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14. ABSTRACT

North Carolina A&T State University (NCAT) DURIP project efforts focused on the acquisition, installation, training and initial evaluation, use of the acquired 3D additive manufacturing system for developing hierarchical, tailored material morphology, configurations, and lattice structures for research investigations. The 3D printer system Stratasys PolyJet J750 that was procured and installed is a current top of the line system in the field of 3D print additive manufacturing with multi-material capabilities from rigid to flexible polymers, eight print heads,

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Final Report: Additive Manufacturing 3-D Printer for Hierarchical Material Composition-Morphology-Lattice Structure Developments and Investigations

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North Carolina A&T State University (NCAT) DURIP project efforts focused on the acquisition, installation, training and initial evaluation, use of the acquired 3D additive manufacturing system for developing hierarchical, tailored material morphology, configurations, and lattice structures for research investigations. The 3D printer system Stratasys PolyJet J750 that was procured and installed is a current top of the line system in the field of 3D print additive manufacturing with multi-material capabilities from rigid to flexible polymers, eight print heads, listed layer thickness of 14 microns; ability for voxel level printing; capability for tailoring morphologies with nanomodified material resins with open configuration. J750 capabilities provide NCAT with a unique technology for development of hierarchical, multi-layer materials configurations and complex morphologies meeting our current research education and training, as well as new research directions and initiatives. New fundamental and applied research activities driven by this system is expected to motivate students (attracted by the capability and new technology) and lead them to the relevance, application of computational and mathematical methods that are required for understanding complex material morphologies, associated material behavior and mechanisms of failure and mitigation resulting in future masters thesis, doctoral dissertations, and refereed publications as well as trained work force.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

NCAT Research Excellence Award - Interdisciplinary Team Research Award (PI: Dr. Ram Mohan).

Graduate Students

NAME	PERCENT_SUPPORTED	DISCIPLINE
Ingrid Padilla Espinosa	0	Other (Please Specify) Nanoengineering
Furkan Ulu	0	Other (Please Specify) Nanoengineering
Ravi Pratap Tomar	0	Other (Please Specify) Nanoengineering
Adrian Goodwin	0	Other (Please Specify) Nanoengineering
Smith Woosley	0	Other (Please Specify) Nanoengineering
Taiseer Eldirdiri	0	Other (Please Specify) Nanoengineering
FTE Equivalent:	**0.00**	
Total Number:	**6**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Ram Mohan	0.00	No
Ajit Kelkar	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME	
Taiseer Eldirdiri	
Total Number:	**1**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Steven Crawford	0.00
David Chaplin	0.00
Karen Ryan	0.00
Alex Aboyagye	0.00
FTE Equivalent:	**0.00**
Total Number:	**4**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Discussions on research and technology capability and collaborative use of this DURIP equipment with DOD scientists, university visitors to nanoengineering department, other departments at NCAT, and local industry.

<u>DURIP AWARD W911NF-16-1-0202</u>

FINAL REPORT
April 20, 2016 – April 19, 2017
ARO Award Number: W911NF-16-1-0202
Proposal Number: 68565-MA-RIP

Additive Manufacturing 3-D Printer for Hierarchical Material Composition-Morphology-Lattice Structure Developments and Investigations

Award Institution

North Carolina A&T State University (PI: Prof. Ram Mohan)

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DURIP AWARD W911NF-16-1-0202

Additive Manufacturing 3-D Printer for Hierarchical Material Composition-Morphology-Lattice Structure Developments and Investigations

Ram Mohan
Department of Nanoengineering
Joint School of Nanoscience and Nanoengineering
North Carolina A&T State University

Objective

To acquire and make available research instrumentation for additive manufacturing of hierarchical material composition-morphology-lattice structures to enable research capability and equipment for prototyping and manufacturing hierarchical layered, tailored morphology and material composition structures; procure and provide a functional equipment resource for research on experimental validations and computational modeling investigations of gradient material morphology on failure, damage behavior and protective characteristics - contributing to the research and research-related education in areas of relevance to Department of Defense. DURIP awarded additive manufacturing 3-D printer (Stratasys PolyJet J750) with a listed layered deposition capability of a minimum layer thickness of 14 microns, voxel level material and geometrical feature printing; multi-material (hard, soft), gradient and core lattice structures through effective use and design of removable support material now provides a new capability at North Carolina A&T State University (NCAT), Department of Nanoengineering, Joint School of Nanoscience and Engineering (JSNN).

Approach

Project efforts focused on the acquisition, installation, training and initial evaluation, use of the acquired 3D additive manufacturing system for developing hierarchical, tailored material morphology, configurations, and lattice structures for research investigations. The equipment identified and requested under this award in the proposal is a Stratasys 3D printer that has multi-material capabilities allowing additive manufacturing of hierarchical, graded, tailored material morphology and lattice configurations. Based on Stratasys product line available at the time of DURIP proposal submission, 3D printer Objet® 500 Connex3 versatile 3D production system from Stratasys was proposed to be acquired. After our DURIP award and at time of acquisition, a new series of 3D print system with state of the art capabilities from Stratasys – a PolyJet 750 was available for an educational discounted pricing within the DURIP award funding.

The 3D printer system **Stratasys PolyJet J750** that was procured and installed using DOD DURIP funding is a current top of the line system in the field of 3D print additive manufacturing. It has eight heads, capable of building material layer configurations to a listed resolution of 14 microns. Stratasys J750 is a single complete system with unparalleled 3D printing versatility, wide ranging multi-material capability from rigid to flexible polymeric materials; ability for voxel level printing; capability for tailoring morphologies with nanomodified material resins using an open and unlocked configuration. These capabilities are now providing us and NCAT with a unique technology for developent of hierarchical multi-layer materials configurations and complex morphologies meeting our research education and training in multiple research projects as well as new research directions and initiatives.

The acquired Stratasys J750 3D print system is based on PolyJet jetting print technology with simultaneous eight heads, 1000+ material capabilities that allows additive manufacturing of material textures and gradients; allows single horizontal build layers down to a possible material thickness of 14 microns. Stratasys PolyJet Studio 3D printing software allows capability of build layer material selection; add texture and gradients in material deposition configurations. This along with next generation print heads capable of handling multi-materials increases the speed and quality of 3D print additive manufactured parts. Larger part build size (19.3 x 15.35 x 7.9 inches) along with ability to 3D print material layers to a possible resolution level of 14 microns allows a unique capability for developing hierarchical and graded material configurations. The ability to use two different support materials allows 3D print building of complex composite-morphology and lattice structures with internal voids, intricate and delicate features using a range of hard to soft materials. These capabilities along with voxel and open, unlocked control capability provided in our procured J750 from Stratasys would allow us to apply and control different 3D print parameters (curing, temperature, light intensity, speed, etc.) that are required for successful 3D print and additive manufacturing with nano modified resin material configurations, and investigating robustness of such manufacturing processes.

