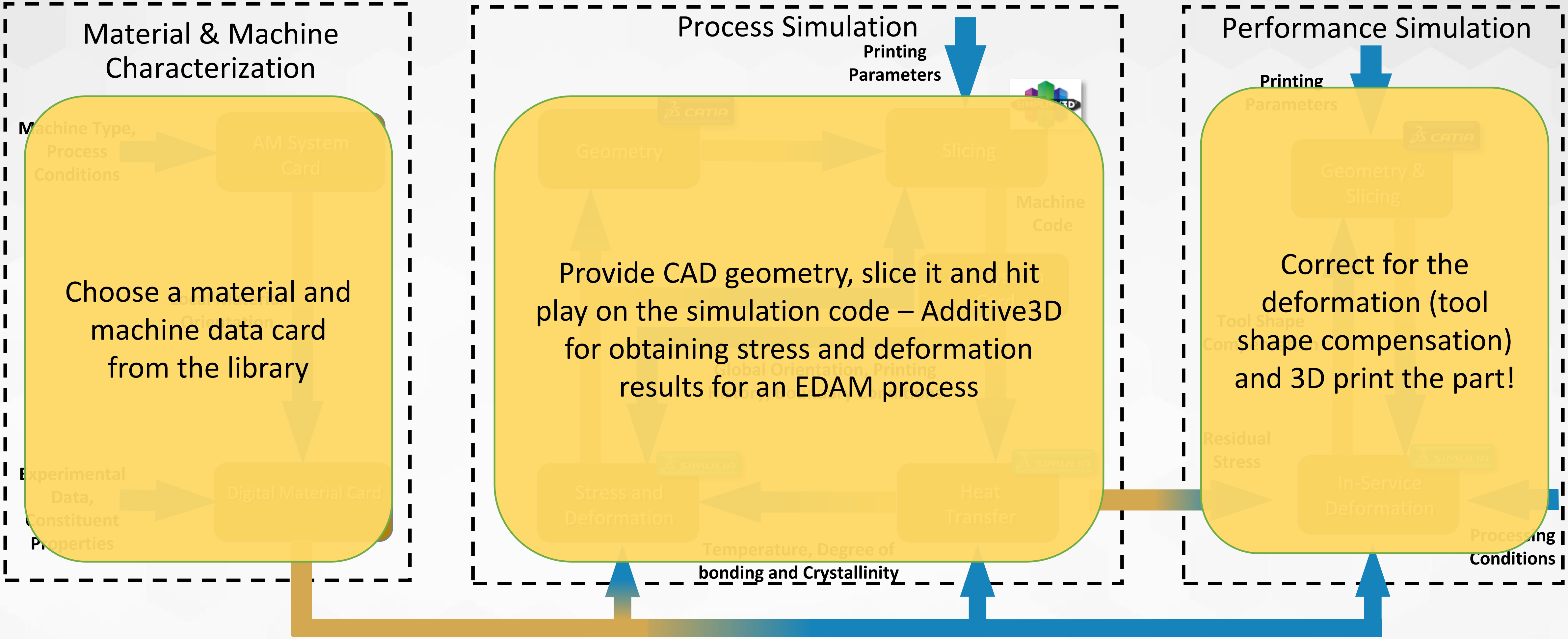
Tool Shape Compensation

Residual Stress

In-Service Deformation

Processing Conditions

Process and Performance Simulation



Material & Machine Characterization

Choose a material and machine data card from the library

Process Simulation

Provide CAD geometry, slice it and hit play on the simulation code – Additive3D for obtaining stress and deformation results for an EDAM process

Performance Simulation

Correct for the deformation (tool shape compensation) and 3D print the part!

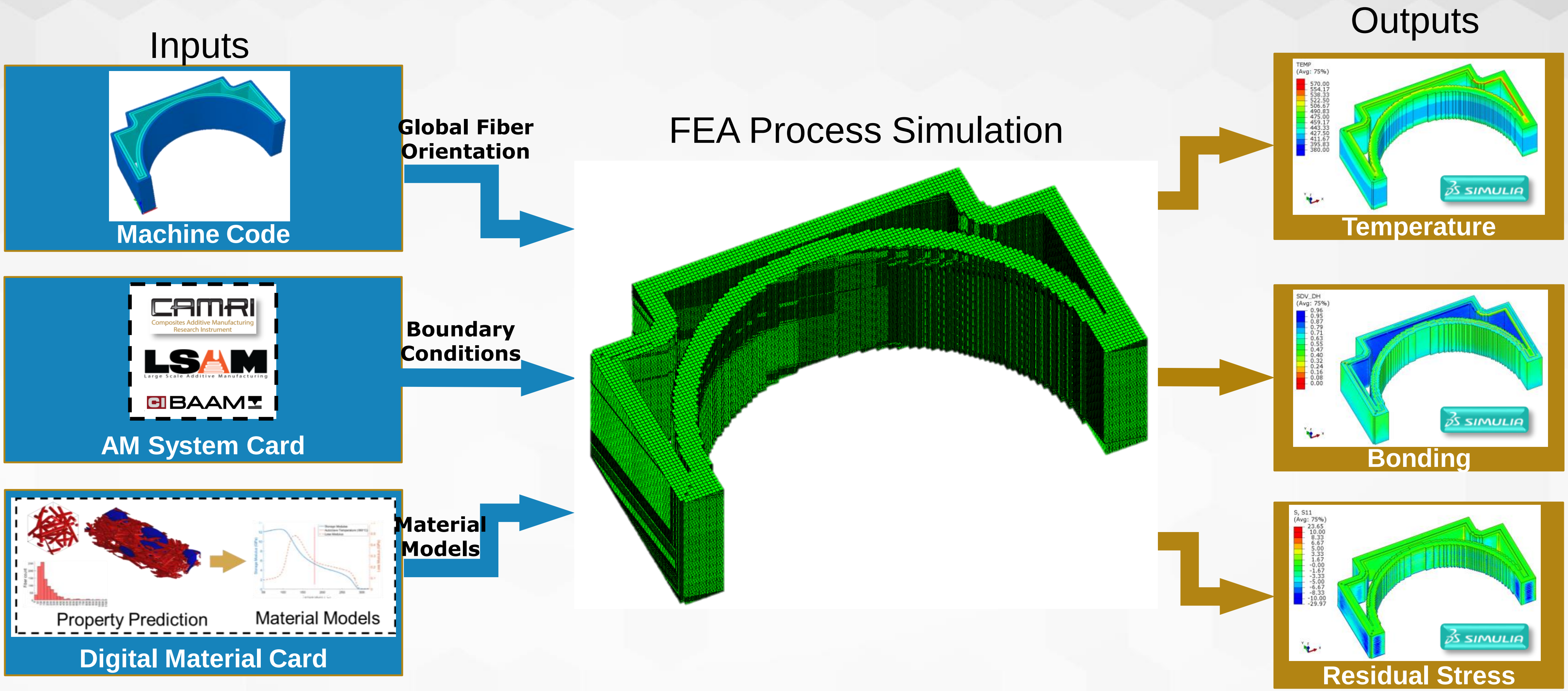
Case Studies

1. Inner Tracker Service Cylinder Stiffener Bonding Jig
2. Inner Tracker Service Cylinder Layup Tool
3. ITST Center Section Trimming/Machining Tool
4. ITST Rails/Tracks
5. CMS Inner Track – forward pixel Dees perimeter seal

On behalf of CMS Partially supported by NSF

#1 - Inner Tracker Service Cylinder Stiffener Bonding Jig

Process Simulation



Inputs

Machine Code

AM System Card

Property Prediction

Material Models

Digital Material Card

Global Fiber Orientation

Boundary Conditions

Material Models

FEA Process Simulation

Outputs

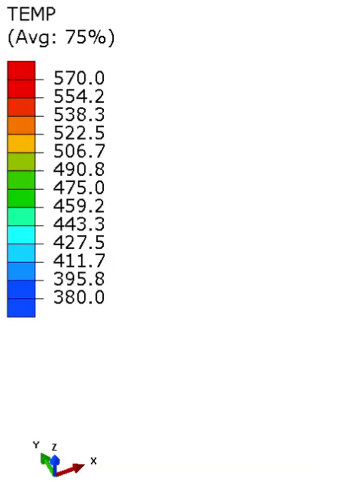
Temperature

Bonding

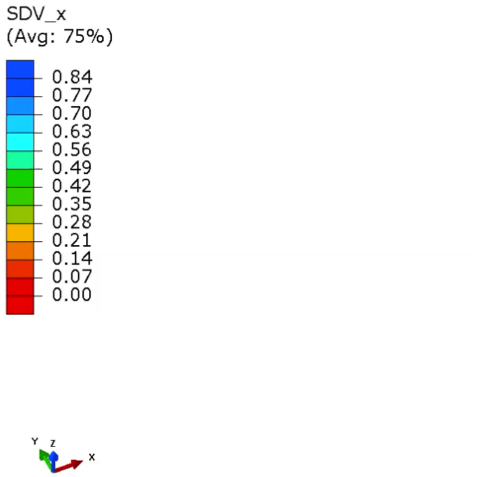
Residual Stress

Process Simulation Results

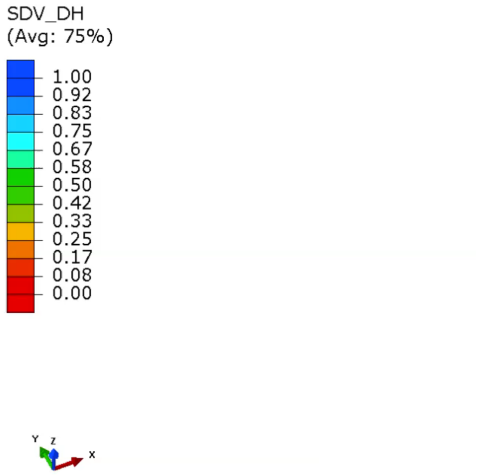
Temperature (K)



Crystallinity



Interlayer Bonding



80x Printing Speed

Process Simulation Results

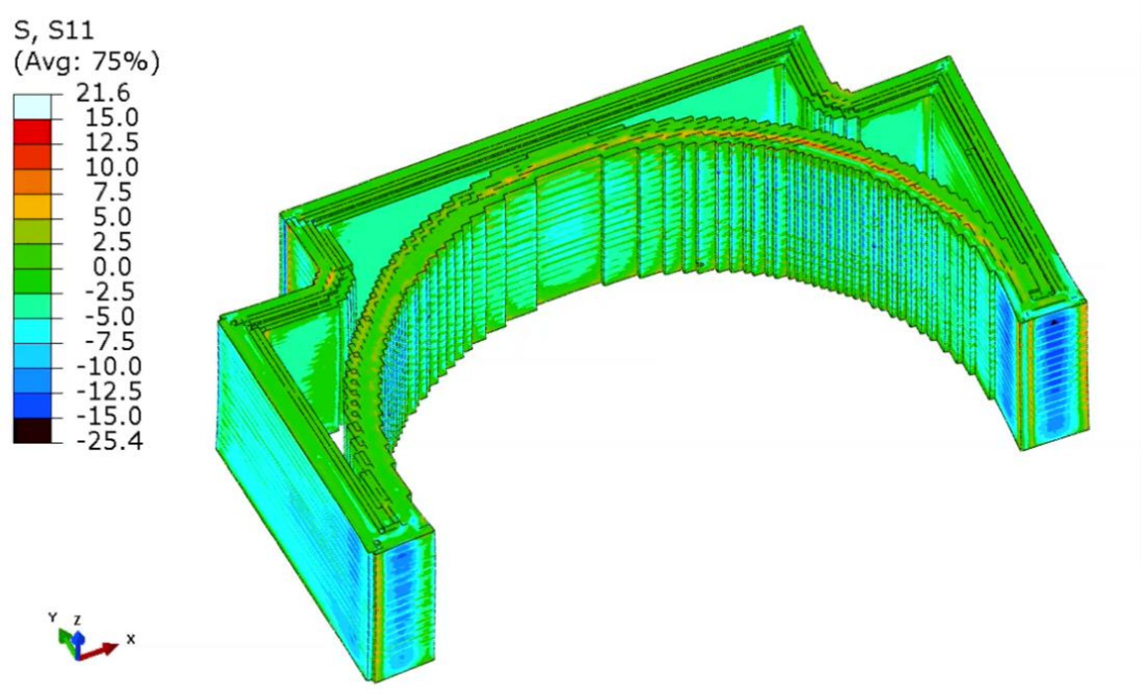
Stress - σ_{11} (MPa)

Deformation - $U_x - (mm)$

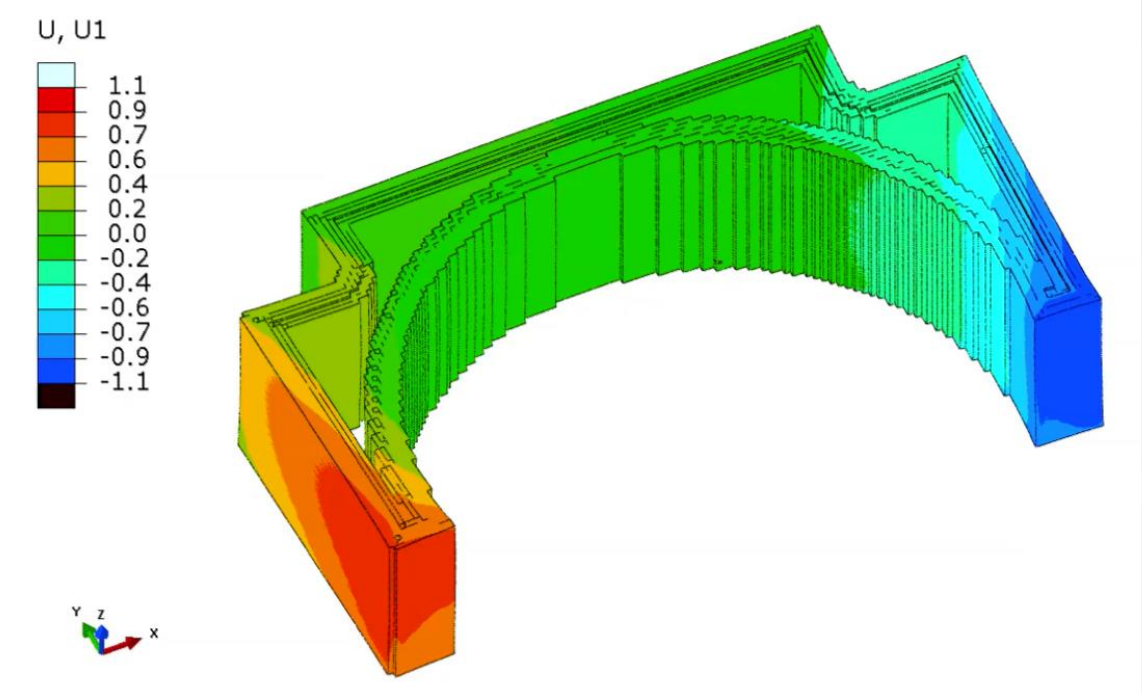
10x Deformation & 80x Printing Speed

Process Simulation Results

Stress - σ_{11} (MPa)

