Additive Manufacturing with Steels feedstock (excluding Stainless Steel)

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COMPETENCE UNIT 27: Additive Manufacturing with Steels feedstock (excluding Stainless Steel)

Behaviour in AM – General Considerations

• Introduction
• Overview of Steels Used in Additive Manufacturing (AM)
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• Solidification of Molten Pool & Physical Phenomenon
• Modelling and Finite Element Analyses
• Thermal Cycles and Heat Flow
• Microstructure, Grain Size and Overview of Defects
• Mechanical Properties
Introduction

• General expectations from steels include but not limited to:
  • Relatively lower prices
  • Variety of achievable microstructure features
  • Strength, ductility, hardness, toughness and wear resistance
  • Corrosion resistance and general longevity under harsh environmental conditions
  • Functionalities such as ferromagnetism or invar effects
• During additive manufacturing (AM), steels are subjected to time temperature profiles which are very different from the ones encountered in conventional process routes, and hence the resulting microstructures differ strongly as well.
• This may lead to several advantages as well as challenges [1].
Overview of Steels Used in Additive Manufacturing (AM)

- The solidification structure, grain structure, texture and microstructure are highly dependent on the process and the chemical composition of the alloys, which, in turn, significantly affect the properties of the AM components [2].

- AM of steel looks to be still in its middle stages of maturity and adoption, where new grades of steel more suitable for AM and with better performances are expected to be designed in the future [3].
Overview of Steels Used in Additive Manufacturing (AM)

- There are mainly two AM classes which are used to process for the majority of steel parts as Powder Bed Fusion and Directed Energy Deposition.
- Additional to these, minor applications exist using Binder Jetting and Material Extrusion.
- Together with these, welding based Directed Energy Deposition processes are also commonly found in the literature.

[1]
General Information on AM

• The process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining [5].
• A manufacturing process in which the workpiece is built up in successive units or layers [6].
General Information on AM

1. AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software.

2. This file should be converted to a STL or AMF file format.

3. There may be some general manipulation of the file so that it is the correct size, position, and orientation for building.

4. The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, etc.

5. Building the part is mainly an automated process and the machine can largely carry on without supervision.

6. Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine.

7. Once removed from the machine, parts may require an amount of additional cleaning, polishing, machining or thermal treatment up before they are ready for use. [7]
### Categories of Additive Manufacturing

<table>
<thead>
<tr>
<th>Process</th>
<th>Alternative Names</th>
<th>Description</th>
<th>Typical Materials</th>
<th>Strengths</th>
<th>Typical Materials</th>
<th>Typical Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAT</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Powder Bed Fusion (PBF)</td>
<td>LIGA™ - Laminated Object Modeling; DML™ - Direct Metal Laser Sintering; SLM™ - Selective Laser Melting; DSM™ - Direct Sheet Metelling; SD™ - Selective Heat Melting</td>
<td>Powdered materials are successively sintered to create a solid object by melting it together using a laser beam to fuse the powdered metals. This process allows for high accuracy and flexibility.</td>
<td>Plastic, Metal, Ceramic, and Polymers</td>
<td>High level of accuracy and complexity, Smooth surface finish, Accommodates large build areas</td>
<td>Engineered Plastics, Metal, Ceramic, Glass, and Wood</td>
<td></td>
</tr>
<tr>
<td>Binder Jetting</td>
<td>SLM™ - Selective Laser Melting; DML™ - Direct Metal Laser Sintering; SLM™ - Selective Laser Melting; DSM™ - Direct Sheet Metelling; SD™ - Selective Heat Melting</td>
<td>Powdered materials are sintered to create a solid object by melting it together using a laser beam. The process allows for high accuracy and flexibility.</td>
<td>Plastic, Metal, Ceramic, and Polymers</td>
<td>High level of accuracy and complexity, Smooth surface finish, Accommodates large build areas</td>
<td>Engineered Plastics, Metal, Ceramic, Glass, and Wood</td>
<td></td>
</tr>
<tr>
<td>Sheet Lamination</td>
<td></td>
<td>Sheets of material are stacked and laminated together to form an object. The process allows for high accuracy and flexibility.</td>
<td>Paper, Plastic, Ceramics, and Metal Foil/Tapes</td>
<td>High level of accuracy and flexibility, Allows for multiple layers</td>
<td>Paper, Plastic, Ceramics, and Metal Foil/Tapes</td>
<td></td>
</tr>
<tr>
<td>Material Extrusion</td>
<td></td>
<td>Material is extruded through a heated nozzle</td>
<td>Plastic, Metal, and Ceramic</td>
<td>High speed and efficiency</td>
<td>Plastic, Metal, and Ceramic</td>
<td></td>
</tr>
<tr>
<td>Directed Energy Deposition (DED)</td>
<td></td>
<td>Material is deposited layer by layer to create a solid object. The process allows for high accuracy and flexibility.</td>
<td>Metal, Ceramic, and Polymers</td>
<td>High level of accuracy and flexibility, Allows for multiple layers</td>
<td>Engineered Plastics, Metal, Ceramic, Glass, and Wood</td>
<td></td>
</tr>
</tbody>
</table>