Unique capabilities of J750 3D print system allow us to create tailored material morphologies for research investigations, and would allow taking the current state of additive manufacturing to the next level. Stratasys has established themselves as a long term player who are supporting and standing behind their products over the years; have been in the field of addtive manufacturing, and among the 3D print technology industry for commercial, medical, research, and educational applications. Stratasys 3D printers have been a key integral part of many additive manufacturing laboratories for research investigations at leading universitiies in US and the world. Our DURIP award has now enabled the availability of such a system in the Department of Nanoengineering at North Carolina A&T State University (NCAT) in their Joint School of Nanoscience and Nanoengineering (JSNN).

State of North Carolina purchasing regulations were followed in the procurement of this printer. Based on unique features and capabilities of Stratasys J750 system, and an identified equipment vendor in our DURIP proposal, a waiver of competion was requested and approved following State of North Carolina purchase regulations by the purchasing department at NCAT. All required purchasing requirements and regulations were followed and are in compliance with this procurement.

Budget/Instrumentation Procured

$350,000 – Details of Configuration of the Stratasys PolyJet J750 system that is procured; images from installation and training are shown in Appendix – A. State of North Carolina purchasing processes and guidelines were employed with this procurement. The instrument was delivered, with installation and training completed in March 2017. The instrument is now housed in the Composite Processing Laboratory space of JSNN, and is available for student and researcher use. All users are granted access after initial training and clearance. JSNN researcher user access policies are also extended to this instrumentation and are followed.

Collaborations and Research Opportunities

Engineering Research and Development Center, Vicksburg, MS
Air Force Research Laboratory, Dayton, OH
Engineering and Technology Department at NCAT
Other Anticipated Collaborations and Research Opportunities: Army Research Laboratory program in Additive Manufacturing and Material Development, NASA, University of Cincinnati, Local Industries

Relevance to Army and Department of Defense

Department of Defense agencies are interested in development and enhancement of high performance materials. Strategies for military engineering of high performance materials are drawn from several directions depending upon the agency needs. Our research interactions and collaborations with Army’s Engineering Research and Development Center (ERDC) indicated that their high performance material development efforts focus on fundamental understanding of material morphology, hierarchy and composition in biological, nature materials that would provide guidance on the material design and development of high performance man-made engineered materials. Unique properties of resisting cracks, better energy dissipation, and transferring of loads across interfaces in fish scales is not due to material composition, but primarily due to their complex hierarchical material morphology at different length scales.

Several core material configurations in conjunction with traditional woven fabric composite face sheets are considered by Navy for providing polymer composite ship structure materials with enhanced blast mitigation characteristics. Our Air Force Research Laboratory (AFRL) research collaboration program investigates use of micro-vascular channels in conventional aerospace composites to provide multi-functional characteristics, as well as metallic nanoparticle modified polymeric resins for improved electrical conductivity. Research of interest to NASA includes Boron nanotube modified polymeric resins for space radiation protection and their characteristics, where a good controlled dispersion of these nanotubes is needed for efficacy.

Material morphology plays a critical role in failure progression and damage mitigation. Traditional engineering approaches for strength in composite material systems are generally based on weight/volume composition of individual material phases. Our research investigations clearly identify an innovative perspective that material morphology plays an important role in their larger engineering scale behavior and are linked to inherent attributes from material chemistry, and micro, meso structural morphology. Our recent investigations on the material chemistry level modeling of cementitious materials (*ARO HBCU Partnership in Research Transition (PIRT) program; Contract Number: W911NF-11-2-0043; Agency: Army Research Office*) has shown such a direct correlation exists even starting from the material genetic level between material chemistry and engineering scale material characteristics. Cement paste at microstructure to engineering scales is a multi-phase material system that consists of hydrated and unhydrated phases at all levels and is shown to have homogenized isotropic material characteristics through detailed computational modeling at the microstructure and engineering scale level. Recent investigations of macro-molecular material chemistry systems of cement paste via molecular dynamics simulations of hydrated and unhydrated cement paste components have shown that while the predictive material characteristics are *anisotropic* for individual material chemistry structures of cement paste, the same predicted material characteristics are *isotropic* in macromolecular system. Clearly, these findings from our present work have shown that there is a correlation between material chemistry and larger scale engineering properties and material behavior. Our recent studies on the shock wave propagation through heterogeneous cement microstructure have shown a dependency upon the microstructural configuration, though the effective, homogenized material characteristic properties were nearly isotropic for different microstructures. This clearly illustrates a correlation of the material deformation behavior to the underlying material morphology at various length scales.

Additive manufacturing technologies such 3-D printing allow flexibility to “control the manufacturing process” down to tens of microns. It also allows bench scale design of material composition-morphology-lattice structure to be prototyped in a short time period unlike traditional (subtractive) manufacturing process, which requires retooling and resetting of dies whenever there is a change in design. The availability of the Stratasys PolyJet J750 additive manufacturing 3D Printer at NCAT is now providing capabilities for graded material layers, complex lattice structure configurations; exploration of voxel level printing and optimal development of nano modified printable materials and process parameters with open and unlocked configuration. Research capabilities now available with this DURIP resource are beneficial and leading to new research directions of relevance to Army, other defense, federal agencies, and garnishing interest of use of unique resource by local industries.

A collaborative agreement with Stratasys is being established with initial pilot use of voxel level printing to allow development of complex multi-material and geometric structures to enable extensive research investigations on the role of material morphology and not just composition. This is of relevance in obtaining superior engineering scale material performance for defense applications, with additive manufacturing providing effective means of manufacturing such multi-material structures and geometrical morphologies. The J750 printer resource will now enable us new research directions such as use of nano modified resin systems with a good control of nano additive distributions deposited in a repeatable manner and consolidated at local level. Current dispersion properties do not allow a good control of the distribution, and problems with agglomeration limit the efficacy of the manufacturing processes that are required to preserve optimal microstructure for tailored superior performance. Multiple head capabilities of DURIP acquired PolyJet J750 system along with voxel printing capabilities, open and unlocked mode will allow tailoring additive manufacturing process with highly localized mixing of nano additives using controlled supply of polymer and nano additive at the time of printing. This is expected to result in good dispersed morphologies and controllable enhanced properties. Multi-scale computational modeling will be used to identify the optimal configurations in these research investigations by understanding the influence regions due to inclusions and size effects, that will be experimentally investigated by developing material configurations obtained using micron level layer deposition capability of PolyJet J750 print system. Further, additive Manufacturing PolyJet J750 system has garnished the interest of several departments within NCAT, other universities for using to prototype custom and tailored material and design features.

