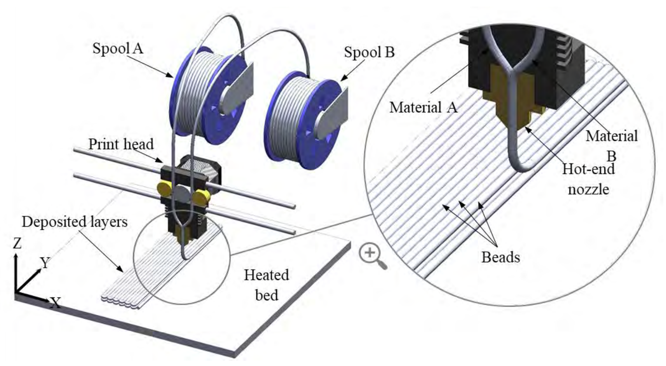
Experimental and numerical characterization of functionally graded materials fabricated by the fused filament fabrication process

Seymur Hasanov, Dr. Ismail Fidan
Center for Manufacturing Research and Mechanical Engineering Department, Tennessee Tech University

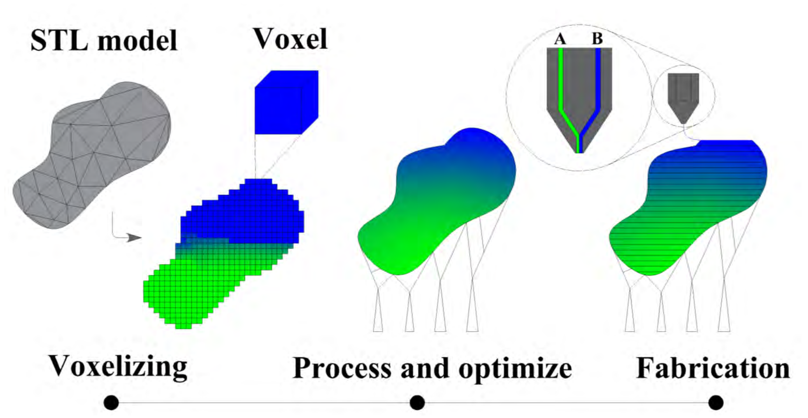
INTRODUCTION

Advances in additive manufacturing (AM) methods enable the fabrication of multi-material structures characterized by complex geometry and printed using a wide variety of materials. AM especially offers potential complexity and freedom in the design and fabrication of function-oriented components[1-2].

In this study, the design and fabrication workflow of functionally graded materials (FGMs) were introduced using the fused filament fabrication (FFF) process. Fabrication process of multi-material AM method is illustrated.



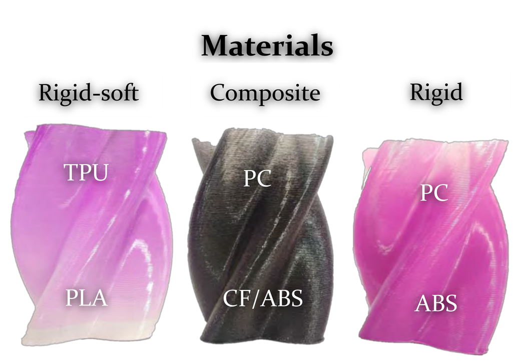
Voxel-based three-dimensional (3D) printing method enables the fabrication of digital structures at meso-scale by controlling the deposition feature of materials at the voxel-scale. In this regard, Voxelizer software is used to fabricate digital materials with heterogeneous compositions by locally varying material properties. Figure below shows the process workflow of voxeling approach to create heterogeneous objects.



Workflow of voxel approach to fabricate materials digital structures

MATERIALS & METHODS

Materials were chosen to investigate amorphous polymers with different material properties. In this research, amorphous polymers, rather than semi-crystalline polymers, were chosen in order to eliminate complications arising from the crystallization process. Acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) are amorphous polymers with glass transition temperatures of 80^{0}C, and 150^{0}C, respectively.

