PMI Network

Cooperazione Transfrontaliera per l’Innovazione

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INTRODUZIONE ALLA MANIFATTURA ADDTIVA DEI MATERIALI METALLICI E AL SUO UTILIZZO INDUSTRIALE

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POLITECNICO
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Interessi scientifici:
Cold Gas Dynamic Spray, caratterizzazione materiali AM, trattamenti superficiali per migliorare la resistenza meccanica e funzionalizzare le superfici, metodi di progettazione.

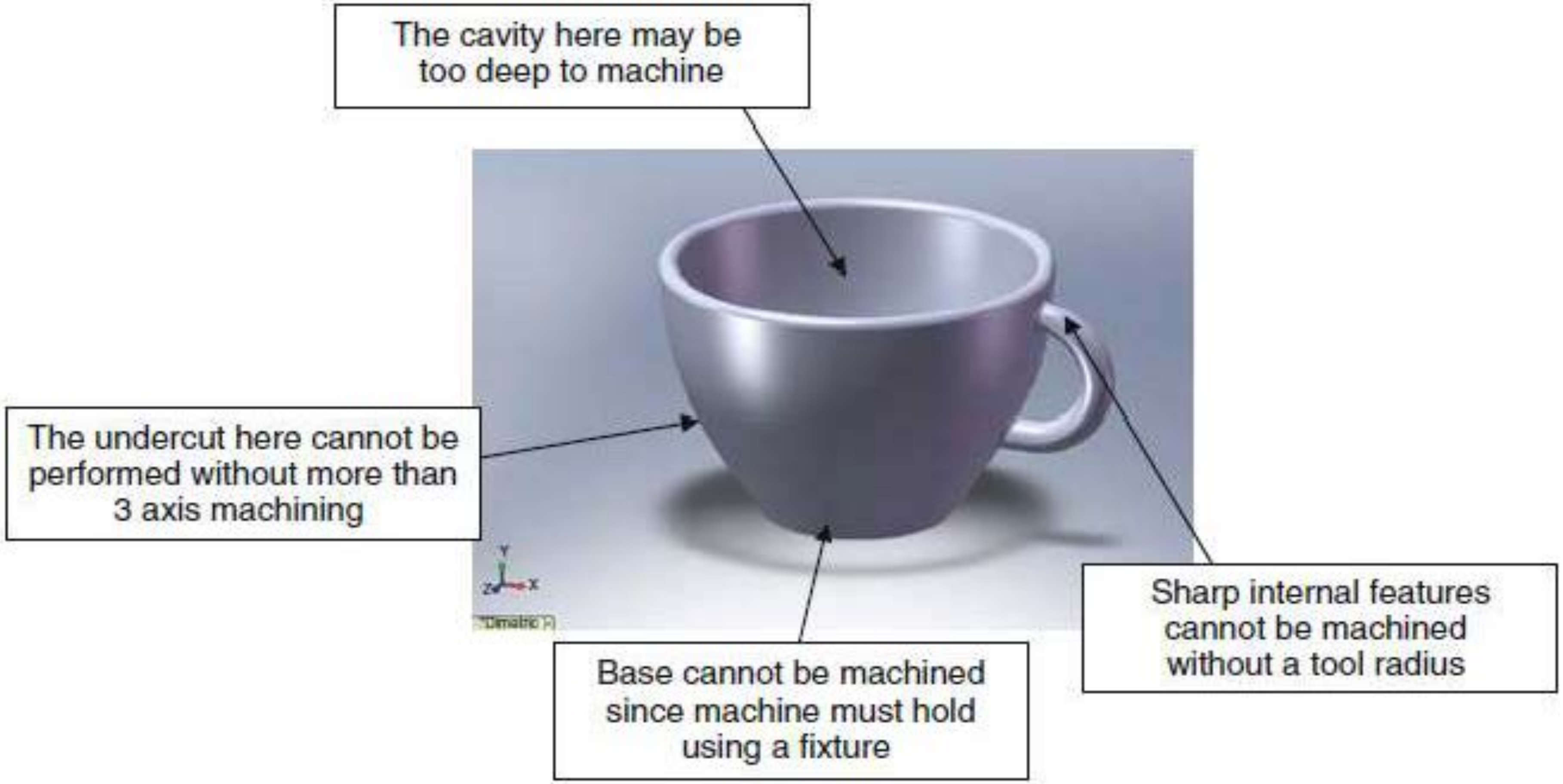
1. Introduzione

2. Le tecnologie additive

3. Design for Additive Manufacturing (DfAM)

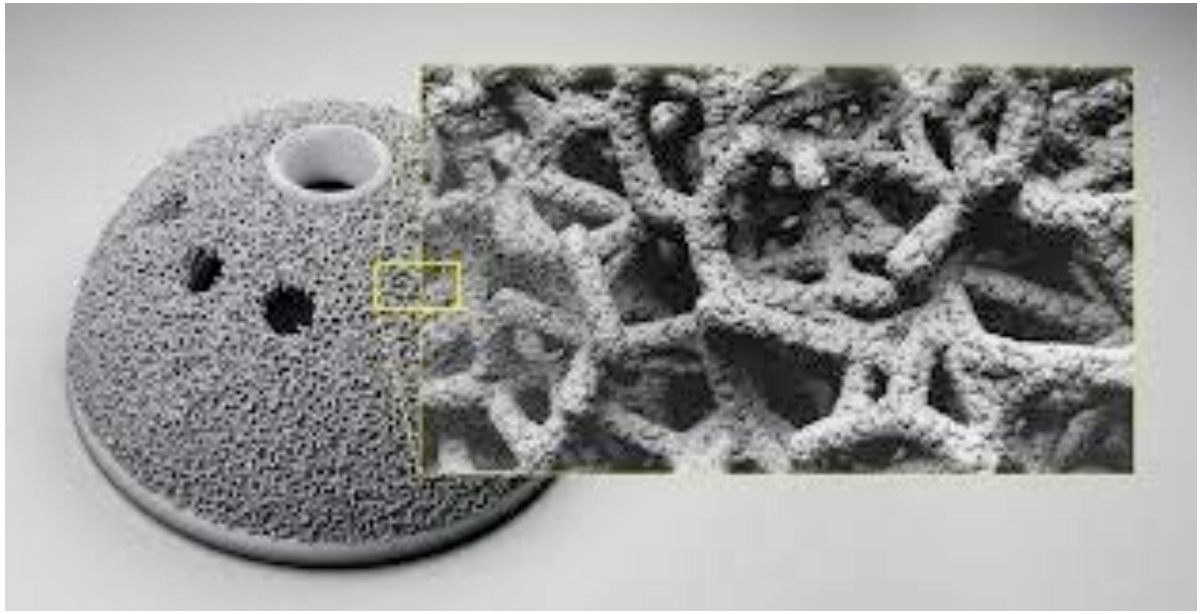
4. Problematche

5. Alcuni esempi



Alcun problemi legati alle lavorazioni sottrattive CNC.

Fonte: Gibson, Additive Manufacturing



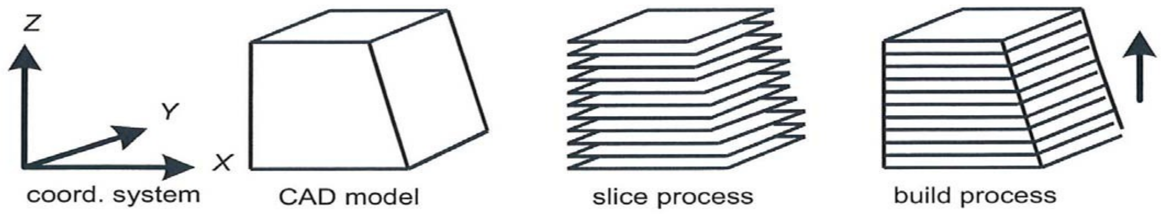
Definizioni

✓ Secondo ASTM F2792-12a: Standard Terminology for Additive Manufacturing Technologies:

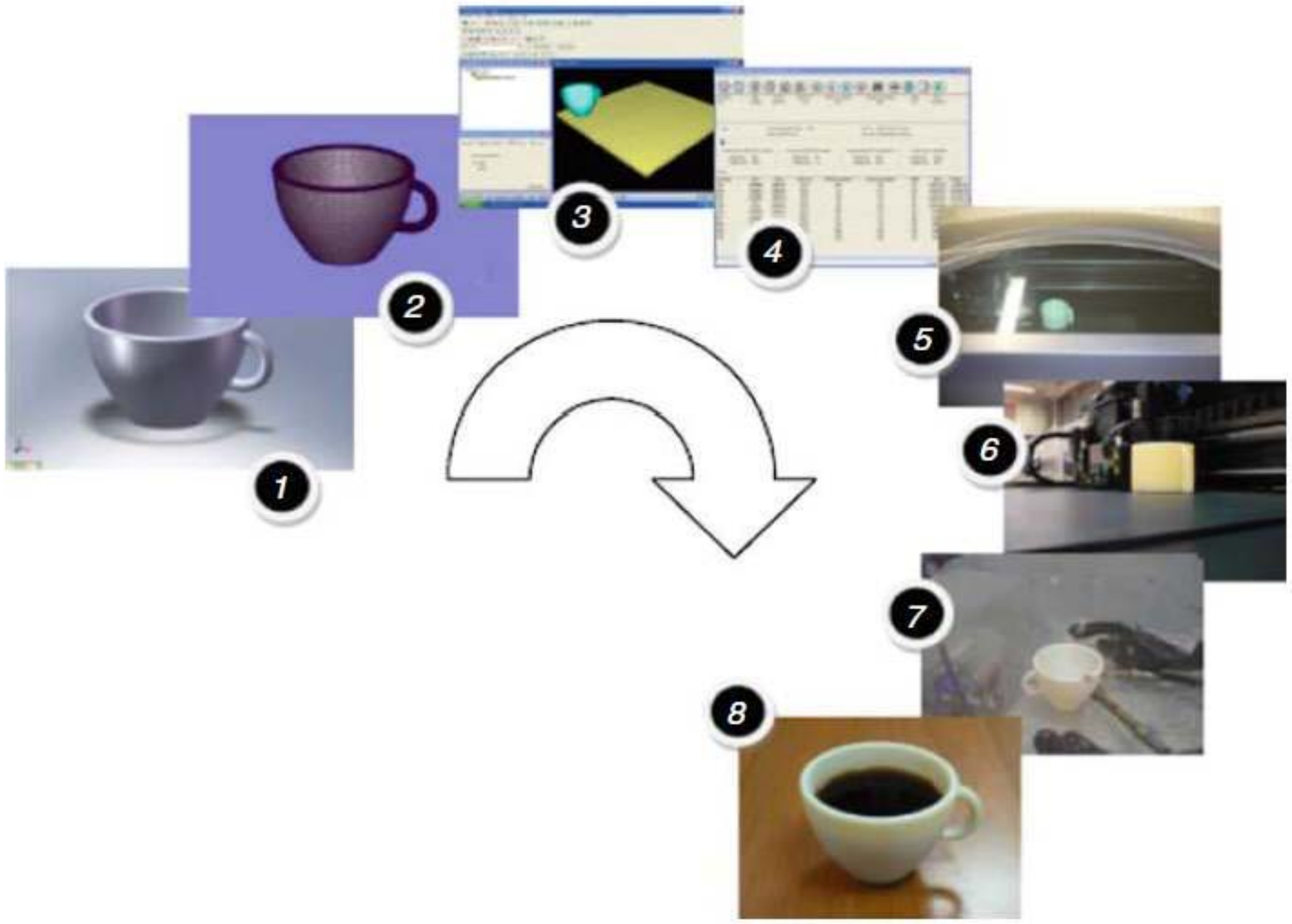
"A process of joining materials to make objects from 3D model data, usually layer upon layer."

