AMable
BOOKLET

TRAINING MATERIAL

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Index

01

Additive Manufacturing Processes Overview

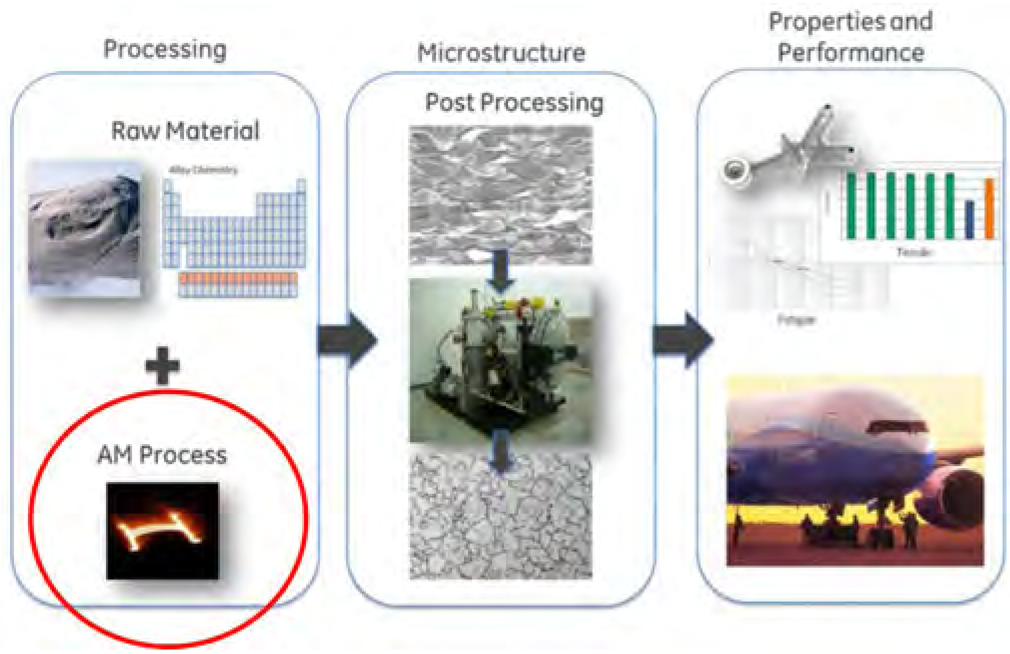
02

Value Chain in Additive Manufacturing

01 Additive Manufacturing Processes Overview

Scope

Additive Manufacturing (AM) is a manufacturing process that allows the construction of 3D parts by processing raw material in various forms (like powder, wire,...).



However, in many cases, to obtain the necessary microstructure that allows the achivement of desired performance and properties, it is necessary to do post-processing.

Knowledge

Actual and broad knowledge of theory, principles and applicability of:

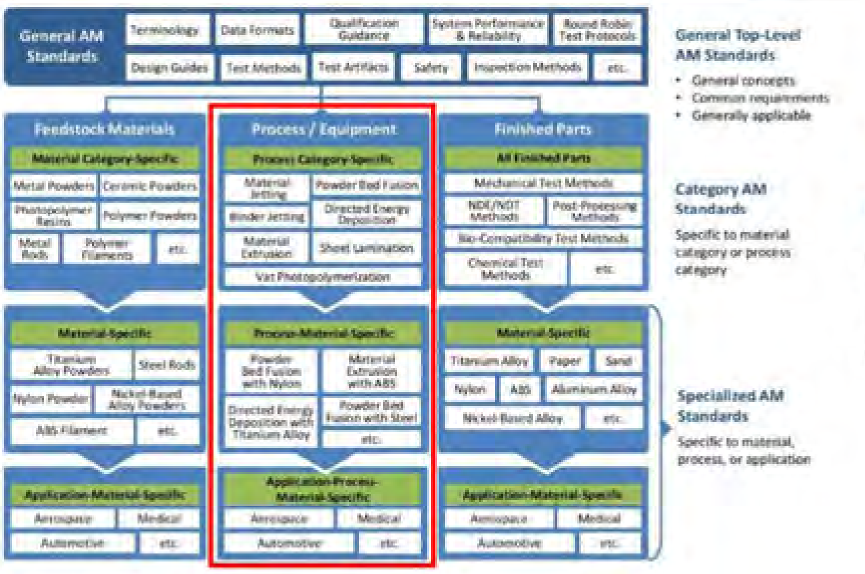
- Directed energy deposition (DED)
- Powder bed fusion (PBF)
- Vat photopolymerization (VPP)
- Material jetting (MJT)
- Binder jetting (BJT)
- Material extrusion (MEX)
- Sheet lamination (SHL)

Objectives

- Distinguish parts produced by different AM processes
- Recognize the advantages and limitations of AM processes
- Identify the applicability of different AM processes
- Post-Processing can also be applide to achive the required surface quality.

Process Defined By Standards

Additive Manufacturing Standards Structure



Additive Manufacturing Technologies

	TECHNOLOGY	MATERIALS	TYPICAL MARKETS	RELEVANCE FOR METAL
Fusion	**Power bed fusion** - Thermal energy selectively fuses regions of powder bed	Metals, polymers	Prototyping, direct part	●
	Directed energy deposition - Focused thermal energy is used to fuse materials by melting as the material is deposited	Metals	Direct part, repair	◑
	Sheet lamination - Sheets of material are bonded to form an object	Metals, paper	Prototyping, direct part	◔
Sintering	**Binder jetting** - Liquide bonding agent is selectively dispensed through a nozzle or orifice	Metals, polymers, foundry sand	Prototyping, direct part, casting molds	◔
	Material Jetting - Droplets of build material are selectively deposited	Polymers, waxes	Prototyping, casting patterns	○
	Material extrusion - Material are selectively dispensed through a nozzle or orifice	Polymers	Prototyping	○
	Vat Photopolymerization - Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Photopolymers	Prototyping	○

AM technologies for metal objects

Source: ASTM international Committee F42 on Additive Manufacturing Technologies; Roland Berger

Photo: GE Aviation

Definitions

The standard ISO/ASTM 52900-18 stands for Additive manufacturing - General principles – Terminology. It defines the basic terminology to be used for everything related to additive manufacturing.

Additive Manufacturing (AM)

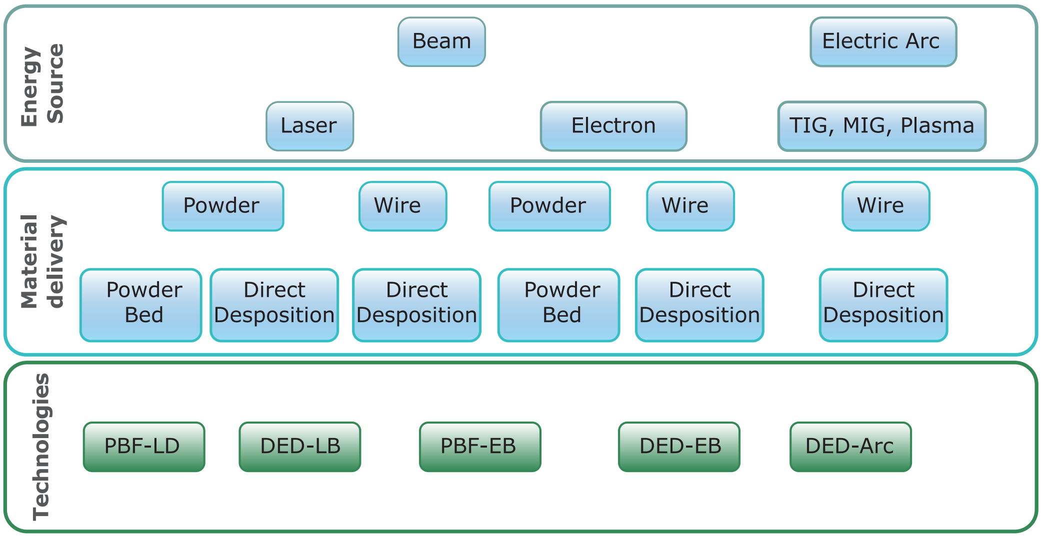
“process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”. Historical terms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication.

