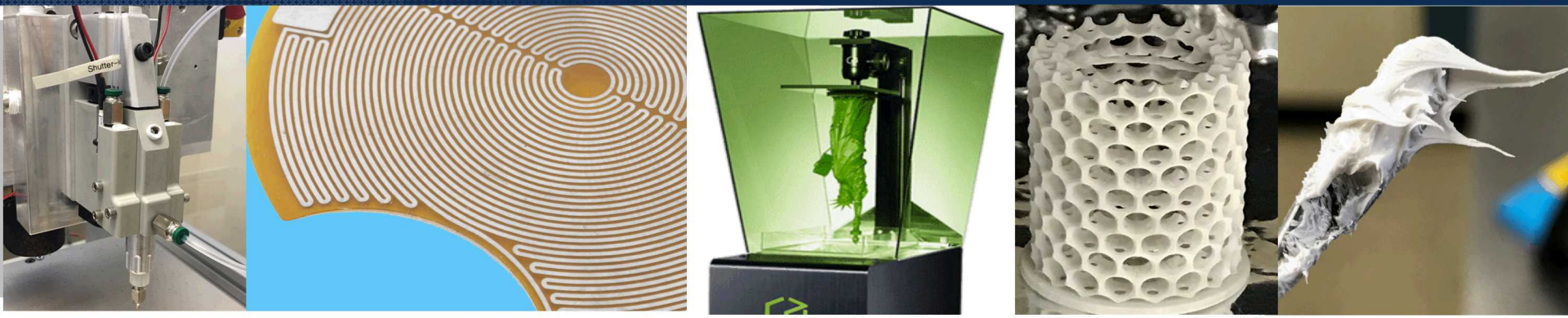
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-4230C



DIRECT WRITE AND 3D PRINTING OF CERAMICS: APPROACHES, MATERIALS AND APPLICATIONS

28th Annual International *Solid Freeform Fabrication Symposium*, Austin Texas

Judi Lavin, David Keicher*, Seethambal Mani, Lok-Kun Tsui, Erin Maines, Matthew Roach, Lindsey Evans.

*Integrated Deposition Solutions Inc.

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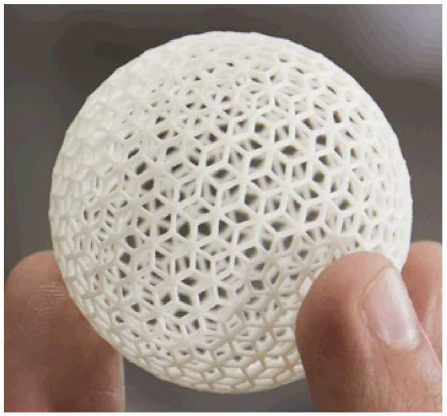
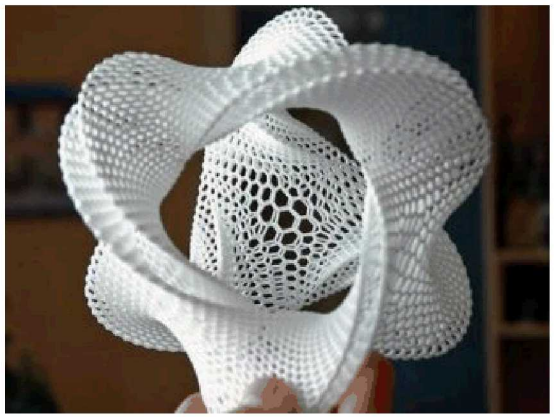
Outline

- Additive Manufacturing and Direct Write in the Printing of Ceramics: Bigger Picture
- Ceramic Printing for Wider Applicability at SNL
- Approaches
  - Aerosol based printing - Nanojet
  - Stereolithographic Printing – Formlab 2; Kudo Titan 2; Custom DLP
  - Extrusion Based printing – Hyrel
- Materials:
  - How materials dictate approach
  - Variables and their effects
  - Properties
- Applications

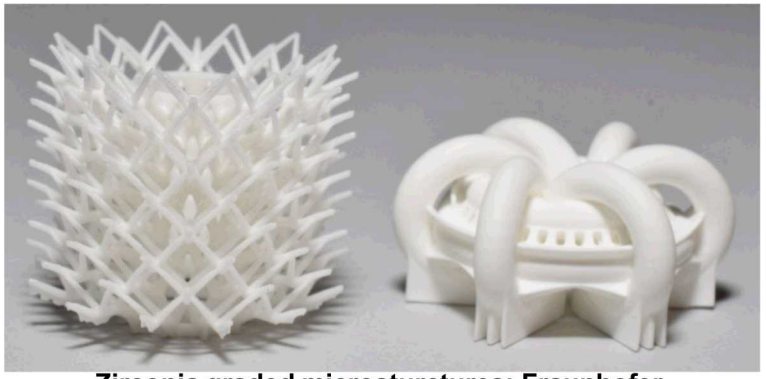
AM of Ceramics and Multi-Material Printing: Bigger Picture