Key enabling concepts and underlying principles for use of 3-D printing technology and enabling tools is computational geometric modeling. While 3D printing with single material systems does not pose significant computational geometric model challenges, use of 3D printing requires good understanding and critical thinking skills to define correct CAD models with embedded material features for multi-material 3D printing. For example, while it is relatively easy to print a simple cube with a single material using 3D printing, the same cube with different material regions and morphologies (especially built at voxel level of material deposition) would require skills in geometry development, interfaces and CAD designs to define several voxel level regions that define the same cube with multiple interconnected material geometry regions for correct deposition. Printing hardware of J750 system has capability of mixing multiple material resources at time of printing to create custom material composition; however the geometric region of such material deposition has to be uniquely defined. This provides an excellent educational opportunity for research and education of students on computational geometry and modeling to use the attractiveness of this new technology.

Societal awareness and futuristic technology impact of additive manufacturing and 3-D printing is now well known at a larger level, and is attracting interest of several students. With the new PolyJet J750 printer at NCAT, we notice that this is helping us to attract students (esp. underrepresented minorities) who seem have an overall general apprehension with mathematics and complex geometry concepts. Further mentoring and guidance is bringing them to understand that while simple material prototyping of parts is commonly possible with 3D printing - there is a need for underlying research and robust practices for optimal tailored material-morphology-lattice structure configurations; introducing them to the relevance, application of computational and mathematical methods for such understanding. The desired material composition, graded thickness microstructures, lattice structures with complex geometries, that they are possible to create using the PolyJet J750 3D-printer equipment is anticipated to motivate more students, and lead them to computational and mathematical modeling. We envision capitalizing the novelty of building geometrically complex and multi-material configurations (where many of our students have been seen to show interest) to research-related education of multi-scale computational test beds that consist of molecular dynamics modeling, microstructure level modeling, continuum and engineering scale modeling. The material and morphology complexity of their tailored engineered material systems require large scale modeling configurations, further steering them into the large-scale, high performance computing and data analysis methods in a systematic way. Army and other federal laboratory developed capabilities such as Asymptotic Expansion Homogenization (AEH, Para-AEH - Army Research Laboratory), Discrete Element Method (DEM - Engineering Research and Development Center), LAMMPS (Sandia Labs), academic and other commercial analysis codes based on molecular dynamics, finite element and particle based methods will be employed in these research-related education. The capabilities of PolyJet J750 system for depositing multi-material and complex geometry morphologies is effective for printing material prototypes needed for multi-faceted experimental characterization needed to provide insights into material and morphology of the tailored, man-made engineered materials. Experimental characterization using these complex material prototypes is expected to enable tailored validation for computational modeling developments, and provide deeper insights on the progressive mechanisms of deformation, damage, failure at a high fidelity that is not always possible.

Availability of DURIP acquired additive manufacturing 3-D printer is now providing an urgently needed advanced material composition-morphology-lattice structure prototyping tool at JSNN-NCAT to not only augment other material analytical and microscopic facilities at JSNN, but also train students from the Triad region of the state of North Carolina. The availability of this equipment will considerably benefit fostering new research directions, other current and future projects, while providing an incredible opportunity to educate and train graduate/undergraduate American and under-represented minority students on defense related projects and technologies of relevance to meet future workforce needs for Army and defense laboratories. Research and fundamental understanding of the material performance, behavior and mechanisms enabled through availability of an advanced 3-D printer and other resources has significant impact on the development of high performance material systems.

We are planning to incorporate and introduce PolyJet J750 and additive manufacturing techniques with polymers and nano-additive modified polymers and complex morphologies in process modeling and nano processing courses. These include: NANO 812 Process Modeling in Composites, NANO 811 Nano Processing, NANO 853 Nanomaterials Laboratory, and NANO 731 Nanomodeling and Applications.

Accomplishments for Reporting Period

Procurement: Stratasys PolyJet J750 system was successfully procured after going through University and State of North Carolina purchasing requirements and guidelines. Our DURIP proposal identified and requested (Based on Stratasys product line available at time of DURIP proposal submission in 2015) 3D printer Objet® 500 Connex3 versatile 3D production system to be acquired. After our DURIP award and at time of acquisition, a new series of 3D print system with state of the art capabilities from Stratasys – a PolyJet 750 was found to be available with an educational discounted pricing that was within the DURIP award. As per University and State of North Carolina guidelines, a request with justification for a Waiver of Competition for this purchase was made and approved by the Purchasing department at NCAT. A copy of the purchase agreement for this acquisition is included in the Appendix.

Facilities: After the purchase award to Stratasys, facilities and other requirements in terms of exhaust, clearance, material storage, temperature, venting, ambient conditions; plumbing and drains for cleaning stations were iterated with Stratasys. These followed recommendations for Stratasys J750 and the two cleaning stations to remove support material (needed to make lattice structures that require support material during printing to allow support layers for deposition during 3-D printing), site guidelines for space, power, HVAC, plumbing and drainage connections, noise and vibration, etc., to obtain the optimal location for this equipment at JSNN – NCAT. Based on these extensive exchanges, space and ingress requirements, two different laboratory location options at JSNN – NCAT for PolyJet J750 were studied. Recommendations and guidelines for J750 and two cleaning station locations (Belco Water Jet and CSIIP cleaning station, their plumbing and drainage, easiness of printed part transport from the printer to cleaning stations, etc.), space constraints and separation requirements were extensively analyzed with JSNN facility team. After careful study of various considerations for the equipment location, Stratasys PolyJet J750 system is now placed in the polymer composite processing laboratory space at JSNN – NCAT, with cleaning stations placed in a utility room that is configured with required plumbing and drainage of removed support material. PolyJet J750 location and cleaning stations are at the same floor level and allows for easy transfer of printed parts for cleaning. These locations provide a good foot print and floor space; meet necessary power, venting, and other site requirements for J750 printer and cleaning stations.

Installation and Training: The procured Stratasys PolyJet J750 was delivered in middle of January 2017. Site preparations were completed and installation was scheduled and completed in early March 2017. Installation required complete calibration and acceptance testing of the instrumentation that was assembled and calibrated on site at NCAT. Installation involved J750 system and two cleaning stations required for removal of support material. Stratasys had extensive testing and calibration procedure and all testing and calibration were successfully completed. All initial tests showed compliance well within the factory acceptable limits for this equipment. Hardware and driving software were tested and equipment design limits for deposition and other processing parameters were studied.

