Modeling and Validation of 3D Printed PAEK Composites

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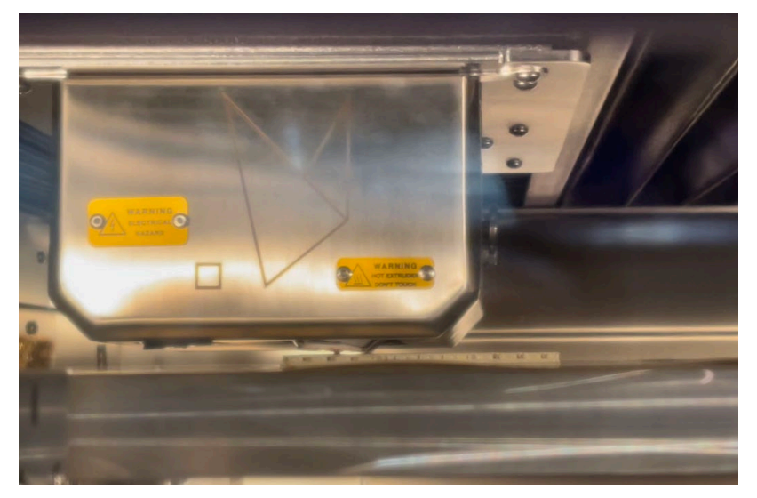
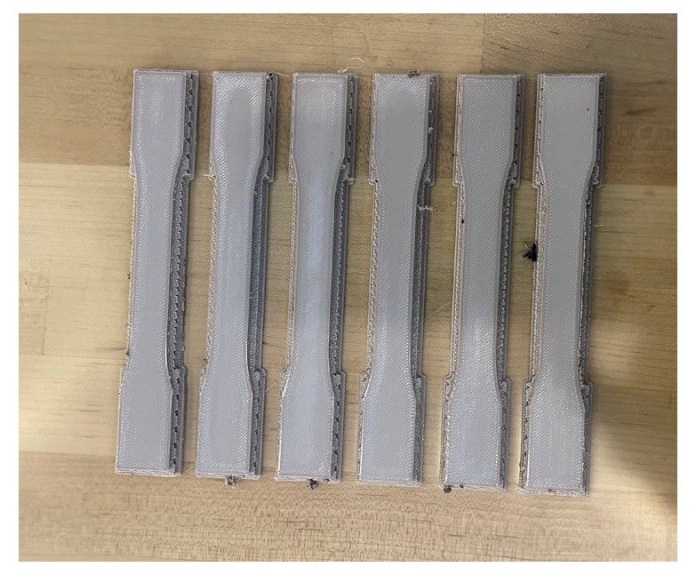
PAEK (poly aryl-ether-ketone)

- **Family of high-performance thermoplastic materials known for high:**

Glass-transition temperatures (150 -158 0c)
Melting & processing temperature (400-470 0c)





- **Processing high temperature polymers are difficult**

Post processing for intricate PAEK composite parts are labor intensive

Its costly and should be matched to product needs

- **Few machines are commercially available to print high quality aerospace grade parts**

UD-CCM is the first university to have dual nozzle commercial 3D printer

PAEK Properties and Applications

- **Mechanical Robustness UAV (Lightweight ,High Stiffness & Impact Resistance Structure) → Aviation Industry**

- **Resistance to Hydrolysis (don't break under sterilization) Gears and Medical Implants → Biomedical Industry**

- **Corrosion and Chemical Resistance Chemical Pumps → Chemical Plants**
- **Electrical Insulator High Voltage Appliances → Electronics Sectors**

