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6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

University of South Carolina
1600 Hampton Street
Suite 414
Columbia, SC 29208 -0001

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19a. NAME OF RESPONSIBLE PERSON: Subramani Sockalingam

19b. TELEPHONE NUMBER: 803-777-9821

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INVESTIGATOR(S):

Name: Addis Kidane
Email: kidanea@cec.sc.edu
Phone Number: 8037772502
Principal: N

Name: Ph.D. Subramani Sockalingam
Email: sockalin@cec.sc.edu
Phone Number: 8037779821
Principal: Y

Organization: **University of South Carolina**
Address: 1600 Hampton Street, Columbia, SC 292080001
Country: USA

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Phone: (803) 777-2502
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Major Goals: The original goal of the proposal was to develop multiscale additive manufacturing (AM) through acquisition of state-of-the-art light-based digital light synthesisTM (DLS) (Carbon® M1 3D Printer) and layer-by-layer (Stratasys J735TM) 3D printing equipment that will provide unprecedented capability to design and fabricate novel architectured materials with multiscale resolution. Since the agency approved the purchase of a layer-by-layer 3D printer, the revised major goal is to design and fabricate novel heterogeneous architectured materials at the meso-scale to activate multiple damage/failure mechanisms as a driver for enhanced ballistic performance. Architectured materials constitute merger of structure and material. Together with existing high performance computational and dynamic impact testing facilities in our department (shared memory cluster, high speed cameras, split Hopkinson pressure bar, shock tube, drop-impact tower), the specific goal is to investigate processing-structure-property relationships of additively manufactured architectured composites materials. This research will enable rapid design of emerging game change materials with spatially tunable superior impact-resistant properties for defense applications; and enable design of high-throughput additive manufacturing process for development of materials for extreme conditions.

Equipment: Layer-by-layer Stratasys J735TM multimaterial 3D printer utilizes PolyJet technology that can print distinct multiple material phases with a 14-micron layer resolution with any combination of rigid, flexible, opaque or transparent materials. The jetting heads carry jets of photopolymers depositing them layer-by-layer and simultaneously curved via UV light. Raster scanning of the head provides smoothest precision with an in-plane resolution of 42 ?m. The combination of these two technologies provide unprecedented levels of multiscale fabricating capability to produce architectured materials for superior properties and performance.

Potential Research Impact: Modernization priorities for the United States Army is to make Soldiers and units more lethal. Soldier lethality includes mastering fundamentals of moving, protecting and sustaining. Development of ultra-lightweight body armor systems (helmets, body armor panels) are, in turn, critical for enhancing soldier lethality. The layer-by-layer 3D printer will support research at the forefront to enable ultra-lightweight soldier protection systems to improve the mobility and survivability of personnel. Specifically, the equipment will be used to (1) fabricate novel meso-architectured materials informed by integrated physics-based multi-scale computational and data-driven machine learning (ML) models; (2) design and fabricate functionally graded foam and soft materials for army applications to mitigate impact loads and injuries sustained by soldiers; (3) facilitate the development of a combined FEA-DIC approach to characterize heterogeneous material properties and (4) advance fundamental understanding of impact response in additively manufactured polymers and composites. The proposed equipment will enhance investigators currently funded ARO research on functionally graded foams and fibers/fiber-based composites.

Potential Research-related Educational Impact: We also plan to use the 3D printer to research-related education and training for graduate and undergraduate students. Investigators have ongoing collaborations with DoD (ARL) labs and realize continued collaboration is critical to achieve revolutionary breakthroughs in research important to DoD missions. Participation of US students is key for a successful collaboration. Enhancing participation of US students, in particular women, for DoD research areas will be aimed through internships and 3D printing workshops that will include 3D printing of DoD materials and structures such as armor helmets, airfoil wings and ship hulls.

Accomplishments: A PDF file is uploaded in the "Upload" section.

