Additive Manufacturing and 3D Printing driving research and innovations

The Digital Manufacturing Era

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IIT Kharagpur

Workshop on
Make in India: Transforming Research to Reality
Tuesday, 5th September 2017 @ Anna University
Coverage

• In the domain of Industry 4.0
• Transformation for the Digital Manufacturing
• Relevance in Manufacturing as a design to manufacturing integration and the ecosystem
• Evolution of the digital twin concept
• 3D Printing / Additive Manufacturing driving innovations
• Research efforts at IIT Kharagpur
Generations of Industries

1st: Mechanization, water power, steam power
2nd: Mass production, assembly line, electricity
3rd: Computer and automation
4th: Cyber Physical Systems

Trending Today – Industry 4.0 / Manufacturing 4.0

A time line of different manufacturing paradigms that compares their enabling technology and hardware

Danfang Chen, Steffen Heyer, Suphunnika Ibbotson, Konstantinos Salonitis, Jón Garðar Steingrímsson, Sebastian Thiede

Direct digital manufacturing: definition, evolution, and sustainability implications

Journal of Cleaner Production, Volume 107, 2015
Digitization of Manufacture

Modelling, Simulation, Analytics and big data

Cyber-physical systems / IoT

3D printing

Robotics and automation

Laser-based manufacturing

Courtesy: EU Commission (Complex Systems)
Internet of Things in Manufacturing

Monitor production flow in near-real time

Remotely Manage Equipment

Identify and correct quality issues. Inventory Management

Condition-based maintenance. Predictive maintenance

Transmits operational information to the partner (e.g. OEM) and to field service engineers

Provide cross-channel visibility into inventories.

I can see my production line status and recommend adjustments to better manage operational cost.

I know when to deploy the right resources for predictive maintenance.

I gain insight into usage patterns from multiple customers and track equipment deterioration.

I know when to deploy the right resources for predictive maintenance.

Internet of Things in manufacturing – the Microsoft view – source SlideShare presentation – License: CC Attribution-ShareAlike License
Digital maturity of the manufacturing industry

- Digital innovation and control
- Digital expansion and flexibility
- Digital enrichment and process automation

Level of digital maturity

- Single value circle function
- Breadth of digital coverage
- All value circle functions

Digital footprint of the manufacturing sector

Source: Capgemini Consulting Analysis
WHAT IS DIGITAL MANUFACTURING?

80 percent of production costs are determined in the design phase.
McKinsey

PRODUCT LIFECYCLE

DESIGN | FABRICATE | FABRICATE | ASSEMBLE | QUALIFY | SELL & DELIVER | AFTER-SALES SERVICE | END OF LIFE REUSE RECYCLE

INDUSTRIAL INTERNET

DATA IS GATHERED ALONG ‘DIGITAL THREAD’ AND AGGREGATED BY THE INDUSTRIAL INTERNET OF SMART, CONNECTED PRODUCTS

Image Courtesy: DLM Georgia Tech
Disruptive technologies increase the value of digital information along the entire product lifecycle

The digital thread is the digital representation of the physical product lifecycle

<table>
<thead>
<tr>
<th>Physical product lifecycle</th>
<th>Research and design</th>
<th>Source</th>
<th>Make</th>
<th>Distribute</th>
<th>Service</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital thread</td>
<td><img src="32x32" alt="Database" /></td>
<td><img src="32x32" alt="Database" /></td>
<td><img src="32x32" alt="Database" /></td>
<td><img src="32x32" alt="Database" /></td>
<td><img src="32x32" alt="Database" /></td>
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</table>

End-to-end information flow across lifecycle

4 activities are required to manage the digital thread

**Information capturing and recording**
- Relevant set of data to prevent information overflow
- Automated, real-time capturing via sensors
- Recording and storing of both historical and new data in a single information system

**Information transfer**
- Digitally transfer information across departments, production sites, value chain steps, and company borders

**Information analysis and synthesis**
- Identification of relevant data and analysis (ideally, automated)
- Synthesis of analysis into relevant insights

**Turning information into outcomes**
- Translation of analysis results into recommendations that suggest actions for workers or automatically trigger actions of machines
- Feedback and continuous improvement

SOURCE: McKinsey
A comparison of manufacturing paradigms and their main actors (modified from Abel et al., 2011).