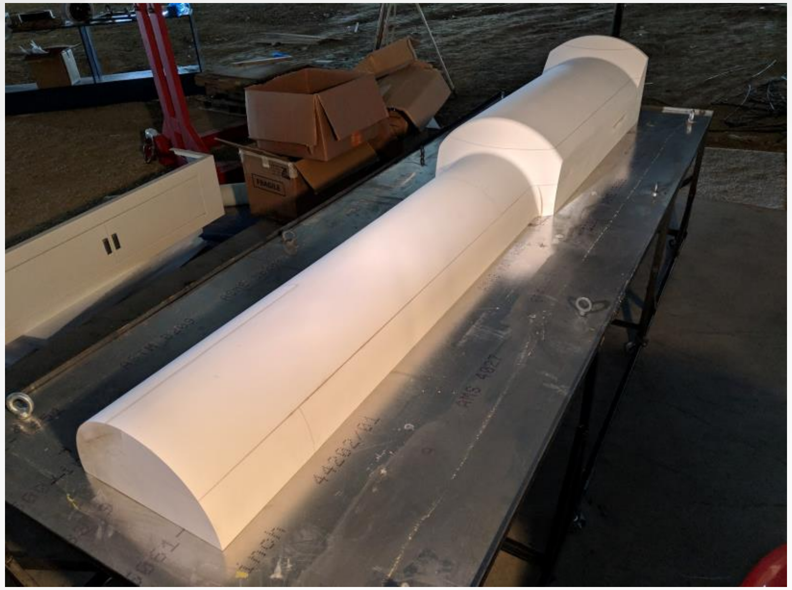


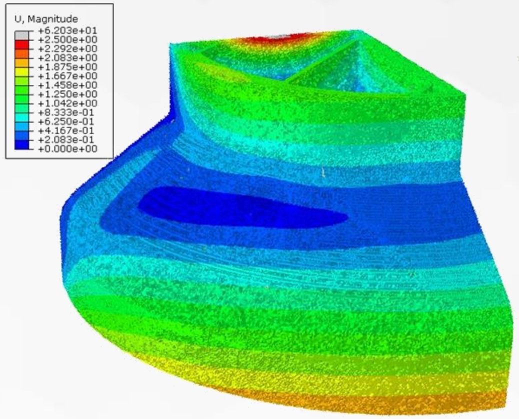
Deformation - $U_x - (mm)$



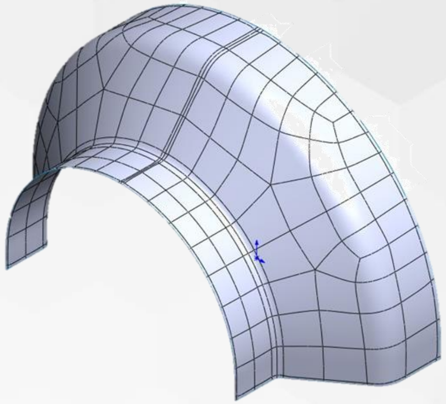
10x Deformation & 80x Printing Speed

#2 - Inner Tracker Service Cylinder Layup Tool

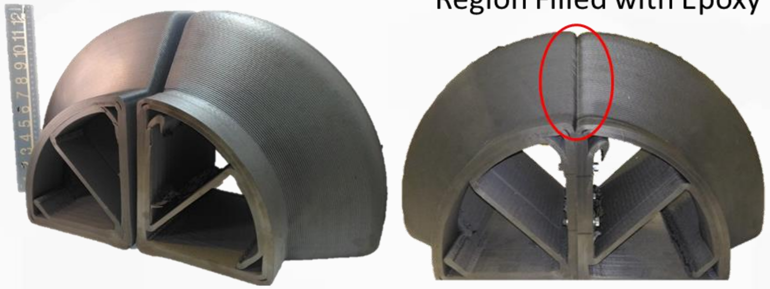




Nodal Deformation for the Part Performance Analysis in Autoclave



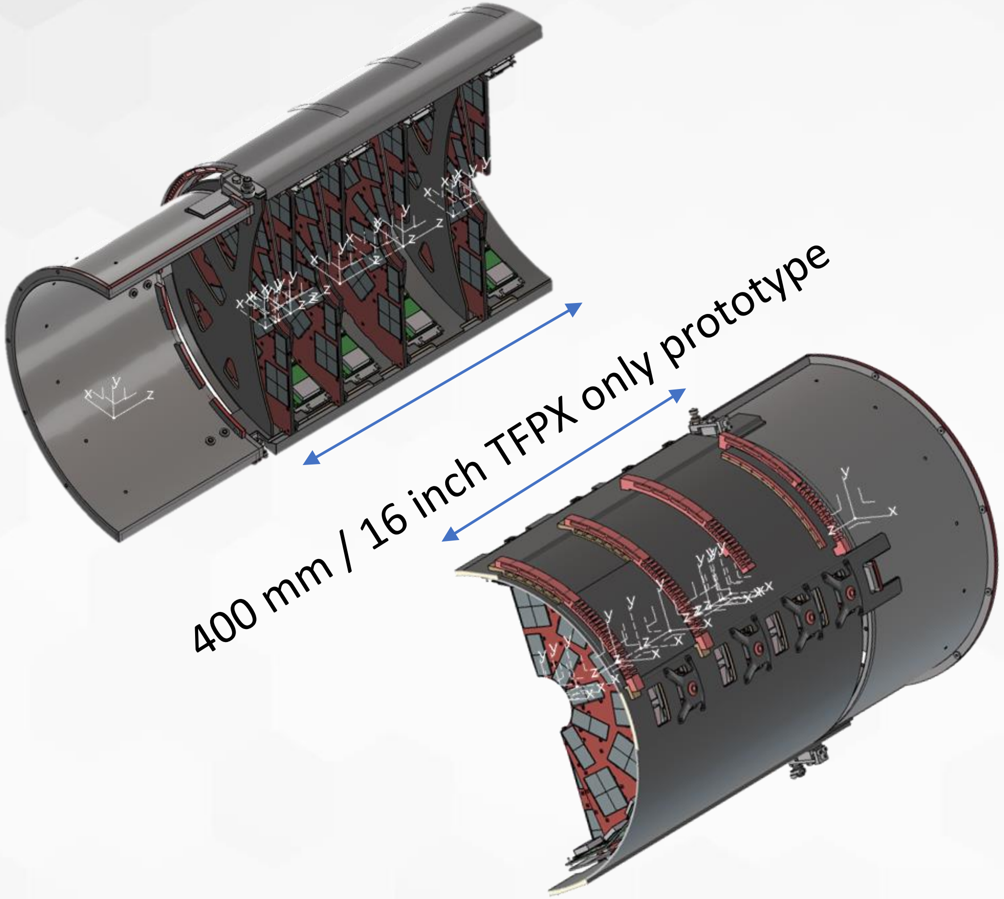
Compensated Tool Surface Generated for Machining the Printed Tool



Finished tool surface coated with mold release

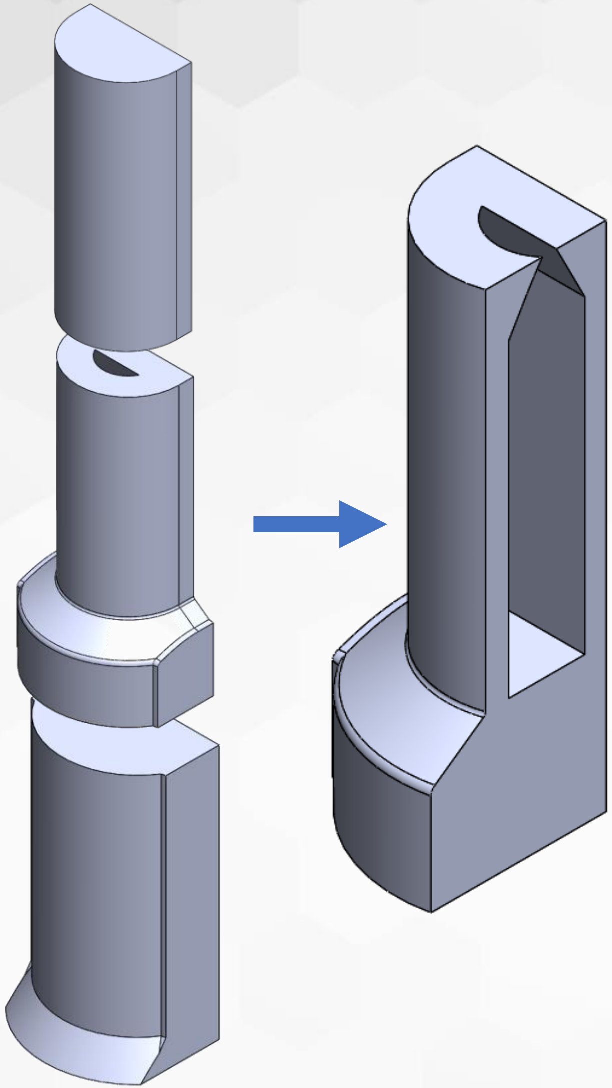
Layup and vacuum bagging

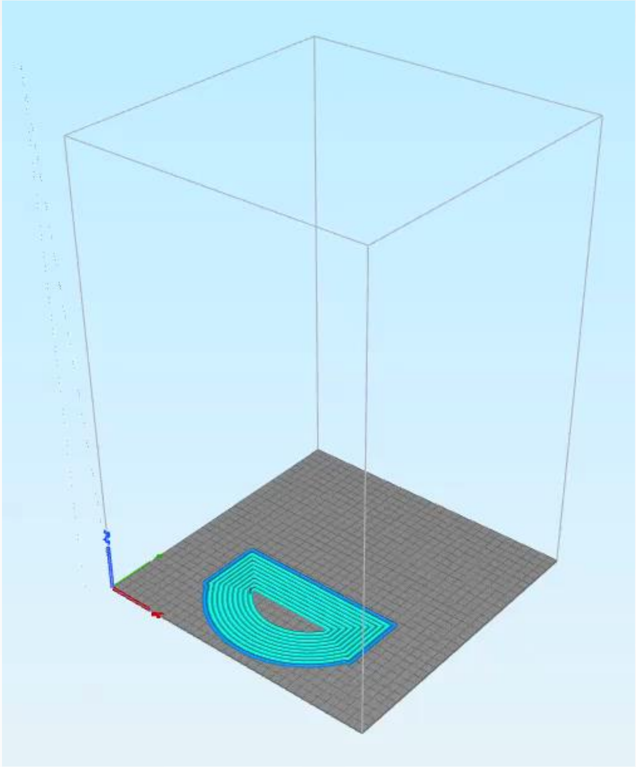
Current Iteration on Service Cylinder Tool – in progress (Fall 2022)



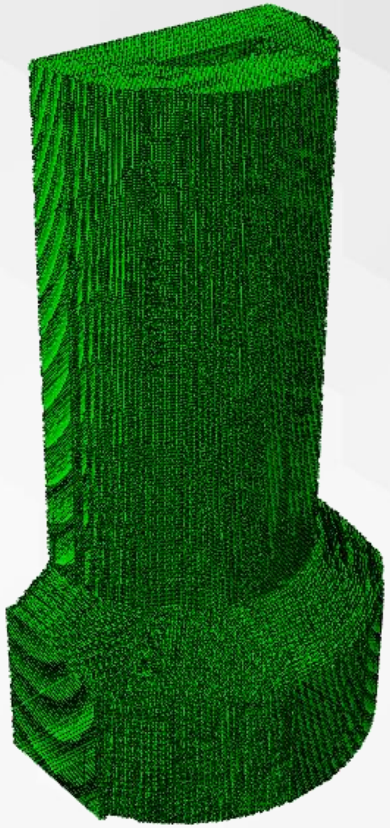
- We have tried to achieve the precision for the service cylinder layup tool using EDAM in the past but failed.
- This time with the better development of the Additive3D simulation code we are going to try to make a 16inch (400 mm) TFPX only prototype for TBPX – TFPX flange mounting as well as Dees mounting practice
- Proof of concept for the EDAM tooling application

Preliminary Simulation Results – Service Cylinder – in progress (Fall 2022)