- **Thermal Stability Valves, Seal, Bearing → Oil and Gas Industry**

PEAK Additive Manufacturing

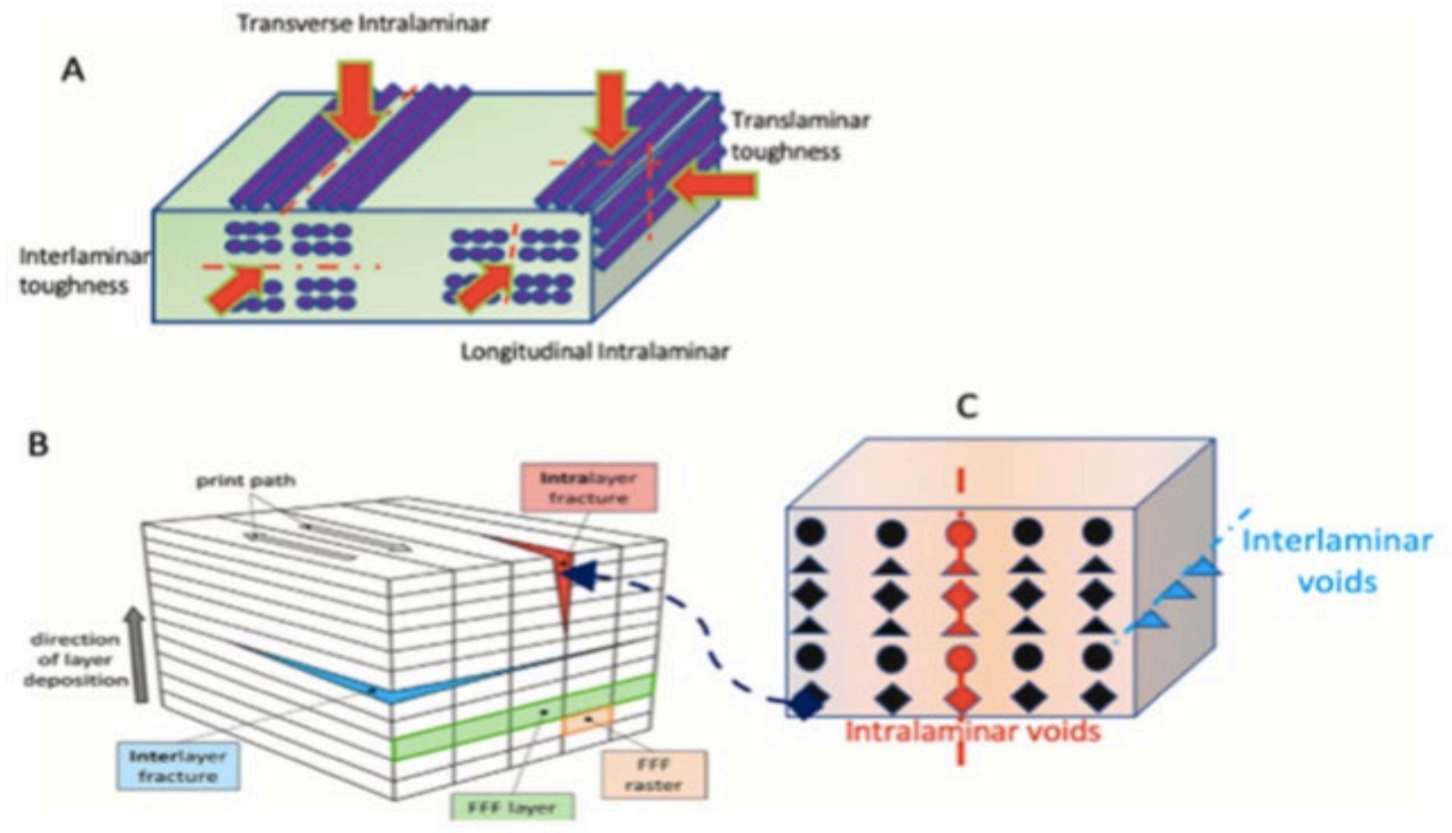
- Design freedom (complicated and customized components)
- Accelerated speed of manufacturing
- Reduced the assembly cost, machining

Challenges

- **Operating 3D printing machine and troubleshooting** (nozzle clog and gap with build plate)
- **Offline design** (optimize design and processing parameters)
- **3D printed part's properties affected by void** (shapes and content) **and processing parameters**.
- **Structural integrity depends on offline design and 3D printing machine capabilities**.
- **Diverse processing parameters** (infill density , infill shape, extrusion width layer height, bed temperature, extrusion temperature, overlap between deposited lines, raster angle, nozzle size, deposition speed, no. of shells and support layers) **cause variability.**

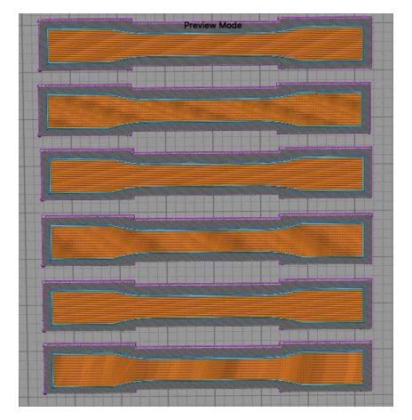
• Goal : Optimize Layer Adhesion

- **Bead to bead adhesion (Interlayer)**
- **Between layer adhesion (Intralayer):** along deposition direction
- **Between Layer Adhesion (Translaminar):** perpendicular to the deposition direction