Journal of Cleaner Production, Volume 107, 2015, 615–625
Aerospace, Defense and Automotive Industry Solutions
A Typical Process Taxonomy
PLM-ERP-MES

**PLM**
- Teamcenter
  - BOM
  - BOP
  - Work Order
- AI Web Service
  - PLM XML
  - HTTP

**ERP**
- Work Order
  - Work Orders
    - as planned
  - Skill Levels
  - Certifications
  - Production Perf.
  - Unplanned Maint.

**Downstream PLM-MES**
- BOM
- Components
- Process Plan
- Operation
- Work Instructions
- Re-Eng Work Order
- Testing program
- Data Collection
- Data Type
- Operation Certif.
- Work Center
- Resource Type
- Resource
- Part Program (i.e., CNC, control devices)

**MES**
- SIMATIC IT
  - As-built (product & process)
- CIL-PLM Interface
  - B2MML
  - HTTP

**Closed-loop PLM-MES**
- Product & Process data
- SPC/OEE data
- Change Request w/ Markup
- Updated Work Instructions
- Generic issues
- Selected and evaluated KPIs...

**PLM XML**
- HTTP

Siemens PLM Software
Typical Manufacturing Organization

Courtesy [https://www.slideshare.net/technomgtsood/production-operations-management](https://www.slideshare.net/technomgtsood/production-operations-management)

source SlideShare presentation – License: CC Attribution-ShareAlike License
Digital Transformations

Digital Manufacturing: The digital transformation journey to smart, connected products and plants

The transformations of the Supply Chain

Digitized manufacturing takes adaptability to the next level

**Conventional manufacturing**
- Mass production
- Large quantities
- Small margins
- Sequential value chain
- Long turnaround time
- Low flexibility

**Digitized manufacturing**
- Custom production
- Small quantities, short run
- High margins
- Changing collaborative partnerships
- Short turnaround time
- Highly flexible and adaptive

Source: GPS Consulting
Integrated Product development

Integrated Product/Process Development

- Strategic Design
  - System Concept
- System Design
  - System Req.
    - Sys Req. Valid
    - Operations/ Maint Concept
    - System Architecture
    - System Safety
- Detailed Design
  - System Integration
    - Subsys Reqt Alloc
    - Production Planning
- Development/Fabrication
  - System Verification and validation
    - Lean - Six Sigma Process Improvement
- Operations & Life Cycle Support
  - Identification of upgrades
  - Capture lessons learned
  - MRO

Led by SE
Significant SE role

Deployment of The Product

PRODUCT LIFE-CYCLE ENGINEERING

PRODUCT/SIMULATION LIFE-CYCLE MANAGEMENT
Modelling & Simulation Enabled Product Development

Re-engineering the design and manufacturing
Role of Systems Engineering
Digital Twin

Use of Simulation Technologies to bridge the real and digital model

Michael Grieves, 2014

Reengineering Aircraft Structural Life Prediction Using a Digital Twin
Eric J. Tuegel,$^1$ Anthony R. Ingraffea,$^2$ Thomas G. Eason,$^1$ and S. Michael Spottswood$^1$International Journal of Aerospace Engineering Volume 2011 (2011), Article ID 154798,
Model-based Systems Engineering (Product Life Cycle)

Evolution of Model Based Engineering

Single Source of Truth Between Design Models, Manufacturing and Operations

Requirements Analysis
Product Definition

Evolution of MBE
Digital continuity
Digital continuity & interoperability

Design & Analysis

Sub-systems
Requirement
Design
Analysis

Components
Requirement
Design
Analysis

Integrated Design & Analysis

Digital Thread (MBE, PLM)

Digital Twin (MBE)

System Integration

Physical Verification

Hybrid Tests
HIT

Subsystem Integration
Component Tests

Multidisciplinary Optimization

Integrated Design & Analysis

Realization of MBE

Changes & Upgrades

Operation & Maintenance

Commissioning

Digital continuity: 3D ⇒ Multiphysics
Interoperability ⇒ Collaborative Platform

Digital continuity: 3D ⇒ ROM ⇒ System Model
Interoperability ⇒ B2B Model Share

Courtesy: Ansys
A hypothetical creation in practice
Smart and Optimal Manufacturing

Fig. 3. Three dimensions of smart and optimal manufacturing (this figure and some opinions are inspired by Implementing 21st Century Smart Manufacturing from Smart Manufacturing Leadership Coalition). HSE: health, safety, and environment.

