TRUE POLYMER-BASED ADDITIVE MANUFACTURE: CARBON’S TECHNOLOGY AT 5 YEARS

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CARBON is transforming the ways things are designed, to engineered & manufactured

- Design tools have been limited because manufacturing technology hasn’t been able to execute on amazing designs.
- Now that we have the technology, we are elevating the opportunities with design.
- Hardware, software, materials and **design**.
THREE FUNDAMENTAL BREAKTHROUGHS: Our Technology

Continuous Printing (CLIP):
New 3D Printing Process
• Layerless
• Injection molded qualities
• Best-in-class printer uptime
• US Patent 9,498,920
• US Patent 9,360,757
• US Patent 9,211,678
• US Patent 9,205,601

Dual-Cure Materials:
New 3D Materials
• Wide range of proprietary materials
• Unmatched mechanical properties
• US Patent 9,676,963
• US Patent 9,598,606
• US Patent 9,453,142

Modern Software:
Securely Connected Architecture
• Cloud-based
• Regular upgrades until production
• Traceability of digital process
• New design tools (lattices, textures)
At the Interface

Radical formation: \[ PI \xrightarrow{h\nu} PI^\cdot \xrightarrow{k_d} 2R^\cdot \]

Chain initiation: \[ R^\cdot + M \xrightarrow{k_i} RM^\cdot \]

Chain propagation: \[ RM_n^\cdot + M \xrightarrow{k_p} RM_{n+1}^\cdot \]

Consumption of photoinitiator by \[ O_2 + PI^\cdot \rightarrow Quenching \]

Polymer chain termination by \[ O_2 + RM_n^\cdot \rightarrow RM_nOO^\cdot \]
At the Interface

Radical formation \( PI \xrightarrow{k_v} PI^\cdot \xrightarrow{k_d} 2R^\cdot \)

Chain initiation \( R^\cdot + M \xrightarrow{k_i} RM^\cdot \)

Chain propagation \( RM_n^\cdot + M \xrightarrow{k_p} RM_{n+1}^\cdot \)

Consumption of photoinitiator by \( O_2 \xrightarrow{Q_3} PI^\cdot + O_2 \rightarrow \text{Quenching} \)

Polymer chain termination by \( O_2 \xrightarrow{k_d} RM_n^\cdot + O_2 \rightarrow RM_nOO^\cdot \)

\[ \Phi = \Phi_0 e^{-\alpha z} \]
Photo-Rheology

Experimental Set-Up:

- Strain = 1.0 %
- f = 10 Hz
- H = 100 um
- 385 nm LED

- Our customized photo-rheometer is integrated into our 1st generation printer and sheds light into the time scales of curing for various formulations.
Photo-DSC

Experimental Set-Up:

• Photo-DSC can be used to quantify conversion but also sheds light into the reaction enthalpy at various temperatures. Here we see signs of an auto-acceleration at elevated temperatures. Chemical bond resolution is needed.
Photo-FTIR

Experimental Set-Up:

- LED (385nm, I = 9mW/cm², t = 4.6s)
- Infrared Light (25μm)
- T = 25°C

- This technique measures conversion and kinetics by directly measuring the IR transmission through the acrylate double bond (810 cm⁻¹). Photo-FTIR and Photo-DSC agree when considering conversion but give complimentary information that tell the story behind what is happening during printing.
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CARBON’S EXPANDING FAMILY OF RESINS

**UMA** Urethane Methacrylate
Rigid, fast prints

**RPU** Rigid Polyurethane
Tough + abrasion resistant, stiff

**EPU** Elastomeric Polyurethane
Highly elastic, resilient

**CE** Cyanate Ester
High temperature resistance, strength, stiffness

**EPX** Epoxy
Temperature resistant, strong, accurate

**FPU** Flexible Polyurethane
Tough, impact + abrasion resistant, moderate stiffness

**SIL** Silicone-Urethane
Soft touch, biocompatible, and tear resistant

**Dental Production**
Prints fast and accurately

**Third-party Materials**
Clear, biocompatible, and print fast and accurately
Programmable Dual-Cure Resins

1. Dual-cure Resin
Programmable Dual-Cure Resins

1. Dual-cure Resin
2. UV Light Cured Green Part

Continuous Liquid Interface Production sets the shape

Green Young’s Modulus
250-280 MPa
Programmable Dual-Cure Resins

1. Dual-cure Resin
2. UV Light Cured Green Part
3. Thermally Cured Final Part

Continuous Liquid Interface Production sets the shape

Green Young’s Modulus
250-280 MPa

Thermal baking provides ultimate mechanical properties

Cured Young’s modulus
3800 – 4000 MPa

US Patent 9,676,963
Acrylate blocked polyurethanes (ABPUs) as a platform for high performance 3d-printed materials
Acrylate blocked polyurethanes (ABPUs) as a platform for high performance 3d-printed materials