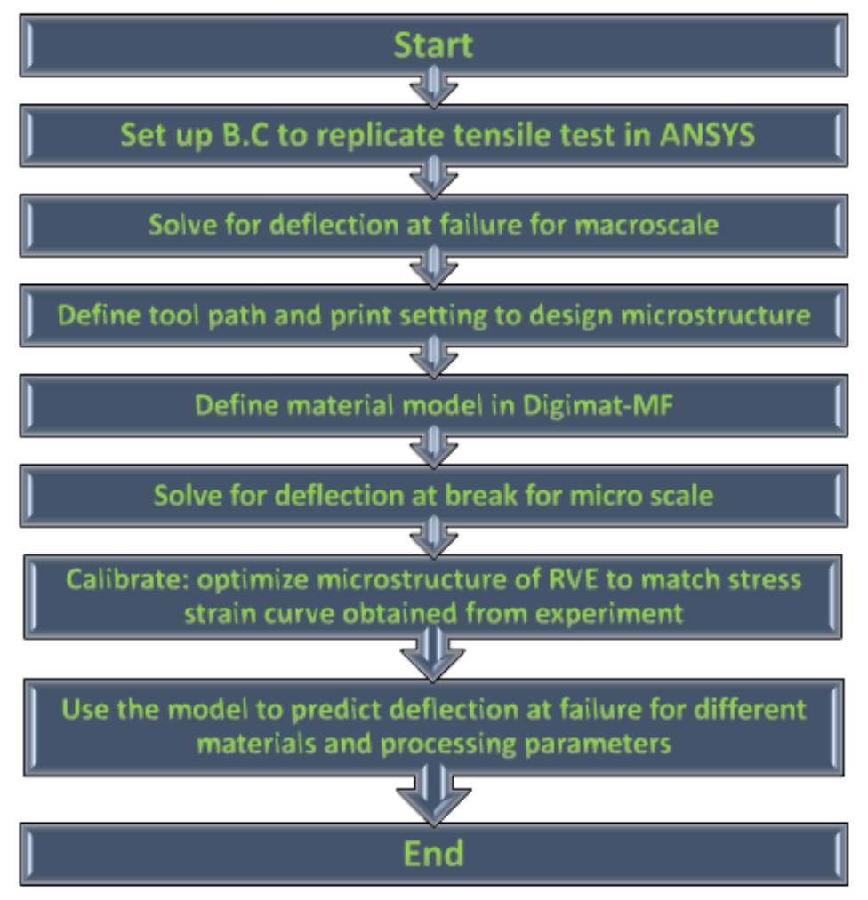
Modeling Framework

- Predict effect of processing parameters on mechanical performance
- Sensitivity analysis to identify major processing parameters