Fundamental Theories and Key Technologies for Smart and Optimal Manufacturing in the Process Industry; Feng Qian*, Weimin Zhong, Wenli Du; Engineering 3 (2017) 154–160 (Science Direct)
Additive Manufacturing/3D Printing

• A recent development in advanced manufacturing
• Material addition instead of removal in traditional secondary manufacturing processes
• Cost effective in terms of material savings
• Green manufacture in term of reduced wastages
• Freedom of Design: Extremely Complex shapes feasible in fabrication
• Flexibility with materials and properties
• Digital process flow for Design to Manufacture
Gartner Hype cycle

- Gartner Hype Cycles provide a graphic representation of the maturity and adoption of technologies and applications.
- Gartner Hype Cycle methodology gives you a view of how a technology or application will evolve over time.
- Each Hype Cycle drills down into the five key phases of a technology's life cycle:
  - Technology Trigger
  - Peak of Inflated Expectations
  - Trough of Disillusionment
  - Slope of Enlightenment
  - Plateau of Productivity

http://www.gartner.com/technology/research/methodologies/hype-cycle.jsp#
Gartner Projection of 3D Printing
Additive Manufacturing Adoption Timeline

Additive Manufacturing has been slowly gaining traction, specifically within design, however, new technologies have the potential to amplify growth and extend usage within production.

Additive Manufacturing Timeline: The Shift in Additive Manufacturing Applications

- **Product Design: Prototyping and Customization**
  - **1986**: AM Invented (SLA)
  - **1989**: AM Rapid Prototype System (FDM)
  - **2007**: RepRap Movement
  - **2008**: User Generated Art
  - **2009**: FDM Patent Expires – Growth in Consumer 3DPs

- **Production: Scaling in Volume, Size, and Availability**
  - **2014**: Selective Laser Sintering Patent Expires

**AM Milestones**
- **1986**: AM Invented (SLA)
- **1989**: AM Rapid Prototype System (FDM)
- **2007**: RepRap Movement
- **2008**: User Generated Art
- **2009**: FDM Patent Expires – Growth in Consumer 3DPs
- **2012**: 3D System Acquires Z Corp
- **2016**: Mass Production LEAP engine part
- **2030-2050**: (Estimated) Completed Product

**Impacts on Aerospace Industry**
- **1986**: Rapid Prototyping
- **2004**: Component Manufacture
- **2007**: Real-time Spare Parts Manufacture
- **2011**: SULSA Prototype
- **2012**: 3D System Acquires Z Corp
- **2016**: Mass Production LEAP engine part
- **2030-2050**: (Estimated) Completed Product