- Ease and rapid fabrication of complex parts
- Tailorable material composition and properties
- Lower cost

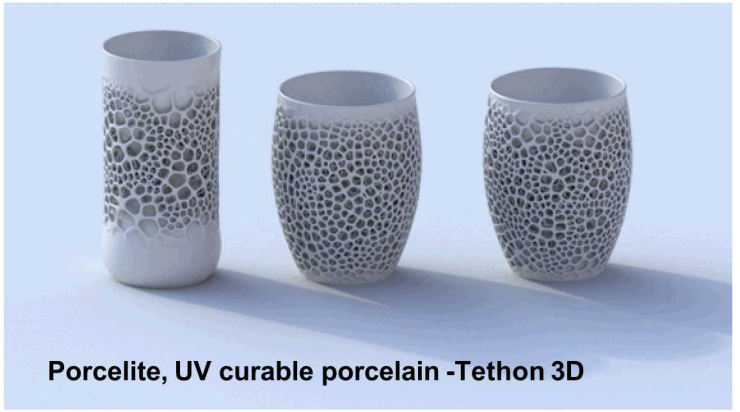




Lithoz - metals, ceramics and polymers at different length scales (nm-cm)



Zirconia graded microsturctures: Fraunhofer Institute for Ceramic Technologies and Systems



Porcelite, UV curable porcelain -Tethon 3D

Why AM and Ceramics Combined?

- *Additive Manufacturing* enables construction of highly complex objects close to their final near-net-shape
  - No need to develop specific tools
  - Much more versatile form of producing parts
- Detailed and intricate parts can be printed (curves/sharp transitions)
- Rapid prototyping of designs and circuits
- Small volume production and throughput
- Customization; adaptability; rapid and cost effective material/designs experimentation
- Miniaturization - integration of passive components directly into IC package

- *Ceramics* offer superior material properties including, high corrosive resistance, high wear resistance, low density, high hardness, excellent biocompatibility, high temperature resistance and low thermal expansion

Combining ceramics with AM leads to production of high quality parts with all of the advantages associated with AM

Ceramic Printing at SNL

Sandia National Laboratories

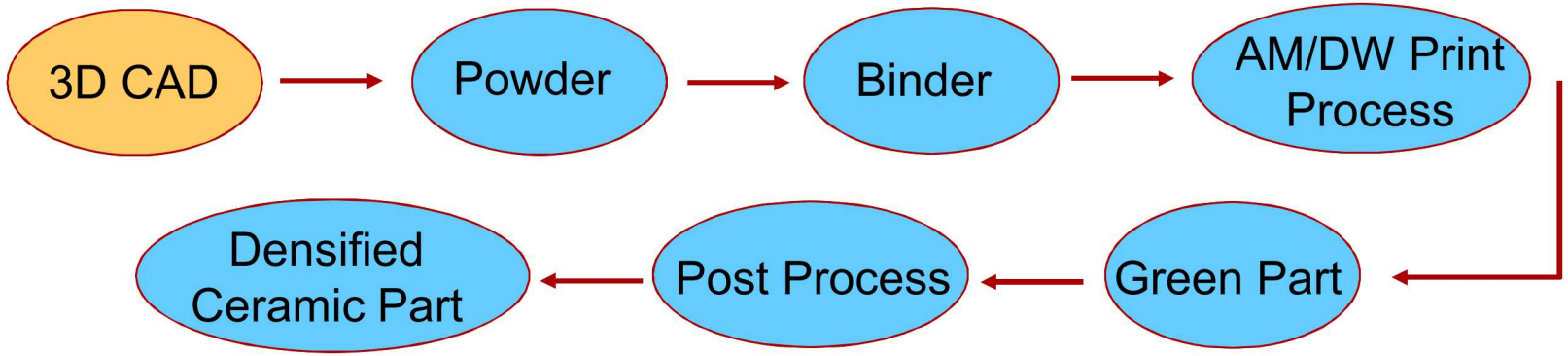
Areas of Interest

- Microsystems integration packaging/Printed circuit boards/Embedded electronic components
- Densified & Heterogenous integration components
- Chris D'Antonio and Adam Cook: ceramic formulation and thermoplastic printing

Our Approach

- Expansive toolbox of systems and materials to meet labs and customers needs
- Modifying commercial systems; formulate and compound new materials
- Understand and explore material & print requirements for a range of ceramics and identifying print capabilities/limitations of the systems