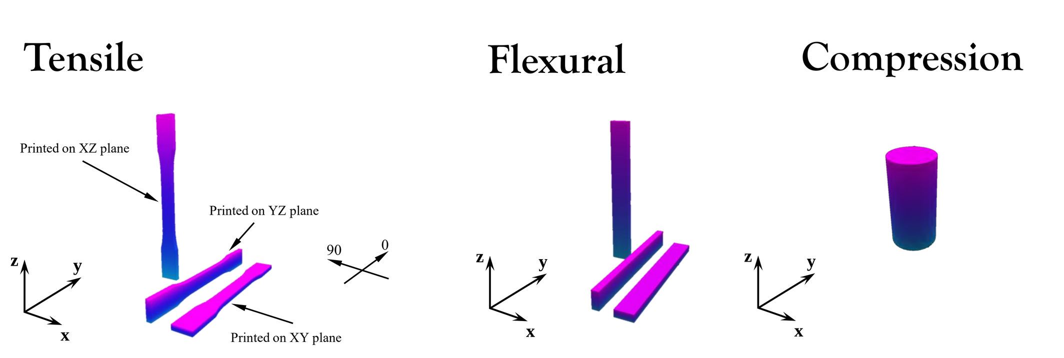


Sample material combinations

Fixed printing parameters

Parameters	values
Nozzle temperature (^{0}C)	250
Bed temperature (^{0}C)	107
Infill density (%)	100
Infill pattern	Line (0/90)
Chamber temperature (^{0}C)	50
Layer width (mm)	0.35
Layer height (mm)	0.15
Printing speed (mm/sec)	35

Printing directions and orientations of the tensile, flexural, and compression specimens are shown below.



Specimen orientations and printing directions

Overall workflow of the research study is shown below:

Microstructural analysis
- PC - ABS sample
- Formation of voids

Tensile behavior analysis
- Flexural behavior
- Compression behavior
- PC/ABS

Interface analysis
- Gradient transition
- Interlock transition
- Direct transition

Statistical analysis
- PC – ABS material
- ZX – orientation
- 0, 20, 40, 60, 80, 100 % vol. fraction

Prediction of properties
- Regression model
- Homogenization
- Finite element analysis

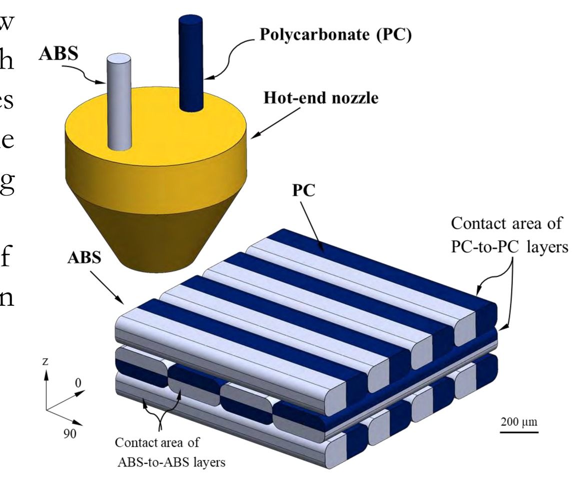
Effective properties
- Validation of the approach