**Main Applications**
- End Product
- Mass Production
- Democentric Printing

**GE Acquires**
### AM Value Chain

<table>
<thead>
<tr>
<th>Material</th>
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<tbody>
<tr>
<td>&gt; Mainly: Creation of metal powder</td>
</tr>
<tr>
<td>&gt; Powder with high purity and a very narrow distribution of the granular size (usually 30µm)</td>
</tr>
<tr>
<td>&gt; Hard to get from large providers due to small orders</td>
</tr>
<tr>
<td>&gt; Usually sold by AM system providers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
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<tbody>
<tr>
<td>&gt; Usually stand-alone powder bed fusion systems</td>
</tr>
<tr>
<td>&gt; System providers with low levels of vertical integration, standard components usually made by contract manufacturers</td>
</tr>
<tr>
<td>&gt; Providers integrate components, opt. system &amp; software</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Software</th>
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</thead>
<tbody>
<tr>
<td>&gt; Differentiation between process control and enhancement software</td>
</tr>
<tr>
<td>&gt; Process control from system prov.</td>
</tr>
<tr>
<td>&gt; Add-on software such as automatic support generation, design optimization by specialized companies</td>
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<table>
<thead>
<tr>
<th>Application Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; Support for end customers</td>
</tr>
<tr>
<td>&gt; Can be complex and demanding</td>
</tr>
<tr>
<td>&gt; Done by system providers, software developers and/or service providers</td>
</tr>
<tr>
<td>&gt; Not every service provider is able to design applications</td>
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<table>
<thead>
<tr>
<th>Production</th>
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<tbody>
<tr>
<td>&gt; Different production scenarios:</td>
</tr>
<tr>
<td>&gt; Large OEM</td>
</tr>
<tr>
<td>&gt; Contract manufacturer/service provider</td>
</tr>
<tr>
<td>&gt; Specialized part manufacturer</td>
</tr>
<tr>
<td>&gt; Production is normally not done by AM system providers</td>
</tr>
</tbody>
</table>

### Players:

- **Material**
  - Höganas
  - TLS Technik
  - Sandvik
  - etc.

- **EOS**
- SLM Solutions
- Concept Laser
- etc.

- **Materialise**
- netfabb
- Within
- etc.

- **3T PRD**
- Material Solutions
- EOS
- etc.

- **3T PRD**
- Bego
- LayerWise
- etc.

Source: Expert interviews; Roland Berger

Source: “Roland Berger, Additive Manufacturing: A game changer for the manufacturing industry?”
The AM Business Ecosystem

Revenue streams of AM system manufacturers

- **SYSTEM**
  - Standard AM systems
  - Customized systems developed for specific needs

- **SERVICES**
  - Maintenance contracts
  - Spare parts/consumables (e.g. gas, filters, wipers)

- **LICENSES**
  - Granting of licenses to competitors

- **TRAINING AND SEMINARS**
  - Extended introduction to AM and AM systems
  - Seminars/training on AM design, AM production, etc.

- **POWDER**
  - Sales of metal powder with high markup
  - Readying powders for specific needs

- **APPLICATION DESIGN**
  - Consulting on AM readiness
  - Support in developing applications

- **SOFTWARE**
  - Access to restricted parameter settings
  - Add-on software like QM modules, process software

Source: Roland Berger

Source: “Roland Berger, Additive Manufacturing : A game changer for the manufacturing industry?”
Expertise Throughout the Entire AM Process

Research & Design
- 3-matic®
- analysis & design on STL format
- link to FEA

Communication & Quoting
- MiniMagics®PRO
- communications and file exchange
- fast generation of quotations

AM Preparation
- Streamics Robot
- file fixing
- build preparation
- support generation
- labelling

Production
- Magics e-Stage
- link with machine
- material development tool
- hatching strategies

Quality Control
- Build Processor
- AutoFab R&D
- inspection
- validation
- reporting

Post Processing & Shipping
- MiniMagics®PRO
- 3-matic®STL
- measurement
- fixtures
- shipping solutions

Streamics AM automation & control system

Automation of operations with Streamics Robot
Communication, data management, traceability, repeatability, reporting with Streamics Control System
Complexity associated with the processes

Source: “Roland Berger, Additive Manufacturing : A game changer for the manufacturing industry?”
A geometry-material-machine-process roadmap for AM and Maker Movement.

The status, challenges, and future of additive manufacturing in engineering

Facilities created to drive innovations and research at IIT Kharagpur

- Laser based AM Powder Bed Fusion
- Laser + Electron Beam Work Stations
- Fused Filament Deposition 3D Printer

EOS M270 Dual Mode Ti Extended customized for multi materials and environment
- 4 heads+nozzles and 3 axis control

Laser head, delivery system and 5 axis control

Nanoscribe Photonics GT Professional for micro- and nano-scale printing with photo polymers

IIT Kharagpur: Contact Prof. C.S.Kumar (kumar@mech.iitkgp.ernet.in)
Direct Digital Manufacturing Lab