Training Opportunities: Training and professional development opportunities were provided for 2 undergraduate (Ms. Hannah Skerkis and Ms. Hannah O’Brien) and 5 graduate students (Mr. Karan Kodagali, Mr. Karan Shah, Mr. Frank Thomas, Mr. Vijendra Gupta and Mr. Chizoba Onwuka) in both the PI Sockalingam and co-PI Kidane’s research group. Stratasys personnel trained these students in the usage and maintenance of 3D printer.

Professional development opportunities were provided to Ms. Hannah Skerkis and Mr. Karan Kodagali in the form of undergraduate research internship and graduate research assistantship respectively. These students performed majority of the preliminary activities described in the “Accomplished” section resulting in increased knowledge and expertise of these students in 3D printing composites.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: We are collaborating with ARL scientists and Engineers through a cooperative research agreement established in August 2020 to study processing-structure-property relationships in ultrahigh molecular weight polyethylene (UHMWPE) fibers/composites and develop a combined digital image correlation (DIC)-finite element method (FEM) methodology for inversely determining/optimizing material model parameters for heterogeneous materials. This 3D printing equipment will facilitate validating the DIC-FEM methodology via printing heterogeneous materials.

PARTICIPANTS:

Participant Type: Undergraduate Student
Participant: Hannah Skerkis
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Karan Kodagali
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI

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Participant: Addis Kidane
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: PD/PI
Participant: Subramani Sockalingam
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Partners

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I certify that the information in the report is complete and accurate:
Signature: Subramani Sockalingam
Signature Date: 8/31/21 10:28AM

Multiscale 3D Printing System for Fabrication of Next Generation Multiscale Architectured Armor Materials

2. ACCOMPLISHED

2.1 Purchase and Installation of Stratasys J750 PolyJet 3D Printer

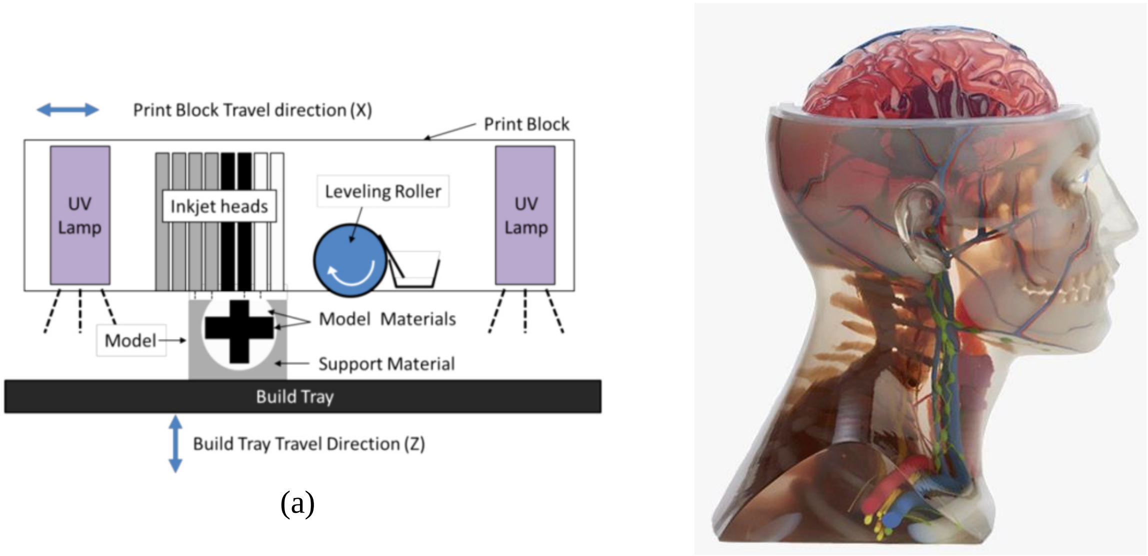
As shown in Figure 1, we successfully purchased and installed a Stratasys J750^{TM} PolyJet 3D printer in our lab in February 2021. Although the proposal had requested a Stratasys J735^{TM} printer, the vendor went out of stock and provided the J750 instead, which is an upgrade to J735 model. Key specifications of this 3D printer is listed in Table 1.