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## Powder Bed Fusion

<table>
<thead>
<tr>
<th></th>
<th>L-PBF</th>
<th>E-PBF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Source</strong></td>
<td>Laser</td>
<td>Electron</td>
</tr>
<tr>
<td><strong>Pre-heating</strong></td>
<td>Up to 250°C</td>
<td>Up to 1100°C</td>
</tr>
<tr>
<td><strong>Processing Atmosphere</strong></td>
<td>Protective gas (Argon or Nitrogen)</td>
<td>Vacuum (Supported by Helium)</td>
</tr>
<tr>
<td><strong>Powder Size</strong></td>
<td>15 µm - 45 µm</td>
<td>45 µm - 105 µm</td>
</tr>
<tr>
<td><strong>Layer Thickness</strong></td>
<td>20 µm - 50 µm</td>
<td>50 µm - 100 µm</td>
</tr>
<tr>
<td><strong>Dimensional Accuracy</strong></td>
<td>100 µm - 200 µm</td>
<td>400 µm - 500 µm</td>
</tr>
<tr>
<td><strong>Surface Quality Ra</strong></td>
<td>5 – 10 µm</td>
<td>25 - 35 µm</td>
</tr>
<tr>
<td><strong>Geometric Complexity</strong></td>
<td>High</td>
<td>Intermediate</td>
</tr>
<tr>
<td><strong>Melting Rates</strong></td>
<td>7 cm³/h - 70 cm³/h</td>
<td>55 cm³/h - 80 cm³/h</td>
</tr>
<tr>
<td><strong>Maximum Available Build Volume to be used for Superalloys</strong></td>
<td>Up to 500 mm by 500 mm or 400 mm by 800 mm x 500 mm height</td>
<td>Up to Ø 250 mm x 400 mm height</td>
</tr>
</tbody>
</table>
Laser Powder Bed Fusion (L-PBF)

- Single or multiple fibre lasers having a laser power between 100 and 1000 W, a wavelength between of about 1064 nm and a focused spot size between 50 – 100 µm are preferred.
- Having a powder particle size range of 15 µm- 45 µm, L-PBF AM employs argon or nitrogen as a protective atmosphere and processes parts generally below 250°C by heating the base plate [9].

- PBF AM processes are characterized with many parameters.
- Each layer and/or exposure area such as upskin, contour, downskin or support, has its own process parameters including input power, layer thickness, hatch distance and scanning speed.
L-PBF (Solidification of Molten Pool & Physical Phenomenon)

- Re-coated powders of the current layer and the powders of preceding layers are melted in L-PBF using fibre lasers to have Gaussian distribution.
- This fact and thermal cycles like conduction, convection and radiation together with liquid flow influence the melt pool shapes.

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L-PBF (Modelling and Finite Element Analyses)

- Modelling and finite element analyses in L-PBF are conducted for several reasons such as heat flow - temperature estimation, related microstructural predictions including melt-pool shape – dimensions, residual stresses and induced distortions.

- Among traditional manufacturing methods, welding process is the most similar comparing to additive manufacturing in terms of both moving heat source and addition of molten filler material to the base part.

- The very first analytical models for a moving heat source along one axis are represented in two different publications to form the onset of further studies [11,12]. The initiated models are developed in order to cover Cartesian coordinates for the conduction of heat in a stationary medium [13]. Later on, analytical models are converted to dimensionless form including the travel speed of heat source [14]. Initiatory analytical modeling of a laser application was accomplished for laser welding, adopting the laser as a line source [15].
L-PBF (Modelling and Finite Element Analyses)

- Rosenthal’s equation is provided below [11].
- T0 is the temperature at locations far from the top surface, k is the thermal conductivity, V is the scanning velocity, and α is the thermal diffusivity.
- The laser moves along the x-axis, in which the moving coordinate of x – Vt is replaced by ξ.
- Since the Rosenthal equation does not account for any temperature-dependent material properties, the properties at room temperature.

\[ T = T_0 + \frac{\lambda P}{2\pi k r} \exp \left[ -\frac{V(r+\xi)}{2\alpha} \right] \]

- \( r \) is the distance from the heat source, defined as:

\[ (\xi^2 + y^2 + z^2)^{0.5} \]

- Another drawback of Rosenthal’s equation that it considers the heat source as a point source.
• If the moving heat source is not modelled as a point heat source, it is distinguished according to two characteristics which are the shape and the size of the heat source, and the distribution of the heat flux.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Method</th>
<th>Source shape</th>
<th>Heat flux</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carslaw and Jeager [9]</td>
<td>1959</td>
<td>A</td>
<td>Point, line, and infinite strip</td>
<td>Uniform</td>
<td>- Introduced the heat source approach.</td>
</tr>
<tr>
<td>Takazawa [26]</td>
<td>1966</td>
<td>N</td>
<td>Infinite strip</td>
<td>Uniform</td>
<td>- Approximate relationship for the maximum temperature rise within a half-space as a function of Peclet number.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Width of the source in the moving direction as a length scale.</td>
</tr>
<tr>
<td>Paek and Gagliano [27]</td>
<td>1972</td>
<td>A/E</td>
<td>Circle</td>
<td>Uniform</td>
<td>- Half-space and finite body.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Instantaneous point source method.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Transient solution is the form of the modified Bessel function of first kind.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Integral over the surface of the heat source is numerically solved.</td>
</tr>
<tr>
<td>Weichert and Schoner [12]</td>
<td>1978</td>
<td>A</td>
<td>Line, plane, and cube</td>
<td>Uniform</td>
<td>- Exponential transformation is used.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Effect of aspect ratio and source speed are numerically investigated.</td>
</tr>
<tr>
<td>Eager and Tsai [28]</td>
<td>1983</td>
<td>A/E</td>
<td>Circle</td>
<td>Gaussian</td>
<td>- Superposition of instantaneous point sources with different powers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Single integral that is solved numerically.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Heat source radius as the length scale.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Effect of the aspect ratio is investigated.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Width of the source in the moving direction and source radius as the length scale for rectangular and circular heat sources, respectively.</td>
</tr>
<tr>
<td>Tian and Kennedy, Jr.</td>
<td>1995</td>
<td>A</td>
<td>Ellipse/rectangle</td>
<td>Uniform/parabolic</td>
<td>- Green’s function method and point source method are used.</td>
</tr>
</tbody>
</table>
L-PBF (Modelling and Finite Element Analyses)