- Facility created to rapidly convert designs to functionally suitable manufactured prototypes
- Several critical and customized applications seek rapid solutions for manufactured products
  - Biomedical Implants
  - New material test specimens for aerospace, automotive and related industries
- Train manpower and establish a knowledge centre in rapid manufacturing
- **Strategic investment of IIT Kharagpur in high tech material processing and manufacture**
Direct Digital Manufacturing Lab

- State of Art Machines
- E-Manufacturing Solution from Electro Optical Systems (EOS) Germany
  - Build Size: 250 x 250 x 215 mm
  - Layer Thickness: 20 microns onwards
- Machine enabled to manufacture
  - Reactive Metals: Ti, Al and alloys
  - Non-Reactive metals: Bronzes, Cobalt Chrome,
  - High strength metals: Stainless Steel, Inconel etc.
- Machine has been setup to with high safety and quality standards as required in state of the art materials research
- Applications in Biomedical, aerospace and automotive areas
- Unique capabilities of fine shapes and features including conformal internal cooling channels
- Unique Machine of this kind in South Asia installed in 2009

Nanoscribe Photonics GT Professional for micro- and nano-scale printing with photo polymers

Manufacture Meso-scale, Micro-scale and Nano scale structures for various applications

First system in India – installed in November 2016

© IIT Kharagpur : Contact Prof. C.S.Kumar (kumar@mech.iitkgp.ernet.in)
EOS DMLS setup

Courtesy EOS GmBH
The DMLS process concept

Layer by layer addition process
A typical AM process cycle (Laser based PBF)

Figure 2. Principles of the laser sintering process (Schleifenbaum et al., 2010, p.162).
Powder to part manufacture

Laser-sintering process: Key-technology for e-Manufacturing

material (powder)  laser-sintering  part

Courtesy EOS GmbH
Typical flow in Additive Manufacturing
Layer by Layer Melting/sintering

Laser-Sintering: the Key Technology for e-Manufacturing

Machine software

Courtesy EOS GmbH
Typical process flow
( case customized implants)

- Development the CAD model from scanned model
- Designing 3D model in CAD
- CAD model/ STL file to RP conversion
  (a) Magics Software for DMLS RP
  (b) SRP Player CAM Software for subtractive RP
- Manufacturing by RP
Development the CAD model from scanned / digitized model data

1. CT or MRI Scan
2. 2-D Cross section
   - Data from Hospital on Optical Disk or Magnetic Tape.
3. Materialise Software
   - Import into Software
   - Data Manipulation in Software
4. 3-D Computer Model
CAD model/STL file to RP conversion process: Using Magics Software

1. Selection of platform:

2. Import project part:

3. Placing the part at the platform:
   • Translate
   • Rotate
   • Selection of Bottom plane

4. Fixed wiser

5. Support generation

6. Marking triangles of an STL File
Procedure of STL to RP conversion using Magics Software

7. Slicing the job part as well as support part (SLI file)
   - The file of triangles is sent to the prototyping machine and sorted into layers by the z-dimension of the triangles.

8. It is required to load the SLI files of support and part in EOS software for making the metallic model.
Manufacturing Process: DMLS

- Metallic powder loading into the dispenser.
- Uploading the SLI file of job part and it’s support together into the RP (EOS) software.
- Job parameter setting.
  - Laser power
  - Laser scan speed
  - Laser scan type
  - Laser beam diameter
  - Layer thickness
Process control in DMLS

- Reduction of $O_2$ level around 0.1% using inert gas (Argon) in the process chamber.
- Preheating of base plate is 40°C
- Start machining
A video of the DMLS process

Additive Manufacturing - Direct Metal Laser Sintering DMLS Technology
Courtesy Solid Concepts

Bio medical implant by DMLS at IIT Kharagpur
Current state of Technology

• Due to increased performance and better properties AM with laser based systems is gaining attention
• Cost of production and application in niche areas is making it attractive.
• Expensive process due to laser and environment
• Cost of processes is expected to fall over next few years with increasing acceptance.
Observations on state of technology