3D Printing

“fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology”. Term often used in a non-technical context synonymously with additive manufacturing; until present times this term has in particular been associated with machines that are low end in price and/or overall capability.

Process for Metals

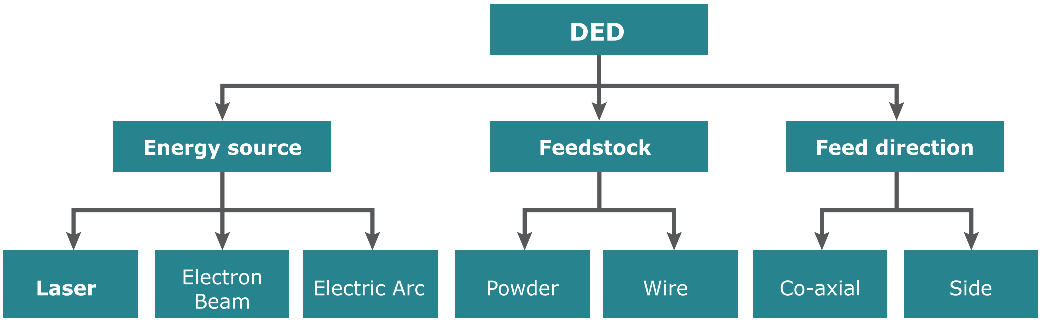
Classification Directed Energy Deposition and Powder Bed Technologies



Directed Energy Deposition (DED)

General Classification

Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited (ISO/ASTM 52900-18). “Focused thermal energy” means that an energy source (for example: laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

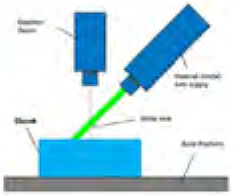


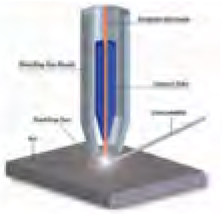
Feedstock

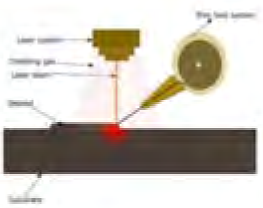
WIRE | POWDER

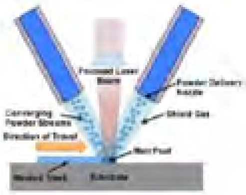
Energy Source

ELECTRON BEAM | ARC / PLASMA | LASER









Technology Nomenclature

DED-EB | DED-ARC / DED-PB | DED-LB | DED-LB

Electron Beam

Advantages

- Higher deposition rate
- Large pieces (larger manufacturing space)
- Materials difficult to weld
- Reactive metals (Ti, Al, TiAl)
- Wire material (cheap, inflammable)
- High energy efficiency (> 95%, x5-10 LPBF)
- Minor residual stress
- Lower support requirements

Photo: Arevo Labs

Disadvantages

- Big and complex equipment
- High cost investment
- High cost maintenance equipment
- Vacuum chamber needed
- Higher roughness (Ra> 40µm) (x3 LPBF)

Photo: Lockheed Martin

Applications & Sectors

- Turbine Blades
- Nuclear Components
- Refractory Metal Components
- Ballistic Materials
- Industrial Pump Components
- Semiconductor Manufacturing
- Tooling Repair and Reconditioning
- Aero components

Photo: Forgemasters

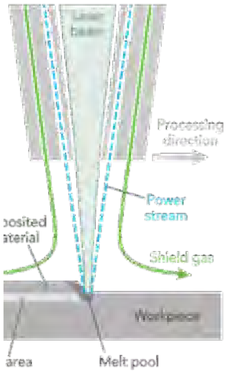
Materials

- Steel, 4340
- Stainless Steel
- Titanium and Titanium alloys, Ti64
- Aluminum, 2319, 4043
- Tantalum
- Tungsten
- Niobium
- Inconel 718, 625
- Cobalt-chrome ASTM F75
- TiAl
- Pure copper

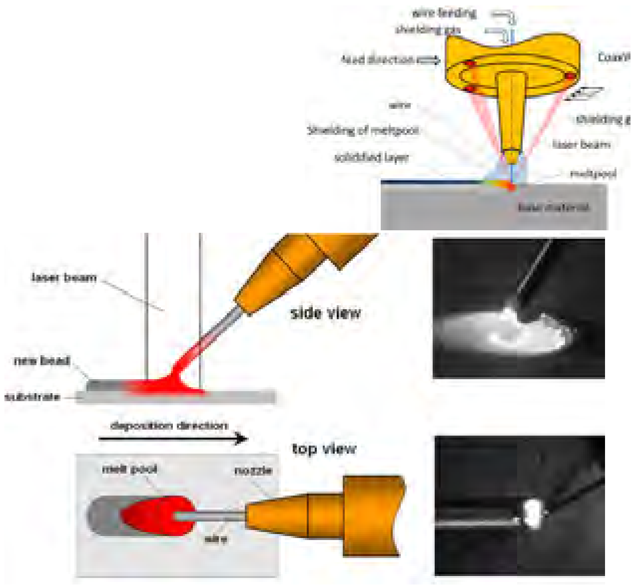
Photo: GE Additive

Directed Energy Deposition (DED)

Laser Beam



3D representation of the laser cladding process



Advantages

- Medium to High deposition rate
- Medium size parts
- near-net shape components
- Wide range of materials
- Multi-material and FGMs
- Repair and remanufacturing

Disadvantages

- Equipment cost
- Low resolution
- Needs of post-processing

Photo: Arcam

Applications & Sectors

- Turbomachinery
- Aero components
- Molds and Tooling
- Automotive
- Subsea and offshore