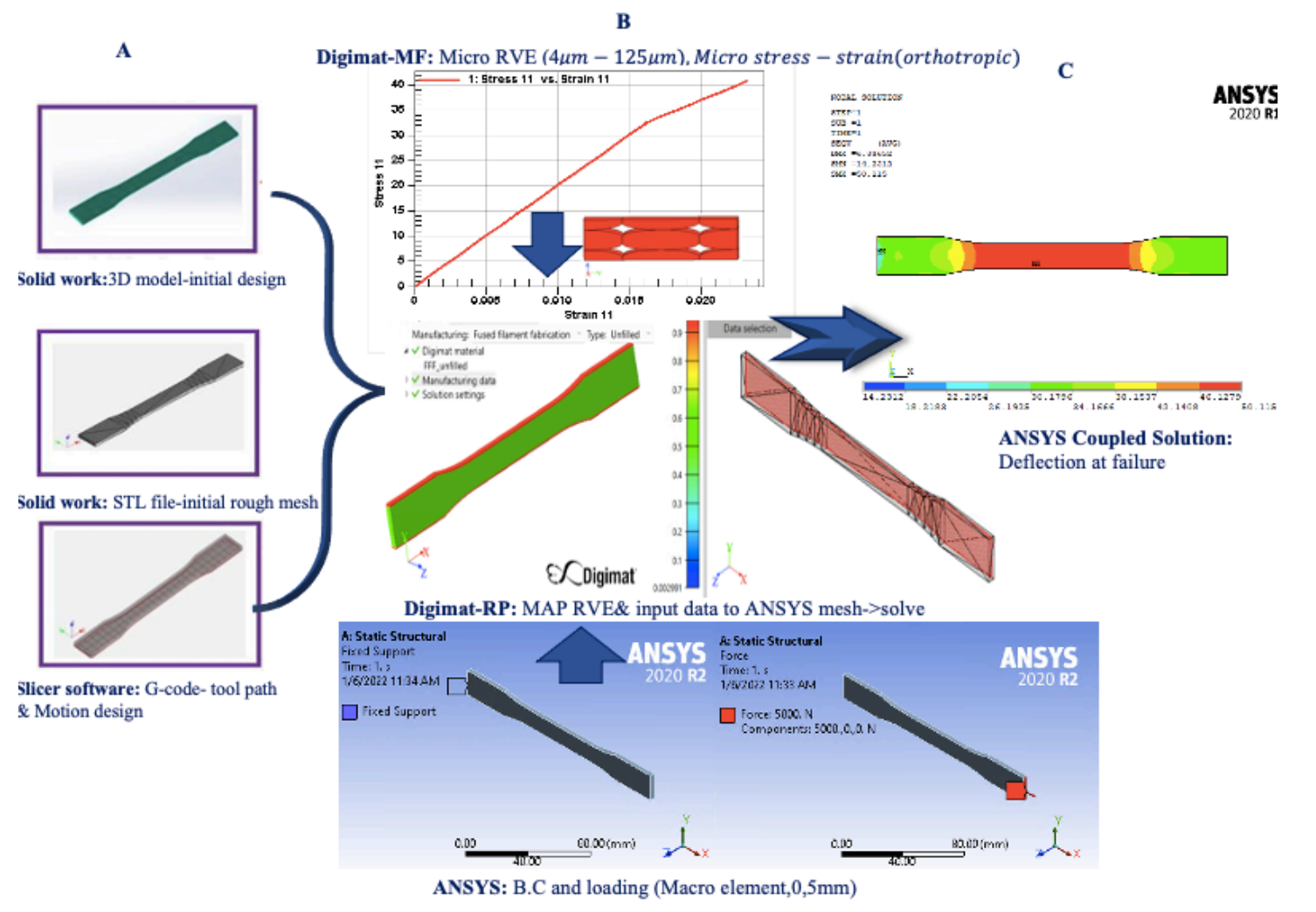


- Reduce number of experiments
- Optimize individual processing parameters to obtain tailored mechanical properties (toughness or stiffness)

Approach

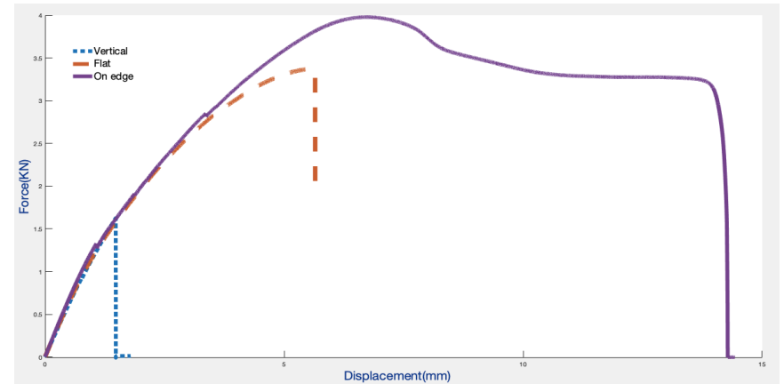


Start
Set up B.C to replicate tensile test in ANSYS
Solve for deflection at failure for macroscale
Define tool path and print setting to design microstructure
Define material model in Digimat-MF
Solve for deflection at break for micro scale
Calibrate: optimize microstructure of RVE to match stress strain curve obtained from experiment
Use the model to predict deflection at failure for different materials and processing parameters
End