- For laser powder bed fusion AM processes, heat input is commonly assumed to have a horizontal distribution and a vertical absorption.

- Since most of the laser intensity is reflected and only a fraction is absorbed, heat input is frequently modeled as a surface heat source with a horizontal intensity similar to a bell shaped form.

- A widely accepted model for such intensity is the Gaussian distribution function [18].

\[
Q(x, y, z) = \frac{8qP}{\pi d^2} \exp \left( -\frac{(x-x_0)^2 + (y-y_0)^2}{d^2} \right) \frac{1}{h_p} \exp \left( -\frac{abs(z-z_0)}{h_p} \right)
\]

- \( \rho \): Density
- \( C_p \): Heat capacity
- \( k \): Thermal conductivity
- \( h \): Heat convection coefficient
- \( q \): Input heat flux
- \( n \): Unit normal vector
- \( Q \): Laser heat generation
- \( P \): Total laser power
- \( \eta \): Laser absorption coefficient
- \( d \): Diameter of the laser beam
- \( x_0 \): Pulse center x-coordinate
- \( y_0 \): Pulse center y-coordinate
- \( z_0 \): Pulse center z-coordinate
- \( h_p \): Penetration depth of the laser
- \( \sigma \): Stefan-Boltzmann constant
- \( k_{\text{powder}} \): Thermal conductivity (powder)
- \( k_{\text{eq}} \): Effective thermal conductivity of powder bed
- \( k_g \): Thermal conductivity of gas (between particles)
- \( k_s \): Thermal conductivity of the skeletal solid
- \( B \): Deformation parameter of the particle (\( B = 1 \) when the particle surface is that of a sphere)
- \( \varphi \): Porosity
- \( k_R \): Conductivity by radiation
- \( \phi \): Flattened surface fraction of particle in contact with another particle
- \( k_{\text{contact}} \): Contact conductivity between two particles according to the value of \( \phi \)
L-PBF (Modelling and Finite Element Analyses)

- With the application of thermal modelling practices, thermal cycles, heat flow and peak temperature of Steel L-PBF can be predicted as difficult to measure quantities, especially during process.
L-PBF (Thermal Cycles, Heat Flow, Transitions)

- Such information can be used to compare the temperature changes during process with significant limits of Ae1 to Ae3 (the lowest temperature at which the single phase austenitic structure is stable).

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[21]
L-PBF (Molten Pool Shape and Heat Affected Zones)

• Additional to these, temperature profile prediction of steels are crucial since they provide important information on the regime of the process according to number of passes or layers.

• Other important results to derive from such information are primary and secondary heat affected zones.

Schematics on L-PBF modelling of 4130 steels

[21]
L-PBF (Mechanical Modelling)

• Although mechanical modelling and simulations can be conducted for L-PBF of steels, the resultant situation is much more complicated comparing to other materials, such as nickel based super alloy, and special care should be given.

• Distortions predictions are relatively easy among these, while residual stress predictions need additional work. In this regard, residual stress generation cannot be simplified to restricted thermal expansions, but transformations should also be considered.
• L-PBF offers the highest steel grade variety among all AM processes.
Energy Density

- A widely accepted practice to initiate the utilization of basic process parameters is to calculate energy density and conduct process trials followed by density measurements and microstructural evaluations.
- Line Energy Density (LED), Surface Energy Density (SED) or Volumetric Energy Density (VED) can be used in accordance with the scope of the study.
- In these equations, the input power value (P) is divided by scanning speed (V), scanning speed and hatch distance (h) or scanning speed, hatch distance and layer thickness (t) depending on the dimension being surveyed.

\[
\text{LED} = \frac{P}{V} \\
\text{SED} = \frac{P}{V \cdot h} \\
\text{VED} = \frac{P}{V \cdot h \cdot t}
\]