• Currently there is no complete set of design, layout, material, machine and process rules (ASTM T/F 42 being formalized)
• Need to tailor production process for each specific object / part
• Adaptations, such as use of new material, requires more than 1 year of development time
• Much more experience needed in next 5-10 years before new objects can be made with less effort
• Simulation models will shorten development times in the future
Relook at the AM Product Cycle

- The AM Process Chain is quite involved
- Requires a special ecosystem to support the AM Processes
- Quite a few pre- and post- processes involved
- Modelling and Simulation assists in evaluating conditions for these processes and expected outcomes
Research Studies on Process Control in DMLS

• Materials: Stainless Steel (17-4 PH Steel) and Aluminium Alloy (AlSi10Mg – EN4500)

• Metallurgical and Mechanical Properties of concern
  – Porosity
  – Strength
  – Dimensional Accuracy and stability
  – Surface roughness (finish)

• Novel Material + Geometry and Mechanical + Metallurgical properties
### Product dependency on process parameters

- **Laser power**
  - Process time
  - Surface roughness
  - Mechanical strength
  - Dimensional accuracy

- **Scan speed, Hatching distance, Layer thickness**
  - Process time
  - Surface roughness
  - Mechanical strength
  - Dimensional accuracy
  - Cost

- **Scan strategy**
  - Surface roughness
  - Dimensional accuracy
Powder bed fusion processes

Classification based on the way the initial powder is converted to final product

Metals

Binding mechanism classification

1. Solid State Sintering
   - 2.1 different binder and structural materials
     - 2.1.1 separate structural and binder particles
     - 2.1.2 composite particles
     - 2.1.3 coated grains particles
   - 2.2 no distinct binder and structural materials
     - 2.2.1 single phase material partially molten
     - 2.2.2 fusing powder mixture

2. Liquid Phase Sintering Partial Melting

3. Full Melting
   - 3.1 single component single material
   - 3.2 single component alloyed material
   - 3.3 fusing powder mixture

4. Chemically Induced Binding

Steel

Titanium
Laser Beam Material Interaction

Input-parameters
- Laser power
- Laser spot size
- Layer thickness
- Hatch distance
- Scanning speed

Laser beam-material-interaction

Output-parameters
- Penetration depth
- Bead width
- Bead height
- Metallurgical properties

Understanding relations between input and output parameters (for example how laser power affect on penetration depth)
Generic laser AM powder bed system

- Power variation
- Scan Speed variation
- Scan line spacing variation

Constant:
- Layer Thickness
- Particle size

Fig. 1  Generic illustration of an AM powder bed system
Characteristics of each processes

- Common (direct) parameters in control:
  - Scan Speed
  - Laser Power
  - Hatching Distance

- Indirect parameters in control:
  - Laser Energy Density (LED)
  - LED/HD

- Scan Direction and Parameters Control

Fig. 8  Relationship between build rate, power, and feature definition
Examples of Manufacturing @ IIT Kharagpur
Parts for various applications
Bio medical implants manufactured

Dental Implants

Finger implants for CGCRI and Sancheti

Hip Stem and acetabular cup

© IIT Kharagpur : Contact Prof. C.S.Kumar (kumar@mech.iitkgp.ernet.in)
Medical Application (Assistive Devices) Design and Manufacture

CAD Design and Analysis

Direct Digital Manufacture using Laser based PBF AM
Part of project under IMPRINT Scheme
Further Research directions

• Custom powders
• Ex-situ nano composite additions
• New product geometries
• Laser process monitoring and control
• New materials
• Mixed atmospheres
• Micro systems, engineering, sensors
• Micro Robotics
Some software activities in AM@IIT Kgp

- Property function mapping in slicing
- Motion planning in 6 axis robots for AM
- Modelling of shrinkage and thermal effects
- Adaptive Slicing
- Curved Layer FDM
A Typical Simulation strategy

- Finite Element methods as one of the key analytical tools
- Coupled models for Thermal and Mechanical Analysis
- Recent combination with Materials processes
Initial models assumed

Figure 4. Physical mechanisms during additive processes.\textsuperscript{31}

Figure 5. Locally refined mesh.\textsuperscript{45}

Figure 6. Coarse mesh used at the substrate.\textsuperscript{31}

Figure 7. Gaussian heat source.