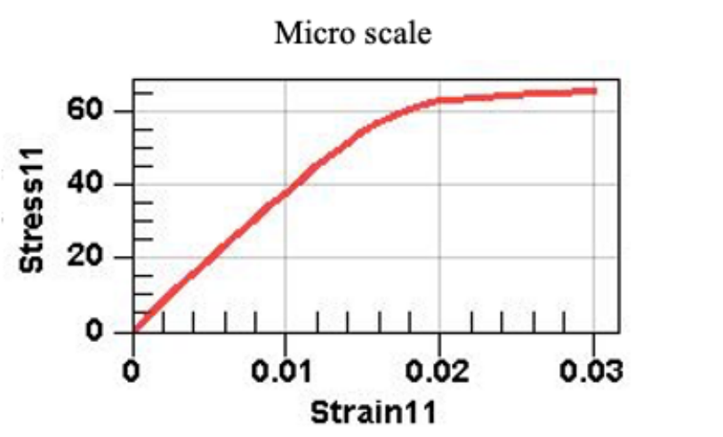


Model Parameters

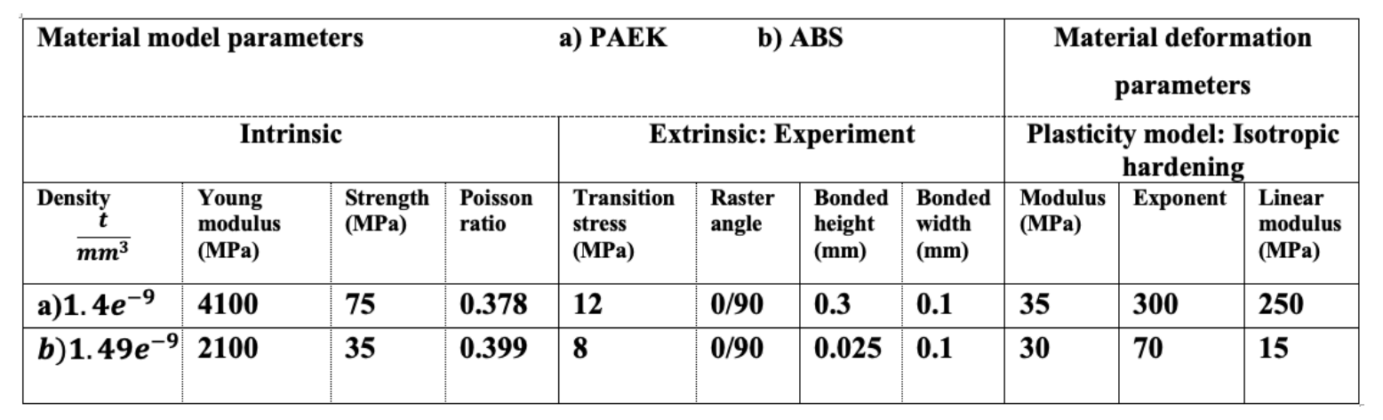
Experimental characterization



Material model

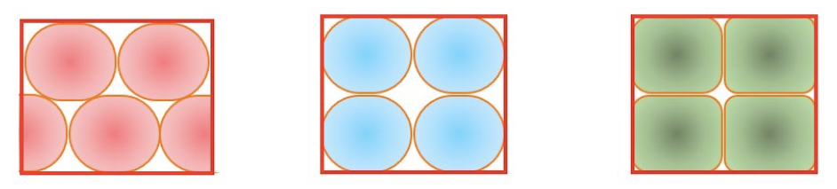


Material parameters



Material model parameters				a) PAEK b) ABS				Material deformation parameters		
Intrinsic				Extrinsic: Experiment				Plasticity model: Isotropic hardening		
Density $\frac{t}{mm^3}$	Young modulus (MPa)	Strength (MPa)	Poisson ratio	Transition stress (MPa)	Raster angle	Bonded height (mm)	Bonded width (mm)	Modulus (MPa)	Exponent	Linear modulus (MPa)
a)$1.4e^{-9}$	4100	75	0.378	12	0/90	0.3	0.1	35	300	250
b)$1.49e^{-9}$	2100	35	0.399	8	0/90	0.025	0.1	30	70	15

