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Additive Manufacturing Techniques for the realization of Pressure Equipment

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Summary

- What Additive Manufacturing is and reasons for using it
- AM Techniques for the production of metal equipment
- Possible uses of the AM processes for pressure equipment
- Power Bed Fusion
- Mechanical properties of alloys produced by Power Bed Fusion Selective Laser Melting process
- Directed Energy Deposition: Wire and Arc Additive Manufacturing (WAAM)
- Conclusions

What is Additive Manufacturing?

The term ***Additive Manufacturing AM*** (as well as the terms Additive Fabrication, Additive Process, Additive Technique, Additive Layer Manufacturing or simply Layer Manufacturing) is used for the

technologies that create physical objects by gradually adding material starting from a geometric representation

The **UNI EN ISO/ASTM 52900 standard "*Additive Manufacturing - General Principles - Terminology*"** defines additive manufacturing as a process of joining materials to create objects from 3D models, usually by layer overlap, **proceeding in the opposite way to what happens in the subtractive processes.**

Why is Additive Manufacturing used?

- to create models and prototypes of parts;
- to allow the direct manufacture of finished products such as components, equipment, functional parts of machines and various types of products made of polymeric, metallic, ceramic and composite materials;
- to repair components and equipment.

The use of additive manufacturing techniques allows:

- to reduce the time-to-market of the product, thanks to production cycles consisting of a single step (in replacement of the traditional machine tool);
- to fabricate components with materials which are difficult to machine tool;
- to create very complex geometries;
- to make lighter objects with the same volume;
- to avoid the costs arising from the use of molds for small series production.

Possible uses of the AM processes

The AM processes can be used both for **construction** and for the **repair** of equipment or components employable in various fields.





The range of achievable products also includes pressure equipment.

The **re-engineering** of construction processes is already possible in many sectors. It is very widespread in aeronautics and automotive industry and is spreading rapidly in the oil & gas sector. Manifolds, filters and valve bodies can be made.

Factors to be considered for the mechanical stability

In the design and construction of AM equipment it is necessary to evaluate the **elements that can affect its mechanical stability** during service:

in addition to the <u>appropriate choice of materials and their thicknesses</u>

- possible presence of **residual stresses** and **distortions in the structure** due to **temperature changes** during the manufacturing process or caused by the **material deposition speed**

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Materials in AM processes

- It is possible to use any type of material (**metallic, polymeric, ceramic** or **composite**)

In the case of metal:

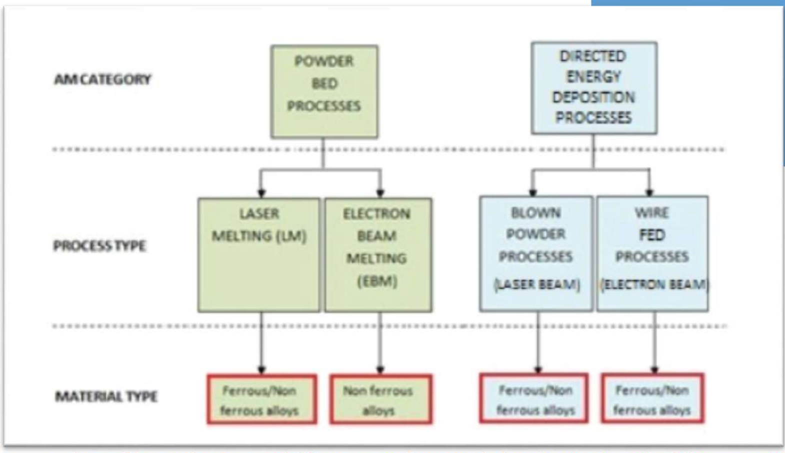
- ✓ AM is a promising alternative for the manufacture of components currently made of **expensive materials**, such as titanium and nickel
- ✓ The main metallic materials available for industrial production in AM, including the manufacture of pressure equipment, are **stainless steels**, **Maraging steel** (high strength and malleability), **alloys with chromium and cobalt** (high specific strength, used to produce turbines), **Inconel** (high temperature application) and **alluminum alloys** (very versatile and light).

