Recent Advances in Wire-Based Additive Manufacturing

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Our Technical Group at a Glance

Our Focus

• A highly interdisciplinary group featuring members from both academia and industries covering a range of topics related to lasers.
• To discuss the technologies used in manufacturing applications that uses lasers for cutting, drilling, and welding processes.

Our Mission

• To benefit YOU
• To provide platform to optical community for connecting, Engaging and Exciting with others.
• To Organize webinars, social media, publications, technical events, business events, outreach
• Interested in presenting your research? Have ideas for TG events? Contact us at TGNonlinearOptics@osa.org.

Where To Find Us

• Website: www.osa.org/FL
• LinkedIn: https://www.linkedin.com/groups/8127636/9
Past/Upcoming Events:

1. Networking Event during OSA Laser Congress at Munich:
   Recent Trends in Laser Technology and Its Applications in Manufacturing
   Date: Monday, 30 Sep 2019 12:30-14:00
   Location: Austria Centre Vienna, Austria

2. Webinar 1:
   Recent Advances in Wire-based Additive Manufacturing
   Date: 09th January 2020, at 12:30 PM - 1:30 PM (Eastern Time (US and Canada))
   Dr. Yashwanth Kumar Bandari, Edison Welding Institute, Buffalo Manufacturing Works, USA

3. Panel Discussion during OSA High Brightness and Light-Driven Interaction Congress at Prague:
   Date: TBD
   Location: Prague Congress centre, Prague, Czech Republic
How to join this Group:

If you are OSA member: Log-in to your OSA Account and chose FL group in Technical Groups Category.

You can also join in our dedicated LinkedIn page:  
https://www.linkedin.com/groups/8127636/9

If you have any interesting activities/ideas or interested in giving a Webinar/Talk/Panel Discussion, do let me know by email nithi.physics@gmail.com
Today’s Webinar

Recent Advances in Wire-Based Additive Manufacturing

Dr. Yashwanth Kumar Bandari

Edison Welding Institute, Buffalo Manufacturing Works, USA
ybandari@ewi.org

Speaker’s Short Bio:
Ph.D. degree from Cranfield University, UK
Postdoc at the Oak Ridge National Lab (ORNL) USA
Large Scale Metal Additive Manufacturing – Processes, Configuration, and Challenges

by

Dr. Yash Bandari

Additive Manufacturing Applications Engineer
Edison Welding Institute (EWI)
OSA Technical Seminar
9th January 2020
Agenda

✓ Overview of Metal Additive Manufacturing (AM)
✓ Processes for building large scale metal parts – wire-based AM
✓ Types of wire AM processes – which is the best?
✓ Case studies
✓ Technicalities and challenges for wide adaption
✓ Futuristic goals and conclusions
What is Additive Manufacturing (AM)/3D-Printing?

• AM is a technology that enables the fabrication of complex, near net shape components by deposition of many consecutive layers of one or more materials.

• Metaphor of Sculptor vs House builder.
The Traditional Approach: Subtractive Manufacturing
Additive Manufacturing (AM)

Plastic

or

Metal

• Stereolithography
• Fusion deposition modelling
• .........
Metal AM // What is it?

Very Simply

- Also known as
  - Additive (Layer) Manufacture (A(L)M)
  - (Laser) Cladding
  - Buttering
  - Digital manufacture
  - Direct Light Fabrication
  - Direct Metal Casting (DMC)
  - Direct Metal (Laser) Deposition (DM(L)D)
  - Laser Direct Casting or Deposition
  - Laser casting
  - Laser clad casting
  - Laser consolidation
  - Laser curing
  - Laser Engineered Net Shaping (LENS)
  - Lasform
  - Laser melting
  - (Metal) Rapid Prototyping
  - Net shape manufacture
  - Net shape engineering
  - Shaped deposition manufacturing
  - Shaped melting
  - Selective Laser Sintering (SLS)
  - Selective Laser Melting (SLM)
  - Shaped Metal Deposition (SMD)
  - Shape Melting Technology (SMT)
  - Shape welding
  - Solid freeform fabrication (SFF)
Three main constituents are needed:

2. Feedstock;
3. Manipulator.

The combinations of different types of each constituent creates a wide range of metal AM processes.
Metal Additive manufacturing processes

- Beam
  - Laser
    - Wire
    - Powder
    - Powder bed
    - Blown powder
  - Electron beam
    - Wire/Powder
    - Wire fed/Powder bed
  - EBAM/Electron Beam Melting
    - WAAM

- Arc
  - TIG, MIG, Plasma
  - Wire

- LMD-w
- SLM
- LMD
Basic metal AM system configuration

- Slicing into layers
- Process Algorithms
- Layer thickness ranges
- Geometric Data Input (3D CAD)

Control System & Software

- Tool Paths and Process Parameters
- Build sequence strategy

Basic AM Hardware

- NC or robot Controller
- Motion System
- Heat Source
- Material Supply

Additional Functionality

- Inspection Shape/Defects
- Integrated Finishing

Additional Processes

- Powder/Wire/Combinations
- Robots, Gantries, Mirrors, Magnetics
- Laser, Electron Beam, Arc
Metal AM // Which system to use?

