THE NEXT GENERATION EQUIPMENT
FOR INDUSTRIAL ADDITIVE MANUFACTURING

Joris Remmers

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Additive manufacturing: key driver

▶ Enhanced innovation by freedom of design
▶ Mass customization vs. personalized manufacturing
▶ Fast design verification, low barriers to entry
▶ Cost-efficient and on-demand manufacturing
▶ Small scale and flexible production
▶ Many new potential applications!
Additive manufacturing: principle and challenges

Manufacturing of three dimensional objects from a digital model by laying down successive layers of materials in an additive process.

However, technology is still in infancy stage:

▶ Poor reproducibility and product quality
▶ Need for large format printing
▶ Required tight tolerances are not met
▶ Limited material portfolio
▶ Insufficient productivity
AM Systems center

- TNO is the national research institute of the Netherlands.
- TNO has a strong technology position in the field of advanced manufacturing, with a 15 year+ track record.
- TNO revolutionized AM by introducing the mass-customization concept PrintValley at the Euromold in 2011.

- The Eindhoven University of Technology (TU/e) is a technical university in the Netherlands.
- The High Tech Systems Center (HTSC) – TU/e has a strong knowledge position in mechatronics concepts and system engineering for manufacturability and product quality.
- The TU/e is establishing a new chair and research group ‘Systems Mechatronics for Advanced Manufacturing’.
AM Systems center: objective

- AMSYSTEMS Center has the ambition to be among the world leading innovation centers in multi-scale Additive Manufacturing Equipment development for OEM companies, materials companies, producers of end-user products, and end-users.

- To achieve this we have a strong and dedicated team of scientists and engineers that can provide exceptional service, quality, and value to our customers.
AM Systems center

- Alliance between TNO and TU/e-HTSC to accelerate the development of the next generation equipment for industrial additive manufacturing
- Shared and bilateral innovation programs, enriched with PhD projects, creating seeds for innovation and incubation ground for startups
- Designed along needs of partners and value proposition for material companies, equipment manufacturers, service providers and end users.
- Focus on high-tech and human-centric applications.
# Applications

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Functional Product</th>
<th>Complex Functional Product</th>
<th>Fully Customizable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHAPE</td>
<td>RECIPE</td>
<td>TEXTURE</td>
<td>FOOD REPLICATOR</td>
</tr>
<tr>
<td>shaped food products</td>
<td>personalized recipes</td>
<td>designer, tunable textures</td>
<td>fully personalized food</td>
</tr>
<tr>
<td><strong>Pharma</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DESIGN</td>
<td>3D PRINTED ORAL DOSAGE FORM</td>
<td>ORAL DOSAGE FORM CONTROLLED RELEASE</td>
<td>MULTI-DRUG ORAL DOSAGE FORMS</td>
</tr>
<tr>
<td>Functional shapes</td>
<td>Functional printed oral dosage forms, single and multi-drug</td>
<td>Designed structure for controlled drug release</td>
<td>multi-ingredient Controlled-drug</td>
</tr>
<tr>
<td><strong>Electronic Devices</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INTEGRATION</td>
<td>MULTIMATERIAL</td>
<td>MULTIFUNCTIONAL</td>
<td>FREEFORM ELECTRONICS</td>
</tr>
<tr>
<td>electrical tracks active and passive components</td>
<td>piezo and responsive materials, ceramics, metals, nanoparticles</td>
<td>optics, fluidics, and electronics functions</td>
<td>fully freeform electronic production, PCB-less with higher form factors</td>
</tr>
<tr>
<td><strong>Medical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODEL</td>
<td>TRAY - BASEPLATE</td>
<td>CROWNS - BRIDGES</td>
<td>FULL DENTURE</td>
</tr>
<tr>
<td>mono-color no biocompatibility</td>
<td>mono-color short/long term biocomp.</td>
<td>multi-color long term biocomp., mechanical properties</td>
<td>multi-material multi-color long term biocompatibility</td>
</tr>
<tr>
<td><strong>High Tech</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DESIGN</td>
<td>CERAMIC PART</td>
<td>INERT CHANNELS</td>
<td>AM NANO STRUCTURES</td>
</tr>
<tr>
<td>cooling plate metal</td>
<td>ceramic</td>
<td>micro-reactors multi-material</td>
<td>3D transistors multi-material</td>
</tr>
</tbody>
</table>
Food AM