Figure 1. Stratasys J750^{TM} 3D printer installed at the University of South Carolina

Table 1. Specifications of Stratasys J750 3D printer

Specifications	**Layer-by-layer multimaterial Stratasys J50**
Technology	PolyJet using multiple printheads
System size and weight	1400 x 1260 x 1100 mm (55.1 x 49.6 x 43.4 in); 430 kg (948 lbs)
Build size	490 x 390 x 200 mm (19.3 x 15.35 x 7.9 in)
Layer thickness	Down to 14 microns
Accuracy	Under 100 mm ±100 μm; above 100 mm ±200 μm
Range of materials	Digital ABS, elastomeric rubber-like, any combination of rigid, flexible, transparent or opaque materials and tough thermoplastics

Stratasys J750^{TM} 3D printer uses acrylic-based photopolymer or photocurable resins to print parts. PolyJet stands for photopolymer jetting. It uses multiple fine printhead nozzles to deposit droplets of photocurable liquid material in layers as fine as 14 microns to form detailed 3D parts. The deposited material is cured simultaneously via UV light as shown in Figure 2. Photopolymer liquid resins changes its physical properties when exposed to UV light. The jetting heads carry jets of photopolymers depositing them layer-by-layer. Raster scanning of the head provides smoothest precision with an in-plane resolution of 42 μm [1].



(a)

(b)

Figure 2. PolyJet 3D printer (a) principle [1] *(b) printed part [2]*

This multimaterial printer allows combining several base resins to create new materials with distinct and desired properties. The technology is capable of combining distinct material phases (stiff and flexible) to produce components with rigid and flexible elements. A wide range of material options include digital ABS, elastomeric rubber-like, transparent, opaque and tough thermoplastics. The combination of multiphases of materials provide signicant opportunities to fabricate and study processing-structure-property rleationships of heterogenous architectures enabling improved manufacturing process and enhanced properties.

2.2 Preliminary 3D Printing and Characterization of Digital materials

As shown in Figure 3, we utilized two distinct materials, a stiff material called Vero (acrylic photo-polymer) and a soft material called Tango+ for preliminary 3D printing and tensile characterization. Additionally, we mixed these two materials to create an array of materials with properties in between Tango and Vero. These include FLX9740, FLX9750, FLX9760, FLX9770, FLX9785, FLX9795, RGD8425 and RGD8430. Here FLX stands for flexible and RGD stands for rigid.

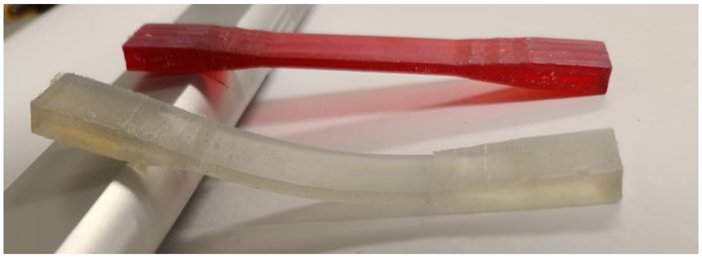


Figure 3. Vero stiff material in red and Tango compliant material in white

The 3D printer allows printing in two modes, “high mix mode” (27 µm layers, faster) and “high quality mode” (14 µm layers, improved finish). We 3D printed dog bone specimens of all these 11 digital materials in “high mix mode” and tested them in quasi-static tension following ASTM D638 V as shown in Figure 4.

(a) (b)

Figure 4. Dog bone specimens of digital materials (a) before testing (b) after testing

Figure 5 shows preliminary tensile testing results. As expected, a range of behavior is observed for these digital materials from stiff to soft and in between. The ratio between stiff and soft material in terms of tensile modulus is ~1000 and tensile strength is ~100, whereas the ratio between soft and stiff material in terms of failure strain is ~4. These results provide the foundation to design and fabricate heterogeneous meso-architectured composites. Future work will study the properties of these materials printed in the “high quality mode”.