Ceramic AM Process Chain



Ceramic Additive Manufacturing 3D Systems

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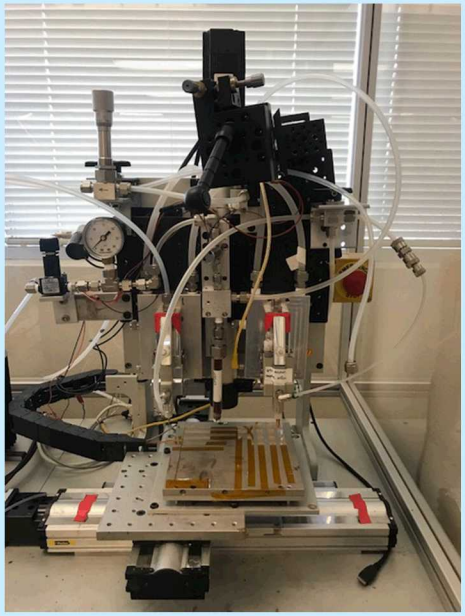
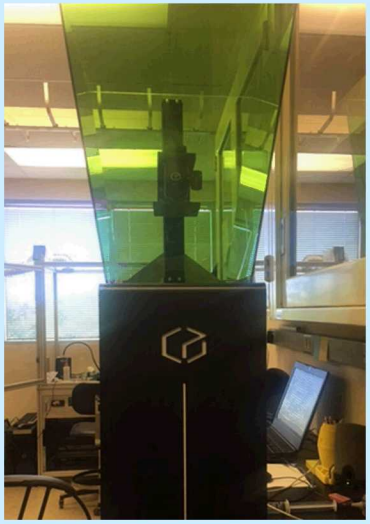
Multi-Material Direct Write Printer

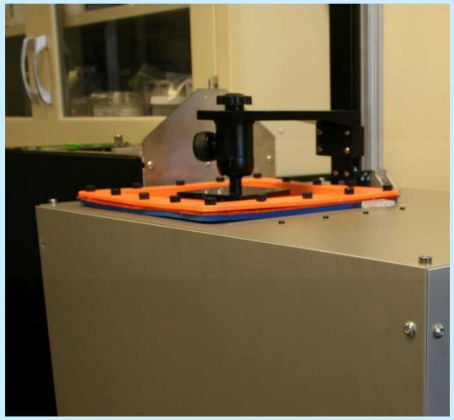


SLA Printers



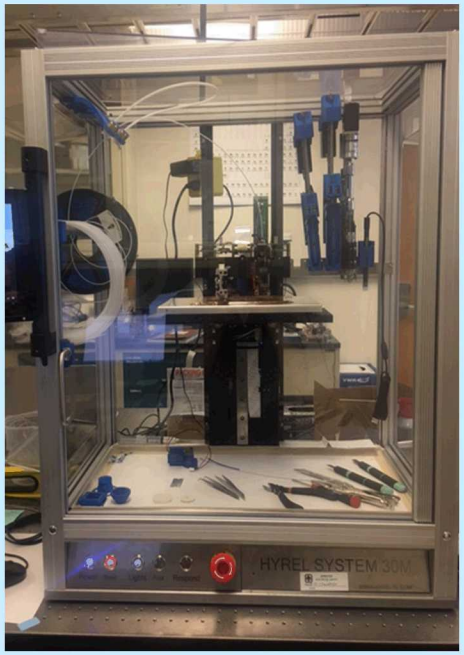
Kudo3D

Formlab 2



Custom Built DLP

Hyrel 30M



Nanojet – Multimaterial Direct Write Printer

SYSTEM

- Aerodynamic transportation of aerosol droplets
- Ink is in direct contact with atomizer/transducer
- Two aerodynamic lenses for focusing of droplets
  - Lends to highly stable deposition process
- Print speeds of approximately 5 to 50 mm/sec
- Interchangeable ink cartridge

SPECIFICATIONS

- Suitable for printing of low viscosity ceramics (up to 50 cPs)
- Films or discrete lines - very fine detail; low volume
- Droplet size: 0.5-3 microns
- Line width: 25-200 microns
- Height on single pass: ~ 3 microns
- Multimaterial printing: ceramics, inks, polymers

Nanojet – Materials & Prints

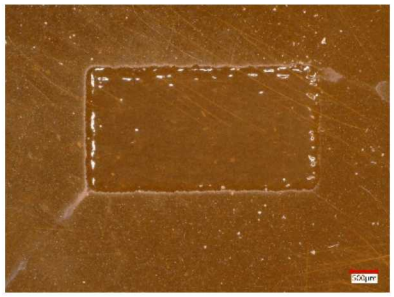
Materials require very low viscosity (< 50cPS)

Materials for NJ print:

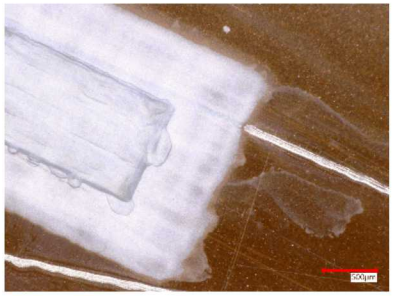
- Ceramics
- Conductive Inks (Gold, Silver, Copper)
- Polymers
- Magnetic materials

Custom formulations:

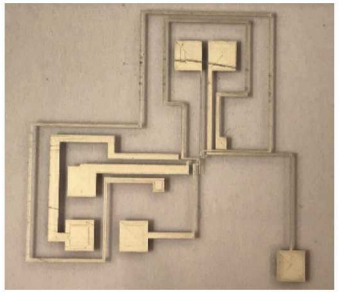
- UTDots
- Intrinsiq
- Sun Chemcials
- SNL



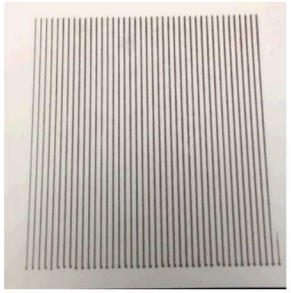
Alumina 25wt% in EtOH



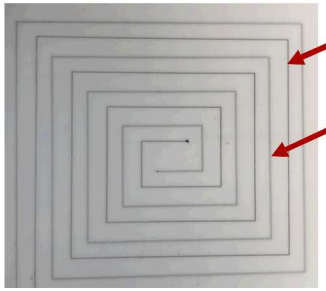
Cured Alumina



Gold on glass

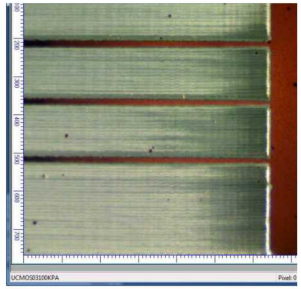


Silver lines on alumina



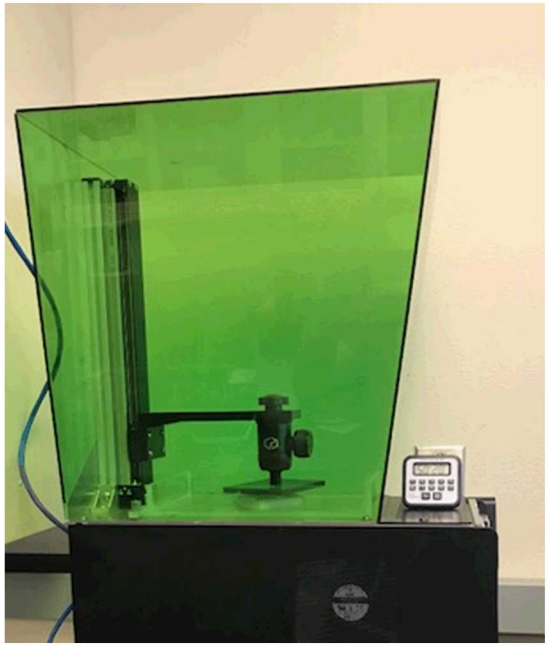
Gold & silver on alumina
30 & 50 micron lines

Silver serpentine
on alumina crucible



Silver on Kapton

DLP 3D Printer - Kudo



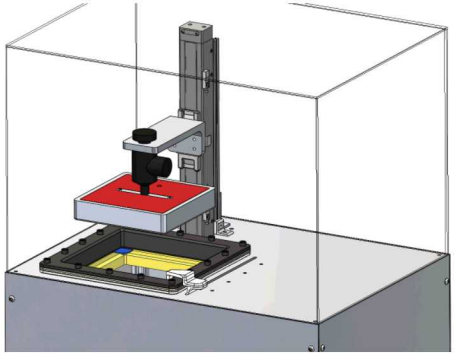
SYSTEM

- Resin based stereolithographic printer
- Parts built off of a base plate submerged in ceramic loaded resin enclosed in transparent bath
- UV digital light projector exposes each layer using continuous layer mask
- Stepper motor moves upwards to built layer-by-layer from bottom up and upside down

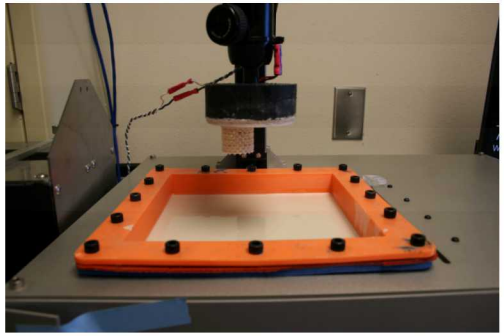
SPECIFICATIONS

- Photocurable resins loaded with ceramics; viscosities up to 3000 cPs
- Resolution range: 38 ~ 75μm
- Layer thickness: 25-50 μm
- Demonstrate feasibility using commercial hardware
  - ➢ Enhanced printing: replaced the digital light projector with industrial high powered light engine