- **Prototype:** Shaped food products
  - Pasta, Chocolate

- **Functional products:** Personalised recipes
  - Hospitals, nursing homes

- **Complex functions:** Engineered food
  - Cookies with a crunch

- **Fully customizable:** Food replicator
  - Fully personalized meals
Pharma (Dental prostheses)

- **Prototype:** Study objects, tools for dental labs
  - Mono color model, not bio-compatible
- **Functional products:** Base plates, components for braces
  - Bio-compatible materials, mono color
- **Complex functions:** Crowns and bridges
  - Bio-compatible, mechanical properties, good surface properties
- **Fully customizable:** Full denture
  - Multi-color, multi-material, long term bio-compatible
Industrial AM equipment

Technology platforms for multi-material industrial AM
PrintValley2020

- SLS system with integrated electronics capability (conductive track, Pick & place)
- Multi-material additive manufacturing
- Assembly and integration of electronic parts
- In-line testing / Quality monitoring
An application: Additive manufacturing of ceramics
Additive manufacturing of large area ceramics

*Technical ceramics, e.g. wafer chucks*
Process overview for ceramics
Process overview for ceramics

- Slurry preparation
- Digital part geometry
- Vat photopol.

Resin → Ceramic powder → Slurry
Process overview for ceramics

- **slurry preparation**
  - resin
  - ceramic powder

- **vat photopol.**
  - digital part geometry
  - green part
  - slurry

- **debinding**
  - ceramic powder
  - resin

Ceramic powder and resin are combined to form a slurry, which is then used in a vat photopolymerization process to create a green part. The slurry is later subject to debinding to remove the resin, leaving a solid ceramic part.
Process overview for ceramics

1. **Slurry Preparation**
   - Resin
   - Ceramic powder
   - Result: Slurry

2. **Vat Photopol.**
   - Digital part geometry
   - Slurry
   - Result: Green part

3. **Debinding**
   - Green part
   - Result: Pyrolyzed part

4. **Sintering**
   - Pyrolyzed part
   - Result: Finished part
Process overview for ceramics

1. **Slurry Preparation**
   - Resin
   - Ceramic powder

2. **Vat Photopol.**
   - Slurry

3. **Debinding**
   - Pyrolyzed part

4. **Sintering**
   - Finished part
Challenges in printing of ceramics

A) Ceramic inclusions causing light scattering [Halloran (2016)]

B) Inhomogeneous shrinkage leading to warpage [Huang, Jiang (2003); Wu (2014)]

C) Formation of cracks [TNO; TNO]
Challenges in printing of ceramics

A) Ceramic inclusions causing light scattering

Area illuminated

Cured polymer

[Halloran (2016)]
Challenges in printing of ceramics

A) Ceramic inclusions causing light scattering

Area illuminated

Cured polymer

[Halloran (2016)]

B) Inhomogeneous shrinkage leading to warpage

[Huang, Jiang (2003)]
Challenges in printing of ceramics

A) Ceramic inclusions causing light scattering

B) Inhomogeneous shrinkage leading to warpage

C) Formation of cracks

[Halloran (2016)]

[Huang, Jiang (2003)]
AM Systems: Large scale ceramics project

Research team:

► 3 PhD students
  ▶ Process monitoring and control (Thomas Hafkamp, Mechanical Engineering)
  ▶ Sensing and controlling resin layer thickness (Andrei Kozhevnikov, Applied Physics)
  ▶ Structure and material properties (Steyn Westbeek, Mechanical Engineering)

► 3 PDEng students
  ▶ LEPUS software and control (Tim Verdonschot)
  ▶ Recoater design (Jordy Senden)
  ▶ Sensing of resin layer height (Remco Smits)

► Supported by TNO and TU/e staff
Process monitoring and control (Thomas Hafkamp)
Sensing and controlling resin layer thickness (Andrei Kozhevnikov)

- recoater velocity
- gap between blade and previous layer
- pressure inside blade (for active blade)
Structure and material properties (Steyn Westbeek)

- Interaction with light
  - Chemical reaction
    - Exothermic
      - Shrinkage

- Mechanical properties
  - Dependence on the slurry composition
Structure and material properties (Steyn Westbeek)

Light

Interaction with light

Uncured slurry

Cured layer

Cured layer

Chemical reaction

Exothermic

Shrinkage

Mechanical properties

Dependence on the slurry composition
Structure and material properties (Steyn Westbeek)