[18]
Energy Density

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# Mechanical Properties

## Tensile properties of various steels, fabricated by LPB

<table>
<thead>
<tr>
<th>Ferrous alloy</th>
<th>Process</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>EL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (electrolytic, annealed) [201]</td>
<td>Wrought</td>
<td>240-280</td>
<td>70-140</td>
<td>40-60</td>
</tr>
<tr>
<td>Iron (0.004% C) [202]</td>
<td>LPB</td>
<td>450</td>
<td>380</td>
<td>20</td>
</tr>
<tr>
<td>Iron (0.02% C) [37]</td>
<td>LPB</td>
<td>350-410</td>
<td>240-300</td>
<td>10</td>
</tr>
<tr>
<td>AISI 1005 [203]</td>
<td>LPB</td>
<td>305</td>
<td>164</td>
<td>-</td>
</tr>
<tr>
<td>AISI 1033 [34]</td>
<td>LPB</td>
<td>-</td>
<td>650&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>AISI 1050 [34]</td>
<td>LPB</td>
<td>-</td>
<td>800&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>AISI 1075 [34]</td>
<td>LPB</td>
<td>-</td>
<td>1150&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>4130 – as built [149]</td>
<td>LPB</td>
<td>1503 ± 69</td>
<td>1344 ± 67</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>17-4 PH SS ASTM A564 [125]</td>
<td>Wrought (ST + PA)</td>
<td>1310</td>
<td>1170</td>
<td>10</td>
</tr>
<tr>
<td>17-4 PH SS [136]</td>
<td>LPB</td>
<td>1255 ± 3</td>
<td>661 ± 24</td>
<td>16.2 ± 2.5</td>
</tr>
<tr>
<td>304 SS [204]</td>
<td>LPB (orthogonal to building direction)</td>
<td>715.5 ± 1.5</td>
<td>568 ± 2</td>
<td>41.7 ± 1.1</td>
</tr>
<tr>
<td>304 [205]</td>
<td>LPF longitudinal</td>
<td>710</td>
<td>448</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>LPF transverse</td>
<td>324</td>
<td>655</td>
<td>70</td>
</tr>
<tr>
<td>18Ni-300 M [77]</td>
<td>Wrought</td>
<td>1000-1170</td>
<td>760-895</td>
<td>6-15</td>
</tr>
<tr>
<td>18Ni-300 M [77]</td>
<td>LPB</td>
<td>1290 ± 114</td>
<td>1214 ± 99</td>
<td>13.3 ± 1.9</td>
</tr>
<tr>
<td>18Ni-300 M [142]</td>
<td>LPB</td>
<td>1165 ± 7</td>
<td>915 ± 7</td>
<td>12.44 ± 0.14</td>
</tr>
<tr>
<td>4340 [53] 593 °C stress-relieved</td>
<td>LPB</td>
<td>1289-1310</td>
<td>1365</td>
<td>16-17</td>
</tr>
<tr>
<td>HY100 [39] as per MIL-S-16216</td>
<td>Wrought</td>
<td>Not specified</td>
<td>690-827</td>
<td>&gt;18%</td>
</tr>
<tr>
<td>HY100 – as built (xy) [39]</td>
<td>LPB</td>
<td>1200 ± 15</td>
<td>1160 ± 15</td>
<td>6 ± 2</td>
</tr>
<tr>
<td>HY100 [39] direct temper 650 °C-2 h-AC (xy)</td>
<td>LPB</td>
<td>880 ± 10</td>
<td>710 ± 30</td>
<td>8 ± 3</td>
</tr>
<tr>
<td>HY100 [39] 900 °C-1 h-WQ + 650 °C-2 h-AC</td>
<td>LPB</td>
<td>780 ± 10</td>
<td>690 ± 10</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>H13 [206]</td>
<td>LPB</td>
<td>1000-1200</td>
<td>-</td>
<td>0.9-1.9</td>
</tr>
<tr>
<td>H13 [207]</td>
<td>LPB</td>
<td>1370 ± 175.1</td>
<td>1003.0 ± 8.5</td>
<td>1.7 ± 0.6</td>
</tr>
<tr>
<td>M2 – heat treated [36]</td>
<td>Wrought</td>
<td>1611</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>M2 [36]</td>
<td>LPB</td>
<td>1286</td>
<td>-</td>
<td>0.6</td>
</tr>
</tbody>
</table>

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Electron Beam Powder Bed Fusion (E-PBF)

- Also known as EBM, this AM type uses a high energy electron beam.
- The power used in E-PBF AM processes can be as high as 3 kW with a limited part resolution due to the larger focus beam size of 180 μm.
- The particle size of the metal powders used for E-PBF AM are between 45 μm and 105 μm in accordance with the larger minimum focus size and the melt pool width/depth associated with it [9].

- The consequences of using high power and large powder particle sizes, brings the risk of spreading the powder and shadowing the electron beam itself.
- Several measures are taken to pack the powder bed and eliminate this risk such as applying vacuum to building chamber or preheating (up to 1100°C) the powder before melting in order to avoid powder smoke in the chamber [9].
Electron Beam Powder Bed Fusion (E-PBF)

• Due to aforementioned issues, E-PBF process cycle is slightly different than L-PBF to include pre/post-heating at each layer.
E-PBF (Process Parameters)

- Process parameters of E-PBF AM is also different than L-PBF having another energy source as well as altered process cycle.

- Although E-PBF AM has additional scanning applications at pre/post-heating steps, melting strategies are similar to L-PBF AM.