AM Techniques for the production of metal equipment

All AM processes have the common objective of obtaining a product by optimizing its **geometric characteristics** with the **material properties.**

Category	Process	Material
Powder Bed Fusion	Direct metal laser sintering (DMLS) Electron beam melting (EBM) Selective laser sintering (SLS) Selective laser melting (SLM)	Metal powder
Directed energy deposition	Electron beam freeform fabrication (EBF) Laser engineered net shaping (LENS) Laser consolidation (LC) Directed light fabrication (DLF) **Wire and arc additive manufacturing (WAAM)**	Metal powder, metal wire

UNI EN ISO/ASTM 52900 standard



Source https://www.farinia.com/additive-manufacturing/3d-technique/metal-additive-manufacturing-production-systems

AM Techniques for the production of metal equipment

Power Bed Fusion

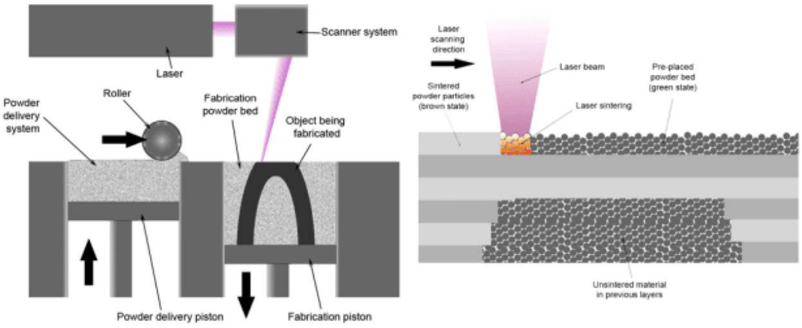
- Technologies that use **laser** (or other forms of energy) to produce melting metals, starting from a bed of metal powders

Limitations: small size of achievable pieces and the production costs are too high compared to traditional manufacturing processes. **Less expensive and suitable for the fabrication of larger equipment are:**

Direct Energy Deposition (DED)

- Technologies use **lasers** (or other forms of energy) and **robotic arms** to produce quite large metal objects, starting from **powder or metal wire**
  - ✓ ***Wire and Arc Additive Manufacturing* (WAAM)** - Welding of metal wires by means of automatic or robotic systems with crane numerical control

Powder Bed Fusion: the process



Wikipedia (https://en.wikipedia.org/wiki/Selective_laser_sintering).

The **powder,** placed on a plate in a uniform way, is **melted or sintered by a heat source**, which may be constituted by a laser source or an electron beam

- ✓ The process allows to obtain products with the same mechanical characteristics, with **more complex geometries and less use of material.** It allows to distribute more material where it is necessary to resist the stresses

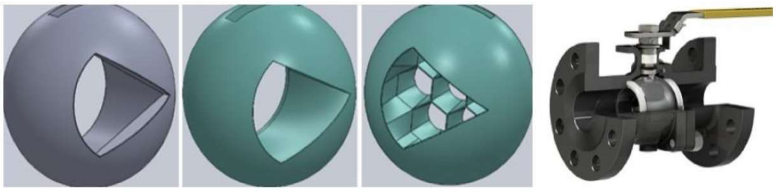
Powder Bed Fusion: main factors to consider

In the powder, gas bubbles could transfer into the final product and could cause excessive porosity of the material. To remove the residual porosity, a post-treatment of **Hot Isostatic Pressing (HIP)** is sometimes carried out.

- The **particle size** and **purity of the powders** must be maintained for all stages of the production process (even in the case of reuse of the powders)
- The production process includes **heating and cooling cycles**, with consequent expansion and contraction of the material, which can lead to the presence of residual stress in the final product. Good control of thermal gradients is required
- Possible **delamination** favored by the presence of not perfectly melted areas in the final material, caused by an inhomogeneous heating of the substrate
- Changes in the **composition of the alloy**: alloy metals with a lower melting point can partially evaporate during the process

Powder Bed Fusion: application examples

Hydraulic components, usually made in stainless steel, such as manifolds and regulating valves.



V-port valve

Hydro manifold

The body of such equipment is completely **re-engineered**, as there is the possibility of obtaining components with more complex forms, greater efficiency in controlling the flow and lighter with the same mechanical strength.

Powder Bed Fusion - Selective Laser Melting (SLM) - IN718

IN718 – As-built

	EOS				Renishaw (30 µm)				Renishaw (60 µm)				RINA CSM
Direction	XY	σ	Z	σ	XY	σ	Z	σ	XY	σ	Z	σ	
Tensile strength [Mpa]	1060	50	980	50	1041	7	791	3	1057	11	943	38	965
Yield strength [Mpa]	780	50	634	50	758	4	636	19	753	8	639	13	670
Elongation at break [%]	27	5	31	5	30	1	36	1	25	3	19	8	33
Modulus of elasticity [Gp	160	20			186	5	158	18	203	10	191	9	151
Hardness HV	302				277	9	302	8	275	14	295	11	304
Surface roughness [µm]	4-6,5		20-50		1,28-1,36		1,72-1,96		1,14-1,7		2,36-3		
Density (min) [g/cm³]	8.15				8.19								