Custom Digital Light Projector

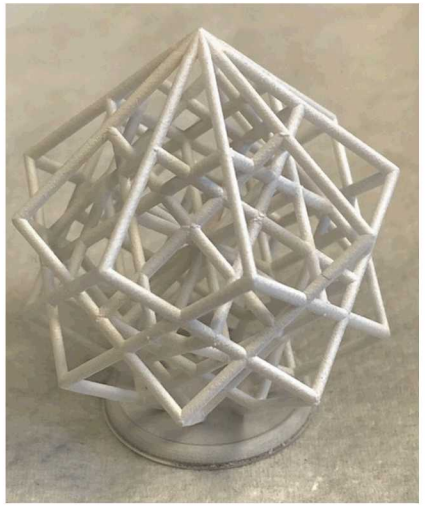


3D Solidworks Drawing



Serial #1 Prototype

- UV backlit build plate
  - Promotes adhesion
- Stretched film resin tray
  - Controlled release of build from resin tray
- Glass support plate
  - Levels the stretched film surface facilitating successful builds
- Wiper Bar
  - Ensures a clean surface on build area and prevention settling of material



DLP – Materials & Prints

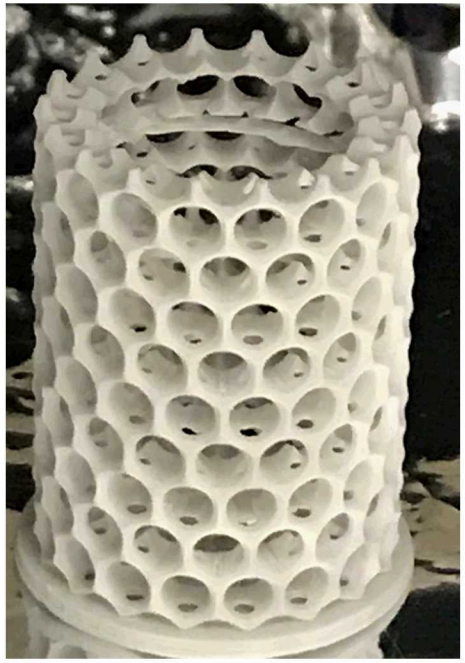
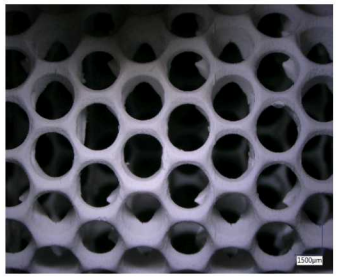
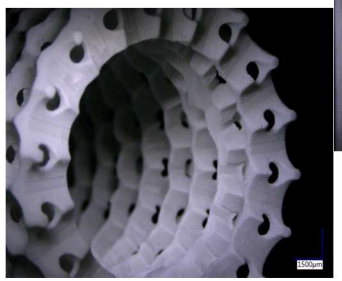
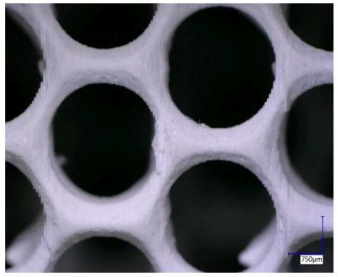
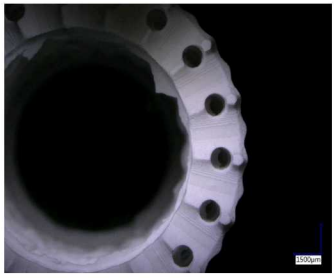
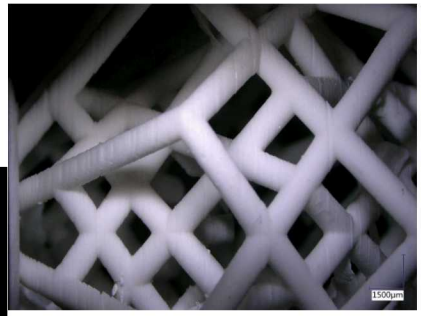
Material Requirements:

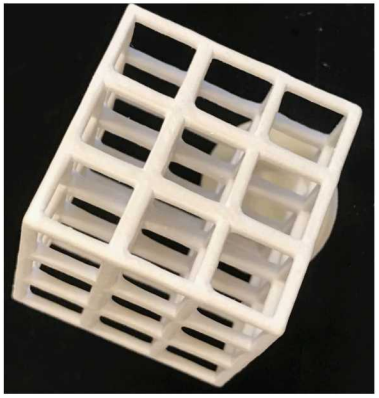
- Viscosities up to 3000 cPs
- Particle size: 0.5 - 4 microns
- Manipulate UV resins by loading with
  - Alumina
  - Silicon Carbide
  - Metal powders
- Concentration >50 vol% of ceramic to achieve clean burnout of resins