Resolution depends on the exact width-to-height ratio and depends on several factors but is usually at best 1.5 times the layer height.

For a single axisymmetric energy source at maximum melting efficiency:
The build rate depends on the square of the layer height.
## Direct feed - powder or wire?

<table>
<thead>
<tr>
<th></th>
<th>Powder</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Quality</strong></td>
<td>Variable</td>
<td>High (Ti, Fe, Ni), variable Al</td>
</tr>
<tr>
<td><strong>Feeding</strong></td>
<td>Complicated unless using side feed</td>
<td>Easy well established industrial process</td>
</tr>
<tr>
<td><strong>Material efficiency</strong></td>
<td>Typical 40 - 60%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Safety issues</strong></td>
<td>Yes – especially Ti/Al</td>
<td>No</td>
</tr>
<tr>
<td><strong>Recycling</strong></td>
<td>Possible with processing</td>
<td>Not required</td>
</tr>
<tr>
<td><strong>Out of position deposition</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Rotation problem</strong></td>
<td>Coaxial – no, side feed yes</td>
<td>CMT – no, plasma - yes</td>
</tr>
</tbody>
</table>
Wire-fed Metal AM

**Slice** an object into layers

**Programme** a robot or machine tool to trace out the layers

Using a deposition tool to **build up** your part
Wire fed Additive Manufacture – History

• **1926** Baker patented “The use of an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers”

• **1971** Ujiie (Mitsubishi) Pressure vessel fabrication using SAW, electroslag and TIG, also multiwire with different wires to give functionally graded walls

• **1993** Prinz and Weiss patent combined weld material build up with CNC milling – called Shape Deposition Manufacturing (SDM)

• **1994-99** Cranfield University develop Shaped Metal Deposition (SMD) for Rolls Royce for engine casings, various processes and materials were assessed – still in production
Electron Beam Additive Manufacturing (EBAM)
Wire + Arc AM (WAAM)

Plasma or TIG based deposition

MIG based deposition
Laser Metal Deposition with wire (LMD-w)
## Direct feed: E-Beam or Laser or Arc?

<table>
<thead>
<tr>
<th>Criteria</th>
<th>E-Beam</th>
<th>Laser</th>
<th>Arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>Capital</td>
<td>High ($400k – 4kW)</td>
<td>Low-Medium ($100k – 4kW)</td>
</tr>
<tr>
<td></td>
<td>Running</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Power efficiency</td>
<td>&gt;80%</td>
<td>10% (CO2 lasers)</td>
<td>&gt;80% (MIG)</td>
</tr>
<tr>
<td>Heat and Mass transfer control</td>
<td>Yes</td>
<td>Yes</td>
<td>No (MIG)</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Good</td>
<td>Very Good</td>
<td>Poor (MIG)</td>
</tr>
<tr>
<td>Feature size</td>
<td>0.5mm (upwards)</td>
<td>0.2mm (upwards)</td>
<td>1mm (upwards)</td>
</tr>
<tr>
<td>Residual stress</td>
<td>Less</td>
<td>Less</td>
<td>High</td>
</tr>
<tr>
<td>Safety issues</td>
<td>Very high</td>
<td>Very high</td>
<td>Medium</td>
</tr>
<tr>
<td>Build rate</td>
<td>High – very high</td>
<td>Medium - high</td>
<td>Medium - high</td>
</tr>
</tbody>
</table>
## Organizations applying wire-based AM

<table>
<thead>
<tr>
<th>Process</th>
<th>Organization/Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBAM</td>
<td>Edison welding institute (EWI), Sciaky, FAMAero, Lockheed Martin, University of waterloo etc.</td>
</tr>
<tr>
<td>LMD-w</td>
<td>Edison welding institute (EWI), Oak ridge national lab, GKN Aerospace, Additec, Fraunhofer, RWTH Achen, SMU Texas, Miller electric, MWES etc.</td>
</tr>
<tr>
<td>WAAM</td>
<td>Edison welding institute (EWI), Oak ridge national lab, Lincoln electric, Cranfield University, IIT Bombay, Gefertec, TWI, University of Nottingham, Wollongong University, Norsk Titanium, Glen Almond Technologies, LM UK etc.</td>
</tr>
</tbody>
</table>
Wire-feed Process features – deposit composition control using multiple feeds