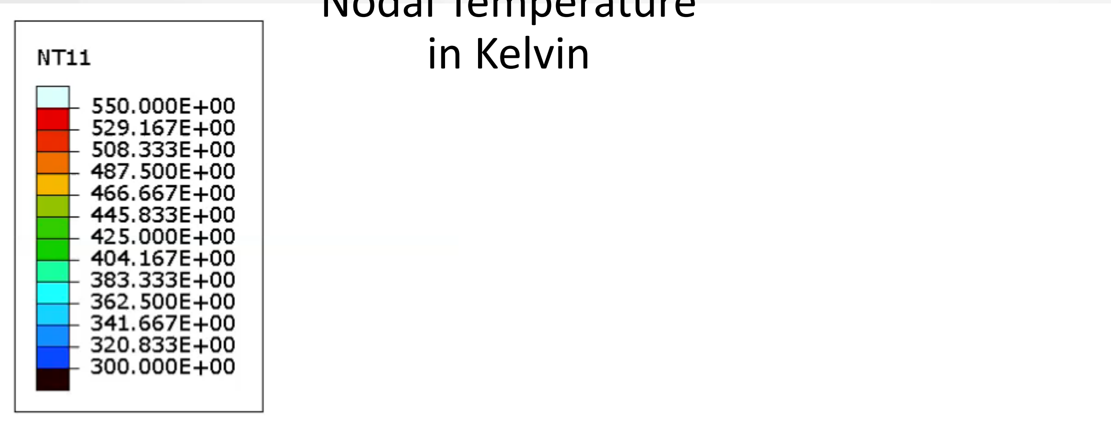


TIME	X-POS	Y-POS	Z-POS	EXTRUSION STATUS	PRINT COND
sec	mm	mm	mm	ON/OFF	
0	164.28	156.84	0	0	3
0.2	173.45	156.05	0	0	3
0.401	180.79	149.58	0	0	3
0.601	198.13	125.82	0	1	3
0.801	221	101.52	0	1	3
1.002	246.77	80.33	0	1	3
1.202	275.01	62.59	0	1	3
1.402	305.27	48.58	0	1	3
1.603	337.06	38.52	0	1	3
1.803	369.86	32.57	0	1	3
2.003	403.16	30.83	0	1	3
2.204	436.41	33.32	0	1	3

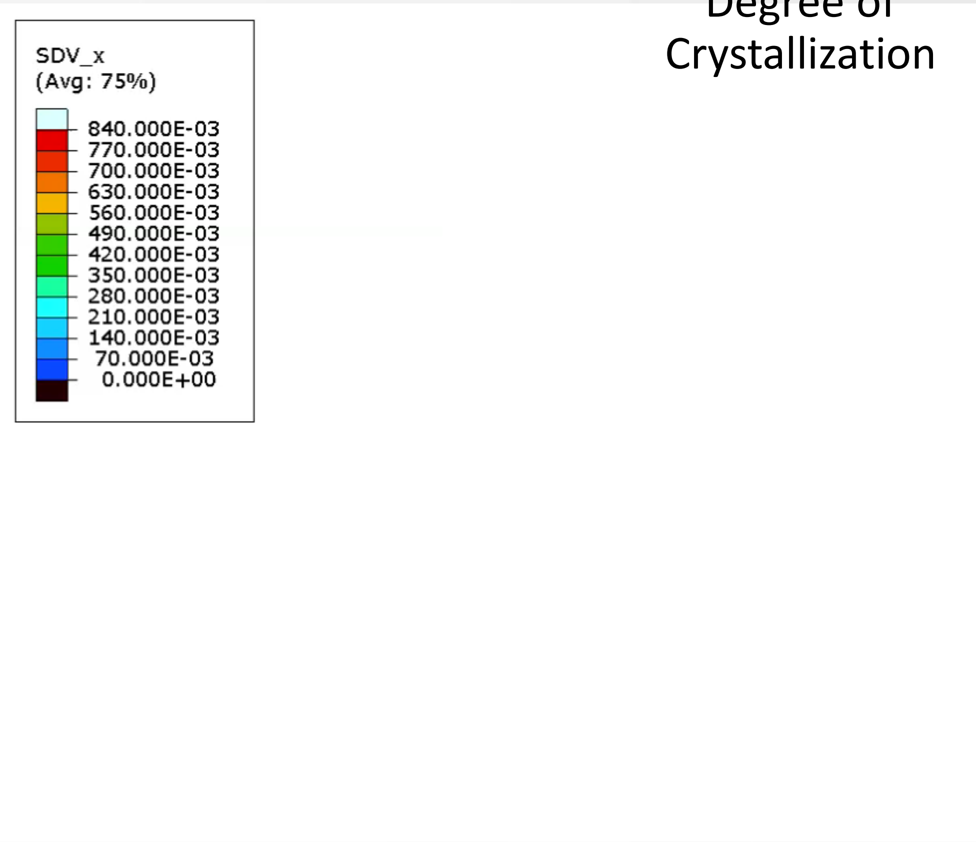


Heat Transfer Analysis

Nodal Temperature in Kelvin

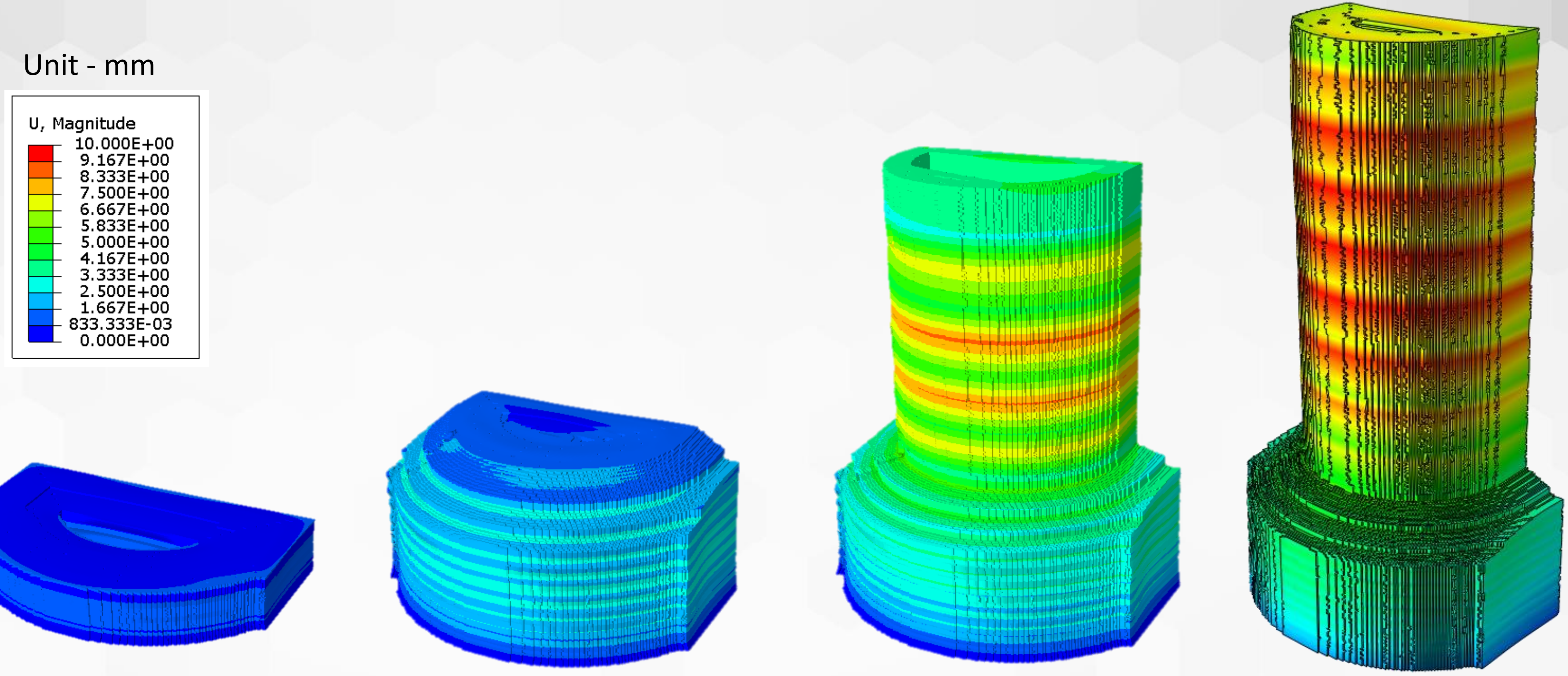


Degree of Crystallization



Deformation Analysis

Unit - mm



Time Step: 2000 sec

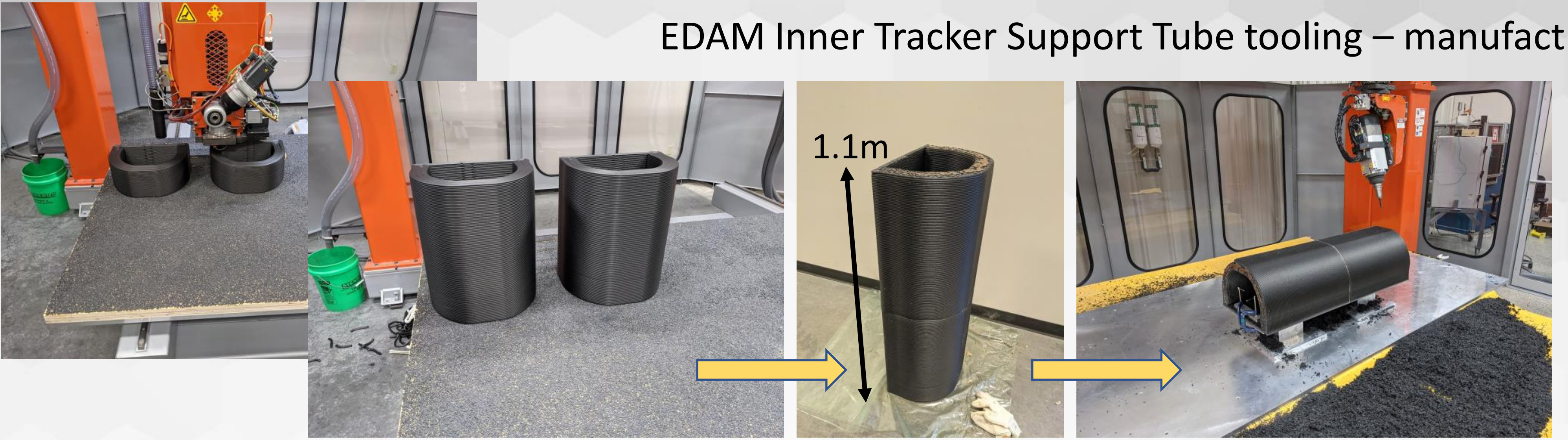
Time Step: 5500 sec

Time Step: 8000 sec

Time Step: end step

#3 - ITST Center Section Trimming/Machining Tool

EDAM Inner Tracker Support Tube tooling – manufacturing process

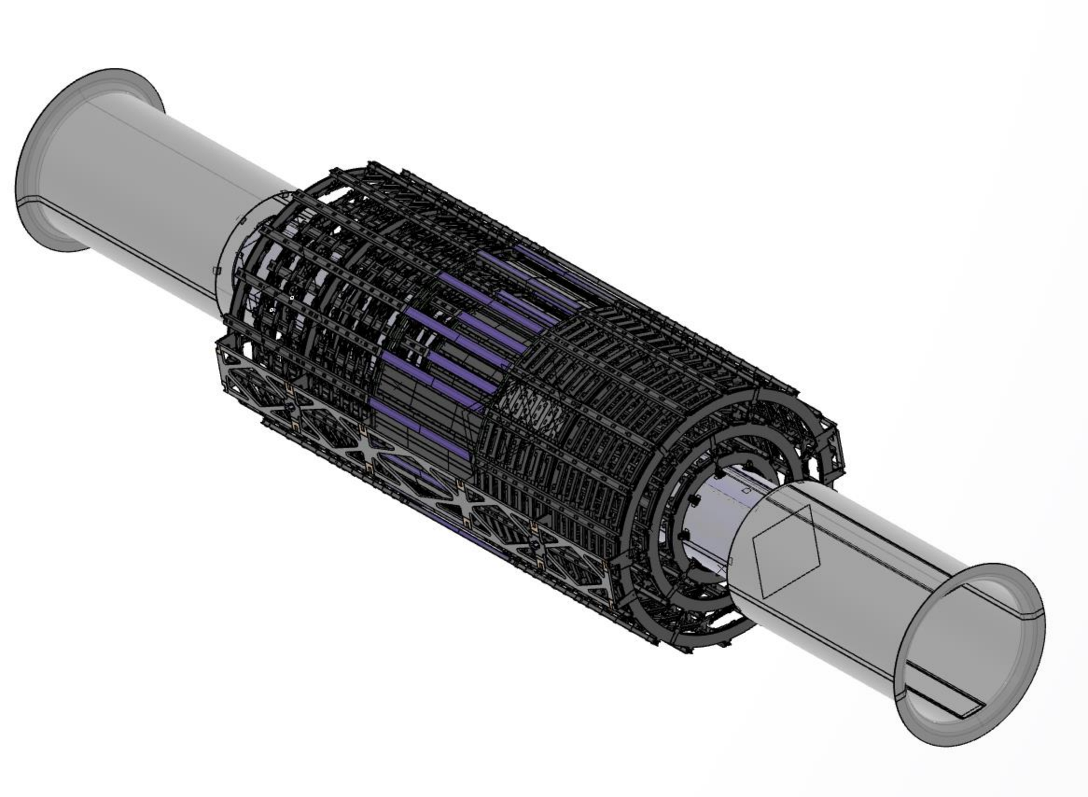


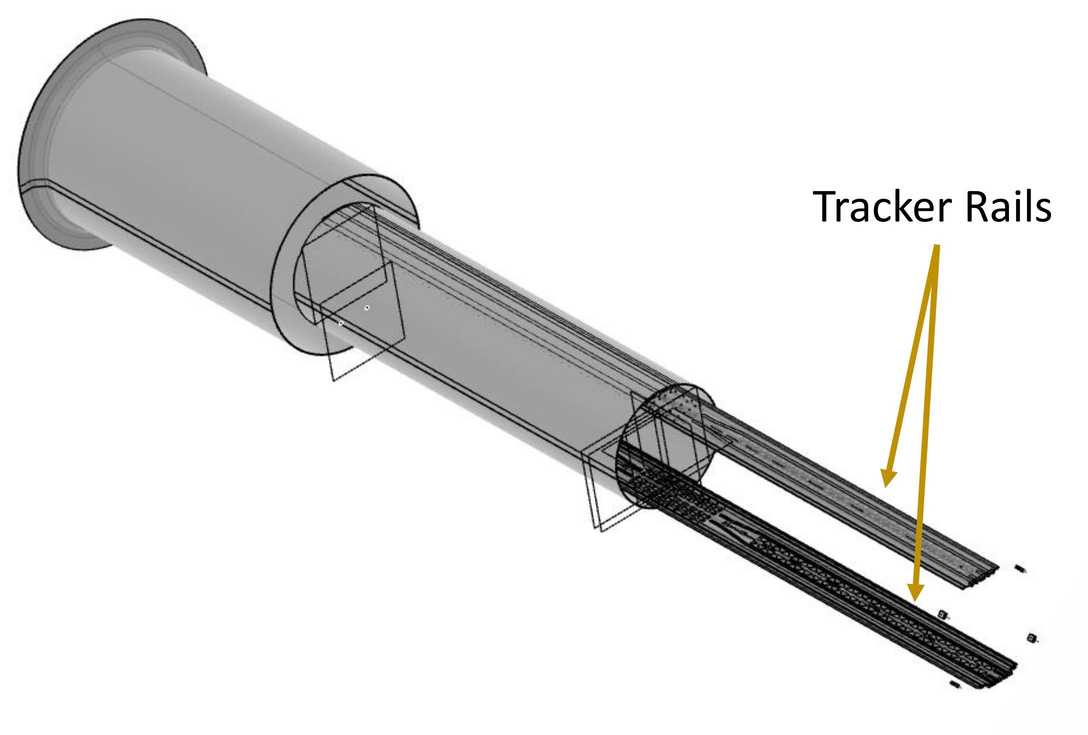
ITST Center Section Trimming/Machining Tool