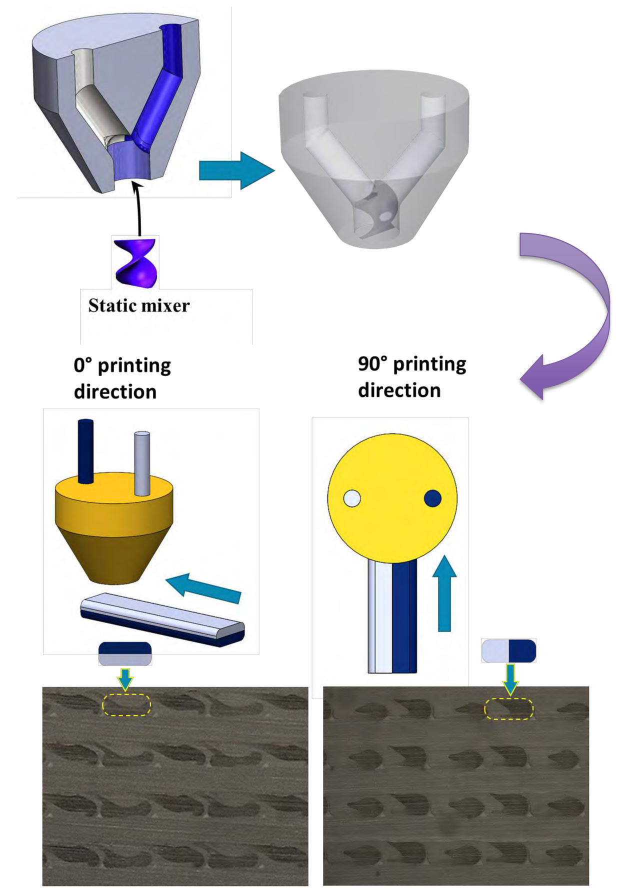
Optimized material distribution

MICROSTRUCTURE

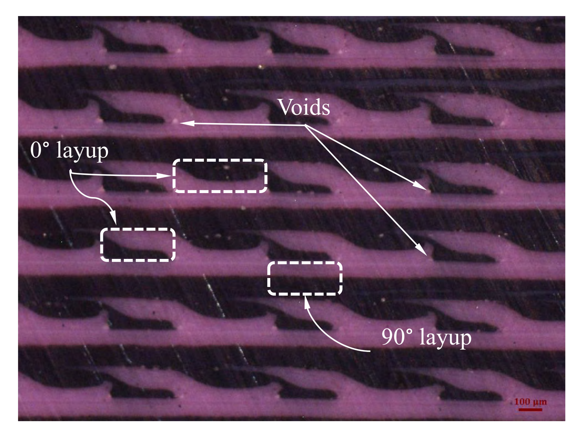
Microstructural analysis was performed to show the formation of layers, beads, and voids which significantly affects the mechanical properties of FFF made parts. In multi-material case, the microstructure changes with respect to printing direction.

The mixer was added o help the mixing of polymers and get homogenized blend as shown below.



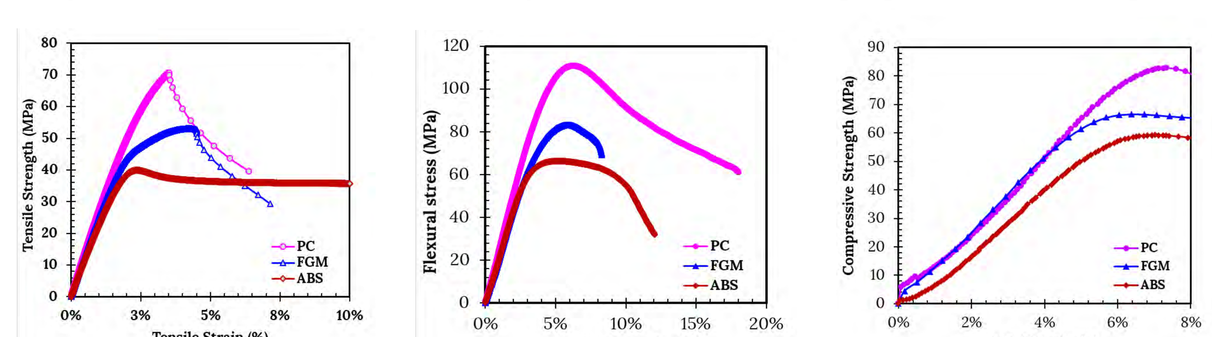


Periodicity is shown in only 90 deg. orientation and this changes in 0 deg orient. Moreover, formation of PC and ABS materials in the beads that make them interlocked which reduced the delamination of polymers between the layers and beads.