Materials

- Steels
- Ni-based alloys
- Co-based alloys
- Titanium
- Carbides

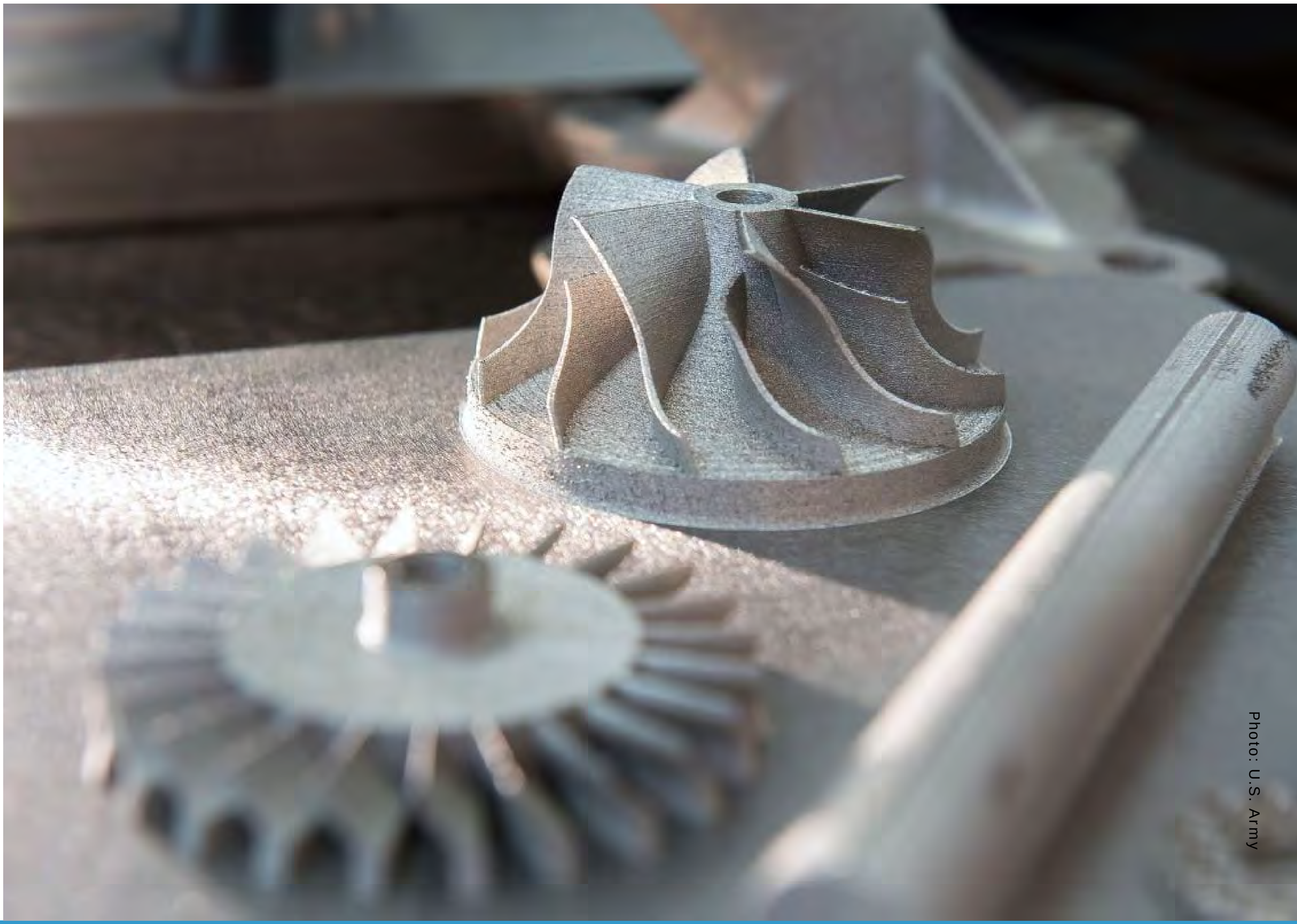


Photo: U.S. Army

Directed Energy Deposition (DED)

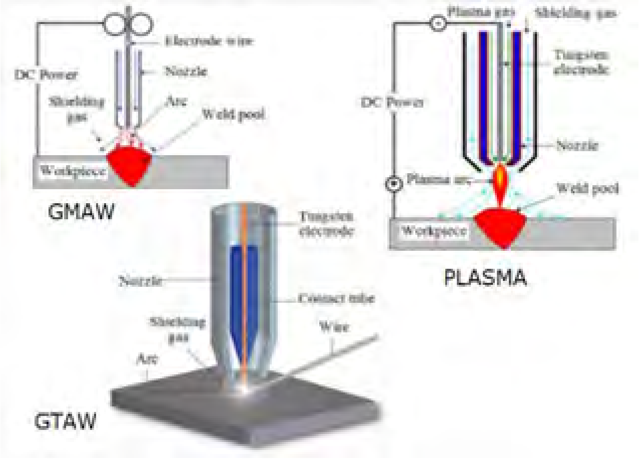
Arc

DED - Arc

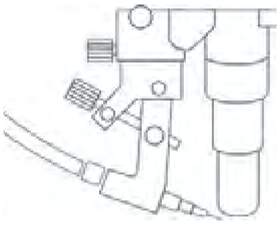
- GMAW and TIG processes
- Feeding of wire
- Low priced technical setup
- Deposition rates up to 5 kg/h and over
- Little material loss compared to powder based technologies

DED - Plasma Beam

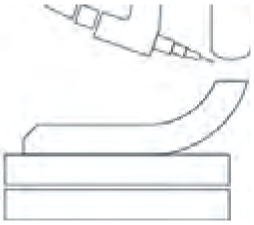
- Plasma and µ-Plasma processes
- Feeding of powder or wire
- Deposition rates up to 10 kg/h
- Powder availability and over spray



Steps



1. Fusion



2. Layer Deposition

3. Solid Part Deposit

Advantages

- High deposition rate
- High size parts
- Good buy-to-fly ratio
- Reduced cost for equipment
- Wide range of materials
- Reduced costs for wires

Disadvantages

- Lower resolution
- Geometric distortions
- Needs of post-processing

Photo: RamLab

Photo: Norsk Titanium

Applications & Sectors

- Naval
- Aero components
- Energy
- Molds and Tooling

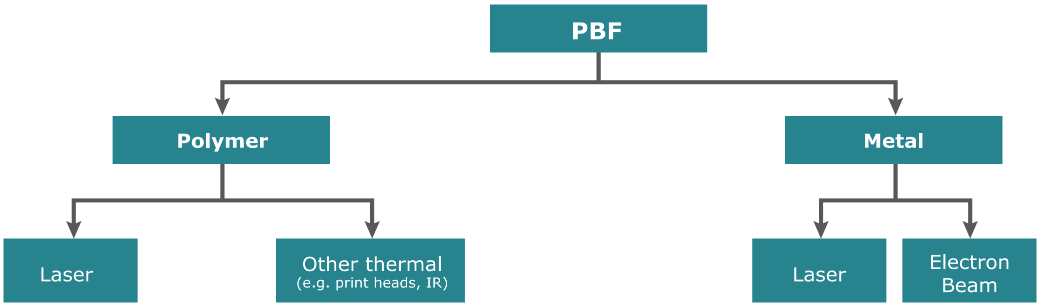
Materials

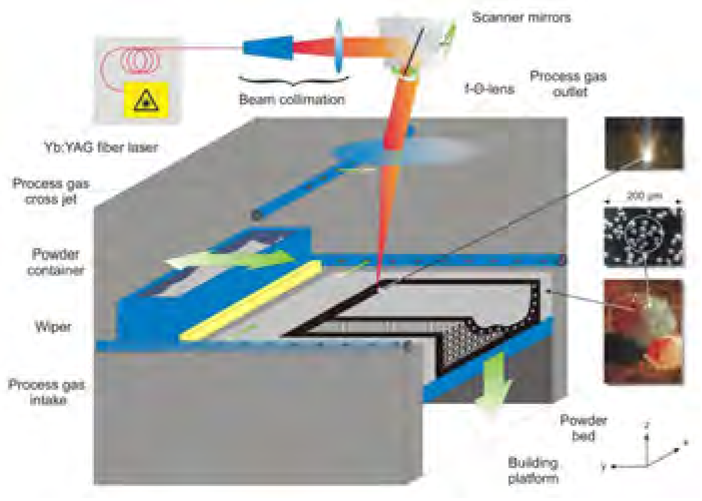
- Steels
- Ni-based alloys
- Titanium
- Aluminum

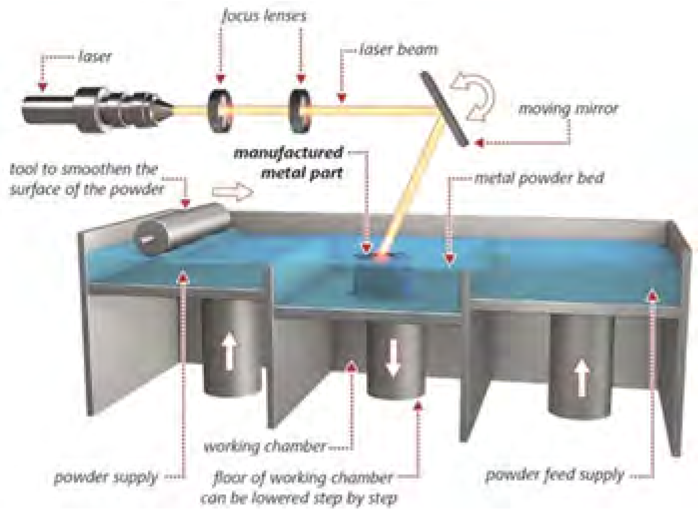
Photo: RamLab

Powder Bed Fusion

Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed (ISO/ASTM 52900-18)