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current [mA]</td>
<td>15</td>
</tr>
<tr>
<td>Max Current [mA]</td>
<td>18</td>
</tr>
<tr>
<td>Speed Function</td>
<td>63</td>
</tr>
<tr>
<td>Beam speed [mm/s]</td>
<td>3425</td>
</tr>
<tr>
<td>Focus offset [mA]</td>
<td>15</td>
</tr>
<tr>
<td>Line offset [mm]</td>
<td>0.125</td>
</tr>
<tr>
<td>Thickness function</td>
<td>2</td>
</tr>
</tbody>
</table>

[25] [26]
**E-PBF (Available Steel Grades)**

- Majority of research is going on for stainless steels, such as 316L, with the application of E-PBF process.
- However, since the scope of this course series excludes stainless steels, I will just highlight H13 tool steel as a grade which can be processable with E-PBF.

![Pie chart showing distribution of steel grades](image)

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>Number of Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maraging steel</td>
<td>50</td>
</tr>
<tr>
<td>420 SS</td>
<td>30</td>
</tr>
<tr>
<td>17-4 PH SS</td>
<td>25</td>
</tr>
<tr>
<td>304L SS</td>
<td>20</td>
</tr>
<tr>
<td>316L SS</td>
<td>15</td>
</tr>
<tr>
<td>M2 tool steel</td>
<td>10</td>
</tr>
<tr>
<td>P20 tool steel</td>
<td>5</td>
</tr>
<tr>
<td>H13 tool steel</td>
<td>3</td>
</tr>
<tr>
<td>HY-100</td>
<td>1</td>
</tr>
<tr>
<td>Low alloy steel</td>
<td>1</td>
</tr>
<tr>
<td>Pure Iron</td>
<td>1</td>
</tr>
</tbody>
</table>

[23] Research on AM of Steels
### PBF (Available Steel Grades)

**Fe-Based Alloys**

- **316L (1.4404)**

---

**SLM Solutions**

- **17-4PH (1.4542)**
- **1.2709**
- **H13 (1.2344)**
- **Invar 36°**

---

# PBF (Available Steel Grades)

## EOS Materials Metal Portfolio Overview

<table>
<thead>
<tr>
<th>Product class</th>
<th>Product name</th>
<th>Material type*</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steels</td>
<td>EOS MaragingSteel MS1</td>
<td>AMS6514, 18Ni300</td>
<td>Series injection molding tools, mechanical engineering parts</td>
</tr>
<tr>
<td></td>
<td>EOS ToolSteel 1.2709</td>
<td>EN 1.2709</td>
<td>Series injection molding tools, mechanical engineering parts</td>
</tr>
<tr>
<td></td>
<td>EOS ToolSteel H13**</td>
<td>ASTM A681</td>
<td>Hot working applications, forgings, die casting tools, hot extrusion tools</td>
</tr>
<tr>
<td></td>
<td>EOS CaseHardeningSteel 20MnCr5**</td>
<td>EN 10084</td>
<td>Automotive and general engineering applications, gears, spare parts</td>
</tr>
<tr>
<td></td>
<td>EOS StainlessSteel QF1</td>
<td>Stainless steel 1.4441 / 1.4542</td>
<td>Functional prototypes and series production parts, mechanical engineering and medical technology</td>
</tr>
<tr>
<td></td>
<td>EOS StainlessSteel PH1</td>
<td>AISI 4540, UNS S15500</td>
<td>Functional prototypes and series production parts, mechanical engineering parts</td>
</tr>
<tr>
<td></td>
<td>EOS StainlessSteel 316L</td>
<td>AISI 316L, UNS S31673, P138</td>
<td>Engineering parts for corrosive environments, can be used for medical parts, e.g. endoscopy and orthopedics</td>
</tr>
<tr>
<td></td>
<td>EOS StainlessSteel 316L VPro</td>
<td>AISI 4404, UNS S31603</td>
<td>Press-and-sinter applications which require high productivity</td>
</tr>
<tr>
<td></td>
<td>EOS StainlessSteel CX</td>
<td>Precipitation hardening tool steel</td>
<td>Series injection molding tools for corrosive plastic and rubber, mechanical engineering parts</td>
</tr>
<tr>
<td></td>
<td>EOS StainlessSteel 17-4PH</td>
<td>AISI 4542, UNS S17400, A564M</td>
<td>Acid and corrosion resistant engineering parts, medical instruments (surgical tools, orthopedic instrumentation)</td>
</tr>
</tbody>
</table>
PBF (Available Steel Grades)
Directed Energy Deposition

• Creates parts by directly melting materials and depositing them on the workpiece, layer by layer.
• Mostly used with metal powders or wire source materials.
• Consists of a nozzle mounted on a multi-axis system or arm inside a closed frame filled with shielding gas or under vacuum.
• Can be applied using various metals and their alloys.
Types of Directed Energy Deposition

Directed Energy Deposition

Powder Feeding Systems
- Laser Directed Energy Deposition
- Arc-Plasma Directed Energy Deposition

Wire Feeding Systems
- Electron Beam Directed Energy Deposition
- Laser Directed Energy Deposition
Atmosphere Control / Shielding Gasses

- Metals during DED can react with oxygen, nitrogen, moisture in air, or combination thereof, forming significant oxides or nitrides.
- Oxygen is one of the most significant causes of poor quality in DED.
- Oxides may cause lack of fusion or porosity, or both, on the outer surface and between layers.
- Generally, oxygen levels at the melt pool typically need to be less than 100 ppm. This level decreases down to 1 ppm for extremely oxygen-sensitive materials, such as some rare-earth materials.
- Processing atmosphere is typically controlled by operating in a vacuum; with a local inert gas purge; or with a fully inert gas purged enclosure [27].
Atmosphere Control / Shielding Gasses

• Vacuum: Processes using an electron beam energy source are normally operated in a vacuum environment; processes using a laser may be operated in a vacuum environment, but typically are not. Processes that operate in a vacuum environment typically use feedstock in the form of wire, which is mechanically fed from a spool. Electron beam systems typically require a vacuum level of 10-2 Pa or lower.