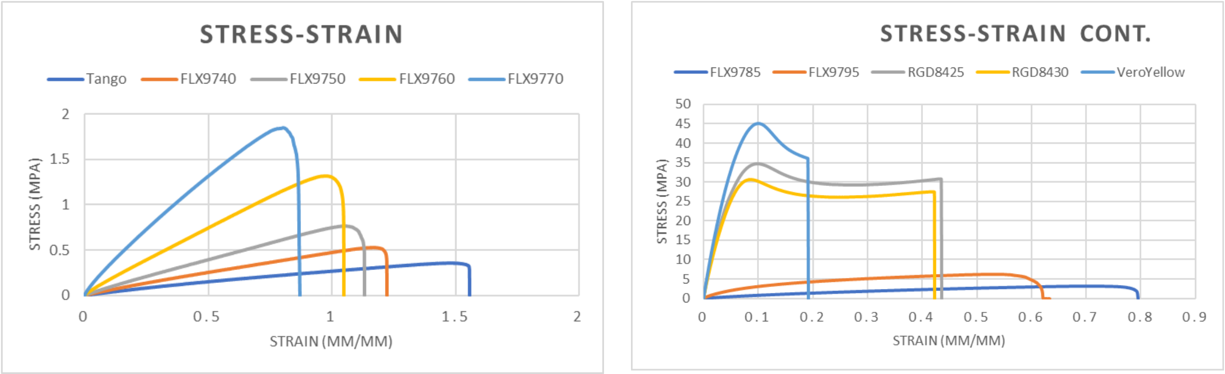
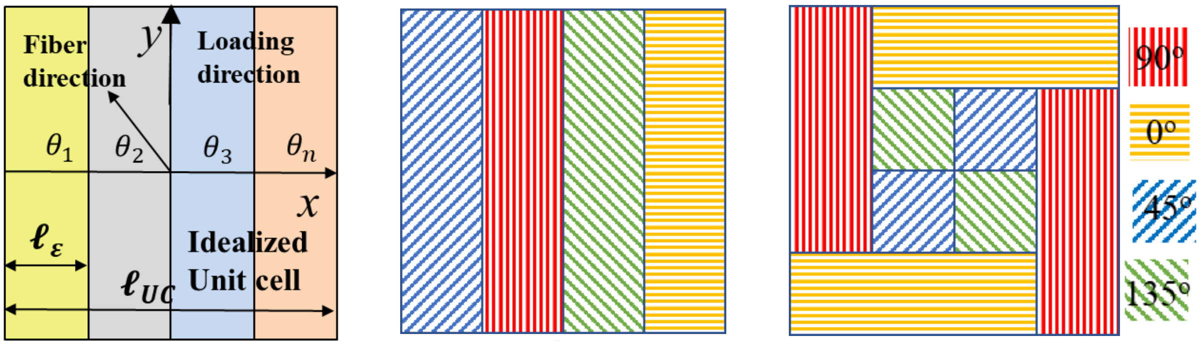


Figure 5. Preliminary tensile stress-strain results

2.3 Preliminary 3D Printing of Meso-Architectured Composite Materials

We are currently investigating the design and fabrication of heterogeneous anisotropic fiber-reinforced meso-architectured composite (MAC) materials for enhancing properties (strength and fracture toughness) compared to traditional unidirectional (UD) composites. In principle, the proposed meso-scale heterogeneity will result in the activation of multiple damage/failure mechanisms *including crack deflection, damage diffusion, and stress-redistribution* that will enhance ballistic performance and soldier protection. As shown in Figure 6, the heterogeneity and anisotropy in MACs are associated with spatial (in-plane and through thickness) variations in the dimensions, arrangement, distribution and orientations of building blocks within individual layers resulting in multiple interfaces. The heterogeneity enables spatially defined crack arrest features, where the elasticity tensor is spatially variable unlike traditional composites with *finite size unit cells* (UCs) at scales not sufficiently small compared to the macro-scale, $\ell_{UC} \nless\nless O(L)$ so that they do not lend themselves to classical homogenization schemes that assume scale separation.