Binder Vehicles:

- Colorado Photopolymer Solutions (CPS)
- Genesis
- Tethon
- Solarez

Modifications of commercial materials to meet our needs

Hyrel 3D Printer

Sandia National Laboratories

SYSTEM

- Extrusion printing of ceramic loaded pastes
  - Thermal and photocurable polymers
- Paste are loaded in disposable syringes, extruded using motion controlled stepping motor in z-axis
- Interchangeable mounting system – multiple compatible heads
- Installed load cell to monitor applied force
- Print speeds up to 2000 mm/min

SPECIFICATIONS

- Print viscosities from 10,000- 1million cPs
- Carrier material – photocurable or thermo-curable
- Material properties change based on ceramic loading
- Minimum line width - 500 microns

Higher loading of ceramics

Higher density parts

Hyrel Materials and Parts

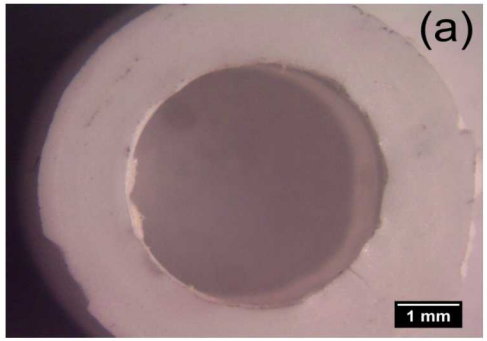
High viscosity materials (10,000-1 million cPS)

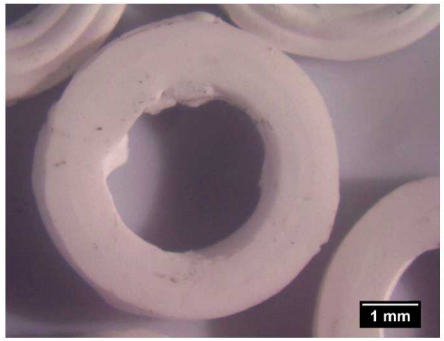
Materials for extrusion printing:

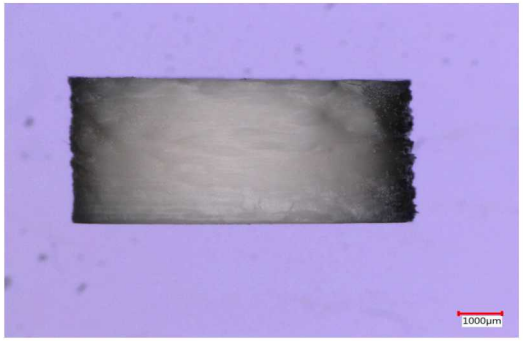
- Photocurable pastes
- Thermally cured pastes
- Particle size: 0.5 - 4 microns
- Full density of sintered parts

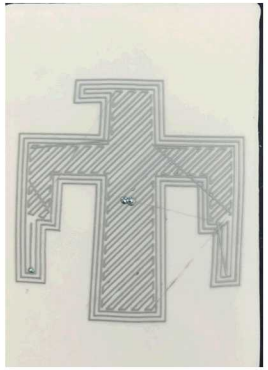
Custom formulations:

- Colorado Photopolymer Solutions (CPS)
- Genesis
- Creative Materials
- SNL









Features and Variables Associated with Multimaterial Printing

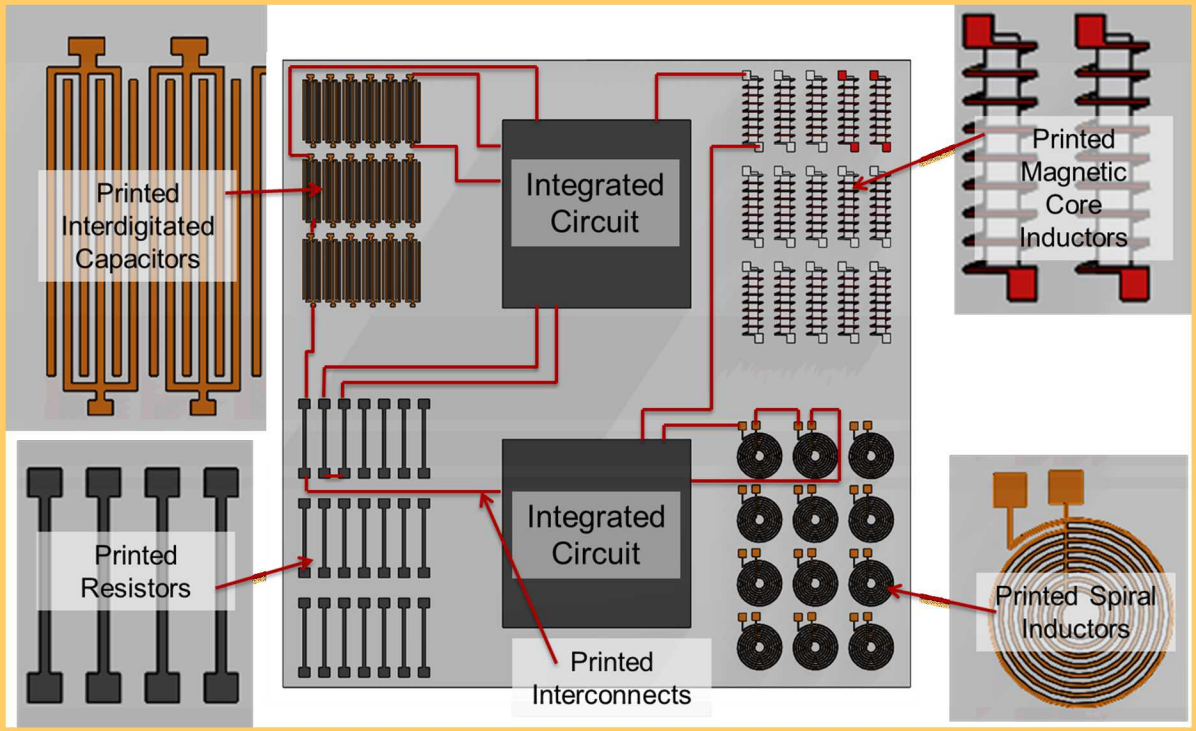
Sandia National Laboratories

	Aerosol Nanojet System	SLA Kudo; Formlab; Custom	Extrusion Hyrel 3D
System			
Differences	• Low viscosity (up to 50 cPs) • Very fine features (25 microns)	• Viscosities up to 3000 cPs • Fine features (150 microns)	• High viscosity (<1 million CPS) • Coarse features (500 microns)
Variables	Materials • Viscosity • Particle size • Loadings	Process • Print method • Tip diameter • Speed	Printed Part • Feature size • Feature definition • Density	Printed Part • Dimensional tolerances • Shrinkage • Electrical properties
Material Properties	• Precursor: Ethanol loaded 20vol% nanoparticle alumina • Precursor viscosity: 30 cPs • Relative print speed: 1X • Avg. full theoretical density: not measured • Shrinkage: none detected/measured • Cracking: not evidenced by microscopy	• Precursor: Genesis loaded 50vol% alumina (2 micron) • Precursor viscosity: 1,500 cPs • Relative print speed: 10X • Avg. full theoretical density: 59.5% (+/-0.97%) • Shrinkage: 58.5% decreased volume • Cracking: not evidenced by microscopy	• Precursor: Genesis loaded 71.5wt% alumina (2 mcron) • Precursor viscosity: 500,000 cPs • Relative print speed: 100X • Avg. full theoretical density: 85.6% (+/-1.59%) • Shrinkage: 43% decreased volume • Cracking: not evidenced by microscopy

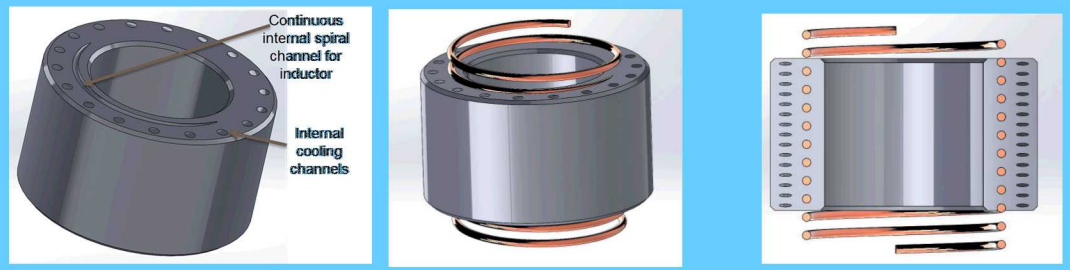
Adapt materials for printing on commercial off the shelf tools