RVE –Different shapes of voids

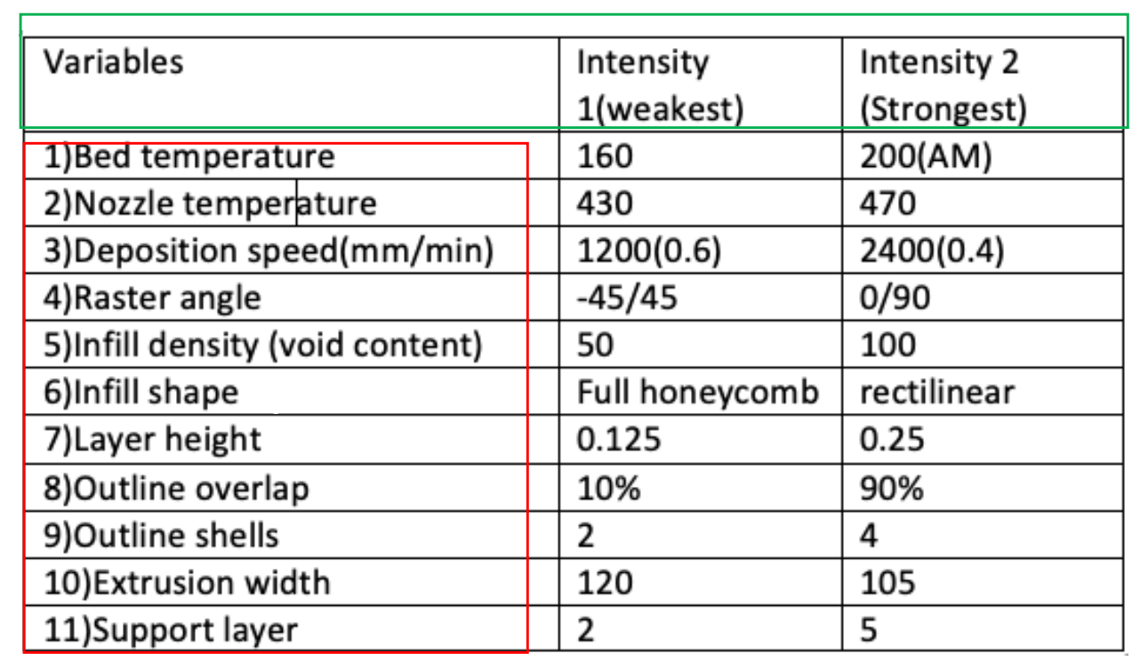


Design of Experiments

Using proposed Taguchi method considering only two intensities for each variables: we need 12 runs to find major parameters.

Total number of samples using ASTM standard:

60 samples

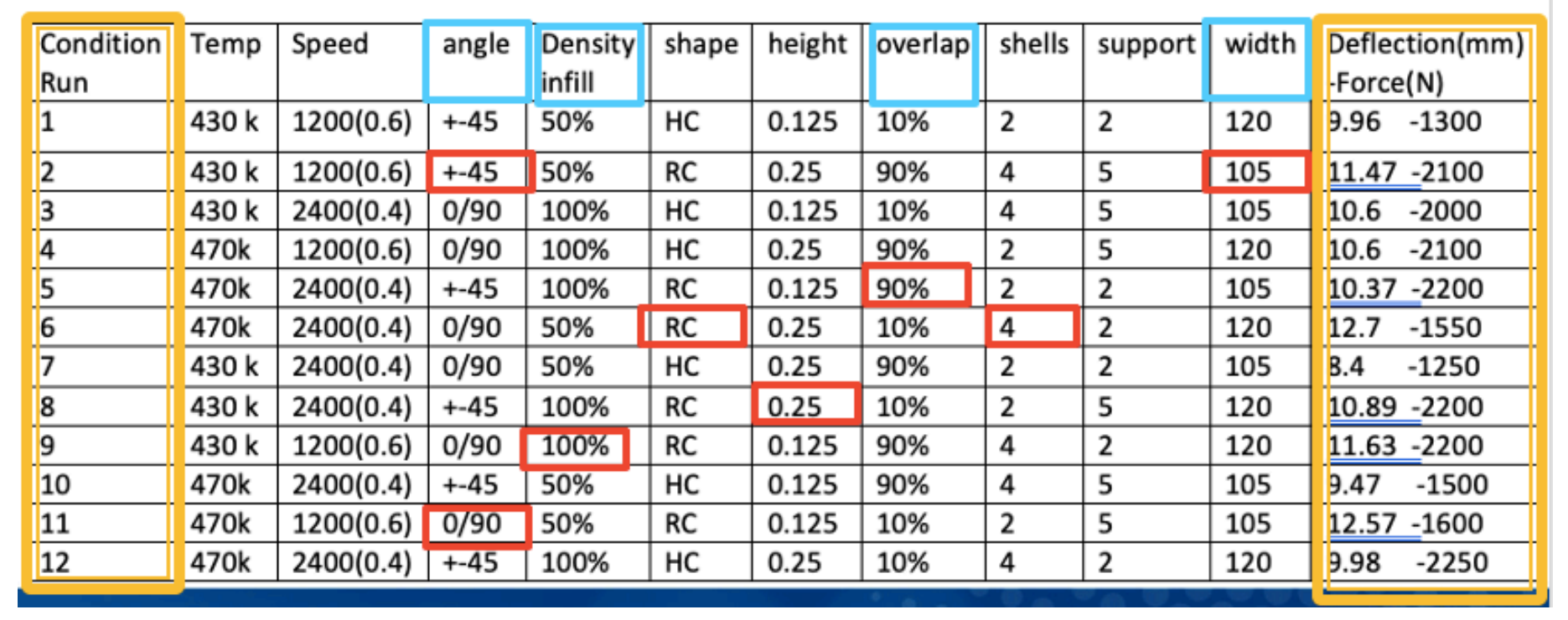


Variables	Intensity 1(weakest)	Intensity 2 (Strongest)
1)Bed temperature	160	200(AM)
2)Nozzle temperature	430	470
3)Deposition speed(mm/min)	1200(0.6)	2400(0.4)
4)Raster angle	-45/45	0/90
5)Infill density (void content)	50	100
6)Infill shape	Full honeycomb	rectilinear
7)Layer height	0.125	0.25
8)Outline overlap	10%	90%
9)Outline shells	2	4
10)Extrusion width	120	105
11)Support layer	2	5

Model Predictions to Identify Important Process Parameters

The sensitivity analysis shows parameters in blue have highest effect on deflection at break and stiffness.

Number of samples needed using proposed modeling: 20



Condition Run	Temp	Speed	angle	Density infill	shape	height	overlap	shells	support	width	Deflection(mm) -Force(N)
1	430 k	1200(0.6)	+-45	50%	HC	0.125	10%	2	2	120	9.96 -1300
2	430 k	1200(0.6)	+-45	50%	RC	0.25	90%	4	5	105	11.47 -2100
3	430 k	2400(0.4)	0/90	100%	HC	0.125	10%	4	5	105	10.6 -2000
4	470k	1200(0.6)	0/90	100%	HC	0.25	90%	2	5	120	10.6 -2100
5	470k	2400(0.4)	+-45	100%	RC	0.125	90%	2	2	105	10.37 -2200
6	470k	2400(0.4)	0/90	50%	RC	0.25	10%	4	2	120	12.7 -1550
7	430 k	2400(0.4)	0/90	50%	HC	0.25	90%	2	2	105	8.4 -1250
8	430 k	2400(0.4)	+-45	100%	RC	0.25	10%	2	5	120	10.89 -2200
9	430 k	1200(0.6)	0/90	100%	RC	0.125	90%	4	2	120	11.63 -2200
10	470k	2400(0.4)	+-45	50%	HC	0.125	90%	4	5	105	9.47 -1500
11	470k	1200(0.6)	0/90	50%	RC	0.125	10%	2	5	105	12.57 -1600
12	470k	2400(0.4)	+-45	100%	HC	0.25	10%	4	2	120	9.98 -2250

Conclusions

- Developed Dual scale modeling approach with Digimat software (for the micro-scale) and ANSYS software (for the macro-scale) to predict mechanical properties of additively manufactured composites.
- The mechanical properties determined at the RVE scale can be allocated to the manufacturing tool at the ANSYS mesh locations to scale up properties and apply the macroscale boundary conditions and loading condition to determine deformation at failure stress.
- PAEK and ABS materials are modeled and show good agreement with experimental results
- Design of experiment reduces the number of experiments needed to identify main processing parameters.

Reference:

1) S. Sharafi, M. H. Santare, J. Gerdes, and S. G. Advani, "A review of factors that influence the fracture toughness of extrusion-based additively manufactured polymer and polymer composites," Additive Manufacturing., vol. 38, p. 101830, 2021, doi: https://doi.org/10.1016/j.addma.2020.101830.

2) S. Sharafi, M. H. Santare, J. Gerdes, and S. G. Advani, "A multiscale modeling approach of the Fused Filament Fabrication process to predict the mechanical response of 3D printed parts," Additive Manufacturing, vol. 51, p. 102597, 2022, doi: https://doi.org/10.1016/j.addma.2022.102597.

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