• Local Inert Gas Shielding: Local inert gas purge is commonly used with arc plasma processes and may be used with laser processes. Local inert gas shielding typically protects the area around the melt pool until it solidifies and cools to the point where it will not oxidize. For some more reactive materials such as titanium, a trailing shield, which provides additional shielding behind the molten pool, may also be used. Typically, the gases used are inert, such as argon or helium.

• Full Inert Gas Enclosures (Chambers): Full inert gas enclosures are often used for laser processes, although they may be used with arc plasma processes as well. Full environmental chambers usually include some gas purification system to continuously remove oxygen and moisture from the chamber gas. These gas purification systems run continuously. Drawbacks of the full environmental enclosure centre on the difficulty of moving parts easily into and out of the enclosure [27].
Laser Directed Energy Deposition

- Also known with various commercial names and acronyms like Direct Metal Deposition (DMD), Laser Cladding (LC), Laser Engineering Net Shaping (LENS), Laser Metal Deposition (LMD).
- Creates parts by directly melting powder materials with the help of laser energy and depositing them on the workpiece, layer by layer.
- Consists of a nozzle mounted on a multi-axis system or arm inside a closed frame filled with shielding gas or under vacuum.
- Available materials include cobalt, iron, nickel alloys, martensitic stainless steel and tungsten carbide, bronze alloys.

The major process parameters involved in L-DED and their effect on various properties are presented in the following table.

<table>
<thead>
<tr>
<th>S. no.</th>
<th>Parameter</th>
<th>Effect on increasing parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Laser power</td>
<td>Width and height increases, Dilution increases, Better bonding with previous layers</td>
</tr>
<tr>
<td>2.</td>
<td>Scan speed</td>
<td>Reduced track width, track height and bonding with previous layer, Refined grains and enhanced strength</td>
</tr>
<tr>
<td>3.</td>
<td>Powder feed rate</td>
<td>Increase in track height, Enhanced deposition rate</td>
</tr>
<tr>
<td>4.</td>
<td>Laser spot size</td>
<td>Increases minimum feature size</td>
</tr>
<tr>
<td>5.</td>
<td>Hatch spacing/Transverse traverse index</td>
<td>Increased porosity</td>
</tr>
<tr>
<td>6.</td>
<td>Layer thickness</td>
<td>Roughness increases and stair-stepping effect</td>
</tr>
</tbody>
</table>
L-DED (Solidification of Molten Pool & Physical Phenomenon)

- L-DED has major differences comparing to L-PBF which comes from feeding the powder via a nozzle and thus creating the beads on a solid surface rather than a powder bed.
- As a result of these and also as indicated in the process parameters, additional aspects affect the solidification and thus the temperature profile.
- In most cases, continuum and static material considerations of L-PBF are not sufficient to define the phenomenon of L-DED which is highly influenced by mass and heat transfer due to the flow of molten metal.
L-DED (Solidification of Molten Pool & Physical Phenomenon)

• Many complicated physical phenomena, such as laser-powder interactions, heat and mass transfer, fluid flow, melting, and solidification are involved in this process.

• In the melt pool of L-DED, convection plays a vital role in the heat transport and the melt pool formation.

• The convection in the melt pool is driven by various driving forces. Marangoni stress has been proven to be the main driving force.

• Owing to the spatial gradient of surface tension driven by the temperature or compositional gradients, the Marangoni stress arises on the melt pool surface [30].
The issues with mass and heat transfer are considered in all stages of a generalized L-DED modelling approach. These include but not limited to gas flows, powder mass flow rate, powder velocity at substrate, solidification front velocities and final track geometry.
L-DED (Modelling and Finite Element Analyses)

- The highlighted material properties of surface tension and viscosity are less likely to be used in L-PBF simulations due to common modelling assumptions.
L-DED (Thermal Cycles, Heat Flow, Transitions)

- Exhibited figures show a clear similarity between the temperature distribution on the melt pool with the mass flow velocity.
- Steep temperature gradients are also observable in the minus distance from the substrate top surface.

Fig. 17. Temperature gradient along the melt pool solidification front.
Following to the prediction of heat flow and thermal cycles, heat affected zones can be identified as the result of subsequent passes in substrate surface or for the consecutive layers.

Phase transformation models then can be used with the temperature distribution to predict the formation of related phase such as martensite.