- Interaction with light
- Chemical reaction
  - Exothermic
  - Shrinkage

Uncured slurry

Cured layer

Cured layer
Structure and material properties (Steyn Westbeek)

- Interaction with light
- Chemical reaction
  - Exothermic
  - Shrinkage
- Mechanical properties

Light

Uncured slurry

Cured layer

Cured layer
Structure and material properties (Steyn Westbeek)

- Interaction with light
- Chemical reaction
  - Exothermic
  - Shrinkage
- Mechanical properties
- Dependence on the slurry composition
Structure and material properties (Steyn Westbeek)

- Interaction with light
- Chemical reaction
  - Exothermic
  - Shrinkage
- Mechanical properties
- Dependence on the slurry composition

Relate process conditions and material properties to the development of residual stresses and deformation
Modeling framework

**Frequency Domain**

- Light propagation
- Electromagnetic waves

**Time Domain**

- Mechanics
  - Material behavior
- Photopolymerization
  - Conversion kinetics
- Thermal balance
  - Heat transfer/generation

Photobleaching, $\Delta$RI

$$\text{Intensity} \rightarrow \frac{d[M]}{dt} \rightarrow \text{Kinetics} \rightarrow \text{Thermal balance}$$

$$\text{Photobleaching, } \Delta\text{RI}$$

$$p \rightarrow \frac{d[M]}{dt} \rightarrow T$$
Modeling framework

**Frequency Domain**
- Light propagation
- Electromagnetic waves

**Time Domain**
- Mechanics
  - Material behavior
- Photopolymerization
  - Conversion kinetics
- Thermal balance
  - Heat transfer/generation

\[ p \]
\[ \frac{d[M]}{dt} \]
Light propagation

![Diagram showing light propagation, photopolymerization, mechanics, and thermal balance in both frequency and time domains.](image-url)
Model problem

unfilled

hexagonal
\[ \phi = 0.4 \]

random
\[ \phi = 0.4 \]
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

\[ t = 0 \text{ s} \]
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

$t = 0.1 \text{ s}$
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

\[ t = 0.2 \text{ s} \]
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

$t = 0.3 \text{ s}$
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

- \( t = 0.4 \) s
- \( t = 0.4 \) s
- \( t = 0.4 \) s
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

$t = 0.5 \text{ s}$
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

- $t = 0.5 \text{ s}$
- $t = 0.5 \text{ s}$
- $t = 0.5 \text{ s}$
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

$t = 0.6 \text{ s}$
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

$t = 0.7 \, \text{s}$

Normalized intensity [-]
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

\[ t = 0.8 \text{ s} \]

\[ t = 0.8 \text{ s} \]

\[ t = 0.8 \text{ s} \]
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

\[ t = 0.9 \text{ s} \]
Light propagation – Results

Normalized intensity, i.e. magnitude of the Poynting vector:

\[
t = 1 \text{ s}
\]
Light propagation – Results

Electric field (z-component) [kV/m]:

$t = 0.5 \text{ s}$
Photopolymerization

Frequency Domain
- Light propagation

Time Domain
- Mechanics
- Photopolymerization
- Thermal balance

$I$, $p$, $R_p$, $T$
Photopolymerization – Results

Degree of conversion [-]:

$t = 0$ s

[Images of patterns at different times]
Photopolymerization – Results

Degree of conversion [-]:

\[ \text{Degree of conversion} = \begin{cases} 0 & t = 0.1 \text{ s} \\ \frac{t}{0.1} & t = 0.1 \text{ s} \\ \frac{t}{0.1} & t = 0.1 \text{ s} \end{cases} \]
Photopolymerization – Results

Degree of conversion [-]:

$t = 0.2 \text{ s}$
Photopolymerization – Results

Degree of conversion [-]:

\[ t = 0.3 \text{ s} \]
Photopolymerization – Results

Degree of conversion [-]:

t = 0.4 s
Photopolymerization – Results

Degree of conversion [-]:

$t = 0.5\ s$

Degree of conversion [-]
Photopolymerization – Results

Degree of conversion [-]:

\[ t = 0.6 \text{ s} \]

\[ t = 0.6 \text{ s} \]

\[ t = 0.6 \text{ s} \]
Photopolymerization – Results

Degree of conversion [-]:

$t = 0.7\text{ s}$

![Image showing the degree of conversion at different times](image-url)
Photopolymerization – Results

Degree of conversion [-]:

- $t = 0.8\, \text{s}$

![Diagram showing degree of conversion](image)
Photopolymerization – Results

Degree of conversion [-]:

\[
\begin{array}{c}
  t = 0.9 \text{ s} \\
  t = 0.9 \text{ s} \\
  t = 0.9 \text{ s}
\end{array}
\]
Photopolymerization – Results

Degree of conversion [-]:

\[ p_{\text{average}} = 0.41 \]

\[ p_{\text{average}} = 0.47 \]

\[ p_{\text{average}} = 0.45 \]
Thermal & Mechanical

Frequency Domain
- Light propagation

Time Domain
- Mechanics
- Photopolymerization
- Thermal balance

\[ I \rightarrow \text{Light propagation} \rightarrow \text{Photopolymerization} \rightarrow \text{Thermal balance} \rightarrow T \]

\[ R_p \rightarrow \text{Photopolymerization} \rightarrow \text{Mechanics} \rightarrow I \]
Thermal & Mechanical

![Diagram showing Thermal & Mechanical relationships]

- **Frequency Domain**
  - Light propagation

- **Time Domain**
  - Mechanics
  - Photopolymerization
  - Thermal balance

- Symbols:
  - $I$ (Input)
  - $P$ (Power)
  - $R_p$ (Reflection)
  - $T$ (Temperature)
Thermal & Mechanical

Frequency Domain
- Light propagation

Time Domain
- Mechanics
- Photopolymerization
- Thermal balance

\[ I \rightarrow [ \begin{array}{c}
\text{Frequency Domain} \\
\text{Light propagation}
\end{array} ] \rightarrow [ \begin{array}{c}
\text{Time Domain} \\
\text{Mechanics} \\
\text{Photopolymerization} \\
\text{Thermal balance}
\end{array} ] \rightarrow \downarrow R_p \rightarrow \downarrow p \rightarrow T \]
Thermal & Mechanical

Frequency Domain

- Light propagation

Time Domain

- Mechanics
  - Photopolymerization
  - Thermal balance

\[
I \quad p \quad T \quad R_p
\]
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0$ s

$t = 0$ s

$t = 0$ s
Solid mechanics – Results

Stress [MPa] and deformation (×2) [μm]:

\[
t = 0.1 \text{s}
\]
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0.2$ s

$t = 0.2$ s

$t = 0.2$ s
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0.3$ s

$t = 0.3$ s

$t = 0.3$ s

Von Mises stress [MPa]
Solid mechanics – Results

Stress [MPa] and deformation (×2) [μm]:

$t = 0.4 \text{ s}$

$t = 0.4 \text{ s}$

$t = 0.4 \text{ s}$
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0.5$ s

Von Mises stress [MPa]
Solid mechanics – Results

Stress [MPa] and deformation (×2) [μm]:

$t = 0.6 \text{ s}$

$t = 0.6 \text{ s}$

$t = 0.6 \text{ s}$
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0.7$ s

Von Mises stress [MPa]
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0.8$ s
Solid mechanics – Results

Stress [MPa] and deformation ($\times 2$) [$\mu$m]:

$t = 0.9$ s

$t = 0.9$ s

$t = 0.9$ s

Von Mises stress [MPa]
Solid mechanics – Results

Stress [MPa] and deformation (×2) [µm]:

\[
\begin{align*}
\sigma_{\text{max}} &= 14 \text{ [MPa]} \\
\sigma_{\text{max}} &= 76 \text{ [MPa]} \\
\sigma_{\text{max}} &= 128 \text{ [MPa]}
\end{align*}
\]
Moving laser

\[ t = 0 \text{ s} \]

Filled resin (\( \phi = 0.40 \))

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

$t = 0.1\ s$

Filled resin ($\phi = 0.40$)
Moving laser

\[ t = 0.2 \text{ s} \]

Filled resin \((\phi = 0.40)\)
Moving laser

$t = 0.3$ s

Filled resin ($\phi = 0.40$)
Moving laser

$t = 0.4 \text{ s}$
Moving laser

\( t = 0.5 \) s

Filled resin \((\phi = 0.40)\)
Moving laser

$t = 0.6 \text{ s}$

Filled resin ($\phi = 0.40$)