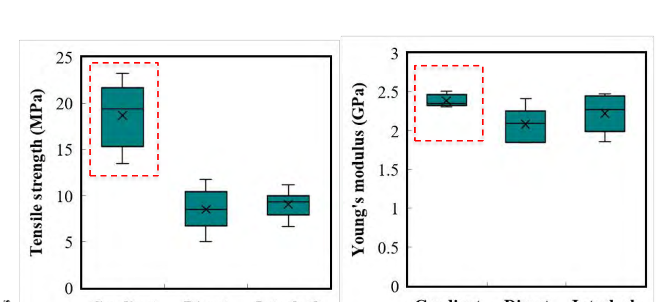
EXPERIMENTAL EVALUATION

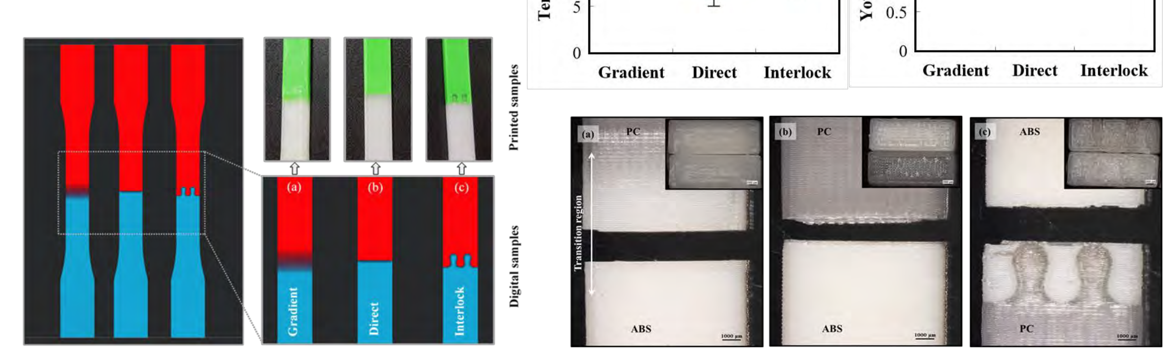
Experimental characterization has been performed for tensile, flexural, and compression test samples to analyze the behavior of FGM composites under various structural loads. The graph below shows that the strength of FGM samples are in between PC and ABS materials. It shows that FGM inherited both strength, stiffness from PC material and toughness from ABS materials which significantly enhanced the properties of the final part.



Variation of properties at interfaces

- Designed interfaces:
  - Continuous gradient
  - Direct transition
  - Interlock mechanism

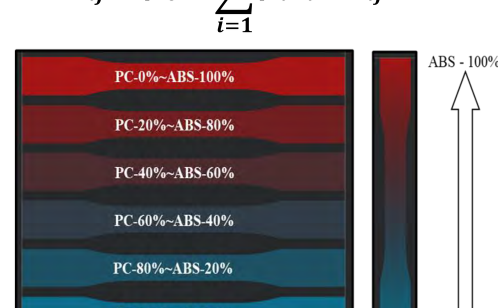


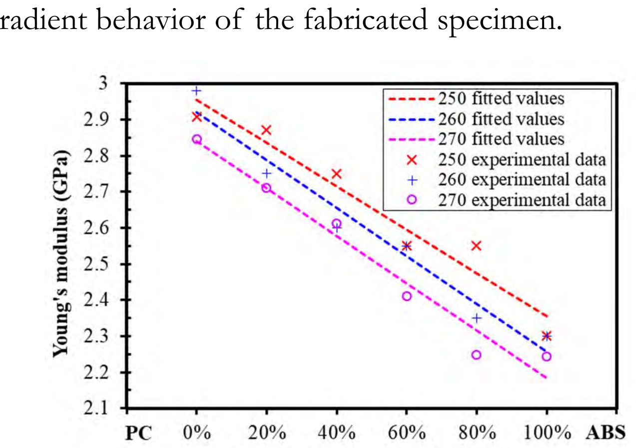


STATISTICAL ANALYSIS

The data obtained for various volume fractions of PC/ABS polymer blend was utilized to construct the regression model for Young's modulus (E) in each printing temperature 250 ^{0}C, 260 ^{0}C and 270 ^{0}C to understand the gradient behavior of the fabricated specimen.

$$Y_{ij} = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \varepsilon_{ij}$$

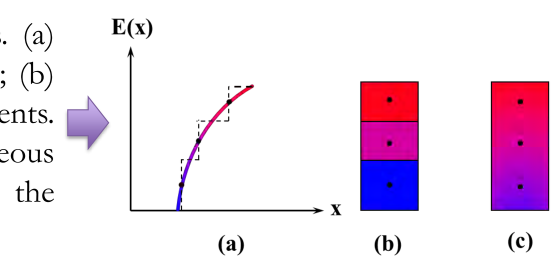




FINITE ELEMENT IMPLEMENTATION

FE implementation was performed to validate the proposed design approach with experimental results and homogenization method. The regression model of Young's modulus printed in ZX direction was employed to understand the elastic behavior of various concentrations of PC/ABS polymer blend. Material properties were evaluated at the quadrature points of each element where the x indicates the position of each quadrature point.