Table 1 Phase strain properties by phase for steel

<table>
<thead>
<tr>
<th>Phase</th>
<th>Thermal expansion coefficient, $\alpha$</th>
<th>Volume change, $\Delta V/V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite, $\alpha_f$</td>
<td>$1.6 \times 10^{-3}/\degree C$ [50]</td>
<td>Pearlite to austenite</td>
</tr>
<tr>
<td>Pearlite, $\alpha_p$</td>
<td>$1.53 \times 10^{-3}/\degree C$ [51]</td>
<td>Ferrite to austenite</td>
</tr>
<tr>
<td>Austenite, $\alpha_y$</td>
<td>$2.20 \times 10^{-3}/\degree C$ [51]</td>
<td>Austenite to martensite</td>
</tr>
<tr>
<td>Martensite, $\alpha_m$</td>
<td>$1.15 \times 10^{-3}/\degree C$ [52]</td>
<td>Martensite to cementite</td>
</tr>
<tr>
<td>Cementite, $\alpha_c$</td>
<td>$1.48 \times 10^{-3}/\degree C$ [52]</td>
<td>Martensite to $\varepsilon$-carbide</td>
</tr>
<tr>
<td>$\varepsilon$-Carbide, $\alpha_{\varepsilon}$</td>
<td>$1.48 \times 10^{-3}/\degree C$ [52]</td>
<td>-0.33% [53]</td>
</tr>
</tbody>
</table>

References:
[34]
L-DED (Available Steel Grades)

- L-DED offers several steel grade variety.

Research on AM of Steels

Research on L-DED of Steels [23]
L-DED (Energy Density)

- If the similar parameters to L-PBF are considered, they would most probably have a similar effect on part densities and/or porosity.
- As an example, the increase in the specific energy decreases the porosity of L-DED AM parts.
- But, there are also different parameters than L-BF AM. For example, the increase in the mass flow rate increases the porosity of L-DED AM parts.

### Influence of some process parameters on porosity of steels made by LPF.

<table>
<thead>
<tr>
<th>Material</th>
<th>Resulting porosity</th>
<th>Mass flow rate</th>
<th>Laser power</th>
<th>Specific energy</th>
<th>Thickness</th>
<th>Stability of flow rate</th>
<th>Scan speed</th>
<th>Linear mass density</th>
</tr>
</thead>
<tbody>
<tr>
<td>H13 tool steel [90]</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H13 tool steel [90]</td>
<td>↑</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H13 tool steel [117]</td>
<td>↓</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316 SS [118]</td>
<td>↓</td>
<td></td>
<td>↑</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316 SS [114]</td>
<td>↓</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316 SS [119]</td>
<td>↓</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>420 SS [116]</td>
<td>↑</td>
<td></td>
<td>↑</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[23]
Arc Plasma Directed Energy Deposition

- Also known as Wire Arc Additive Manufacturing (WAAM), Arc Plasma Directed Energy Deposition (AP-DED) has three common types depending on the heat source. These are Gas Metal Arc Welding (GMAW)-based, Gas Tungsten Arc Welding (GTAW)-based and Plasma Arc Welding (PAW)-based additive manufacturing.

- Apart from the difference in heat sources, they all employ electrodes which are fed from a spool and environmentally protected with shield gasses. Only PAW includes a secondary plasma gas in addition to the shield gas.
Process Parameters for AP-DED AM

- Several process parameters need to be optimized for the completion of a successful build for AP-DED AM. Essential parameters are listed in the following table.

<table>
<thead>
<tr>
<th>GMAW Based</th>
<th>GTAW Based</th>
<th>PAW Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding current</td>
<td>Welding current</td>
<td>Welding current</td>
</tr>
<tr>
<td>Arc voltage</td>
<td>Arc voltage</td>
<td>Arc voltage</td>
</tr>
<tr>
<td>Contact tip to work distance</td>
<td>Contact tip to work distance</td>
<td>Contact tip to work distance</td>
</tr>
<tr>
<td>Electrode type</td>
<td>Electrode type</td>
<td>Electrode type</td>
</tr>
<tr>
<td>Electrode diameter</td>
<td>Electrode diameter</td>
<td>Electrode diameter</td>
</tr>
<tr>
<td>Wire feed speed</td>
<td>Filler wire type</td>
<td>Wire feed speed</td>
</tr>
<tr>
<td>Travel speed</td>
<td>Filler wire/diameter</td>
<td>Travel speed</td>
</tr>
<tr>
<td>Layer thickness / Number of layers</td>
<td>Wire feed speed</td>
<td>Layer thickness / Number of layers</td>
</tr>
<tr>
<td>Shielding gas type</td>
<td>Travel speed</td>
<td>Shielding gas type</td>
</tr>
<tr>
<td>Shielding gas flow rate</td>
<td>Layer thickness / Number of layers</td>
<td>Shielding gas flow rate</td>
</tr>
<tr>
<td>Shielding gas flow rate</td>
<td>Shielding gas type</td>
<td>Plasma gas type</td>
</tr>
<tr>
<td>Shielding gas flow rate</td>
<td>Shielding gas flow rate</td>
<td>Plasma gas flow rate</td>
</tr>
</tbody>
</table>
• AP-DED involves melting of wire by the arc, transfer of molten metal droplets to a molten pool, convective flow of liquid metal inside the molten pool driven by surface tension gradient deformation of the molten pool surface by arc pressure and solidification of the molten pool.

• These physical phenomena govern the temperature and velocity distributions, deposit shape and size, and the structure and properties of the components [36].

• Clarification of fundamental definitions is important to establish a common background between welding and additive manufacturing.

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.
• With the increase of wire feed rate, open circuit voltage and decreasing of welding speed the cooling rate is decreased.

• The grains forms with higher cooling rate are much finer as compare with low cooling rate.

• Low heat input and high cooling rate result in fine grain structure and cause the higher hardness [38].