Conventional tooling – Inner Tracker Support Tube

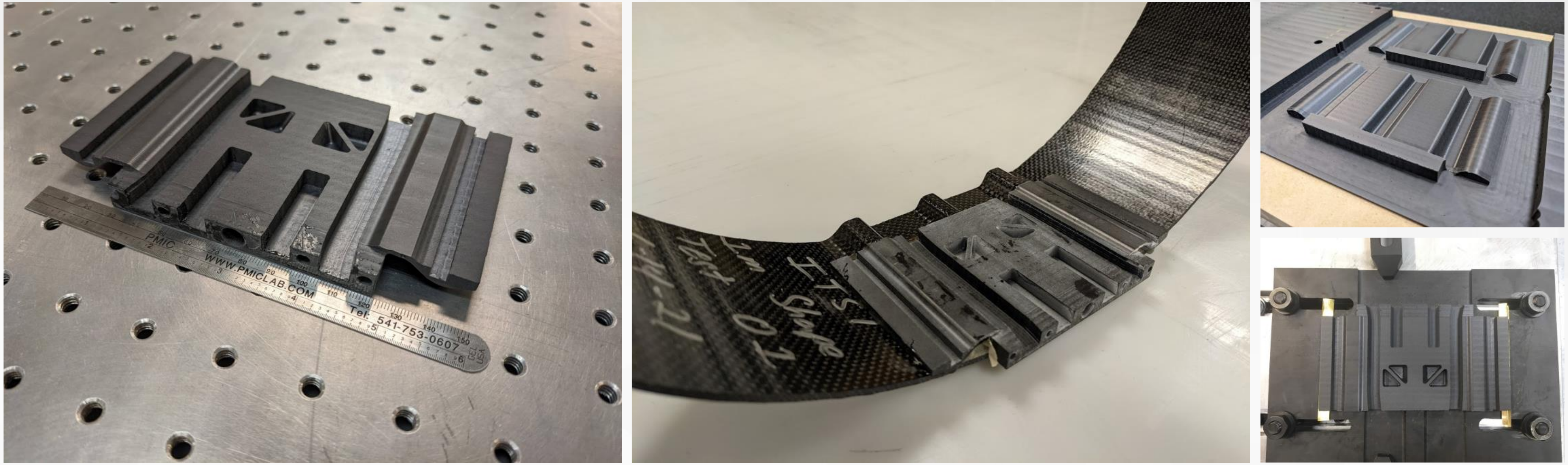
Conventional tooling – Inner Tracker Support Tube

#4 - ITST Rails/Tracks

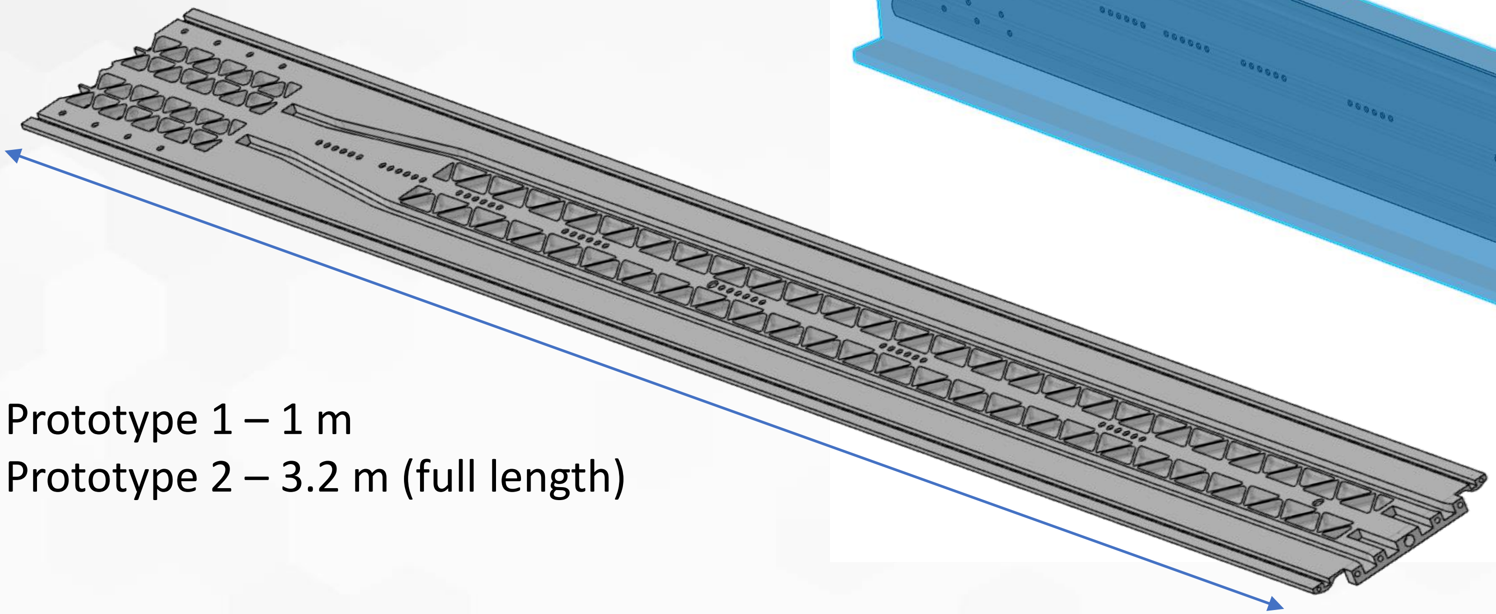




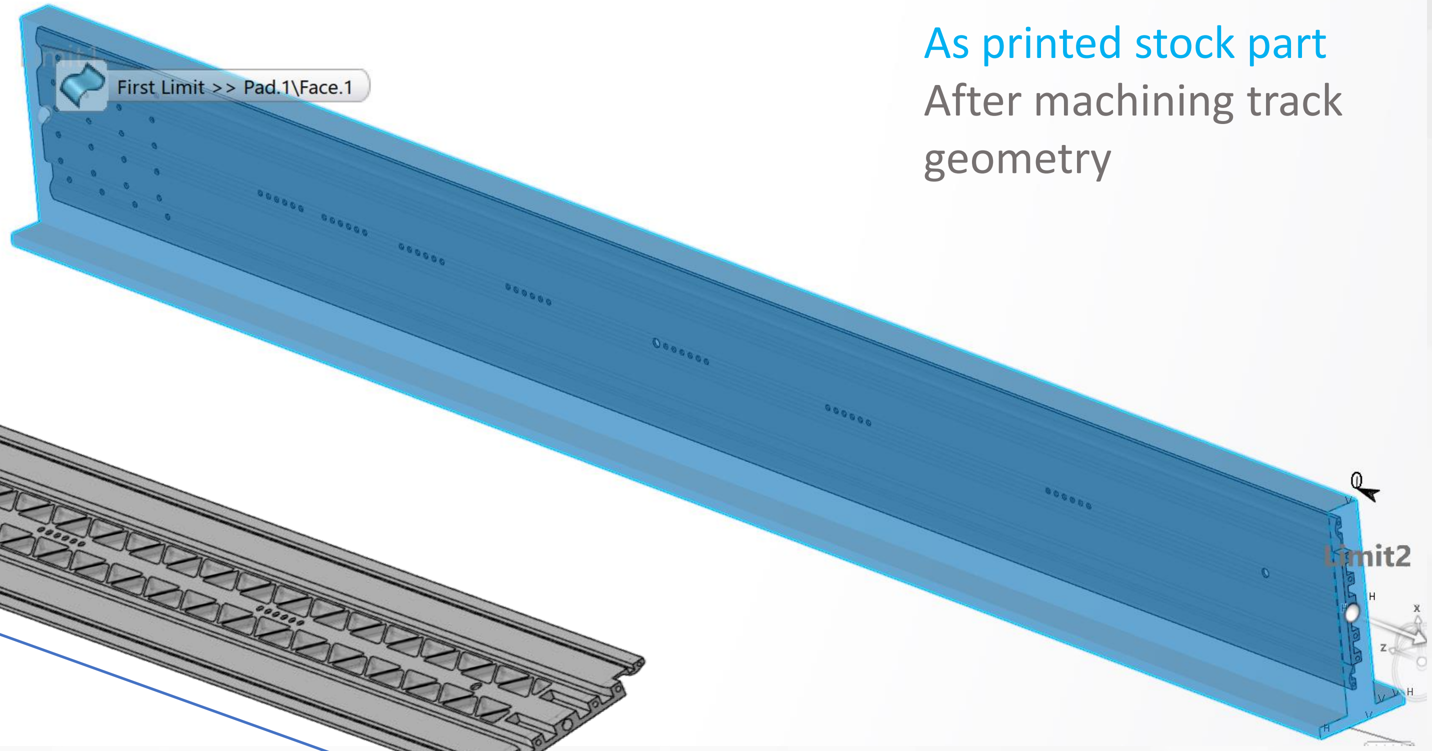
ITST Center Section Rails / Tracks – small prototypes



ITST Rails/Tracks – Coming up early Fall 2022!

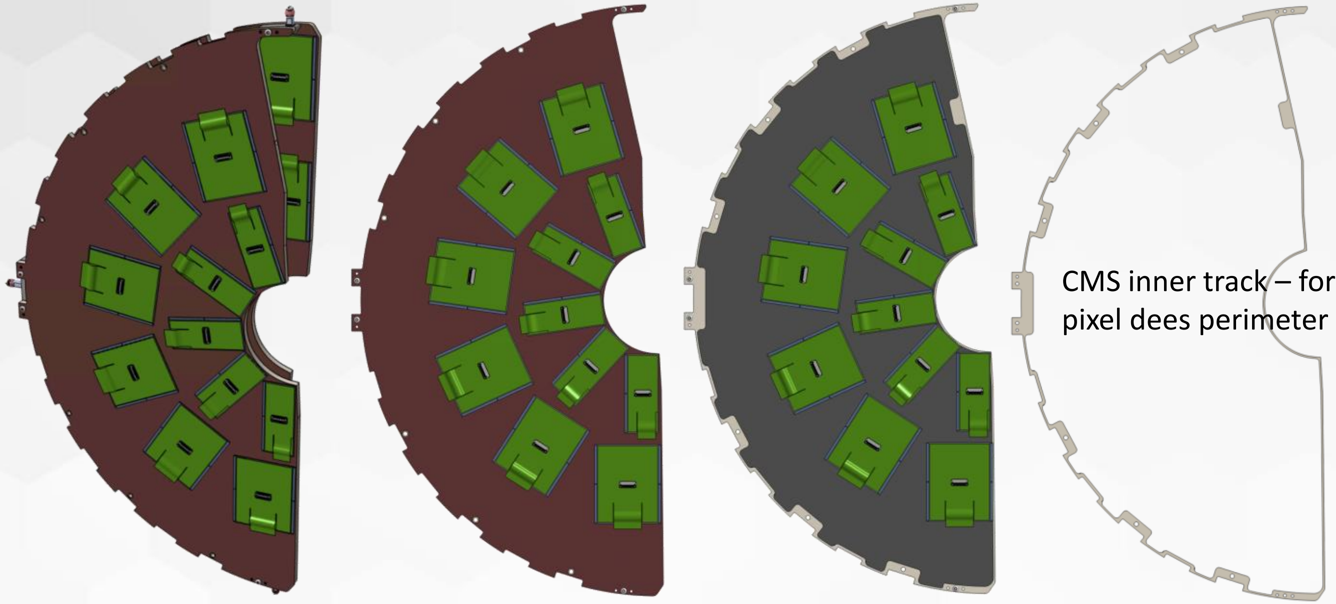


Prototype 1 – 1 m
Prototype 2 – 3.2 m (full length)



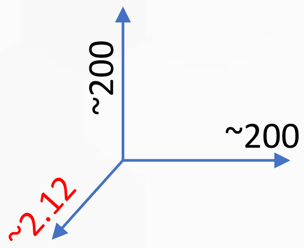
As printed stock part
After machining track geometry

#5 - EDAM for small thermally conductive parts in the Inner Tracker – TFPX scope – Fall 2022



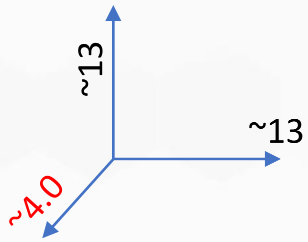
CMS inner track – forward pixel dees perimeter seal

- Requirement – along with stiffness, high thermal conductivity
- Waiting on thermal analysis to see if this lower thermal conductivity is acceptable



Thermal conductivity for conventional EX1515-K13D2U with graphite laminate

Unit – W/mK



Thermal conductivity for EDAM PPS + graphite

EDAM PPS + graphite	**EX1515-K13D2U**
Low cost	Super Expensive
High tooling / CNC time needed	High material wastage
Lower in-plane thermal conductivity	Higher in-plane thermal conductivity
Higher thickness thermal conductivity	Lower thickness thermal conductivity
Survives radiation – 1.2 GRad	
Higher time needed per part	Quicker mass production

Conclusions

- EDAM is currently being used for machining & trimming fixtures and assembly & bonding jigs, we are exploring the use to layup tooling to reduce overall tooling cost and time and make manufacturing of the tool easy
- For applications to large precision parts like ITST track it is easier to 3D print a stock block and machine the tracks than buy stock material
- EDAM is the future for tooling and assembly applications for composite manufacturing !!