Multi wire approach

Wire + Powder

3 wire (Al8%Cu1.5%Mg – 140HV)
Part features

- Angled and horizontal walls
- Straight near net shape Ti thin wall
- Machined intersections
- Medium complexity 2D part
- Weight efficient structure
- With mixed materials
Example parts - 12 x projectiles

Mass 32 kg each // Deposition rate 4 kg/hr

After machining

After assembly and just before firing
## Case studies

Landing gear component

<table>
<thead>
<tr>
<th></th>
<th>Before Machining</th>
<th>After Machining</th>
<th>Buy-to-fly</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>240 kg</td>
<td>21 kg</td>
<td>11.6</td>
<td>91%</td>
</tr>
<tr>
<td>AM</td>
<td>24 kg</td>
<td>21 kg</td>
<td>1.15</td>
<td>13%</td>
</tr>
</tbody>
</table>
Other titanium parts
Tandem robots - Aluminium wing rib – case study
This manufacturing method saved 500kg of material

<table>
<thead>
<tr>
<th>Design option (MRR = 65 kg/h)</th>
<th>BTF</th>
<th>Cost (£k)</th>
<th>Cost red.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machined from solid</td>
<td>45</td>
<td>4.9</td>
<td>-</td>
</tr>
<tr>
<td>WAAM</td>
<td>12.3</td>
<td>2</td>
<td>58%</td>
</tr>
</tbody>
</table>
## Example mechanical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Titanium</th>
<th>Aluminium</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6Al4V</td>
<td>2319</td>
<td>5087</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Horizontal rolled</td>
</tr>
<tr>
<td>2% Yield (MPa)</td>
<td>870</td>
<td>810</td>
<td>1020</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>920</td>
<td>890</td>
<td>1075</td>
</tr>
<tr>
<td>Elong. (%)</td>
<td>12.2</td>
<td>20.3</td>
<td>13</td>
</tr>
</tbody>
</table>
Wire-fed Technicality/Challenges

Technicality

System Development
- WAAM/LMD-w/EBAM
  - Process type
  - Process algorithms
  - Feature building
  - Build strategies
  - New processes
- Other processes
  - 2.5D rolling
  - Laser peening
  - Grain structure measurement
  - Hybrid manufacture
  - Integrated NDT

Hardware
- Precision wire feeding
- Local shielding
- Ruggedisation
- Process monitoring
- Robotic/Gantry systems
- Machine tools

CAM Software
- Wall width control
- Build sequence GUI
- Feature building
- Feature recognition
- Auto build strategy

Commercial systems

Materials
- New
  - High strength aluminium
  - Refractory metals
  - Maraging steels
  - Super-alloys
  - Metal foams
  - MMCs
  - Low CTE materials
  - Mixed material systems
- Performance
  - Tensile
  - Fatigue
  - Fracture toughness
  - Crack propagation
  - Corrosion

Qualified materials

Design Tools
- Optimisation
  - Part to build design
  - Hybrid manufacture decision support system
  - Knowledge expert system
  - Computer aided planning

Mature Wire-based AM

Industrial Applications

Design capability
Implementing smart manufacturing (Ideas)

- Cobots – personal assistant like siri, alexa etc.
- Remote operator access – operator less part building
- Data logging – save all the process data
- Cloud computing – save the data in cloud for anyone to access
- Machine learning – predict when to change consumables, safety concerns
- Data analytics – perform in-situ monitoring and analyse
- Process simulation (not only visualization) – predict distortion, residual stresses etc
- Sharing economy – anyone can use the machine
Future - Tandem operations (Hybrid)

Deposition robots

Machining robots
AM cell of the future (Hybrid)

Machining

Deposition robots
Conclusions

- **Wire-fed Additive Manufacturing** is a feasible solution for low to medium complexity, **medium to large scale metal parts**

- **Any material** available in the form of wire can be applied

- **High deposition rates**, unlimited build volume, low capital and material costs

- WAAM, LMD-w, EBAM – each of them has pros/cons

- Qualification and certification still a bottle neck

- **Smart manufacturing** can be applied like cobots, cloud computing, remote access, machine learning, data analytic etc.
Thanks for your attention!

Dr. Yash Bandari
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