Normalized intensity [-]  

Von Mises stress [MPa]

29
Moving laser

t = 0.7 s

Filled resin (\(\phi = 0.40\))

Normalized intensity [\(-\)]

Von Mises stress [MPa]

29
Moving laser

\[ t = 0.8 \text{ s} \]

Filled resin (\( \phi = 0.40 \))
Moving laser

\[ t = 0.9 \text{ s} \]

Filled resin \((\phi = 0.40)\)
Moving laser

\[ t = 1 \text{ s} \]

Filled resin \((\phi = 0.40)\)

![Diagram showing a laser moving over a surface with normalized intensity and von Mises stress maps.](image-url)
Moving laser

\[ t = 1.1 \text{ s} \]

Filled resin (\( \phi = 0.40 \))
Moving laser

\[ t = 1.2 \text{ s} \]

Filled resin (\( \phi = 0.40 \))
Moving laser

\[ t = 1.3 \text{ s} \]
Moving laser

$t = 1.4$ s
Moving laser

\( t = 1.5 \text{ s} \)

Filled resin (\( \phi = 0.40 \))

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

\[ t = 1.6 \text{ s} \]

Filled resin (\( \phi = 0.40 \))

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

$t = 1.7 \text{ s}$

Filled resin ($\phi = 0.40$)

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

\[ t = 1.8 \text{ s} \]

Filled resin (\( \phi = 0.40 \))

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

\[ t = 1.9 \text{ s} \]

Filled resin (\( \phi = 0.40 \))
Moving laser

\[ t = 2 \text{ s} \]

Filled resin (\( \phi = 0.40 \))

- Normalized intensity [-]

- Von Mises stress [MPa]
Moving laser

$t = 2.1 \text{ s}$

Filled resin ($\phi = 0.40$)

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

$t = 2.2$ s

Filled resin ($\phi = 0.40$)
Moving laser

\[ t = 2.3 \text{ s} \]

Filled resin \((\phi = 0.40)\)

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

\[ t = 2.4 \text{ s} \]
Moving laser

\[ t = 2.5 \text{ s} \]
Moving laser

\[ t = 2.6 \text{ s} \]
Moving laser

\[ t = 2.7 \text{ s} \]

Filled resin (\( \phi = 0.40 \))

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

$t = 2.8 \text{ s}$

Filled resin ($\phi = 0.40$)
Moving laser

\[ t = 2.9 \text{ s} \]

Filled resin (\( \phi = 0.40 \))

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

\[ t = 3 \text{ s} \]

Filled resin \((\phi = 0.40)\)
Moving laser

\[ t = 2.5 \text{ s} \]
Moving laser

\( t = 2.6 \, \text{s} \)

Unfilled resin

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

$t = 2.7$ s
Moving laser

\[ t = 2.8 \text{ s} \]

Unfilled resin

Normalized intensity [-]

Von Mises stress [MPa]
Moving laser

$t = 2.9 \text{ s}$
Moving laser

\[ t = 3 \text{ s} \]
Part scale simulation – Homogenization

- Resolving the micro-structure is computationally expensive.

micro-scale DNS sim.
Part scale simulation – Homogenization

- Resolving the micro-structure is computationally expensive.
- Homogenization approach to capture effective response.
- Classical representative volume element (RVE) approach is not sufficient.
Relevant time scales

$t_t \ll t_K \ll t_e \approx t_{E_c} \ll t_{s,0} < t_{s,c} \ll t_d$

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_t$</td>
<td>Photon absorbed and radicals created</td>
<td>single ps</td>
</tr>
<tr>
<td>$t_K$</td>
<td>Chemical kinetics of molecular free radical polymerization</td>
<td>few $\mu$s</td>
</tr>
<tr>
<td>$t_e$</td>
<td>Characteristic exposure time</td>
<td>70–2000 $\mu$s</td>
</tr>
<tr>
<td>$t_{E_c}$</td>
<td>Time to reach critical exposure</td>
<td>200 $\mu$s</td>
</tr>
<tr>
<td>$t_{s,0}$</td>
<td>Interconnection and start of macroscopic shrinkage</td>
<td>0.4–1 s</td>
</tr>
<tr>
<td>$t_{s,c}$</td>
<td>Completion of shrinkage</td>
<td>4–10 s</td>
</tr>
<tr>
<td>$Dt_D$</td>
<td>Drawing a whole layer</td>
<td>20–300 s</td>
</tr>
</tbody>
</table>