• Cooling rate is calculated from 800°C to 500°C, because this temperature range is useful to phase transformation. It is observed that when heat input is increased the cooling rate of weldment is reduced. Cooling rate is calculated by the following equation.
• Cooling rate may have direct influence on microstructure, HAZ and thus micro hardness.
AP-DED (Multi-Pass Effects)

• Since AM processes are repeated regularly until the part is completed, and AP-DED processes are mainly based on welding technologies, it is logical to consider multi-pass welding know-how for a better understanding.

• As in welding, additive manufactured parts experience non-equilibrium solidification, due to fast cooling rates observed. The effect of multiple thermal cycles over these non-equilibrium structures may promote the formation of new phases and precipitates if the permanence time at a specific temperature for the solid-state transformation to occur is reached [37].
Electron Beam Directed Energy Deposition

• Also known as Electron Beam Additive Manufacturing (EBAM) or Electron-beam Freeform Fabrication (EBFF), Electron Beam Directed Energy Deposition (E-DED) uses a focused electron beam with a spool fed metal wire to manufacture metal alloys under vacuum environment.

[42] [43]
E-DED (Process Parameters)

• Essential process parameters for E-DED AM are listed in the following table.

• Different than previous DED AM processes, E-DED AM is performed under vacuum and in this respect, there is no parameter such as shielding gas type or gas flow rate.

<table>
<thead>
<tr>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current</td>
</tr>
<tr>
<td>Acceleration voltage</td>
</tr>
<tr>
<td>Wire diameter</td>
</tr>
<tr>
<td>Wire feed speed</td>
</tr>
<tr>
<td>Travel speed</td>
</tr>
<tr>
<td>Layer thickness / Layer Height</td>
</tr>
</tbody>
</table>
Materials

The best material candidates for EBAM applications are weldable metals that are available. These materials include:

- Titanium and Titanium alloys
- Inconel 718, 625
- Tantalum
- Tungsten
- Niobium
- Stainless Steels (300 series)
- 2319, 4043 Aluminum
- 4340 Steel
- Zircalloy
- 70-30 Copper Nickel
- 70-30 Nickel Copper
Binder Jetting

- In metal binder jetting (BJ), a liquid binder is selectively applied to join powder particles, layer by layer.
- The process begins by spreading a thin layer of powder, with printheads strategically depositing droplets of binder into the powder bed. The printing plate then lowers and another layer of powder is spread.
- The process repeats until the green part is complete [45].
Binder Jetting

• Still, there several steps to follow for the completion of overall BJ AM production.

BJ (Available Steel Grades)

Research on AM of Steels

Research on L-PBF of Steels [23]
## 1. Third-Party Qualified Materials

These materials have passed ExOne's rigorous testing for uniformity, dimensional tolerance, and build quality. Please see the attached data sheets for third-party testing results based on MPIF standards.

### Single Alloy Metals
- 1. 17-4PH SS
- 2. 304L SS
- 3. 316L SS
- 4. M2 Tool Steel
- 5. Inconel 718

### Metal Composites
- 1. 316 SS i/w Bronze
- 2. 420 SS i/w Bronze
- 3. Tungsten i/w Bronze

## 2. Customer-Qualified Materials

The materials below have been qualified for use by ExOne customers, using standards for their own applications, and are being successfully printed today. Additionally, a number of ExOne customers also print proprietary powders on our machines that are not listed below. If you have a question about 3D printing the materials below, please contact us.

### Single Alloy Metals
- 1. 17-4PH SS*
- 2. 304L SS*
- 3. 316L SS*
- 4. Cobalt Chrome
- 5. Copper
- 6. H13 Tool Steel
- 7. Inconel 625
- 8. Titanium
- 9. Tungsten Heavy Alloy

### Ceramics
- 1. Alumina
- 2. Carbon
- 3. Natural Sands
- 4. Synthetic Sands
- 5. Silicon Carbide
- 6. Tungsten Carbide Cobalt

### Metal Composites
- 1. 316 SS i/w Bronze*
- 2. 420 SS i/w Bronze*
- 3. Tungsten i/w Bronze*
Desktop Metal

17-4 Stainless Steel

316L Stainless Steel

H13

4140

Co-funded by the Erasmus+ Programme of the European Union

This project has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.
Summary and Highlights

• Four classes of AM available to process steel alloys are Powder Bed Fusion, Directed Energy Deposition, Binder Jetting and Desktop Metal (Binder Jetting & Material Extrusion).

• These classes differ from each other regarding the energy source, feedstock form, solidification principles and metallurgical properties.

• Among the so called AM classes, steel alloys are frequently processed with PBF and DED classes.

• Most of the scientific and industrial applications are focused on stainless steels and tools steels. Rare applications also exist for other steel groups.

• In AM of steels, process modelling practices are important to analyse process characteristics such as temperature distribution, heat affected zones, cooling rates and residual stresses.
References


References


41. Liu, T. Y., Qiu, X. B., Lu, Z. Y., & Dong, L. M. Estimation of Cooling Rate from 800 C to 500 C in the Welding of Intermediate Thickness Plates Based on FEM Simulation.


References


46. https://amfg.ai/2019/07/03/metal-binder-jetting-all-you-need-to-know/


49. https://www.desktopmetal.com/materials
Thank you for your attention!

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