Thank you

- Thank you to Eduardo Barocio and Additive Manufacturing Group at CMSC for providing help with slides.
- For those looking at the pdf version of this talk – the videos can be seen at this link - FTDM_2022_EDAMandCMS_SRK

On behalf of CMS Partially supported by NSF

Back Up Slides

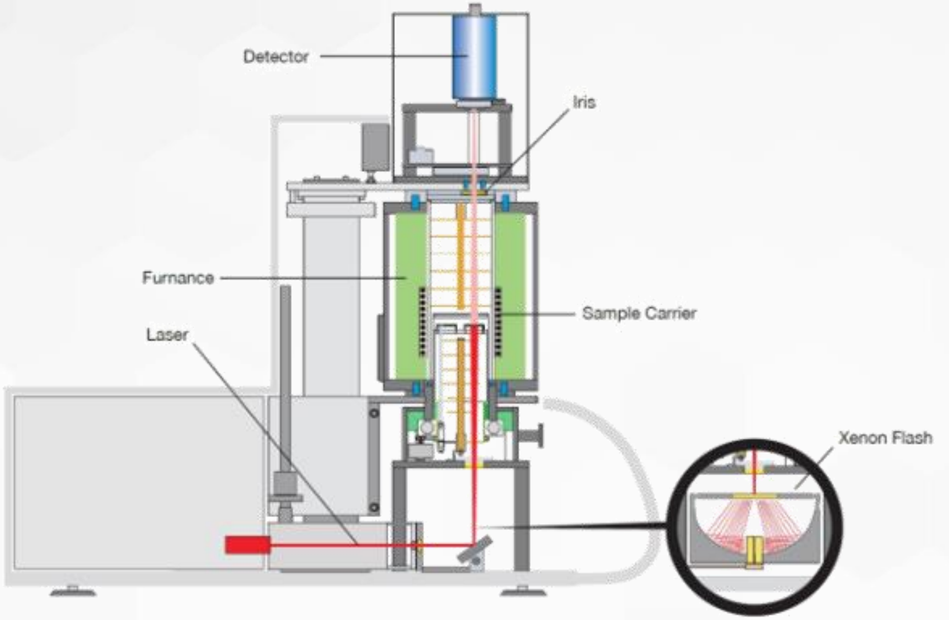
- Material Characterization for EDAM process simulation and material card development
- Case study – Stringer Geometry for oven cure EDAM tool