[Jacobs (1992)]

![Time scale comparison diagram](image-url)
Relevant length scales

\[ d_m \ll \lambda \ll S \ll D_p \ll B \ll R \ll L \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_m)</td>
<td>Length of “long-chain” polymer</td>
<td>1–7 nm</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Light wavelength</td>
<td>300–400 nm</td>
</tr>
<tr>
<td>(S)</td>
<td>Average characteristic size of “polymerization-islands” just prior to macroscopic cross linking</td>
<td></td>
</tr>
<tr>
<td>(D_p)</td>
<td>Photopolymer penetration depth</td>
<td>150–300 (\mu m)</td>
</tr>
<tr>
<td>(B)</td>
<td>Laser spot diameter</td>
<td>150–300 (\mu m)</td>
</tr>
<tr>
<td>(R)</td>
<td>“Zone of influence” for photo-polymer exposure</td>
<td>150–300 (\mu m)</td>
</tr>
<tr>
<td>(L)</td>
<td>Size of an SL part</td>
<td></td>
</tr>
</tbody>
</table>

[Jacobs (1992)]
Identify the required level of detail, i.e. study the permittance of simplifying assumptions
Comsol – Time/space dependence study
Comsol – Multi-layer

- Intensity [W/m²]
  - High: Red
  - Low: Yellow

- Degree of conversion [-]
  - High: Blue
  - Low: Yellow

- Temperature [K]
  - High: Red
  - Low: Purple

- Von Mises stress [MPa]
  - High: Dark Blue
  - Low: Light Purple
Comsol – Multi-layer

- Intensity [W/m²] with high and low color scales.
- Temperature [K] with high and low color scales.
- Degree of conversion [-] with high and low color scales.
- Von Mises stress [MPa] with high and low color scales.
Comsol – Multi-layer

- Intensity [W/m²]
- Degree of conversion [-]
- Temperature [K]
- Von Mises stress [MPa]
Comsol – Multi-layer

- Intensity [W/m²]
- Degree of conversion [-]
- Temperature [K]
- Von Mises stress [MPa]
Comsol – Multi-layer

Intensity [W/m²]

Degree of conversion [-]

Temperature [K]

Von Mises stress [MPa]

low

high

low

high

low

high

low
Comsol – Multi-layer
Comsol – Multi-layer

Intensity [W/m²]

Degree of conversion [-]

Temperature [K]

Von Mises stress [MPa]
Comsol – Multi-layer

- Intensity [W/m²]
- Degree of conversion [-]
- Temperature [K]
- Von Mises stress [MPa]
Comsol – Multi-layer

- Intensity [W/m²]
- Degree of conversion [-]
- Temperature [K]
- Von Mises stress [MPa]
Comsol – Multi-layer

- Intensity [W/m²]
- Degree of conversion [-]
- Temperature [K]
- Von Mises stress [MPa]
Comsol – Multi-layer

Intensity [W/m²]

Degree of conversion [-]

Temperature [K]

Von Mises stress [MPa]
Comsol – Multi-layer

- **Intensity [W/m²]**: High at the center, low at the edges.
- **Degree of conversion [-]**: High at the top, low at the bottom.
- **Temperature [K]**: High at the top, low at the bottom.
- **Von Mises stress [MPa]**: High at the top, low at the bottom.
Comsol – Multi-layer

Intensity [W/m²]

Temperature [K]

Degree of conversion [-]

Von Mises stress [MPa]
Comsol – Multi-layer

- Intensity [W/m²]
- Degree of conversion [-]
- Temperature [K]
- Von Mises stress [MPa]

35
Highlights

► Alliance between TNO and TU/e-HTSC to accelerate the development of the next generation equipment for industrial additive manufacturing.

► Shared and bilateral innovation programs, enriched with PhD projects, creating seeds for innovation and incubation ground for startups.

► Multidisciplinary research (control, meterology, material behaviour).

► Designed along needs partners and value proposition for material companies, equipment manufacturers, service providers and end users.

► Focus on high-tech and human-centric applications.
THE NEXT GENERATION EQUIPMENT FOR INDUSTRIAL ADDITIVE MANUFACTURING

Joris Remmers

Symposium 3D Concrete Printing – Eindhoven – June 22, 2018