Integral part of DURIP enabled Stratasys PolyJet J750 installation was two day user training. This training was made accessible to research students and researchers who were expected to be first users of this equipment. About 7 researchers participated in the training exercises. In addition, few researchers and lab engineer/technician participated in the advanced training by Stratasys on calibration and maintenance of the system, material bin changes; issues and resolution. Segments of key training sessions were videotaped to have this start-up training available for future users. Researchers were also encouraged to bring their own CAD part configurations generated from different sources and were trained independent equipment use. All training and documentation are expected to help greatly with user training and access of the DURIP acquired equipment to larger and future users. Representative pictures from installation, calibration, and training are shown in Appendix A.

In-house 3D Printing and Research and Equipment Use:

Subsequent to the installation and training of Stratasys PolyJet J750 system, research students are using and going through a learning curve. This included developing different CAD geometries with holes to understand the effectiveness of the J750 system to create lattice structures, defining support material regions to create different lattices structures of various dimensions, understand quality and efficacy of support material removal; investigate quality and rate of deposition. Such studies are needed to gain full knowledge of the J750 system capabilities and limitations for complex morphology developments envisioned in research and education and not merely use for prototyping of designs, where 3-D printing is commonly now used in commercial industry.

As noted earlier, additive manufacturing technologies such as 3D printing allow the flexibility to "control and tailor the manufacturing process" down to tens of microns. It also allows bench scale design of material composition-morphology-lattice structure to be prototyped in a short time period unlike traditional (subtractive) manufacturing process, which requires retooling and resetting of dies whenever there is a change in design. The quality and characteristics of micron level layer thicknesses that can be deposited were studied in these initial studies. While additive manufacturing allows layer by layer deposition, interfaces between deposited layers define the quality and integrity of the part. Several initial studies to resolve CAD model issues, high quality mode printing that existed between the software and hardware were conducted. Representative images from layer level deposition of different layer thicknesses are presented next. Initial studies employed standard material systems and new digital materials are being investigated. We envision extensive use of DURIP J750 system for creating multi-material and geometry morphologies, graded material layers; nano modified material usage and controlling morphologies that are required for multi-scale understanding of role of morphologies and customizable manufacturing methods on engineering scale behavior. Currently, preliminary investigations are performed during learning period and are focused on developing a good first hand understanding of the equipment, geometry CAD and setting up requirements.

In-house Micron Level Layer Deposition: Results from in-house micron thickness layer deposition performed in April 2017 are presented. The purpose of this is to understand the smallest material deposition layers practically possible in a single print with our PolyJet system. A multi-layered CAD (computer aided design) 3D model configuration was developed that was configured with 12 material layers. For preliminary study, each deposition layer was configured with the Stratasys stock polymer material with different colors (representing different material layers (hard, soft, etc.) in future studies). Five different layer thicknesses were considered, each set with a deposition layer thickness of 200, 100, 50, 27, and 14 microns. The objective is to study the cross-section of layers formed and their characteristics. Figure 1 shows the 3D model of layered configuration.

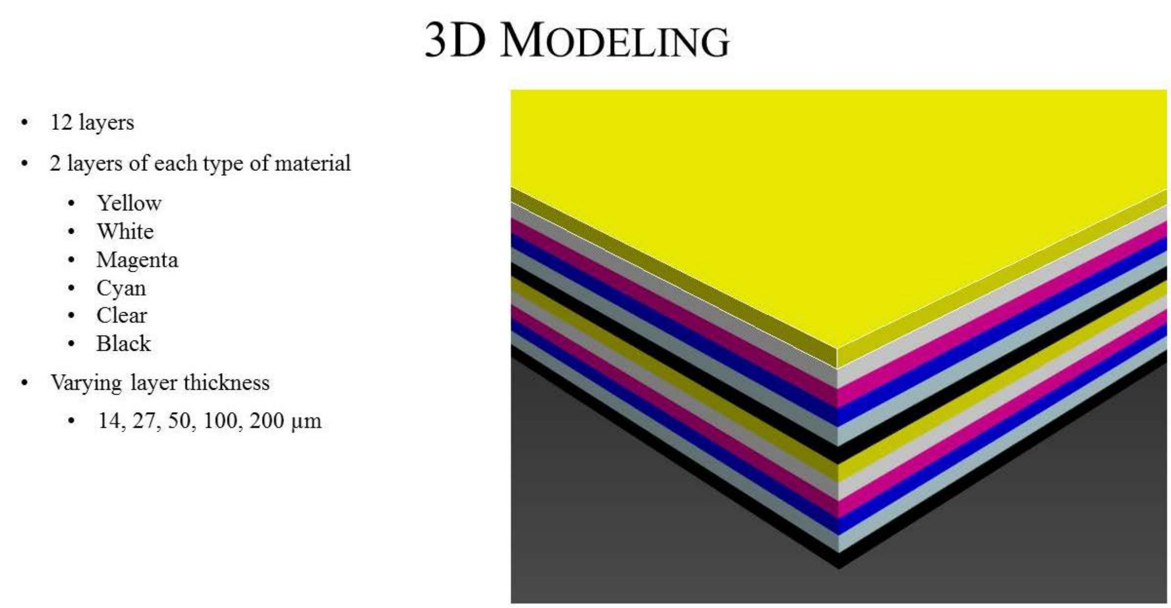

Figure 1: CAD model configuration for layered printing at various micron thicknesses

Figure 2 shows different printed, cleaned and polished 3-D printed specimens for preliminary imaging with Zeiss Axio optical microscope.