Heat Treated

	EOS AMS 5662 (1)		EOS AMS 5664 (2)		Renishaw (30 µm) (3)				Renishaw (60 µm) (3)				RINA CSM		Forged		Cast	
Direction	Z	σ	Z	σ	XY	σ	Z	σ	XY	σ	Z	σ	Z	σ		σ		σ
Tensile strength [Mpa]	1400	100	1380	100	1467	6	1391	9	1504	3	1439	11	1400	11	1380		809	51
Yield strength [Mpa]	1150	100	1240	100	1259	5	1202	15	1306	10	1231	10	1180	10	1192		516	34
Elongation at break [%]	15	3	18	5	17	1	17	1	16	2	16	2	21	2	25		8	2
Modulus of elasticity [Gp	170	20	170	20	195	13	186	15	202	4	198	11	170	9	185		205	
Hardness HV	472		424		418	9	488	11	465	28	467	20	338	10	340	40	266	

HIP

	Renishaw (30 µm)				Renishaw (60 µm)			
Direction	XY	σ	Z	σ	XY	σ	Z	σ
Tensile strength [Mpa]	1379	3	1346	5	1289	4	1228	24
Yield strength [Mpa]	1088	26	1052	4	958	8	929	10
Elongation at break [%]	25	1	24	1	23	2	17	4
Modulus of elasticity [Gp	207	4	201	3	219	6	214	7
Hardness HV	456	11	468	7	408	11	418	16

Mechanical properties of IN718 produced by SLM, compared to conventional products.

(1) Solution Anneal at 980 °C for 1 hour, air /argon cooling. Ageing treatment: holding at 720°C for 8 hours, furnace cooling at 620 °C for 2 hours, holding at 620 °C for 8 hours, air/argon cooling.

(2) Solution Anneal at 1065°C for 1 hour, air/argon cooling. Ageing treatment: holding at 760°C for 10 hours.

(3) Solution Anneal at 980°C for 1 hour, air/argon cooling. Ageing treatment: see (1).

Powder Bed Fusion - Selective Laser Melting (SLM) - IN625

IN625															
	As-built													Forged (CSM)	Cast
	EOS				Renishaw (30 µm)				Renishaw (60 µm)				RINA CSM		
Direction	XY	σ	Z	σ	XY	σ	Z	σ	XY	σ	Z	σ			
Tensile strength [Mpa]	990	50	900	50	1055	3	964	2	922	9	770	56	1030-1070		
Yield strength [Mpa]	725	50	615	50	767	9	676	7	667	11	536	34	720-800		
Elongation at break [%]	35	5	42	5	34	1	42	1	18	2	11	4	8-10		
Modulus of elasticity [Gpa]	170	20	140	20	205	10	186	11	175	16	176	9	130-205		
Hardness HV				302	331	8	332	8	302	13	308	6	340-355		
Surface roughness [µm]		4-6		20-50		2-3		6-7							
Density (min) [g/cm³]				8,4								8,04			
	Heat Treated														
	EOS (4)				Renishaw (30 µm) (5)				Renishaw (60 µm) (5)					Forged (CSM)	Cast
Direction	XY	σ	Z	σ	XY	σ	Z	σ	XY	σ	Z	σ			
Tensile strength [Mpa]	1040	100	930	100	1020	1	955	2	1005	6	985	10		825	710
Yield strength [Mpa]	720	100	650	100	633	1	598	2	600	4	583	2		410	350
Elongation at break [%]	170	20	160	20	39	1	43	1	31	2	32	4		58	48
Modulus of elasticity [Gpa]	35	5	44	5	206	3	200	2	208	4	209	6		214	218
Hardness HV				298	251	13	254	16	279	7	290	8		442	

Mechanical properties of IN625 produced by SLM, compared to conventional products.

(4) Stress relieve, anneal at 870°C for 1 hour, rapid cooling.
(5) Annealing at 1048°C for 1 hour followed by furnace cooling.

Powder Bed Fusion - Selective Laser Melting (SLM)

Mechanical properties of AISI316L

AISI316L												
	As-built (SLM)										Wrought	Cast
	EOS				Renishaw				RINA CSM			
Direction	XY	σ	Z	σ	XY	σ	Z	σ	Z	σ		
Tensile strength [Mpa]	640	50	540	55	676	2	624	17	600	2	560	485
Yield strength [Mpa]	530	60	470	90	574	3	494	14	500	3	235	205
Elongation at break [%]	40	15	50	20	43	2	35	8	55	2	55	30
Modulus of elasticity [Gpa]	185		180		197	4	190	10	185	4	226	184
Hardness HV	180				198	8	208	6	175	8	180	179
Surface roughness [µm]	13	5	80	20	5	1	5	1				
Density (min) [g/cm³]	7,9				7,99							
Melting range [C°]	1371 °C to 1399 °C											

Powder Bed Fusion - Selective Laser Melting (SLM)