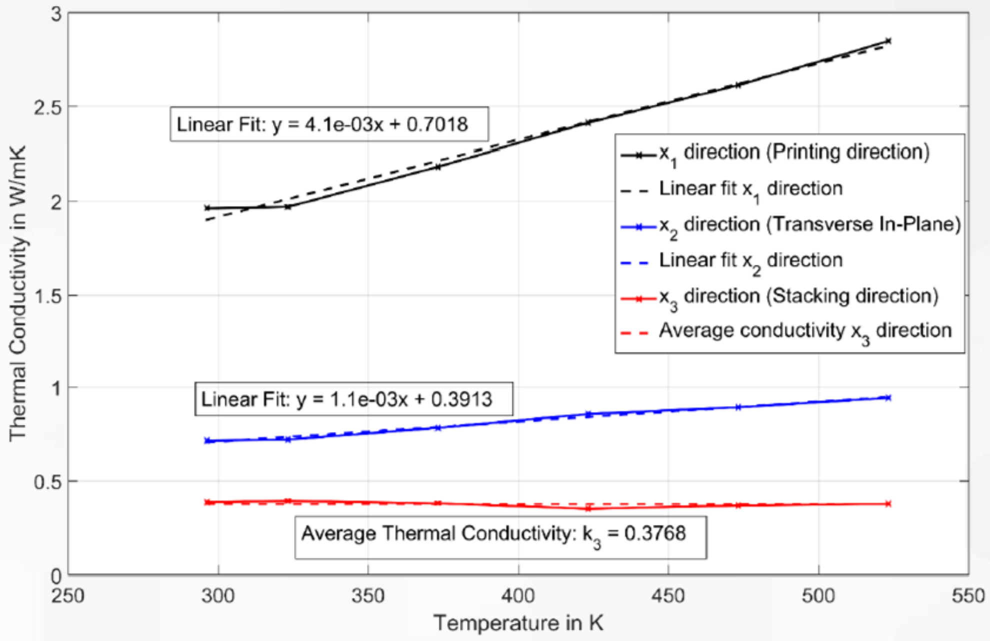
On behalf of CMS

Partially supported by NSF

Thermal Conductivity

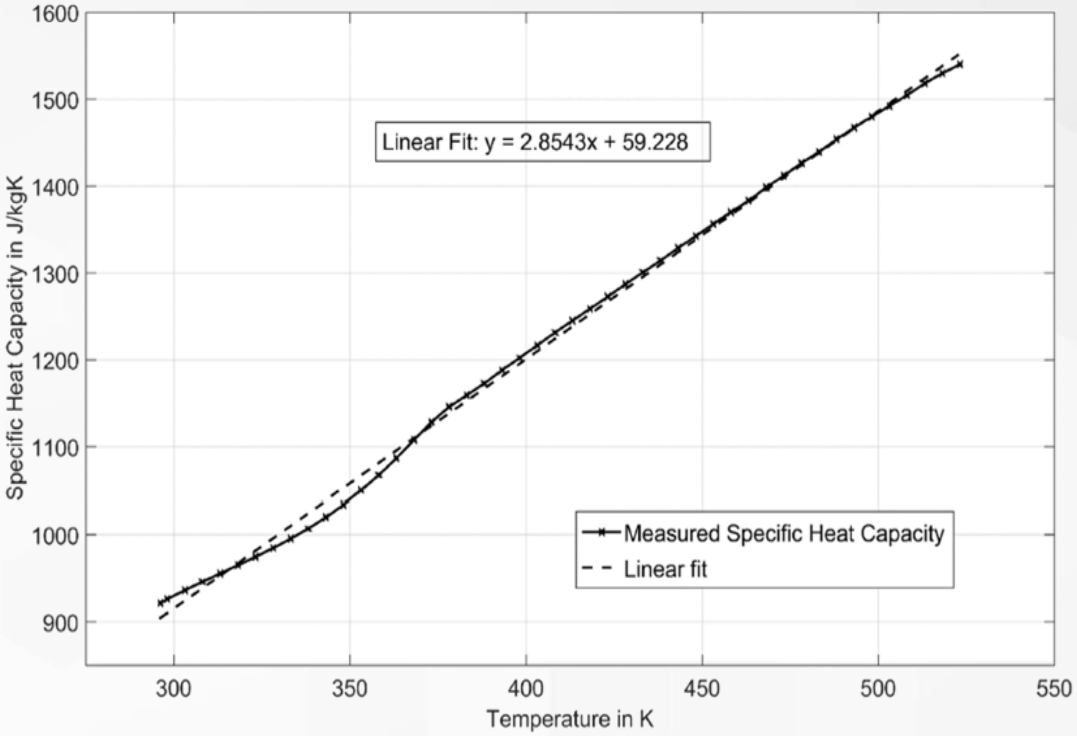
Laser Flash Method





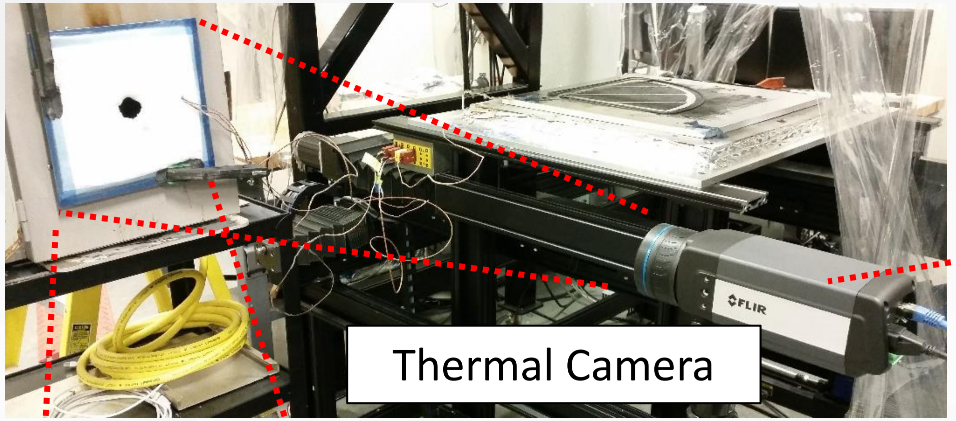
Specific Heat Capacity

Differential Scanning Calorimetry



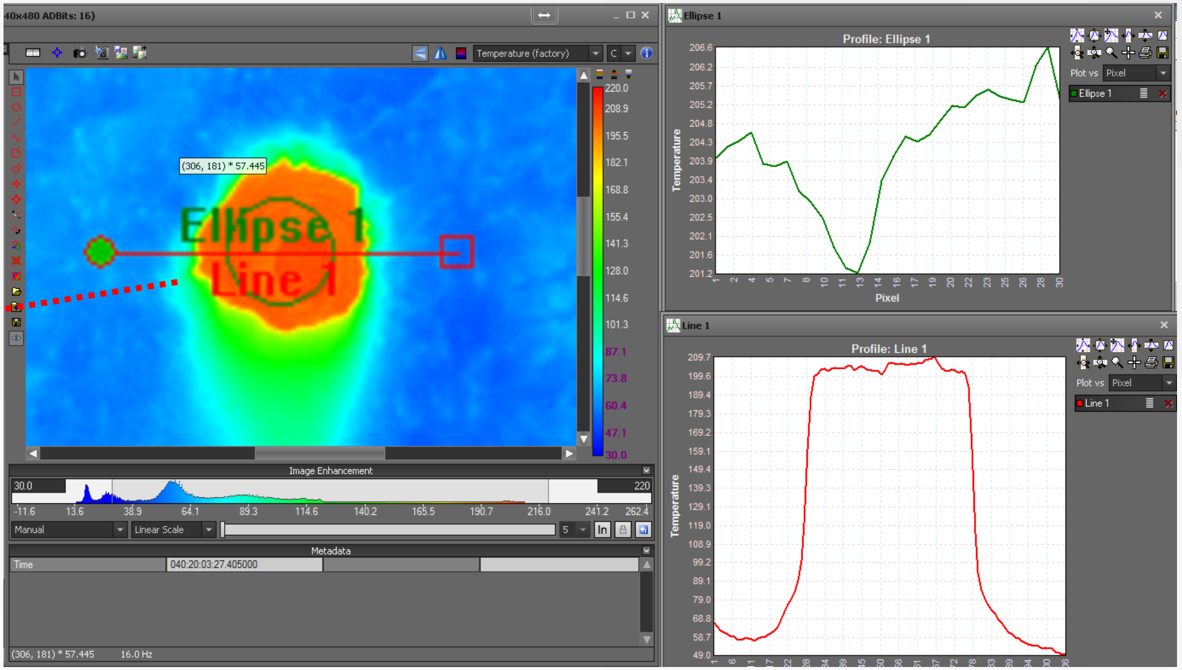
Emissivity Characterization

Black body emission test



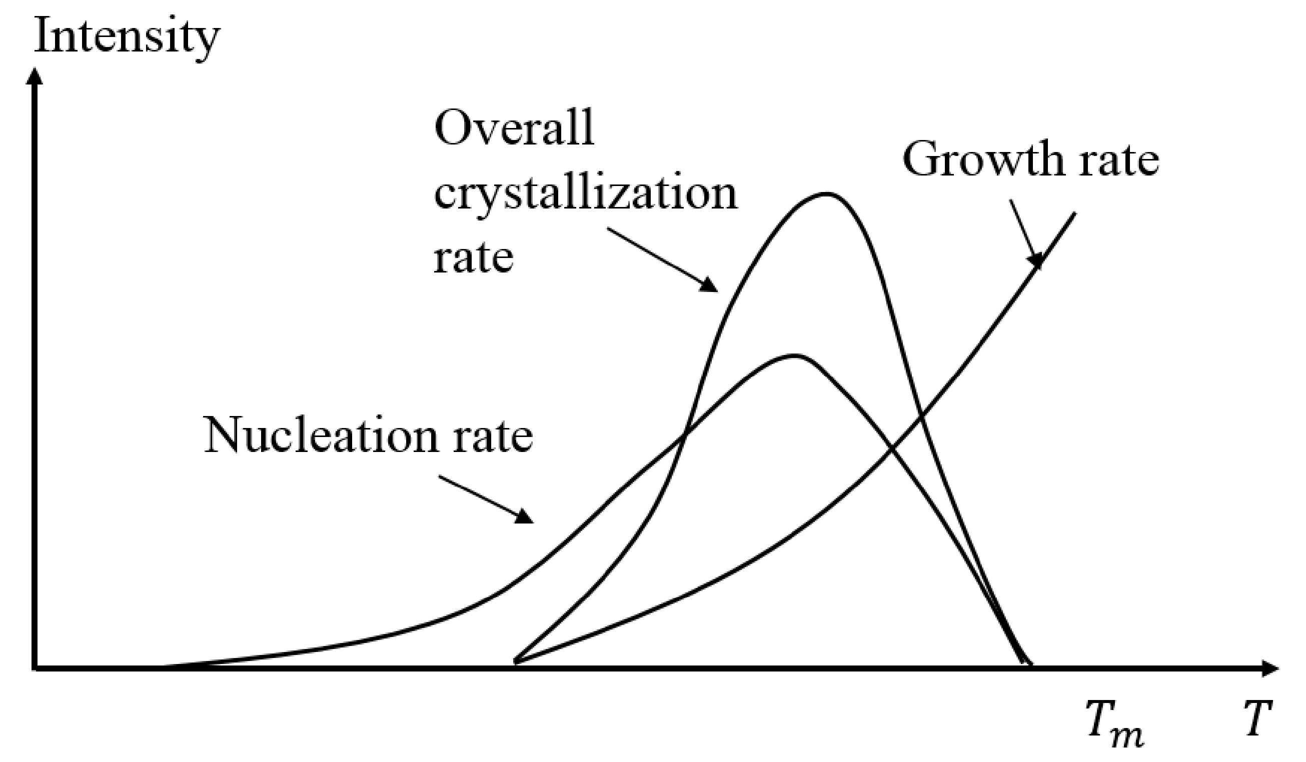
Thermal Camera

Printed blackbody cavity equipped with temperature sensors



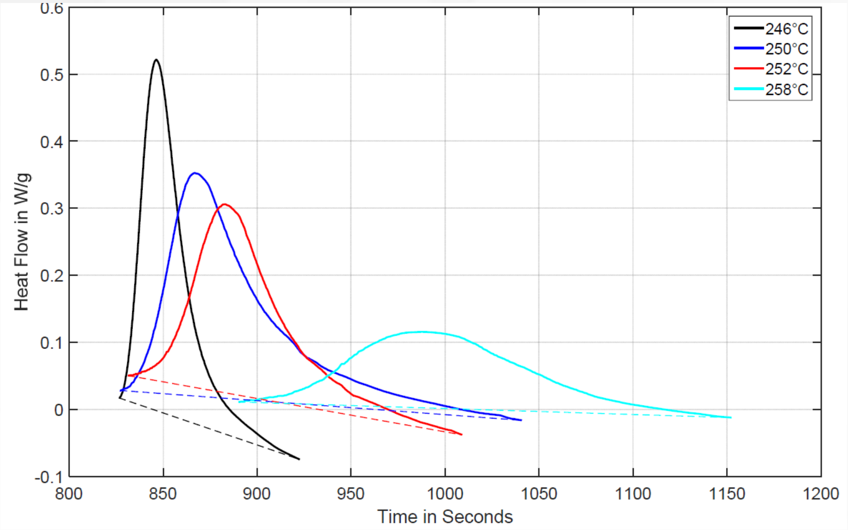
Isothermal blackbody cavity - $\epsilon = 0.92$

Crystallization Kinetic Modeling

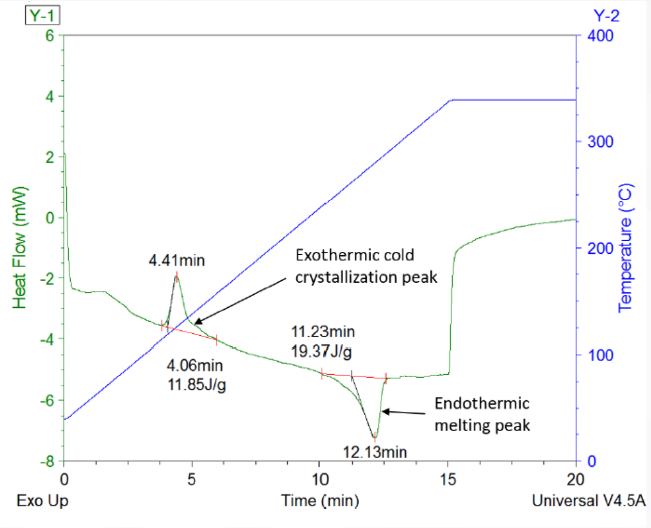


Experimental Measurements

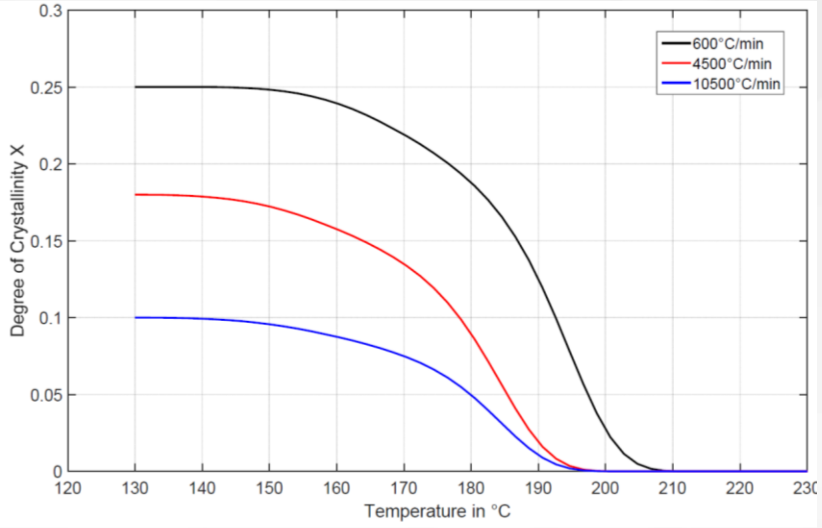
Differential Scanning Calorimetry



Isothermal DSC

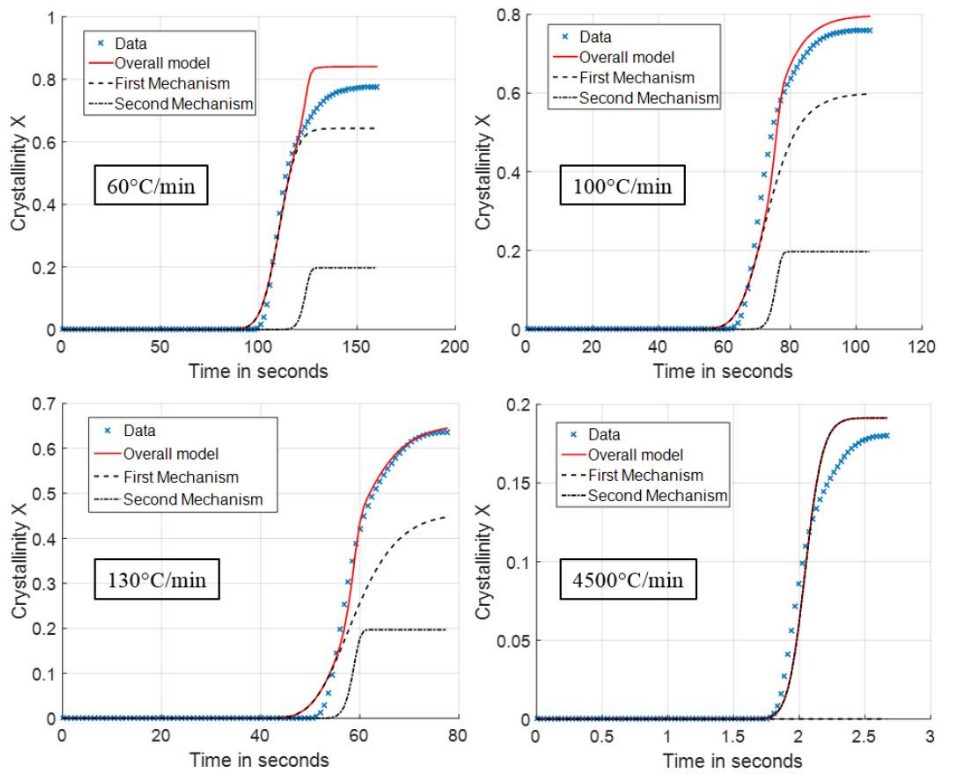


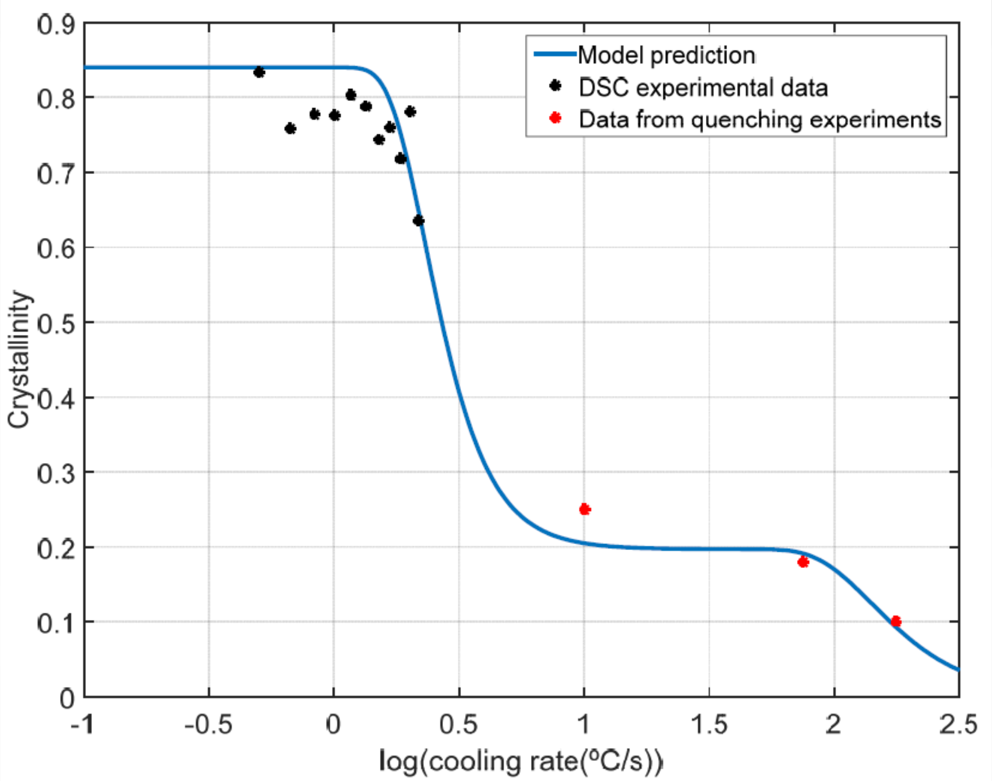
Non-Isothermal DSC



Quenching experiments

Crystallization Model Generation

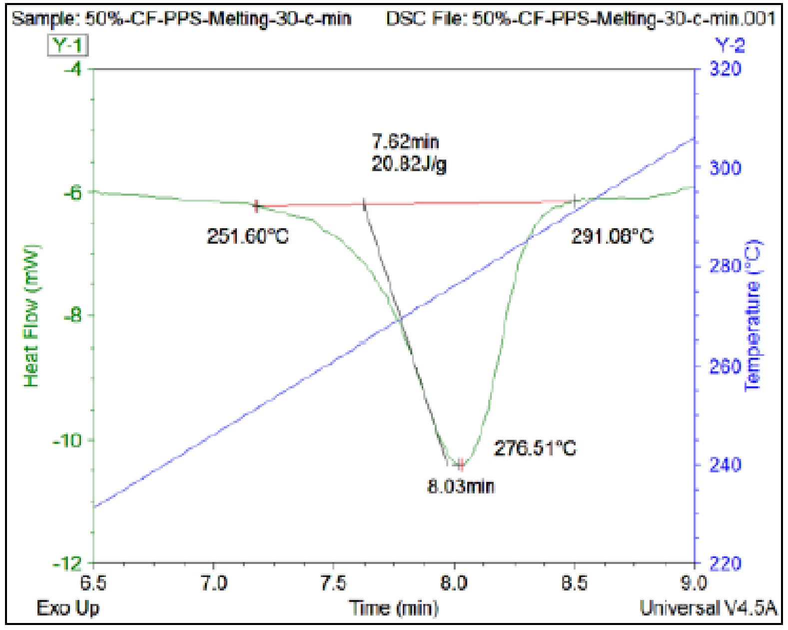




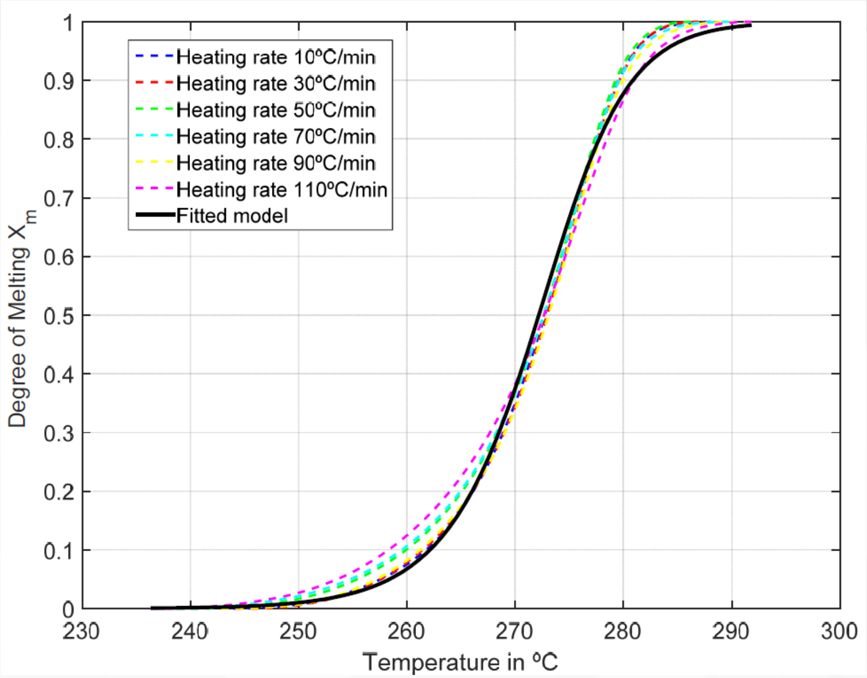
$$X(t,T,p) = X_\infty[w_1F_1(t,T) + w_2F_2(t,T)]$$

$$F_i(t,T) = 1 - exp\left[-C_{i1}\int_0^t T\cdot exp\left\{\frac{-C_{i2}}{T-T_g+T_{add,i}} - \frac{C_{i3}}{T\left(T_{m,i}-T\right)^2}\right\} n_i\tau^{n_i-1}d\tau\right],$$