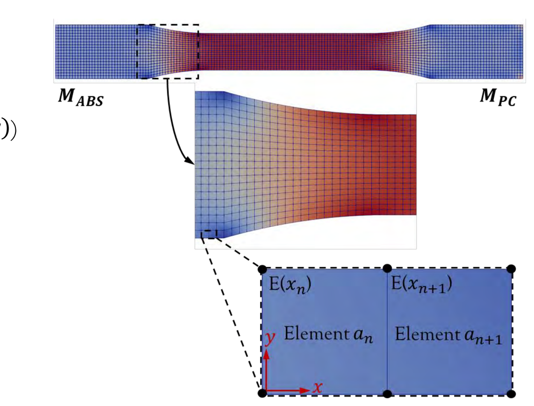
Homogeneous versus graded finite elements. (a) Property variation along one coordinate axis; (b) homogeneous elements; (c) graded elements. Notice that the property of the homogeneous elements corresponds to the property at the centroid of the graded element.



FEA input for material properties derived from regression model

$$M(x) = (M_{PC} - M_{ABS})\frac{x}{\Delta l} + M_{ABS}$$

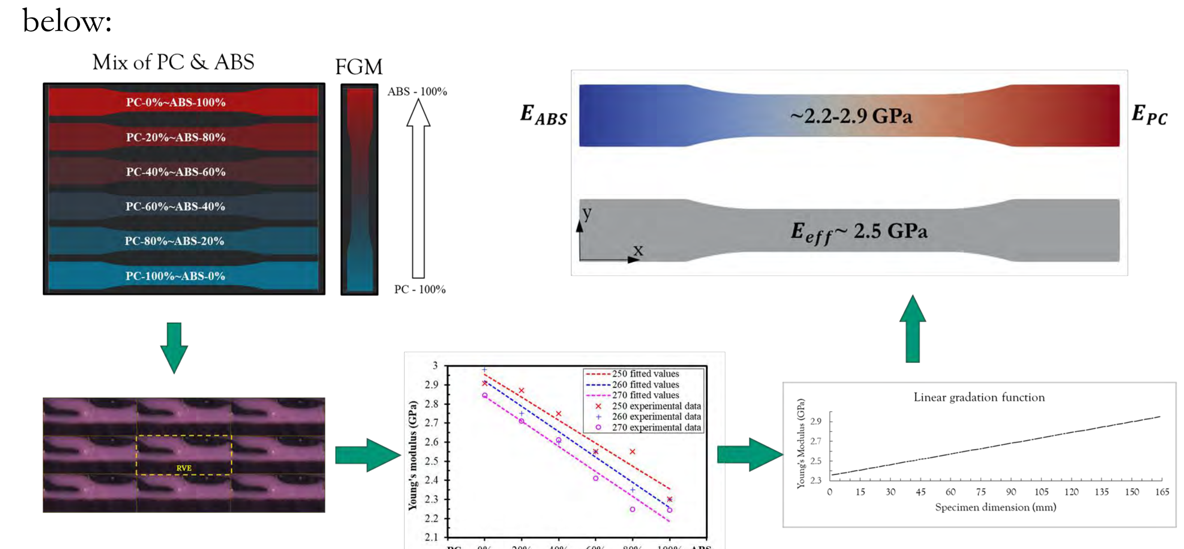
$M(x)$ – material property (Young's modulus $E(x)$, Poisson ratio $\nu(x)$)
M_{PC} & M_{ABS} – input material property of PC and ABS, respectively



The effective elastic modulus was calculated by dividing the average stresses by strain values at the far end of the specimen.

$$E_{eff} = {}^{\sigma_{avg}}/_{\varepsilon_x}$$

The overall approach to find the effective properties of FGMs is shown below:



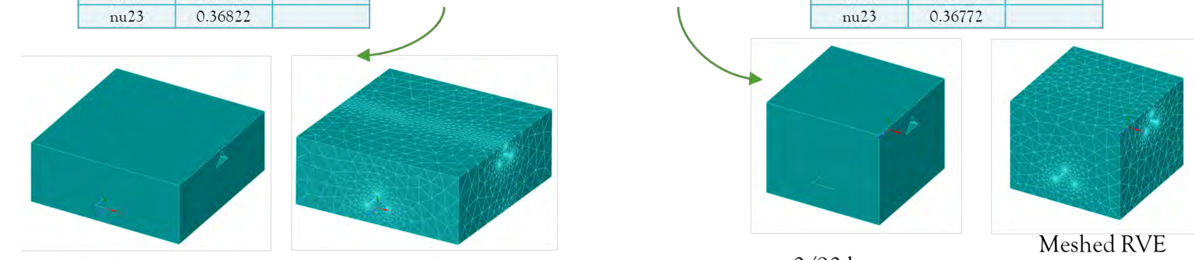
Homogenization method has been applied to find the mesoscale material property for base input materials to perform FEA analysis in order to calculate the effective property of FGM as a second approach.