Advantages

- Innovation in designs and improved functionalities
- Integration of several pieces in one
- Lightening in weight, less use of raw material, less material waste (green technology)
- Individualization and complexity without added cost
- High range of Materials (weldable materials)

Disadvantages

- Medium roughness (Ra> 10μm)
- Limited parts size (< 400x400x500mm)
- Equipment cost
- Residual stresses and distortions in some cases
- Low to Medium Productivity: currently series of small pieces (up to 25000 parts/year)

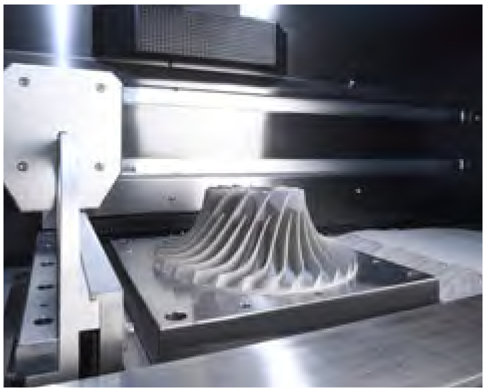


Photo: Monni Pierandrea

Applications & Sectors

- Aero components
- Orthopedic implants
- Automotive
- Tooling (Molds and dies)
- Dental
- Goods

Materials

- Aluminum (AlSi7Mg, AlSi9Cu3)
- Nickel (IN718, IN725, IN939, HX)
- Titanium (grade 2, grade 23)
- Cobalt-chrome (F75, CoCr28Mo6)
- Steel (316L, 17-4PH, 1.2709, H13, Invar36)
- Copper (CuSn10)

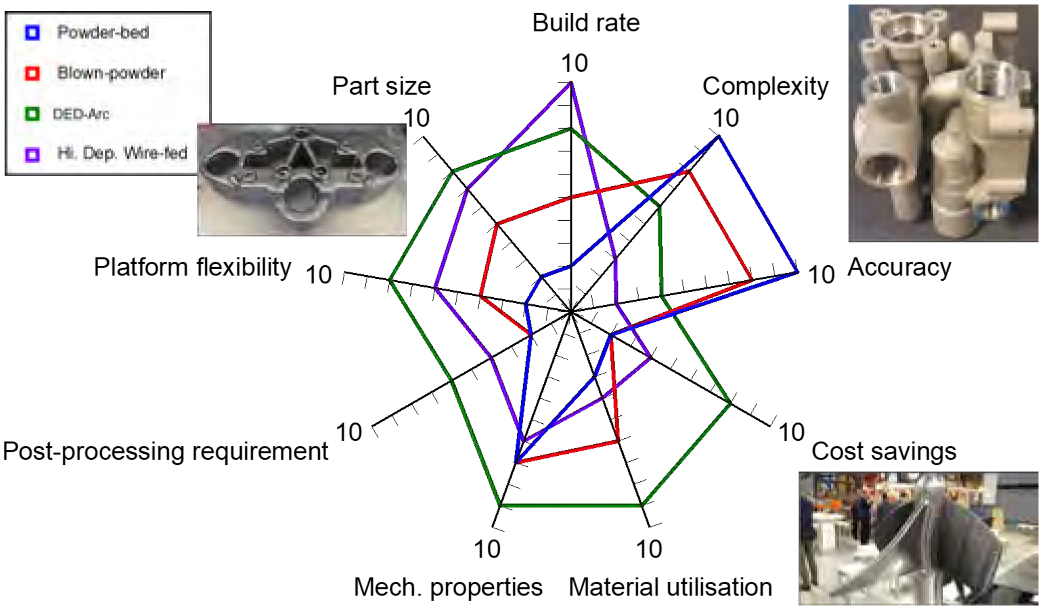
Photo: ExOne

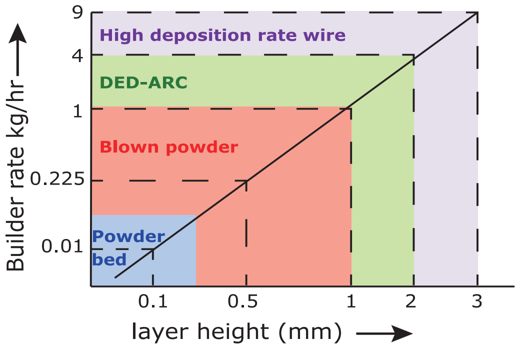
Photo: Materialise

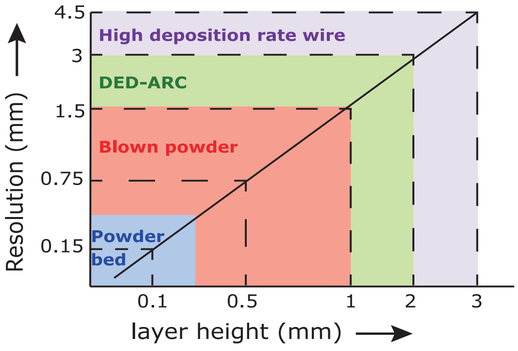
Metal AM

Process Comparison

Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed (ISO/ASTM 52900-18)





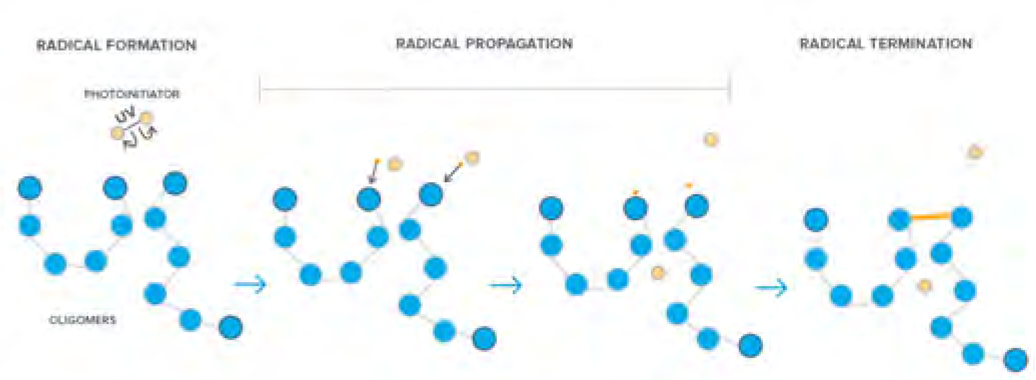


Vat Photopolymerization

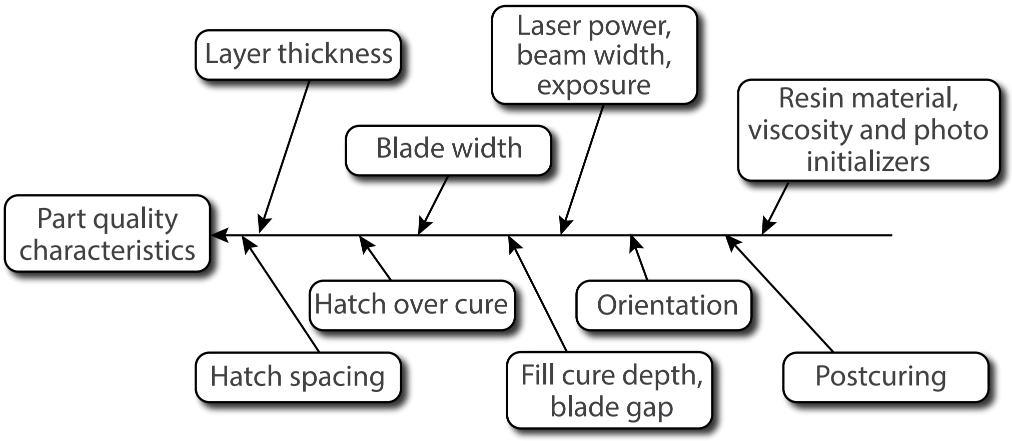
Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerisation (ISO/ASTM 52900-18)

Process

- Monomer and oligomer chains have active groups at their end
- When resin is exposed to UV the Photoinitiator molecule breaks into two
- 2 very reactive radicals
- Reactive radicals are transferred to active groups which then react with other groups



Parameters

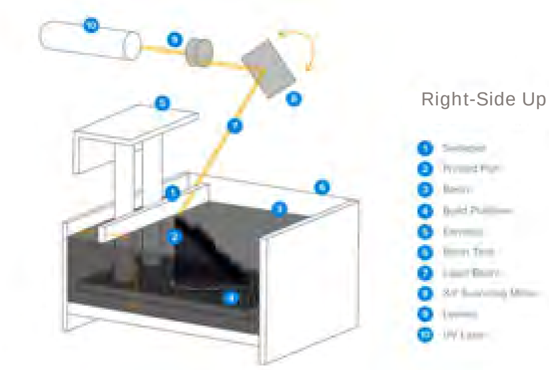


Accuracy

General accuracy of VPP prints is 50 to 200 microns depending on size, resin, model geometry and support generation.