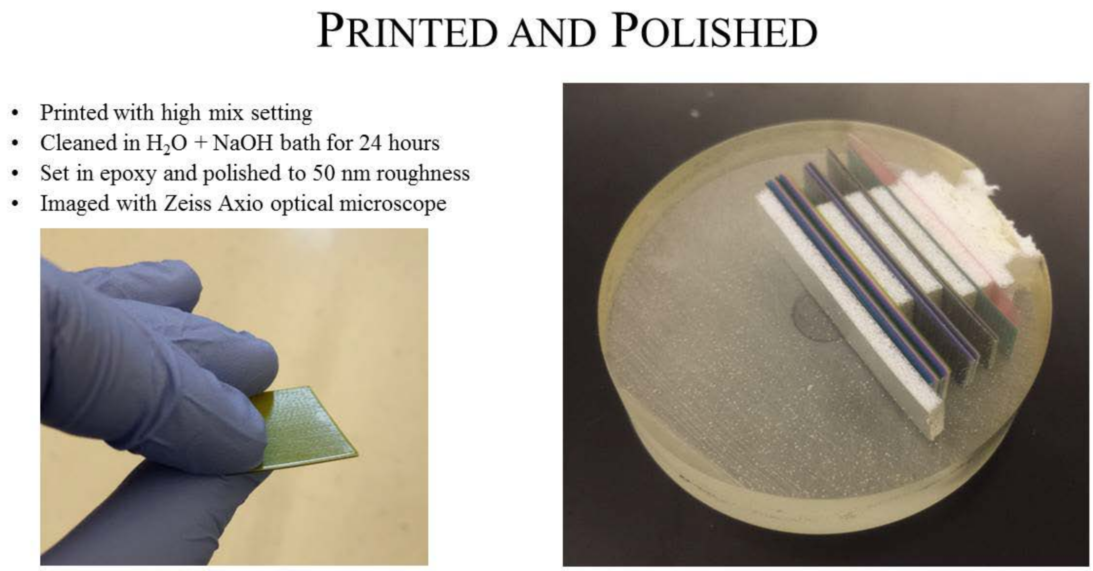

Figure 2: 3-D printed material layers with DURIP PolyJet J750 at NCAT

Figures 3 – 7 show the optical microscopy image of different deposition thickness layers for 200, 100, 50, 27, and 14 microns. Layer thickness of 27 microns is the layer size stated by Stratasys to be the minimum layer thickness that is possible in high mix, faster printing mode using J750.

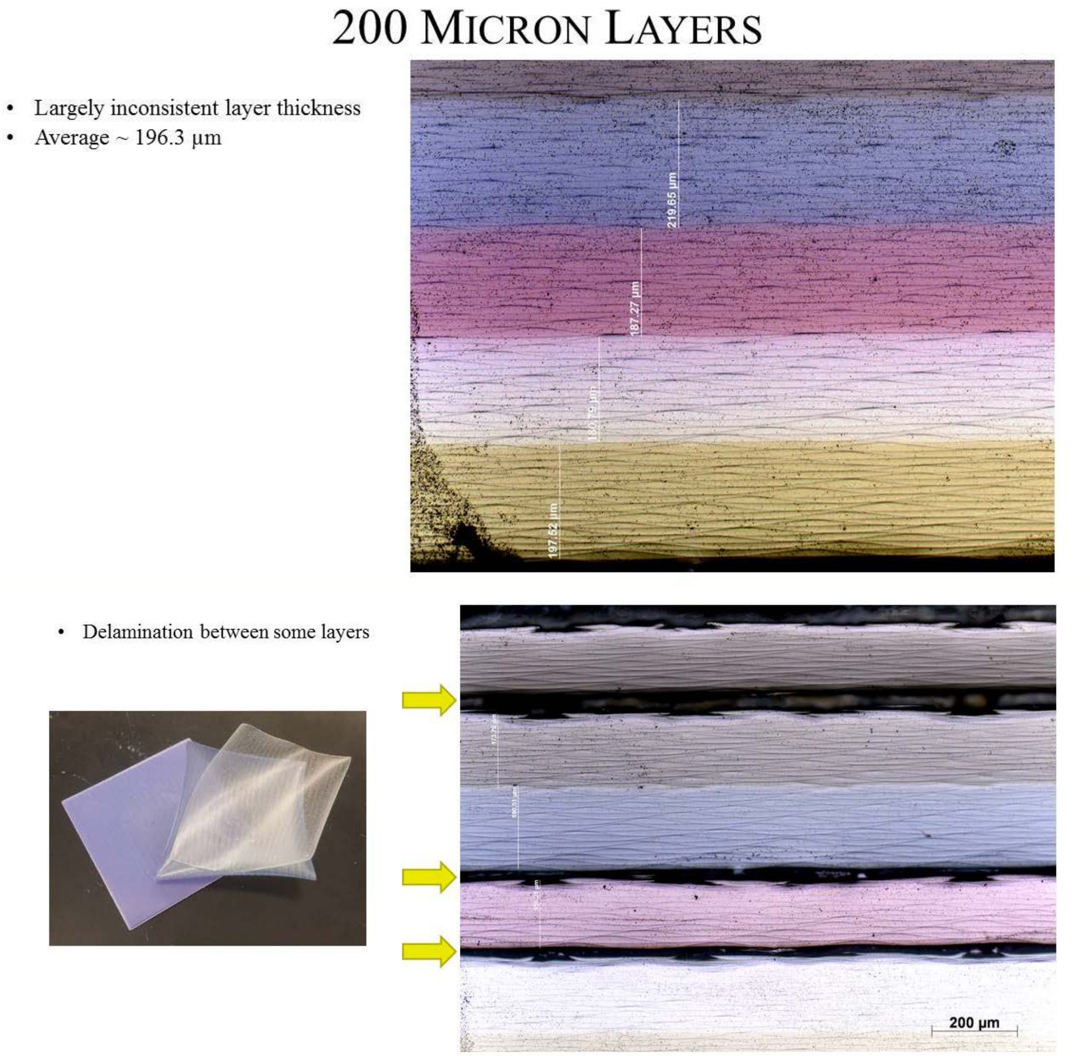

Figure 3: Optical microscopy image of 200 micron layer deposition [Large inconsistency in final thickness of each layer (ranging from 187.27 to 219.65 microns was noticed with an average thickness of 196.3 microns; also delamination between some layers was noticed)).

100 MICRON LAYERS

- Some inconsistency, top layer significantly reduced
- Average (excluding top) ~ 104.88 µm
- Delamination between some layers

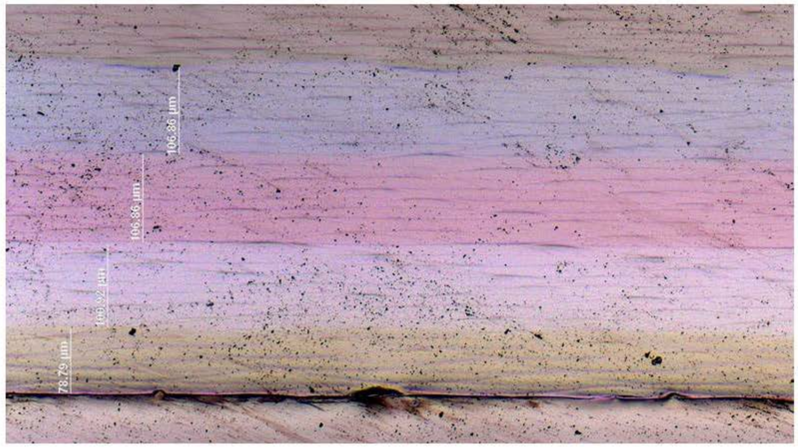

Figure 4: Optical microscopy image of 100 micron layer deposition (Some inconsistency in final thickness of each layer with a smaller top layer deposition; also delamination between some layers were noticed; average thickness not including the top layer is ~104.88 microns).