Mechanical properties of Ti6Al4V

Ti6Al4V												
	As-built (SLM)										Forged	Cast
	EOS				Renishaw				RINA CSM			
Direction	XY	σ	Z	σ	XY	σ	Z	σ	Z	σ		
Tensile strength [Mpa]	1290	50	1240	50	1091	6	1084	8	953	7	931	860
Yield strength [Mpa]	1140	50	1120	80	1020	25	987	22	892	5	855	758
Elongation at break [%]	7	3	10	3	16	1	17	1	14	3	10	8
Modulus of elasticity [Gp	1110	15	1110	15	132	9	128	7	110	5	104	120
Hardness HV	312				363	11	363	13	320	4	342	311
Surface roughness [µm]	9	2	60	20	3	1	6	1				
Density (min) [g/cm³]	4,41				4,42							
Melting range [C°]	1635-1665											

Direct Energy Deposition (DED)

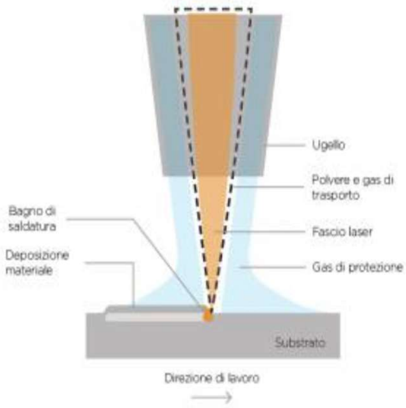
Direct Energy Deposition process allows the construction of metal structures by **depositing and melting powders or metal wires.**

The **heat source** may be constituted by laser, electron beam or plasma transferred arc.

The **metal powder** or **wire**, the **shielding gas** and the **laser** are delivered simultaneously through a **nozzle.**

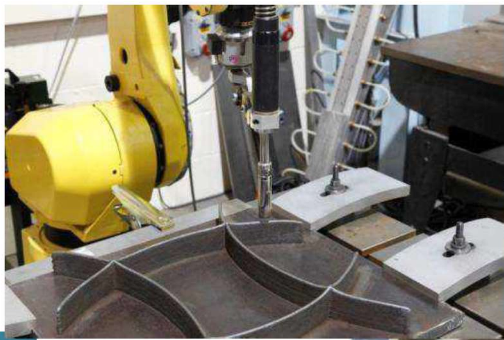
The wires are cheaper and more readily available than metal powders, which must be produced depending on the object to be realized.

The obtained product can be subjected to finishing processes.



Source http://www.addmelab.polimi.it/stampare-in-metallo/la-tecnologia-ded/

Some DED products



www.cranfield.ac.uk

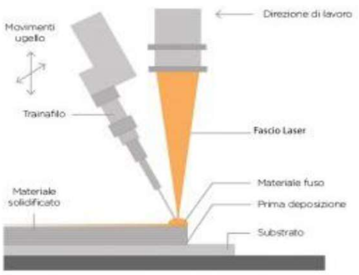
As deposited – 6 hours

After machining

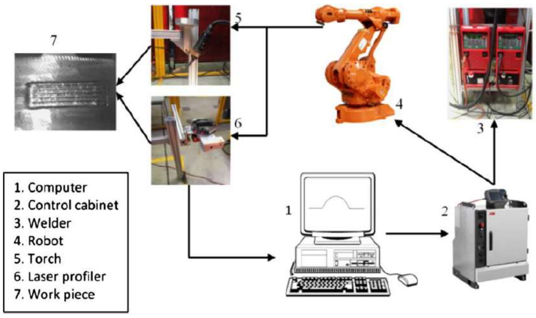
WAAM (Wire and Arc Additive Manufacturing) Process

WAAM is one the most interesting technology for the realization of **large size equipment** and limited geometric complexity, such as flanges or vessels.

It uses **arc welding** with metal under gas protection with tungsten electrode (GTAW) or plasma (PAW). This technology is widely used for the deposition of several layers of material, even different, or for **repairs,** especially in presence of large thicknesses of metal.



Source http://www.addmelab.polimi.it/stampare-in-metallo/la-tecnologia-ded/



Cortesy of Faculty of Engineering and Information Sciences, University of Wollongong, Australia

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Conclusions

The main benefits of additive technologies are:

* rapid prototyping compared to traditional processes;
* reduced manufacturing times and scarcely influenced by the geometry of the product;
* limited waste of material that allows to take into account uncommon alloys (titanium alloys and superalloys);
* lightening of the component through geometry optimization;
* possibility to optimize the fluid dynamics of the component with a customized design of the internal ducts.

Although the additive manufacturing sector already plays a complementary role compared to traditional technologies, its use in the pressure equipment sector is still limited. For some specific applications, AM components can replace those made with standard technologies.


Thank you very much!