Desktop FDM Industrial FDM Desktop SLA Industrial SLA Industrial SLS

Machine Types



Right-Side Up VPP

Top-down (top-cure)

- heat source above the vat
- platform is progressively dipped in the vat
- Large industrial applications
- Build volume: Up to 1500x750x550mm3

Upside-Down (Inverted) VPP

Bottom-up (bottom-cure)

- heat source is placed below the vat
- platform is progressively raised
- The UV laser points at two mirror
- galvanometers, which direct the light to the correct
- coordinates on a series of mirrors
- the final part built upside down
- Build volume: Up to 145x145x175mm3

Machine Examples

Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerisation (ISO/ASTM 52900-18)

Formlabs

145 x 145 x 175 mm

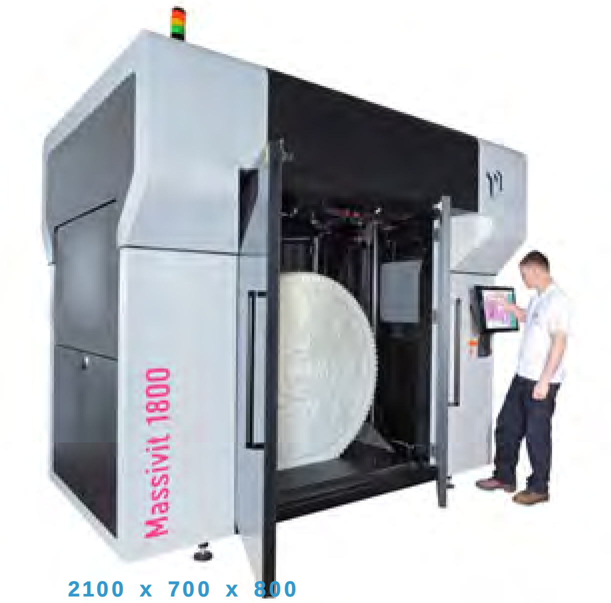
Envisiontec

400 x 400 x 400 mm

3D Systems

1500 x 750 x 550 mm

Materialise



2100 x 700 x 800 mm

Machine Cost Comparison

General accuracy of VPP prints is 50 to 200 microns depending on size, resin, model geometry and support generation.

	Desktop SLA: Inverted	Industrial SLA: Right-Side Up
Price	Starting at $3500	$80,000-$1,000,000+
Print Volume	Up to 145 x 145 x 175 mm	Up to 1500 x 750 x 550 mm
Pros	• Affordable • Easy to use • Low maintance • Small footprint • Easy material swapping	• Large build volume • high production rate • Extensive materials options
Cons	• Medium build volume	• Expensive machinery • High maintance • Operator required

Advantages

- Design freedom;
- Geometric models with great surface quality;
- Fast process;
- Reduced cost equipment;
- Part isotropy is possible.

Applications & Sectors

- Rapid Prototyping;
- Dental;
- Healthcare;
- Impellers and rotating devices;
- Enclosures;
- Investment casting.

Disadvantages

- Low range of materials available (UV curable resins);
- Support structures required;
- Material degradation with continued exposure to light;
- Low working temperatures for components;
- Some resins are toxic.

Materials

- Resin, typically composed of epoxy or acrylic and methacrylic monomers, will polymerize and harden when exposed to light

Feedstock Form

- Liquid or Paste (photoreactive resin with or without filler material)

Processing Operations (Top-Cure, Industrial)

1. The build platform is first positioned in the tank of liquid photopolymer, at a distance of one-layer height from the surface of the liquid.
2. Then a UV laser creates the next layer by selectively curing and solidifying the photopolymer resin.
3. The whole cross-sectional area of the model is scanned, so the produced part is fully solid.
4. When a layer is finished, the platform moves at a safe distance and the sweeper blade re-coats the surface. The process then repeats until the part is complete.
5. After printing, the part is in a green, no-fully-cured state and requires futher post processing under UV light if very high mechanical and thermal properties are required.

Sheet Lamination

Additive Manufacturing process in which sheets of material are bonded to form an object (ISO/ASTM 52900-18)

Processable Materials

- Polymers;
- Metals;
- Composites;
- Ceramics;
- Paper.

Polymers

- Interlayer adhesion achieved through heat/glue
- Cutting performed by laser/blade
- Can create coloured parts
- Typically for prototyping applications

Metal-Ultrasonic Consolidation

- Solid state weld between ‘foils’
- Multi material capability
- Ability to embed parts (low temperature)

Advantages

- High velocity
- Non-existence of residual stress
- Wide range of Materials

Disadvantages

- Post-Processing are required to achieve required effect
- Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect

Applications & Sectors

- Architectural models
- Topography visualization
- Aerospace and automotive industries

Feedstock Form

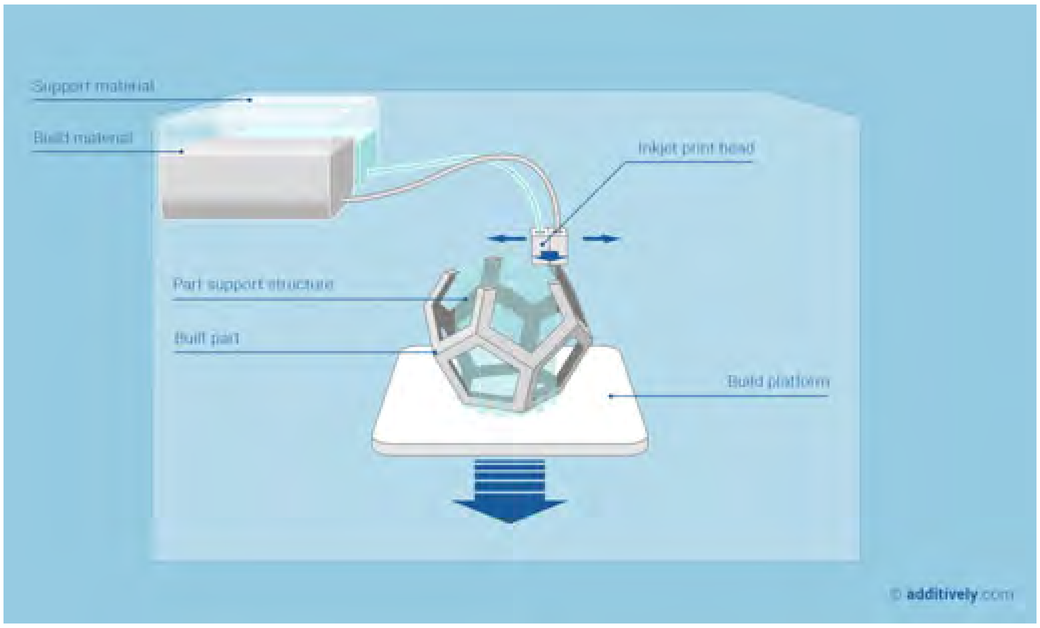
- Sheet material, paper, metal foil, polymers or composites (metal or ceramic poder, helded by a binder)

Processing operations (plastics)

1. Material is positioned in place on the cutting bed.
2. Material is bonded in place, over the previous layer, using the adhesive
3. Required shape is then cut from the layer, by laser or knife, and next layer is added.
4. The Steps two and Three can be reversed and alternatively, the material can be cut before being positioned and bonded.