50 MICRON LAYERS

- More consistent
- Average ~ 50.37 µm
- Delamination between some layers

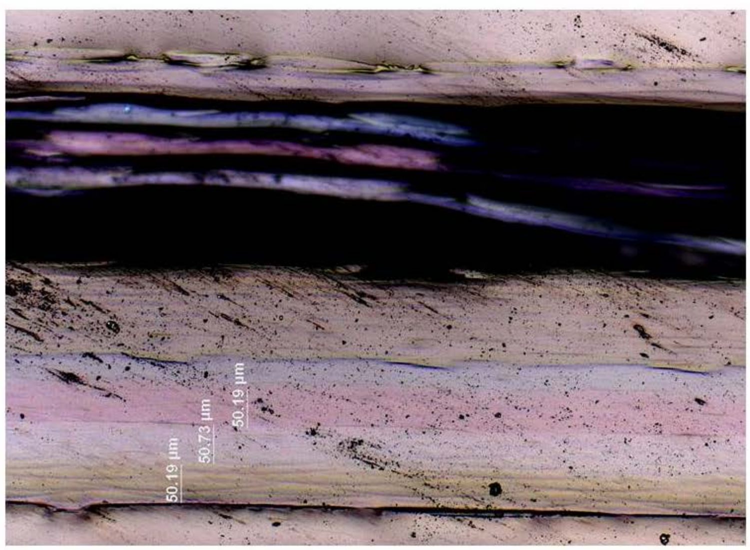

Figure 5: Optical microscopy image of 50 micron layer deposition (consistent thickness of various layers with average layer thickness of 50.37 micron was noted along with delamination between some layers).

27 Micron Layers

- Minimum layer size reported possible by Stratasys for High Mix mode
- Some inconsistency
- Average ~ 25.7 µm

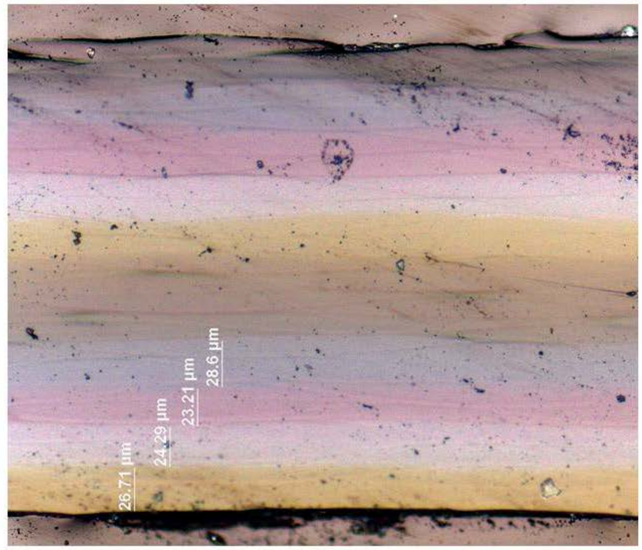

Figure 6: Optical microscopy image of 27 micron layer deposition (Minimum possible deposition layer size reported to be possible by Stratasys in **faster high mix** mode of deposition; some inconsistency in thickness with a reduced average layer thickness of 25.7 microns)

14 Micron Layers

- Minimum layer size reported possible by Stratasys for High Quality mode
- Did not print several layers / materials
- Average ~ 26.5 µm

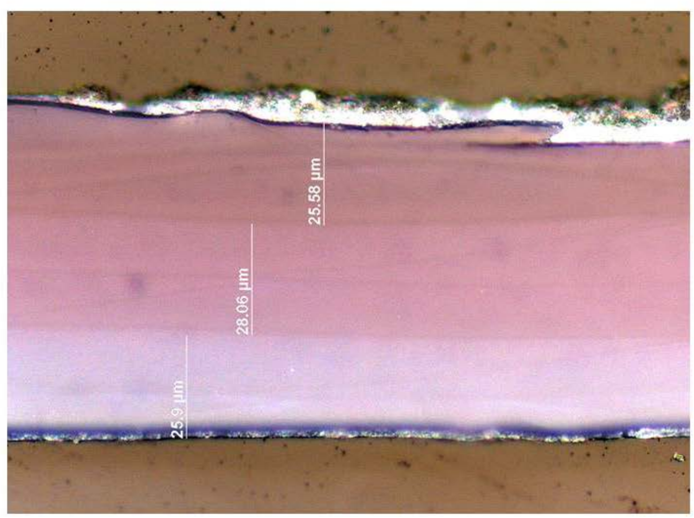

Figure 7: Optical microscopy image of 14 micron layer deposition (Minimum possible deposition layer size reported possible by Stratasys in **high quality** mode of deposition; Had difficulties in printing many layers or materials due to software and hardware interface issues; Deposited layers were found to have a higher average thickness of about 26 microns, higher than 14 micron layer thickness set in CAD)

These preliminary studies indicate:

- ‘High mix mode’ layer thickness resolution of 27 μm reported by Stratasys is accurate, though may vary slightly.
- Need to fix ‘high quality mode’ printing issue to further test reported 14 μm resolution. Software and hardware issues have been subsequently resolved resulting in a lower printed thickness, and better high quality mode of printing.
- PolyJet J750 system will print CAD designs when modeled features are smaller than attainable resolution, but results will not be true to CAD design.
- PolyJet J750 layer thickness is more accurate and consistent when printing discrete, thinner layers (<100 μm).
- Layer delamination is a serious issue and may be caused by soaking parts in NaOH cleaning solution. This is being followed up further.
- Setting printed parts in epoxy and imaging with optical microscope is a useful way to analyze J750 printed material layers.

Further studies on understanding capabilities and resolving the issues for optimal printing with nano material additive resins and tailored local mixing, voxel printing are under investigation.

In summary, availability of the DURIP acquired additive manufacturing 3-D printer is now providing an urgently needed advanced material composition-morphology-lattice structure prototyping tool at JSNN-NCAT to augment other material analytical and microscopic facilities at JSNN, but also train students from the Triad region of the state of North Carolina. The capabilities of PolyJet J750 system for depositing multi-material and complex geometry morphologies is effective for 3-D printing material prototypes for multi-faceted experimental characterization needed to provide insights into material and morphology of tailored, man-made engineered materials; in research education and motivation of students. Experimental characterization using these complex material prototypes are needed for tailored validation of computational modeling developments that provide deeper insights on progressive mechanisms of deformation, damage, failure at a high fidelity that is not always possible with current experiments; and provide excellent opportunities for research education of students transcending materials, manufacturing, multi-scale computational and mathematical modeling and validations.