\[ \text{ABPU} + \text{Reactive diluent} + \text{UV absorber} + \text{Pigment} + \text{Photoinitiator} \]

- Interpenetrating polymer network
- UV-crosslinked polymer swollen with chain extender
INPUT
CAD of primitive, the loading conditions and expected mechanical responses, the cost function (optimize for weight, speed ...)

OUTPUT
DLS manufacturable latticed design(s) with different materials
Output lattice designs can have more than a mechanical response based on different geometric structures.

An algorithm smooths the two different mechanical responses in the single CAD.
WIDE VARIETY OF MECHANICAL RESPONSES

- Difficult to know how best to choose lattice parameters
  - Unit cell, min/max size of cell, cell gradients, strut thickness, printability
- Preferable to describe the performance and response needed across the part—maximum mass allowed—and software should do the rest
LIBRARY OF META MATERIALS

- We can generate a variety of mechanical responses from the same material and bulk volume.

- **Assembled 100+ data points**: mapping geometry structure, strut thickness, and other lattice parameters to mechanical responses.
Customers provide us with the expected mechanical response of the part: stress-vs-strain curve measured on their test setup.

The software module runs a number of optimization simulations to find the set of lattice parameters and resin that can achieve the spec.
We simulate the DLS process for any given part to guide the design optimization.

A completely autonomous FEA module, for closed loop optimization.

Used to validate the design at each optimization iteration and give it a score to choose the best design in terms of manufacturability.

The simulations imitate the DLS process slice by slice and predict deformation of the geometry during the print process.

FEA based simulation software runs on AWS.
VARYING LATTICE DENSITY TO MIMIC RADIAL COMPLIANCE OF THE VESSEL

Stiffer Section (mimics rigid calcification)

Weaker Section (weak vessel wall)
Simulations produce an elastic (deformation) response of the material based on the part geometry and material parameters.

This enables us to compute stress inside, compare that against green yield strength, and guide the design to be robust for manufacturing with DLS.
• Simulations are used to automatically generate supports for any given part.

• We perform elasticity simulations to predict how the part will deform under the effect of suction force applied by the fluid.

• We run an optimization problem at each slice to figure out the minimal supports we need to put to print a geometrically accurate part.
SIMULATION BASED SUPPORT GENERATION
UNIQUE TO DLS: TEXTURE PRODUCTION PARTS
Biomimicry
Friction control
Hydrophobicity
Tunable mechanical properties
Flow control
Micro-needles
Sound and vibration dampening
Ventilation
...
AUTOMATED TEXTURE APPLICATION
53K new pancreatic cancer cases each year

5-year survival rate < 7%

Only 15% of patients eligible for surgery

Iontophoresis drug delivery shrinks tumors by 40%

2 "Local iontophoretic administration of cytotoxic therapies to solid tumors", Byrne JD et al. Sci Transl Med. 2015 Feb 4;7(273).
AnelleO PRO: Anello is a UNC-CH startup founded by Rahima Benhabbour.

IVR for Infertility Treatment

DESCRIPTION
• Intravaginal ring for sustained release of progesterone

UNMET DEVELOPMENT NEEDS
• 1.7 million women treated annually for infertility in the US
• Current treatments: daily gels, inserts, or IM injections
• Total market $1.5B

SOLUTION
• Design controls mechanical properties, release kinetics
• Sustained release of progesterone for 30–90 days
• 100% release vs. 15–20% release with conventional IVRs
• In vivo local and systemic safety data in rodents
TRANSDERMAL DRUG DELIVERY VIA MICRO-NEEDLES

Polyethylene Glycol  Polycaprolactone  Polyacrylic Acid

Dissolvable Tip
Non-dissolvable base
A future fabricated with light