- Homogenization of base material properties

ABS homogenized prop.		
E1	2.22E+09	Pa
E2	2.09E+09	Pa
E3	2.22E+09	Pa
G12	7.71E+08	Pa
G23	7.71E+08	Pa
G31	7.90E+08	Pa
nu12	0.39212	
nu13	0.3878	
nu23	0.36822	

PC homogenized prop.		
E1	2.69E+09	Pa
E2	2.51E+09	Pa
E3	2.68E+09	Pa
G12	9.35E+08	Pa
G23	9.34E+08	Pa
G31	9.56E+08	Pa
nu12	0.39349	
nu13	0.3881	
nu23	0.36772	

Representative Volume Element (RVE)

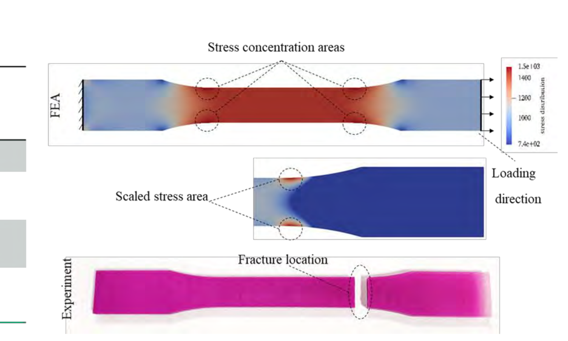


0/90 layup — Meshed RVE — 0/90 layup — Meshed RVE

Comparison of experimental and predicted Young's moduli are given below. The tables shows that both approaches agree well with the experimental test results.

Prediction:
- Based on the experimental input results
- Based on the homogenized input results

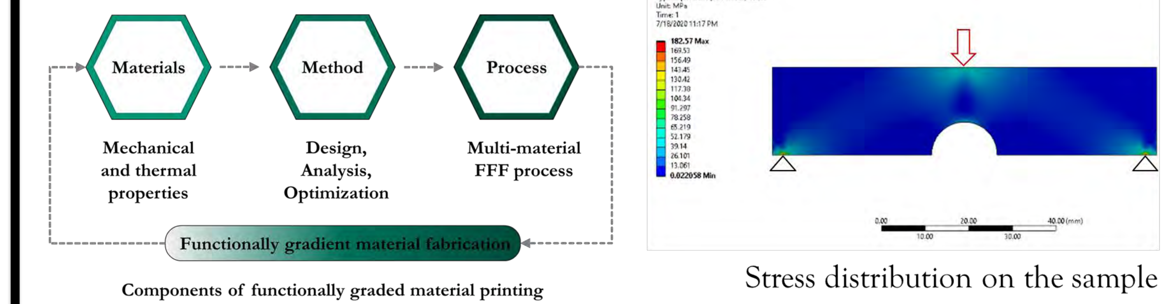
Base input materials (experimental with different print. temp. & hom. At)	Experimental results (GPa)	Effective modulus (GPa)	Error %
250	2.450	2.560	4.51
260	2.580	2.493	3.34
270	2.508	2.419	3.52
B.i.m. from homogenization (250)	2.450	2.370	3.26



As a result, FEA agreed well with the experimental values (with less than 5 % errors) which validated the regression and homogenization approach used to obtain the effective Young's modulus. This research study is the first step developing an integrated design to fabrication workflows for FGM structures based on multi-material voxel-based digital structures.