APPENDIX - A

Quote Number: 59-Q5448 *Vendor: Stratasys, Inc.*

NORTH CAROLINA AGRICULTURAL AND TECHNICAL STATE UNIVERSITY

Refer *ALL* Inquiries regarding this RFQ to: Wendelin Douglas Telephone No. (336) 285-2985 E-Mail: wdouglas@ncat.edu	**Request for Quote # Q5448**
	Quotes will be publicly opened: December 12, 2016
	Contract Type: Open Market
	Commodity No. and Description: 3D additive printer
	Using Agency: Nanoegineering
	Requisition No.: 81367169

EXECUTION

In compliance with this Request for Quote, and subject to all the conditions herein, the undersigned Vendor offers and agrees to furnish and deliver any or all items upon which prices are bid, at the prices set opposite each item within the time specified herein. By executing this quote, the undersigned Vendor certifies that this quote is submitted competitively and without collusion (G.S. 143-54), that none of its officers, directors, or owners of an unincorporated business entity has been convicted of any violations of Chapter 78A of the General Statutes, the Securities Act of 1933, or the Securities Exchange Act of 1934 (G.S. 143-59.2), and that it is not an ineligible Vendor as set forth in G.S. 143-59.1. False certification is a Class I felony. Furthermore by executing this quote, the undersigned certifies to the best of Vendor's knowledge and belief, that it and its principals are not presently debarred, suspended, proposed for debarment, declared ineligible or voluntarily excluded from covered transactions by any Federal or State department or agency. As required by G.S. §143-48.5, the undersigned Vendor certifies that it, and each of its sub-contractors for any Contract awarded as a result of this RFQ, complies with the requirements of Article 2 of Chapter 64 of the NC General Statutes, including the requirement for each employer with more than 25 employees in North Carolina to verify the work authorization of its employees through the federal E-Verify system. G.S. 133-32 and Executive Order 24 (2009) prohibit the offer to, or acceptance by, any State Employee associated with the preparing plans, specifications, estimates for public Contract; or awarding or administering public Contracts; or inspecting or supervising delivery of the public Contract of any gift from anyone with a Contract with the State, or from any person seeking to do business with the State. By execution of any response in this quote, you attest, for your entire organization and its employees or agents, that you are not aware that any such gift has been offered, accepted, or promised by any employees of your organization.

Failure to execute/sign quote prior to submittal shall render quote invalid and it WILL BE REJECTED. Late quotes cannot be accepted.

VENDOR: Stratasys, Inc.			
STREET ADDRESS: 7665 Commerce Way		P.O. BOX:	ZIP: 55344
CITY & STATE & ZIP: Eden Prairie, MN 55344		TELEPHONE NUMBER: 952-937-3000 / 502-263-9630 (Terry Cambron)	TOLL FREE TEL. NO: 1-800-801-6491
PRINCIPAL PLACE OF BUSINESS ADDRESS IF DIFFERENT FROM ABOVE (SEE INSTRUCTIONS TO VENDORS ITEM #11): Same as above			
PRINT NAME & TITLE OF PERSON SIGNING ON BEHALF OF VENDOR: Terry Cambron, Partner Executive - Education		FAX NUMBER: 952-937-0070	
VENDOR'S AUTHORIZED SIGNATURE: [signature]	**DATE:** 05Dec16	E-MAIL: terry.cambron@stratasys.com	

Offer valid for at least 60 days from date of quote opening, unless otherwise stated here: 60 days. After this time, any withdrawal of offer shall be made in writing, effective upon receipt by the agency issuing this RFQ.

FOR STATE USE ONLY: Offer accepted and Contract awarded this 16th day of December, 2016, as indicated on the attached certification, by Montrique "Nikki" Williams Director of Procurement Services (Authorized Representative of North Carolina A&T State University

ACCEPTANCE OF QUOTE

If any or all parts of this quote are accepted by the State of North Carolina, an authorized representative of North Carolina A&T State University shall affix his/her signature hereto and this document and all provisions of this Request for Quote along with the Vendor response and the written results of any negotiations shall then constitute the written agreement between the parties. A copy of this acceptance will be forwarded to the successful Vendor(s).

1.0 PURPOSE AND BACKGROUND

The University is seeking a 3D additive manufacturing printer system.

2.0 GENERAL INFORMATION

2.1 REQUEST FOR QUOTE DOCUMENT

The RFQ is comprised of the base RFQ document, any attachments, and any addenda released before Contract award. All attachments and addenda released for this RFQ in advance of any Contract award are incorporated herein by reference. Vendor may attach its quote to this RFQ for submission; however, any and all additional, modified or conflicting terms and conditions submitted on or with Vendor's quote shall be disregarded and shall not be considered a part of any contract arising from this RFQ. Any attempt to delete or avoid the force of the previous sentence shall render Vendor's quote invalid, and it shall not be considered.

2.2 E-PROCUREMENT SOLICITATION

This is NOT an e-procurement solicitation. Paragraph #17 of Attachment E: North Carolina General Contract Terms and Conditions, paragraphs (b) and (c), do not apply to this solicitation.

2.3 MAILING INSTRUCTIONS

- **Instructions**: Quotes, subject to the conditions made a part hereof and the receipt requirements described below, shall be received at the address indicated in the table below, for furnishing and delivering those items as described herein.