Figure 8. Laser beam modeling by Matsumoto et al.\textsuperscript{26}
Process Modelling

Useful when we are unable to instrument the machine or do online process monitoring.

Gives a reasonable idea of structure and properties in a qualitative sense from an numerical model perspective.
Laser Additive modelling work done at IIT Kharagpur:

3D Finite Element Simulation of Temperature Distribution using Element Birth & Death Technique

**Governing equation:**

\[ \rho_{\text{bed}} C_p(T) \frac{\partial T}{\partial t} = \nabla (K \cdot \nabla T) + Q_g \]

\( \rho_{\text{bed}} = \) Density of the powder bed=2670 Kg/ m\(^3\), \( K = \) Thermal conductivity \( C_p =920 \) J/Kg K, \( Q_g = \) Internal Heat generation due to laser irradiation.

- **Initial and boundary conditions:**
  - The initial temperature (\( T_i \)) is taken as equal to 30\(^\circ\)c, ambient temperature or the temperature of the chamber is taken as 40\(^\circ\)c.
  - \( K \frac{\partial T}{\partial z} \bigg|_{z=h} = h (T_{z=h} - T_a) \)
    - h= on surface
    - a= ambient
  - Note: Radiation is not considered at this stage.
Single layer simulation results:

(a) Index
(b) After 1 second
(c) After 2 seconds
(d) After 5 Seconds
(e) Mesh
Two Layer simulation results:

Fig (i) at 1.25 seconds as laser scans on first layer

Fig (ii) Mesh model

Fig (iii) at 0.5 sec after second layer is placed

Fig (iv) after 2 sec as the laser scans

P=190W, a=0.5mm, Layers of 6X1cm and 50 μm thick are deposited
(iv) Analytical evaluation of temperature field distribution

- The temperature history of the laser melted components has a significant influence on the residual stresses, distortion and hence the fatigue behaviour of the laser melted components.
- Analytical solution: Lot of CPU time could be saved and the post processing or related simulations could be carried out online much more rapidly and conveniently.

3D analytical solution is given by:

\[
T - T_0 = \frac{4P}{\rho C\pi \sqrt{4a\pi}} \int_{t'=0}^{t=t'} dt' (t-t')^{-0.5} \exp\left[ -\frac{2((x-\nu t')^2 + y^2)}{\sigma^2 + 8a(t-t')} - \frac{z^2}{4a(t-t')} \right]
\]  

...(3)

Where \( P = \) laser power, \( \sigma = \) beam radius, \( \nu = \) scanning velocity, \( a = \) diffusivity

P=190W;  
V=1 m/s  
P=2.67 g/cc  
C=920 J/Kg K  
\( \sigma = 0.05 \text{mm} \)

Fig (i) shows a 3D plot of temperature distribution across XY plane on the surface.
(v) Prediction of Microstructure during DMLS process

One dimensional heat equation for heating and cooling cycles.\(^{(23)}\)

**Case I: \(\delta \ll a\)**

\[
\Delta T(z,t) = \frac{P\delta}{AK} \text{ierc} \left(\frac{z}{\delta}\right)
\]

\[\ldots\ldots(4)\]

**Case II: \(\delta \sim a\)**

If thermal diffusion length is of the order of beam diameter, accounting for radial heat loss:

\[
\Delta T(z,t) = \frac{P\delta}{AK} \left[\text{ierfc} \left(\frac{z}{\delta}\right) - \text{ierfc} \left(\frac{z^2 + a^2}{\delta}\right)\right]
\]

\[\ldots\ldots(5)\]

Where \(t < \tau\), \(K\): Thermal conductivity, \(Z\): Depth, \(A\): spot area, \(P\): laser Power \(\tau\): Laser interaction time

**During cooling cycle:**

\[
\Delta T(z,t) = \frac{P}{AK} \left[\text{ierfc} \left(\frac{z}{\delta}\right) - \delta' \text{ierfc} \left(\frac{z}{\delta'}\right)\right]
\]

\[\ldots\ldots(6)\]