OPTIMIZED MATERIAL DISTRIBUTION

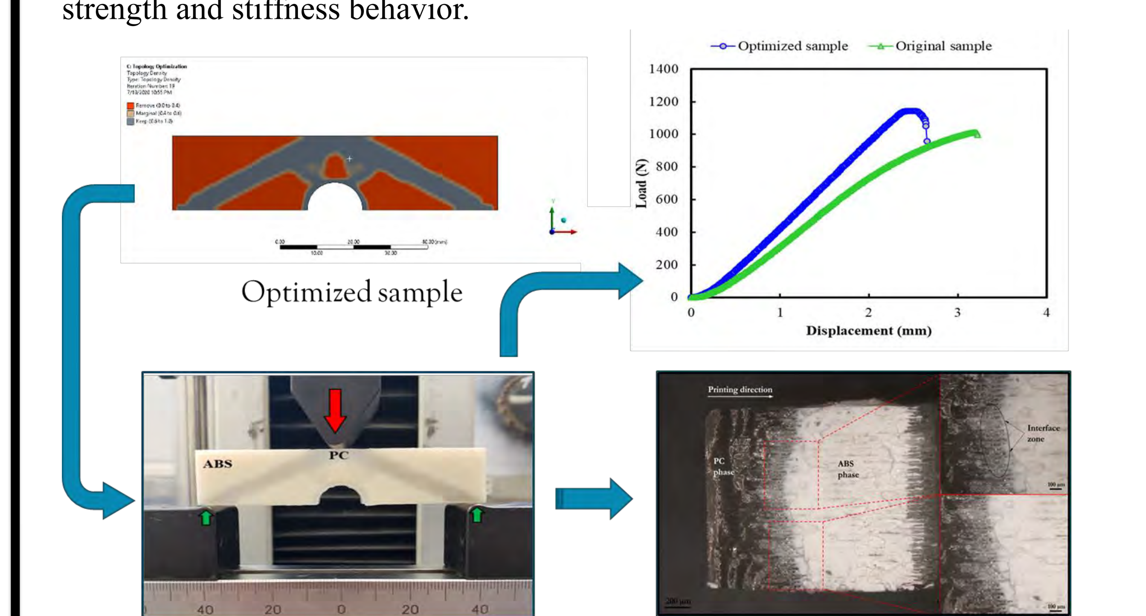
Topology optimization as a practical design tool has been extensively associated with AM due to its ability to generate efficient structures under the prescribed objective and constraints. It is used in the initial phase of the design to predict the optimal material distribution within a given initial design space of a structure and considers functional specifications and manufacturing constraints. In this research study, optimal material distribution was performed using Ansys TO module and the PC and ABS phases were extracted for Voxelizer software to fabricate the optimal structure.



Components of functionally graded material printing

Stress distribution on the sample

The experimental setup for optimized sample and the comparison of the tests results are shown below. In this context, optimized sample indicates better results in terms of strength and stiffness behavior.



Optimized sample

Experimental setup

Cross-section of fracture

Significant improvement in Young's modulus, from 2.3 GPa to 3.1 GPa in the bending specimen, was observed.

Optimized sample
- Strength - 68 MPa
- Modulus - 3.1 GPa

Original sample
- Strength - 59 MPa
- Modulus - 2.3 GPa

CONCLUSION

- Fabrication of FGM tensile specimen through the FFF process was successfully achieved with the help of a voxel printing technique.
- It was found that the gradient interface transition achieved better strength and stiffness results than other transition patterns.
- Microstructural images of interface patterns showed that the fracture was sensitive due to surficial and interfacial defects in interlock transition shape.
- A data-driven linear regression model was adopted for varying concentration levels of PC/ABS blend.
- FEA implementation of FGMs was successfully presented in order to predict effective Young's modulus. Relative errors between experimental and FEA predicted effective modulus were less than 5% for all printing temperatures.
- Optimal material distribution was achieved using topology optimization method and strength and stiffness of the final part were significantly enhanced.

REFERENCES

- [1] I. Fidan et al., "The trends and challenges of fiber reinforced additive manufacturing," Int. J. Adv. Manuf. Technol., Jan. 2019.
- [2] A. Bandyopadhyay and B. Heer, "Materials Science & Engineering R Additive manufacturing of multi-material structures," Mater. Sci. Eng. R, vol. 129, no. March, pp. 1–16, 2018.

The author would like to acknowledge the support provided by the Center for the Manufacturing Research and The National Science Foundation Award, AM-WATCH: *Additive Manufacturing – Workforce Advancement Training Coalition and Hub.*