Material Jetting

“Additive manufacturing process in which droplets of feedstock material are selectively deposited.”, according to ISO/ASTM 52900-18



Advantages

- Fast process
- Small – medium parts
- Good accuracy (typically ± 0.1%)
- Allows mixture of colors and properties
- Soft and Hard Materials
- No post-processing required
- Reduced cost equipment

Disadvantages

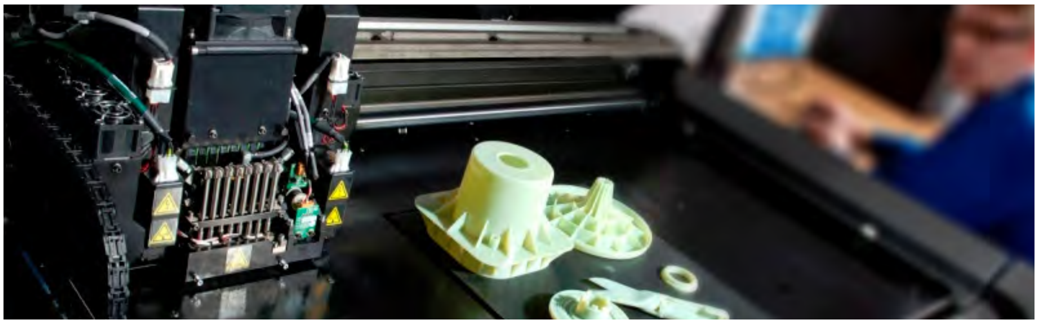
- Reduced resistance

Applications & Sectors

- Rapid Prototyping
- Dental
- Healthcare
- Prosthesis

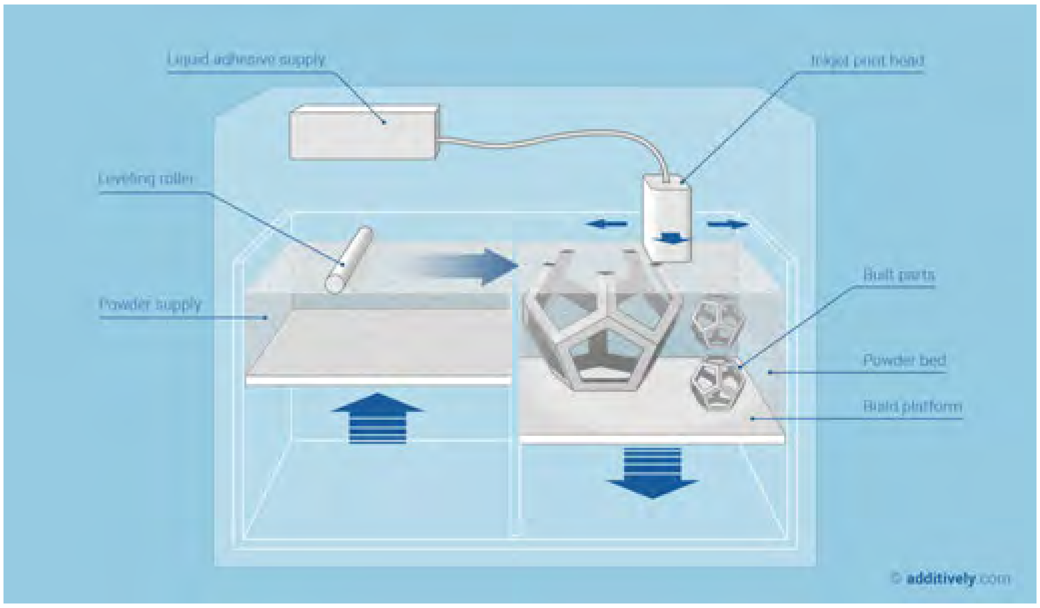
Materials

- UV-photosensitive resins
- Acrylic photopolymers (thermoset)



Binder Jetting

“Additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials”, according to ISO/ASTM 52900-18



© additively.com

Advantages

- X50-100 faster than PBF
- X20 lower cost than PBF
- No supports are required
- Suitable for great complexity parts and large series
- Good resolution

Disadvantages

- Limited size (<400x300x200 mm)
- Various processes for final part (print, debinder, sinter)
- Complex manipulation of green parts
- Contraction control during sintering
- Limited wall thickness (5-10 mm)

Applications & Sectors

- Precision engineering
- Automotive
- Prototyping
- Medical

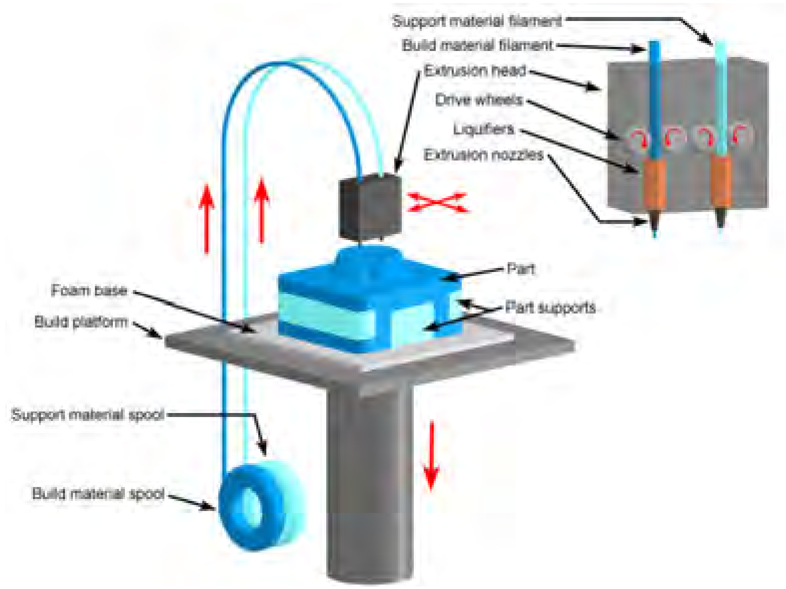
Materials

- Steels
- Nickel-based metals
- CobaltChrome alloys
- Wolfram, WolframCarbide

Photo: Michal Kamaryt / CTK / Alamy

Material Extrusion

“Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice ”, according to ISO/ASTM 52900-18



Advantages

- Wide selection of print material (plastics)
- Easy and user-friendly process (FDM)
- Low initial and running costs
- Small equipment size compared to other AM
- Lower production costs (in Metals)
- Suitable for small, highly complex parts (50 mm)
- Suitable for small series part

Disadvantages

- Toxic print materials (some thermoplastics)
- Sintered shrinkage (in metals)
- Limited wall thickness (in metals: 5-10 mm)

Applications & Sectors

- Rapid Prototyping
- Automotive
- Healthcare

Materials

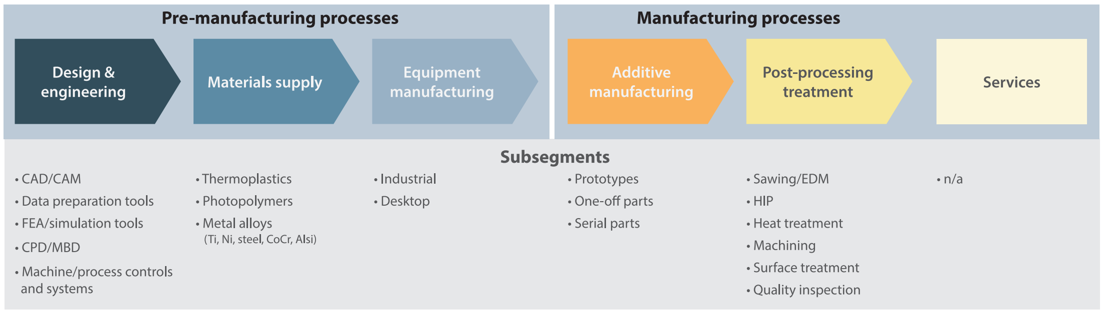
- Thermo Plastics (PLA, ABS, PC)
- Composite material (Plastic reinforced)
- Metals (Steel, Cu, Inco625)


Photo: Michal Kamaryt / CTK / Alamy

02 Value Chain In AM

The value chain here spans across activities from research to market, along a process to generate and add value. For additive manufacturing, significant value is generated at design stage, when geometries are defined and when the build process is determined.