Multimaterial Printing and Parts

Vision: Printed Ceramic Packages & Complex Parts

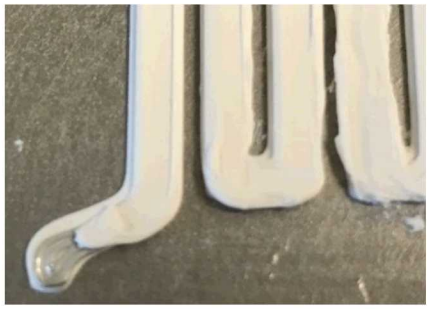


Printed Passives on Ceramic Package

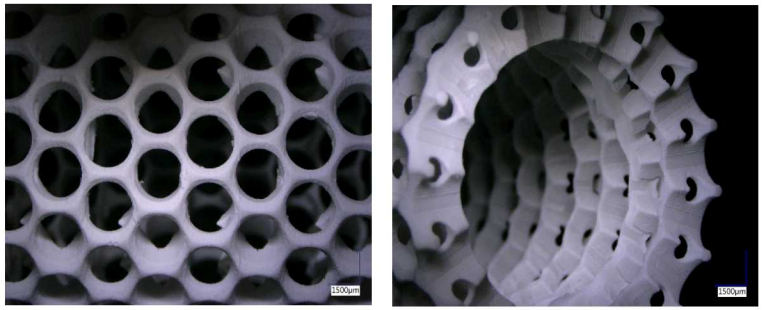


Cooling paths and induction coil embedded in printed part

Working Towards Our Multi-Material Vision

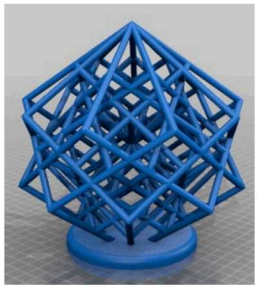


Embedded silver in ceramic

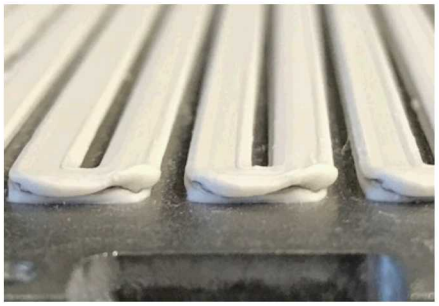


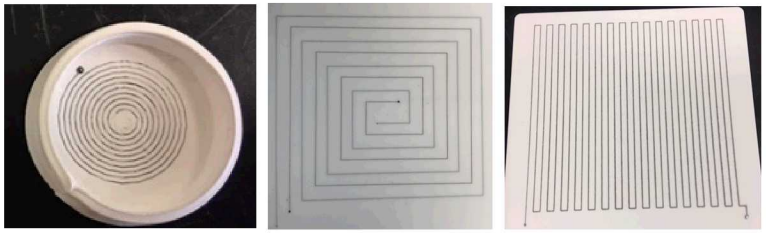
Alumina loaded photocurable resins

Silicon carbide loaded resin

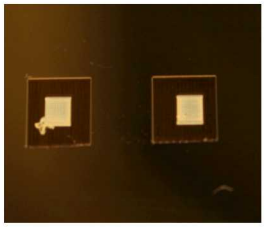


ABS printed using DLP



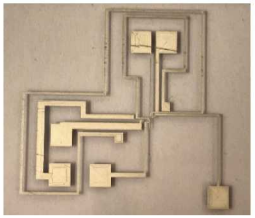


NJ silver & gold ink deposition on alumina

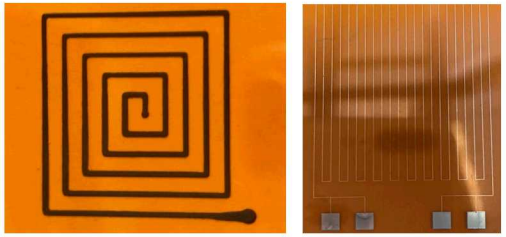


Silver & gold on polyimide: capacitors

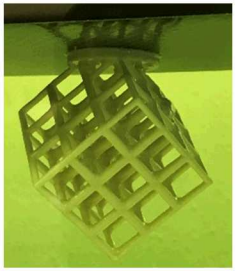
Extrusion print of alumina



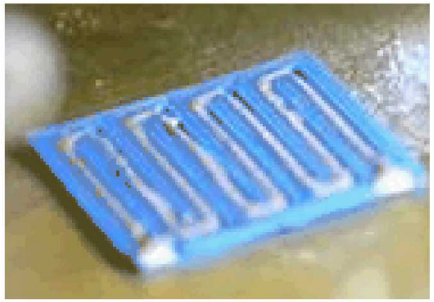
Gold on glass



Copper & silver on Kapton



Alumina loaded slurry



ABS-embedded conductive paste

Acknowledgements

Richard Adcock
Chase Stevens
Ethan Secor
Shawn Whetten
Seth Johannes
Zach Beller
La Rico Treadwell

THANK YOU!

Funding: Sandia National Laboratories LDRD Office

- SLA printer using laser as the UV light source to print high resolution ceramic parts using a UV resin loaded with ceramic material
- Commercially available ceramic resin is silica based
- Custom formulation using alumina loaded resins
- Almatis A15 and A16 with KD1 dispersant in CPS photopolymers.
- Loaded A15 to 65.1 vol%
- Loaded A16 to 55 vol%
- Final part shrinkage 34%+-5%
- Final density 90% +-1.4%