MAILING ADDRESS FOR DELIVERY OF QUOTE VIA U.S. POSTAL SERVICE	OFFICE ADDRESS FOR DELIVERY BY ANY OTHER MEANS, SPECIAL DELIVERY, OVERNIGHT DELIVERY, OR BY ANY OTHER CARRIER
QUOTE NUMBER: Q5448 Attn: Wendelin Douglas Address: North Carolina A&T State University Purchasing 1601 E Market Street Greensboro, North Carolina 27411	*QUOTE NUMBER: Q5448* Attn: Wendelin Douglas Address: North Carolina A&T State University Purchasing 1601 E Market Street Greensboro, North Carolina 27411

Quotes may be submitted via facsimile (FAX) machine or by electronic means, including but not limited to e-mail, in response to this Request for Quote: wdouglas@ncat.edu or (336) 334-7013 Submission by any means shall include this RFQ, as provided in section 2.4

Installation, Calibration, and Training

Installation, Calibration, and Training

stratasys

7665 Commerce Way
Eden Prairie, MN 55344
1.800.801.6491
URL: http://www.stratasys.com

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Invoice Date	30-DEC-16
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BILL TO:

64209
NC A&T State University
Accounts Payable
PO Box 20223
Greensboro, NC, 27420-0223
United States

SHIP TO:

NC A&T State University
1004 Alma Morrow Cir
Fort IRC
General Delivery
Greensboro, NC, 27411-9999
United States

Order	Ship From Org	Purchase Order	Currency	Terms	Due Date	Internal ID
1136751	Stratasys US OU	P0071206	USD	Net 30 Days	29-JAN-17	8412358

Ln	Part Number Description	Country of Origin	Qty Ordered	Qty Shipped	Serial/ Lot (Exp. Date)	U/M	Unit Price	Extended Price
1	OBJ-01342 CSIIP 60 L CLEAN STATION 90-120V	United States	1	1	11606100919A	EA	USD 9,400.00	9,400.00
2	EDU-00054 STRATASYS J750 PRINTER 1 YR EDUCATION PACKAGE	Israel	1	1		EA	USD 324,928.00	324,928.00
2	OBJ-08500 STRATASYS J750 PRINTER	Israel	1	1	8500218	EA		0.00
3	CMP-00019 DELL HOST COMPUTER	United States	1	1		EA	USD 3,500.00	3,500.00
3	OBJ-08503 INSTALLATION AND TRAINING, STRATASYS J750	Israel	1	1		EA		0.00
3	OBJ-TR500 ADVANCED 3D PRINTING APPLICATIONS SEMINAR FOR ACADEMIA	Israel	1	1		EA		0.00
3	RESIN_CREDIT RESIN CREDIT PROGRAM: 14000 USD		1	1		EA		0.00
4	CMP-00104 UPS, Eaton PW9130 L2000T-XL (1800W, 120V)	United States	1	1	GK204A0115	EA	USD 1,425.00	1,425.00
5	OBJ-03200 PACK OF 1, SUP705, RESIN SUPPORT, 3.6KG	Israel	4	4	14305-03200 (15-DEC-17)	EA	USD 234.00	936.00
6	OBJ-03286 PACK OF 1 RGD875, VERO BLACK PLUS, 3.6KG	Israel	1	1	14344-03286 (15-SEP-18)	EA	USD 506.00	506.00
7	OBJ-03271 PACK OF 1 RGD810, VEROCLEAR, 3.6KG	Israel	1	1	14279-03271 (15-SEP-18)	EA	USD 599.00	599.00
8	OBJ-03325 PACK OF 1 RGD843, VERO CYAN, 3.6 KG	Israel	1	1	14011-03325 (15-DEC-17)	EA	USD 531.00	531.00
9	OBJ-03327 PACK OF 1 RGD837, VERO PUREWHITE, 3.6KG	Israel	1	1	13854-03327 (15-NOV-17)	EA	USD 521.00	521.00
10	OBJ-03299 PACK OF 1 OBJET RGD851, VERO MAGENTA, 3.6KG	Israel	1	1	14284-03299 (15-MAR-18)	EA	USD 531.00	531.00
11	OBJ-03302 PACK OF 1 OBJET RGD836, VERO YELLOW 3.6KG	Israel	1	1	14167-03302 (15-FEB-18)	EA	USD 531.00	531.00

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Eden Prairie, MN 55344
1.800.801.6491
URL: http://www.stratasys.com

Invoice	
Invoice Number	1150094
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Ln	Part Number Description	Country of Origin	Qty Ordered	Qty Shipped	Serial/ Lot (Exp. Date)	U/M	Unit Price	Extended Price
12	OBJ-03326 PACK OF 1 SUP706, 3.6KG	Israel	4	4	14166-03326 (15-FEB-18)	EA	USD 253.00	1,012.00
13	MSC-08004-S PRINT HEAD	Israel	1	1	11610L0016	EA		0.00
14	FREIGHT Freight Item for Shipping		1	1		EA		00.00
15	OBJ-03301 PACK OF 1 OBJET RGD851, VERO MAGENTA, 1.44KG	Israel	1	1	13765-03301 (15-OCT-17)	EA		0.00
16	OBJ-03333 PACK OF 1 RGD837, VEROPUREWHITE 1.44KG	Israel	1	1	13407-03333 (15-JUN-17)	EA		0.00
17	OBJ-03334 PACK OF 1 RGD843, VEROCYAN 1.44KG	Israel	1	1	13410-03334 (15-JUN-17)	EA		0.00
18	OBJ-03304 PACK OF 1 OBJET RGD836, VERO YELLOW, 1.44KG	Israel	1	1	13750-03304 (15-OCT-17)	EA		0.00
19	OBJ-03286 PACK OF 1 RGD875, VERO BLACK PLUS, 3.6KG	Israel	1	1	14344-03286 (15-SEP-18)	EA		0.00
20	OBJ-03260 PACK OF 1 FLX930, TANGOPLUS, 1.44KG	Israel	1	1	14170-03260 (15-FEB-18)	EA		0.00
21	OBJ-03006 WATER JET, 500 (110V USA), BALCO	United Kingdom	1	1	2331L	EA	USD 5,580.00	5,580.00

Total Price	350,000.00
Sales Tax	0.00
Sub Total	350,000.00
Prepaid Amount	
Total	350,000.00

email address acctpay@ncat.edu

Payment Schedule:

Amount	Due Date
350,000.00 USD	29-JAN-17

Delivery Data:

Delivery Number	Shipping Date	Shipping Method	Freight/Inco Terms
4653861	30-DEC-16	Expeditors-LTL	Prepay & Add

REMIT TO:
Please send remittance details to accounts.receivable@stratasys.com if payment is:

1. ACH and you are unable to send information via CTX,

stratasys

7665 Commerce Way
Eden Prairie, MN 55344
1.800.801.6491
URL: http://www.stratasys.com

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2. Wire Transfer,
3. Credit Card – (Stratasys, Inc. Accepts Visa, Master Card and American Express).

Payment by Check:	USD Payment by Wire:	EURO Payments:	USD Payment by ACH:
Stratasys, Inc 28043 Network Place Chicago, IL 60673-1280	JP Morgan Chase Bank Routing: 021000021 Acct: 601551695 USD Swift Code: CHASUS33	JP Morgan Chase Bank IBAN: GB02CHAS60924241287679 Swift Code: CHASGB2L Account: 41287679	JP Morgan Chase Bank Routing: 124001545 Acct: 601551695