AM value chain



Pre-manufacturing processes			Manufacturing processes		
Design & engineering	Materials supply	Equipment manufacturing	Additive manufacturing	Post-processing treatment	Services
Subsegments					
• CAD/CAM • Data preparation tools • FEA/simulation tools • CPD/MBD • Machine/process controls and systems	• Thermoplastics • Photopolymers • Metal alloys (Ti, Ni, steel, CoCr, AlSi)	• Industrial • Desktop	• Prototypes • One-off parts • Serial parts	• Sawing/EDM • HIP • Heat treatment • Machining • Surface treatment • Quality inspection	• n/a

Notes: FEA = Finite element analysis; CPD = Composites part design; MBD = Madel-based definition; EDM = Electrical discharge machining; HIP = Hot isostatic pressing

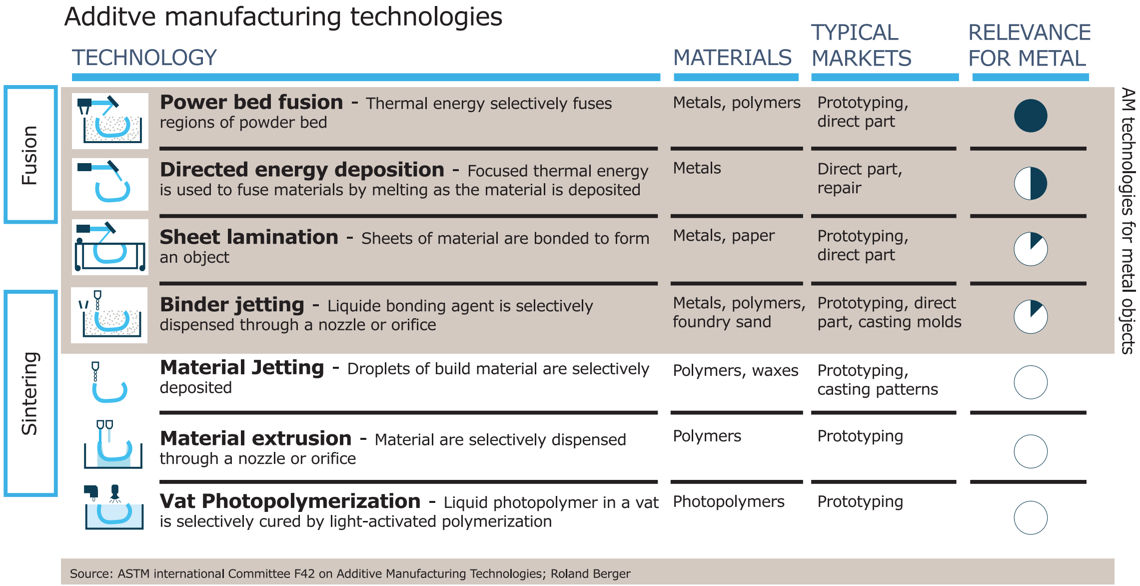
Source: L.E.K. analysis

Added Value By AM

Added value: set of additional product or service characteristics which make them more attractive for the customer against the competence

- Customization
- In-situ and on-demand production (without stocks)
- Minimum time to market
- Sustainability and energy efficiency
- Differential design
- Design improvement:
    - Integration of functionalities or multiple parts into one part
    - Light weight design to leave only material that is needed
- Cost improvement:
    - Small lots
    - High cost materials

Which Is The Best AM Process For My Product?



Additditve manufacturing technologies

	TECHNOLOGY	MATERIALS	TYPICAL MARKETS	RELEVANCE FOR METAL
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	Directed energy deposition - Focused thermal energy is used to fuse materials by melting as the material is deposited	Metals	Direct part, repair	◐
	Sheet lamination - Sheets of material are bonded to form an object	Metals, paper	Prototyping, direct part	◔
Sintering	**Binder jetting** - Liquide bonding agent is selectively dispensed through a nozzle or orifice	Metals, polymers, foundry sand	Prototyping, direct part, casting molds	◔
	Material Jetting - Droplets of build material are selectively deposited	Polymers, waxes	Prototyping, casting patterns	○
	Material extrusion - Material are selectively dispensed through a nozzle or orifice	Polymers	Prototyping	○
	Vat Photopolymerization - Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Photopolymers	Prototyping	○

AM technologies for metal objects

Source: ASTM international Committee F42 on Additive Manufacturing Technologies; Roland Berger

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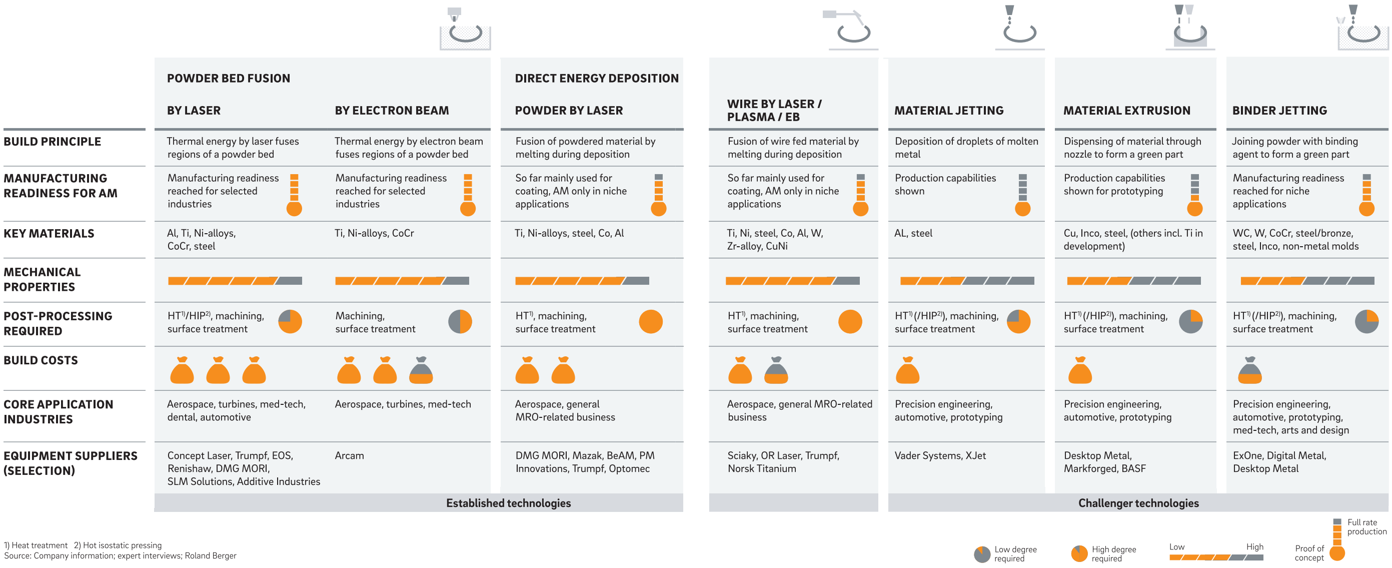
Established and challenger technologies for metal AM