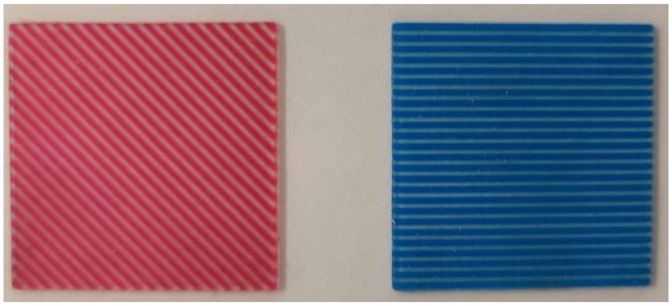


(a) (b) (c)

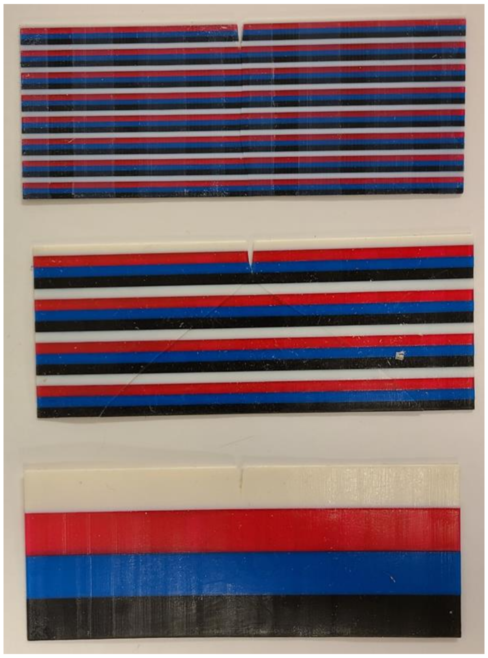
Figure 6. Meso-architectured composites with in-plane variations in fiber orientations (a) idealized unit cell (b) 1D example schematic (c) 2D example schematic

As shown in Figure 7, we explored 3D printing of prototype traditional UD composites and MACs using Vero (stiff material) as fiber and Tango+ (compliant material) as resin. This includes -45° and 0° UD composite (Figure 7(a)), single edge notch tensile 1D layered composite (Figure 7(b)), 2D prototype composites (Figure 7(c)), [+45°/-45°] and [0°/90°] unit cells (Figure 7(d)), and [0° /45°/-45°/90°] unit cell (Figure 7(e)).

Design of optimized meso-scale architectural features requires predictive capabilities in order to accelerate the search process for the vast design space in terms of architecture/processing-property-performance relationships. Future work includes (i) design and characterization of MACs via a data-driven approach and (ii) fabrication and high strain rate characterization of functionally graded foams supporting to advance the development of novel materials for enhanced ballistic performance and to improve the fundamental understanding of impact response of these materials.

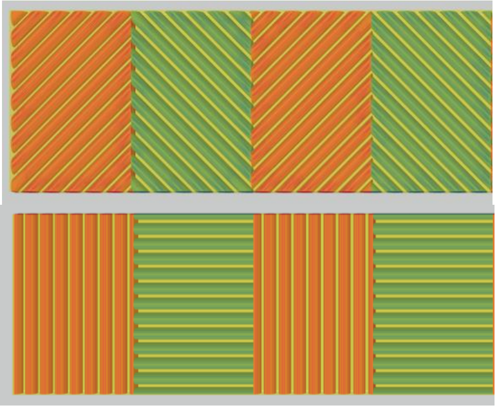


(a) Traditional -45^{o} and 0^{o} UD composite



(b) 1D layered composite

(c) 2D prototype composite



(d) [+45^{o}/-45^{o}] and [0^{o}/90^{o}] unit cell schematic

(e) [0^{o}/45^{o}/-45^{o}/90^{o}] unit cell

Figure 7. Prototype unidirectional and meso-architectured composites

References

[1] Gaynor AT, Meisel NA, Tech V, Hall R. Multiple-Material Topology Optimization of Compliant Mechanisms Created Via PolyJet Three-Dimensional Printing 2014. doi:10.1115/1.4028439.

[2] Stratasys. Stratasys J735 and J750 2019. https://www.stratasys.com/3d-printers/j735-j750.