Polymer Melting



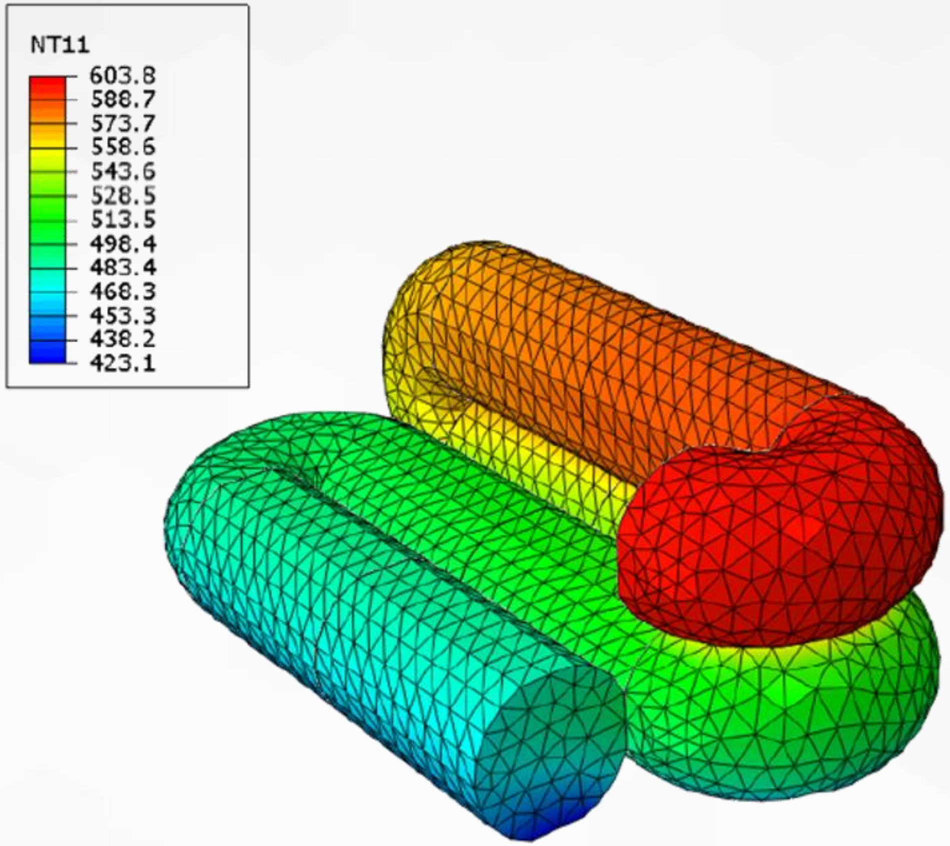
Heating cycle at 30°C

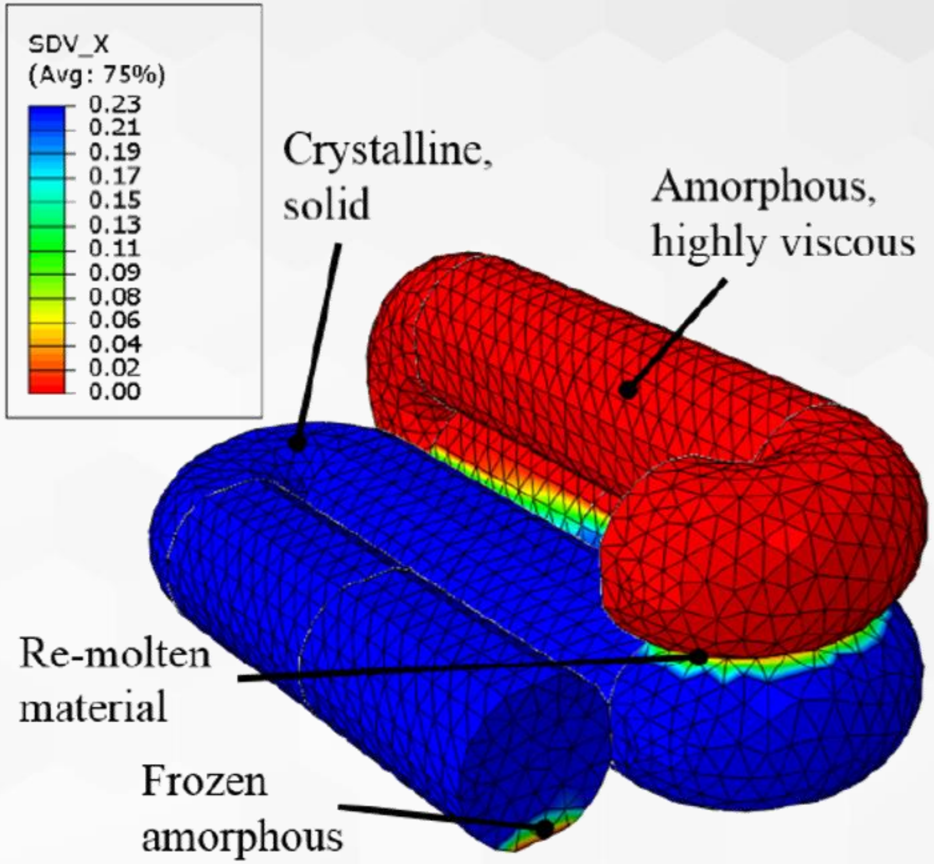


Non-isothermal DSC

$$X_m(T,p) = \{1 + (d-1)\exp[-k_{mb}(T-T_c)]\}^{\frac{1}{1-d}}$$

Melting and Crystallization Models

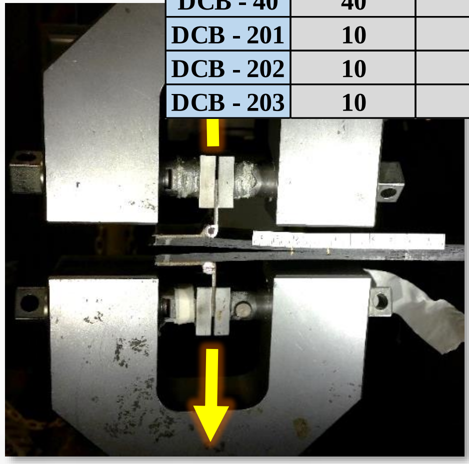


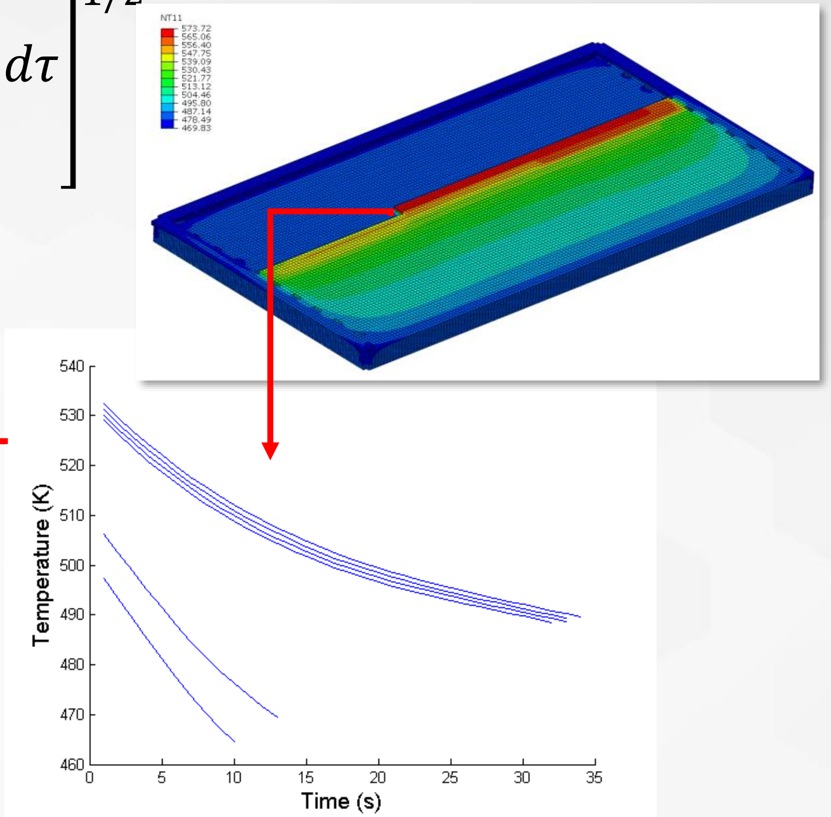


Characterization of Welding Times

$$D_b = \frac{G_1(t)}{G_{1\infty}} = \left[\int_0^t \frac{1}{A \cdot exp\left(\frac{E_A}{RT(\tau)}\right)} d\tau\right]^{1/2}$$

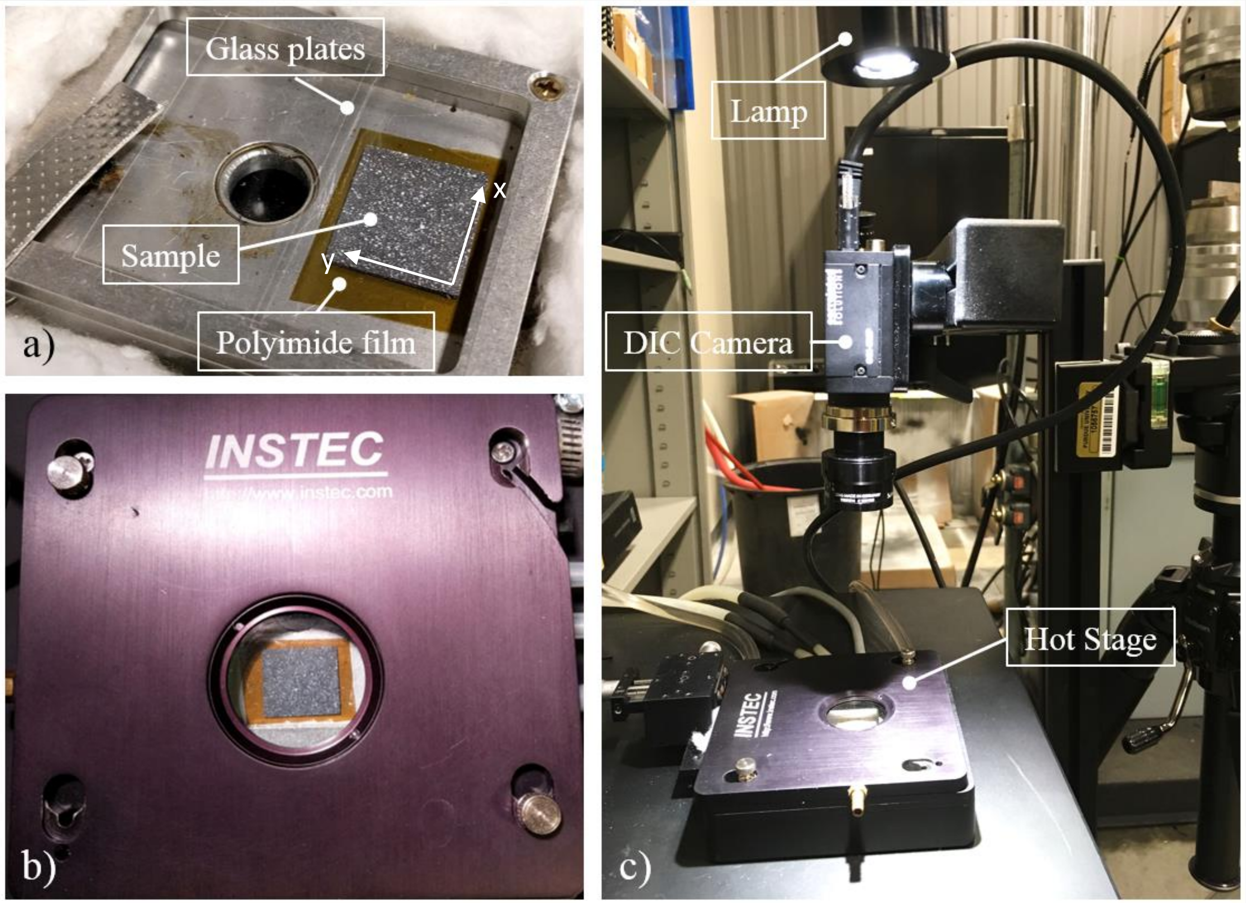
CODE	Dwell Time (s)	Build Platform Temperature (°C)	G1 (J/m^2)		Db
			MEAN	STD	
DCB - 5	5	215	455.58	71.49	0.91
DCB - 10	10	215	450.16	49.45	0.90
DCB - 20	20	215	433.89	40.85	0.86
DCB - 40	40	215	392.77	33.43	0.78
DCB - 201	10	120	58.74	17.73	0.12
DCB - 202	10	140	211.36	60.70	0.42
DCB - 203	10	250	502.47	45.20	1.00