Several new metal AM technologies are emerging alongside powder bed fusion or direct energy deposition – Simplified overview (schematic)



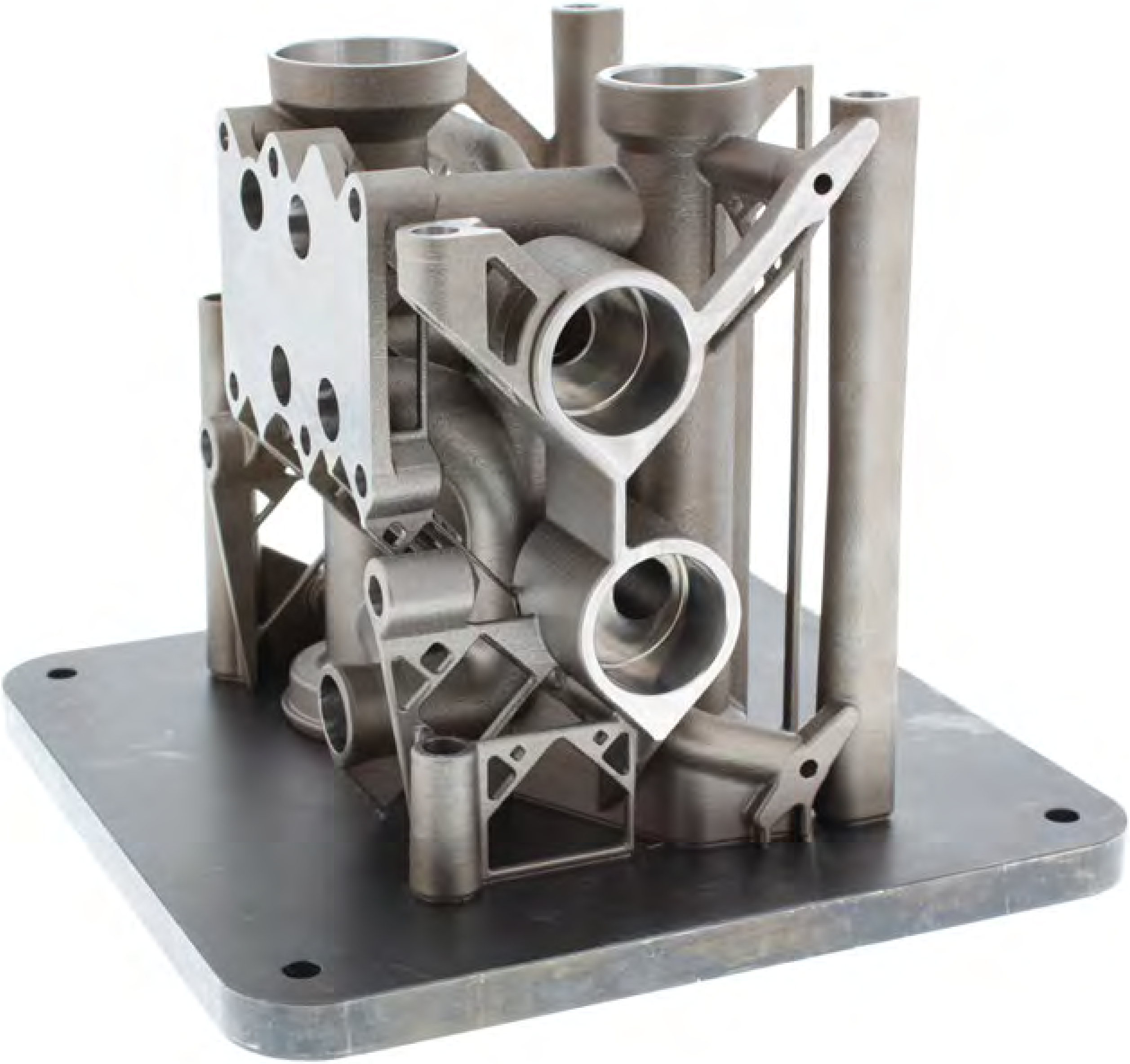
	POWDER BED FUSION		DIRECT ENERGY DEPOSITION				
	BY LASER	BY ELECTRON BEAM	POWDER BY LASER	WIRE BY LASER / PLASMA / EB	MATERIAL JETTING	MATERIAL EXTRUSION	BINDER JETTING
BUILD PRINCIPLE	Thermal energy by laser fuses regions of a powder bed	Thermal energy by electron beam fuses regions of a powder bed	Fusion of powdered material by melting during deposition	Fusion of wire fed material by melting during deposition	Deposition of droplets of molten metal	Dispensing of material through nozzle to form a green part	Joining powder with binding agent to form a green part
MANUFACTURING READINESS FOR AM	Manufacturing readiness reached for selected industries ▰▰▰▰	Manufacturing readiness reached for selected industries ▰▰▰▰	So far mainly used for coating, AM only in niche applications ▰▰▰▱	So far mainly used for coating, AM only in niche applications ▰▰▰▱	Production capabilities shown ▱▱▱▱	Production capabilities shown for prototyping ▰▱▱▱	Manufacturing readiness reached for niche applications ▰▰▰▱
KEY MATERIALS	Al, Ti, Ni-alloys, CoCr, steel	Ti, Ni-alloys, CoCr	Ti, Ni-alloys, steel, Co, Al	Ti, Ni, steel, Co, Al, W, Zr-alloy, CuNi	AL, steel	Cu, Inco, steel, (others incl. Ti in development)	WC, W, CoCr, steel/bronze, steel, Inco, non-metal molds
MECHANICAL PROPERTIES	▰▰▰▰▰▱	▰▰▰▰▰▱	▰▰▰▰▰▱	▰▰▰▰▰▱	▰▰▰▱▱▱	▰▰▰▱▱▱	▰▰▰▱▱▱
POST-PROCESSING REQUIRED	HT[1]/HIP[2], machining, surface treatment ◕	Machining, surface treatment ◐	HT[1], machining, surface treatment ●	HT[1], machining, surface treatment ●	HT[1] (/HIP[2]), machining, surface treatment ◕	HT[1] (/HIP[2]), machining, surface treatment ◔	HT[1] (/HIP[2]), machining, surface treatment ◔
BUILD COSTS	● ● ●	● ● ◐	● ●	● ◐	●	●	◐
CORE APPLICATION INDUSTRIES	Aerospace, turbines, med-tech, dental, automotive	Aerospace, turbines, med-tech	Aerospace, general MRO-related business	Aerospace, general MRO-related business	Precision engineering, automotive, prototyping	Precision engineering, automotive, prototyping	Precision engineering, automotive, prototyping, med-tech, arts and design
EQUIPMENT SUPPLIERS (SELECTION)	Concept Laser, Trumpf, EOS, Renishaw, DMG MORI, SLM Solutions, Additive Industries	Arcam	DMG MORI, Mazak, BeAM, PM Innovations, Trumpf, Optomec	Sciaky, OR Laser, Trumpf, Norsk Titanium	Vader Systems, XJet	Desktop Metal, Markforged, BASF	ExOne, Digital Metal, Desktop Metal
	Established technologies				Challenger technologies		

◔ Low degree required ◕ High degree required

Low ▰▰▰▱▱▱ High

Proof of concept ▰▰▰▱ Full rate production

1) Heat treatment 2) Hot isostatic pressing
Source: Company information; expert interviews; Roland Berger



AMable

About

AMable is a group of people from different organisations that aim to create a new eco-system for the uptake of additive manufacturing. Those people provide a wide based of expertise from technology, business and training. The European Commission supports this consortium under the framework of I4MS with funding from the H2020 framework program and with guidance towards an open platform for European companies.

The prime target group are small and medium sized companies (SMEs) that need support in the uptake of additive manufacturing. AMable aims to empower people in those companies to enhance their skills rather than doing the job for the people. The eco-system however will develop a wide spread offering from scientific support through skills and education to commercial service offers.

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