Where \(t > \tau\), \(\delta' = 2\sqrt{a^* (t - \tau)}\) and \(\delta = 2\sqrt{a^* t}\)
Numerical modelling of the PBF process

Solving the Transient temperature distribution $T(x,y,z)$ for 3D heat conduction in the bed

$$\rho \frac{\partial (C_p T)}{\partial t} = \frac{\partial}{\partial x} \left( K \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right)$$

with boundary conditions

$$T(x, y, z, 0) = T_0$$

$$K \frac{\partial T}{\partial n} + h_c (T - T_0) + \sigma \varepsilon (T^4 - T_0^4) = q \text{ as } (x, y, z) \in S_n, \quad q = \frac{2Q_1 \alpha_a}{\pi R_1^2} e^{-\frac{2R_0^2}{R_1^2}} \text{ as } y = y_0 \quad \text{and } q = 0 \text{ as } y \neq y_0,$$

Finite element thermal model developed to simulate the temperature field during laser densification

Simulation results from model (With and without volume shrinkage)

Alternative models with Lattice Boltzmann methods
Other Emerging Software tools

3DSim founded from University of Louisville
Software for Additive Manufacturing

More traditional route
MSC Software : Simufact (combines welding and forming simulators)
Further Research Involvements

• Investigating Material Properties of parts made using AM
• Ultrasonic Consolidation
  – Multi-functional, multi-material parts
• Dislocation Density based Crystal Plasticity Finite Element Modeling (DDCP-FEM)
• Modeling of metal powder bed fusion
• Magnetic signature
• Porous titanium implants & new materials
• Micro and Nano 3D Printing with Lasers
Micro and Nano 3D Printing

• Use of Femto Second Lasers
• Features of micron and sub micron size
• Wide variety of materials
  – Electronic
  – MEMS
  – Optical
  – Bio Nano
3D Printing

3D: Additive manufacturing along 3D Print Workflow
- Highest resolution 3D printer: Feature sizes down to 200 nm
- Multi-scale: nm, μm and mm sizes
- High-speed fabrication
- Simple workflow
Micro and nano scale printing

Applications

- Scaffolds for Cells
- Photonic Wire Bonding Optical Integration
- Micro-optics
- Maskless Lithography
- Microfluidics
- MEMS
- 3D Photonics
- Rapid Prototyping
Two-photon polymerization (TPP):
- Near-infrared laser
- Ultra-short laser pulses
- UV-curable photoresists
Application in micro & nano robotics

Magnetic Helical Micromachines

Micro Machines

Magnetic Helical Micromachines

Research Directions in AM @ IIT Kharagpur

- Material-Microstructure-Property Characterization
- Process Control strategies for
  - Part geometries
  - Graded properties
  - Cermets
- Surface finishing
- Mathematical Modeling

- Laser Work Station
  - Multi-material joining
  - Coating/cladding
  - Underwater welding
- Laser machining
  - Direct Slicing and Adaptive Slicing

- Surface finishing
- Cladding
  - Environmental protection

- Laser Work Station
  - Multi-material joining
  - Coating/cladding
  - Underwater welding
- Laser machining
  - Direct Slicing and Adaptive Slicing

Parts for Robotic Systems

Research Application areas
- Materials-microstructure-property mapping and control
- Curved layer FDM
- Innovative parts in robotics
- Scaffolds for biomedical applications
- Electron Beam Welding and Electron Beam Machining
- In process monitoring for process control

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Summary

• 3D Printing and additive manufacturing is a new technology and triggering innovations
• In its maturing stage there is need to validate complex theories needed in realisation of design to manufacture workflow
• New materials, processes and constant updates of these is exciting and also a challenge
• Simulation software aids significantly in the adoption of technology and confidence in its use
Concluding Remarks

• Additive Manufacturing and 3D Printing has revolutionized the way product and process innovation is taking place
• New and complex geometries
• New and complex processes
• Meso to micro and nano scale is feasible
• Support for Digital Manufacturing in Indian Ecosystem
• Research opportunities at Universities
Thank you for your kind attention!

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Thank You

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