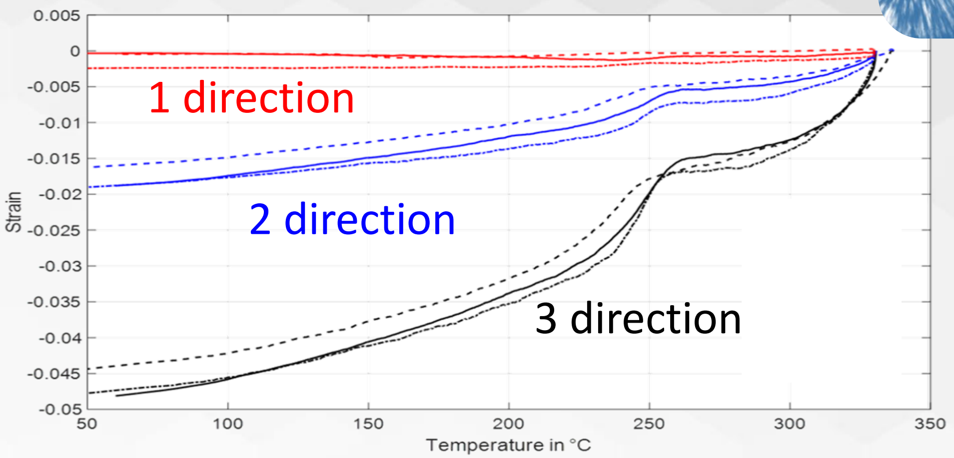


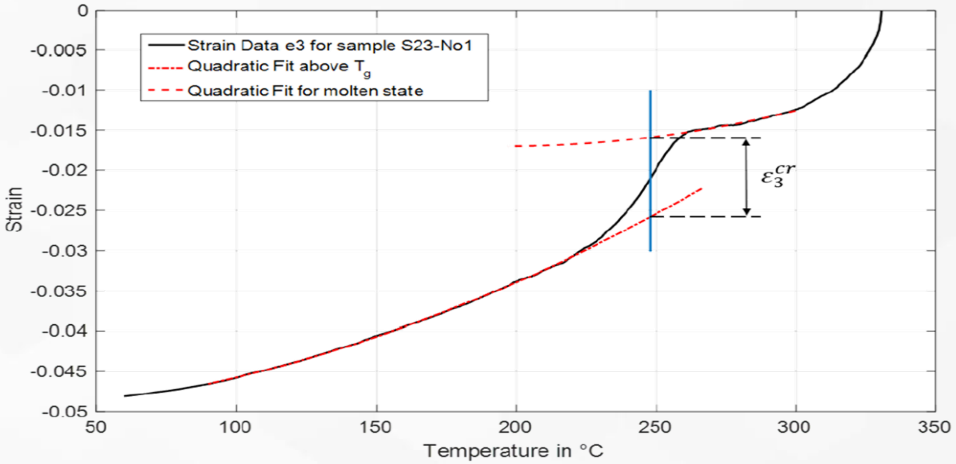


Temperature History Obtained from Printing Simulation

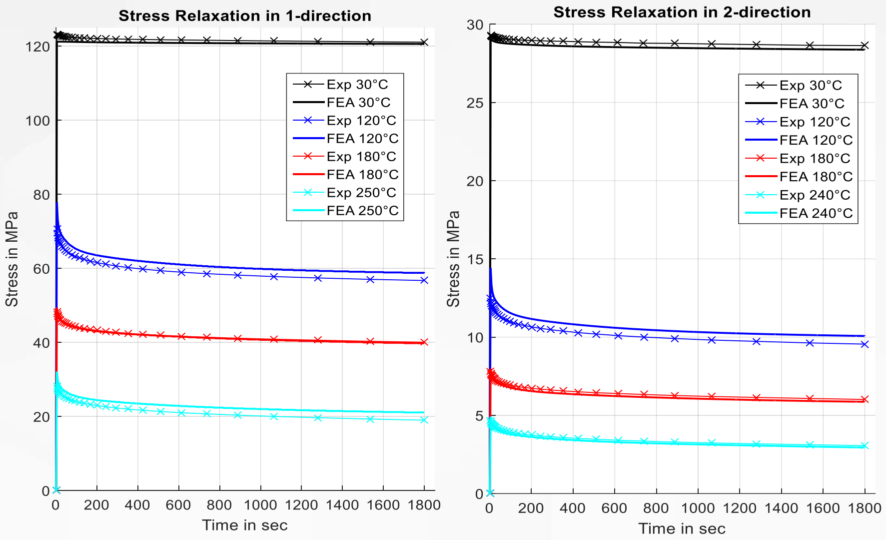
CTE Characterization



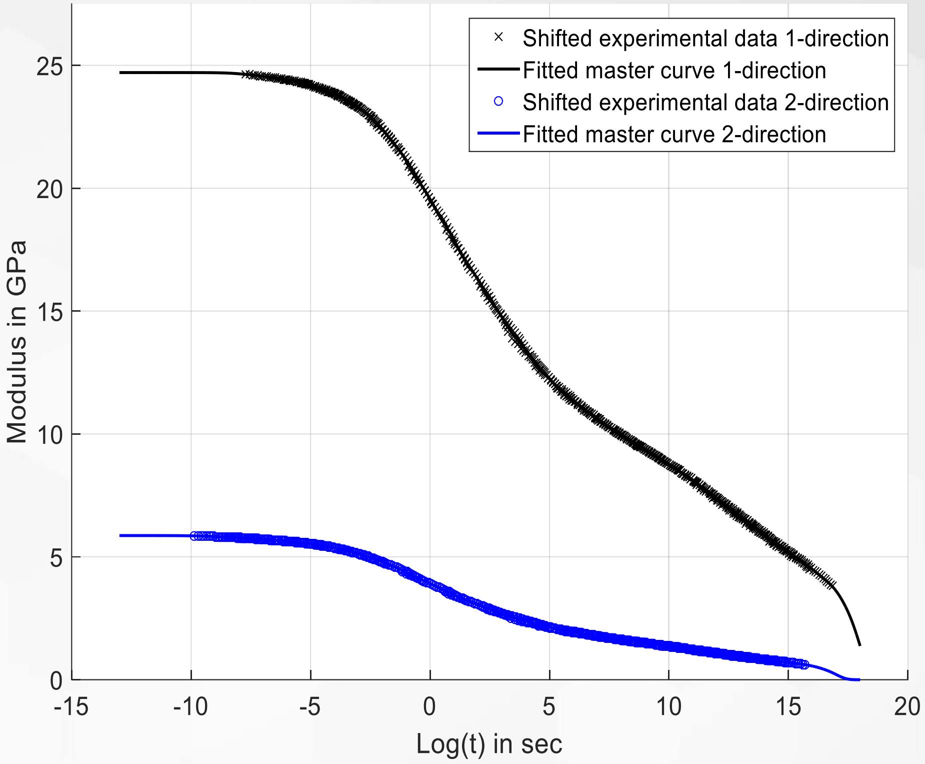




Thermoviscoelasticity



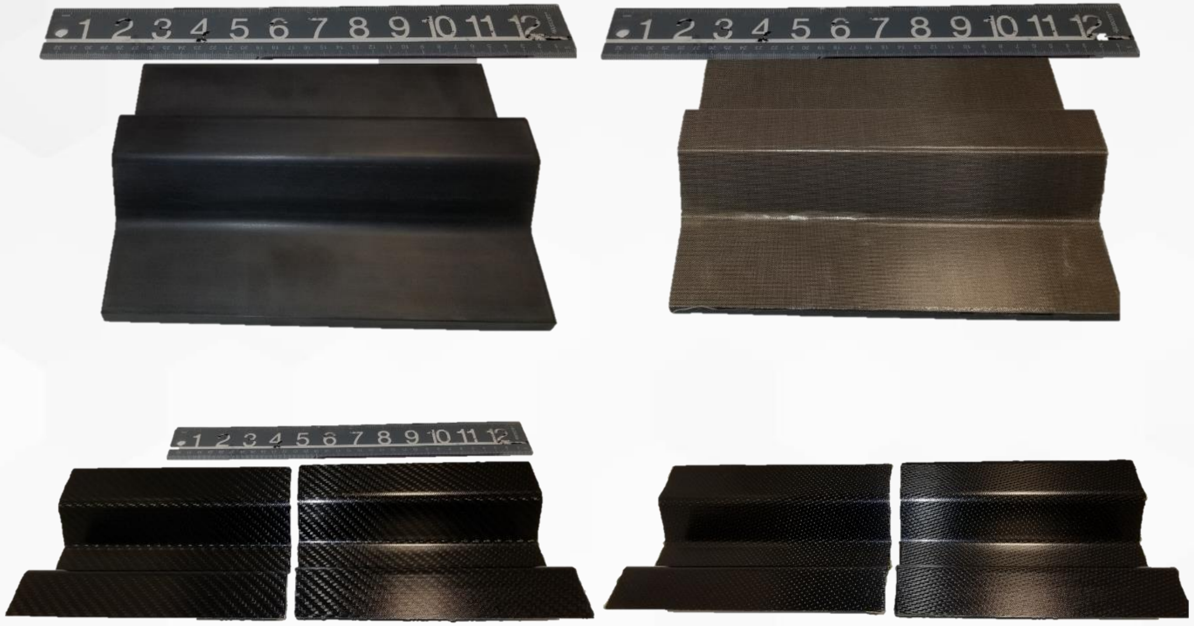
DMA curves



Use TTS to generate master curve

$$C_{ij}\left(T_0, X, \xi_{ij}(t)-\xi'_{ij}(\tau)\right) = f(X)\cdot\left[C_{ij0}+\sum_{w=1}^{N} C_{ijw}\exp\left(-\frac{\xi_{ij}(t)-\xi'_{ij}(\tau)}{\lambda_{ijw}}\right)\right]$$

Case Study - Stringer Tool Geometry



Three parts made.

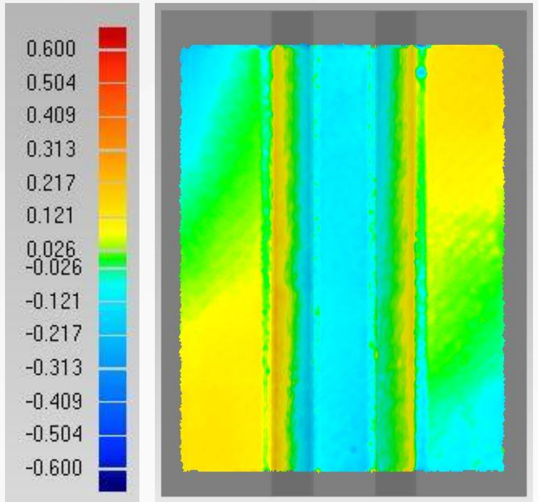
- One machined to Nominal Tool Surface (Printed with Celstran© PPS)
- Two Machined to Compensated Tool Geometry (Printed with Celstran© PPS and Techmer © PPS respectively)

Woven fabric prepreg used to make parts at 250 °F oven cure.

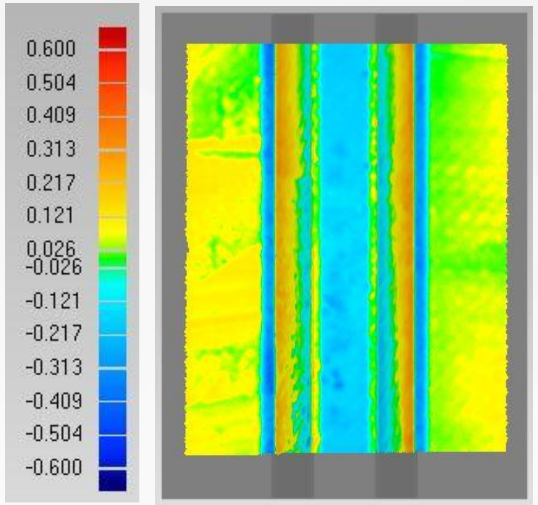
Surface scanned with FARO ScanArm©

Stringer Tool Geometry

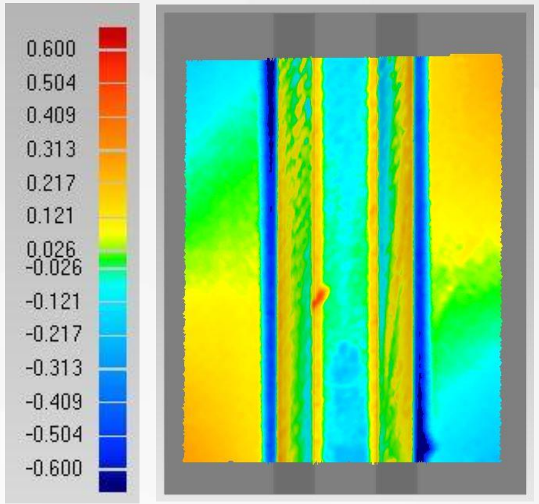
Unit: mm



Nominal Tool Shape



Compensated Tool Shape printed with Celstran© PPS-CF50-01



Compensated Tool Shape printed with Techmer Electrafil© XT1 3DP PPS

Maximum Distance: +0.343/-0.441 mm	Maximum Distance: +0.232/-0.483 mm	Maximum Distance: +0.537/-0.852 mm
Avg. Dist.: 0.010 mm	Avg. Dist.: 0.002 mm	Avg. Dist.: 0.004 mm
Std. Dev.: 0.127 mm	Std. Dev.: 0.083 mm	Std. Dev.: 0.167 mm