✓ Sinonimi: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication

✓ L'additive manufacturing si distingue dai tradizionali processi sottrattivi come tornitura, fresatura, trapanatura...



Source: VDI 3404, 2009



Fonte: Gibson, Additive Manufacturing

Generico processo AM

1. Modello CAD
2. File STL
3. Trasferimento file alla macchina
4. Set up della macchina
5. Costruzione del pezzo
6. Rimozione dalla macchina
7. Post processing
8. Applicazione

Il file .STL

Il formato STL descrive le superfici da costruire con triangolazioni.
Ogni triangolo è descritto come tre punti e un vettore normale che indica la normale uscente del triangolo.

Es:

facet normal 4.470293E02 7.003503E01 7.123981E-01

outer loop
vertex 2.812284E+00 2.298693E+01 0.000000E+00
vertex 2.812284E+00 2.296699E+01 1.960784E02
vertex 3.124760E+00 2.296699E+01 0.000000E+00
endloop
endfacet
….
….
….

Fonte: Gibson, Additive Manufacturing

Quali sono le differenze tra le diverse tecnologie?

- ✓ Tecniche per creare gli strati;
- ✓ Tecniche per «incollare» gli strati;
- ✓ Velocità;
- ✓ Spessore degli strati;
- ✓ Materiali;
- ✓ Accuratezza;
- ✓ Costi.
- ✓ ……

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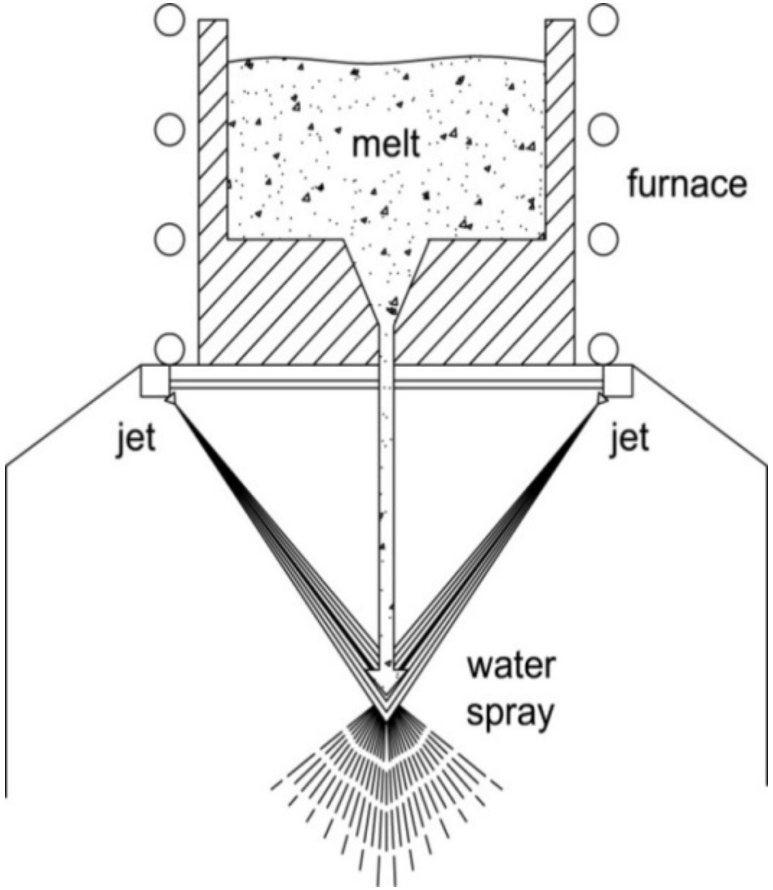
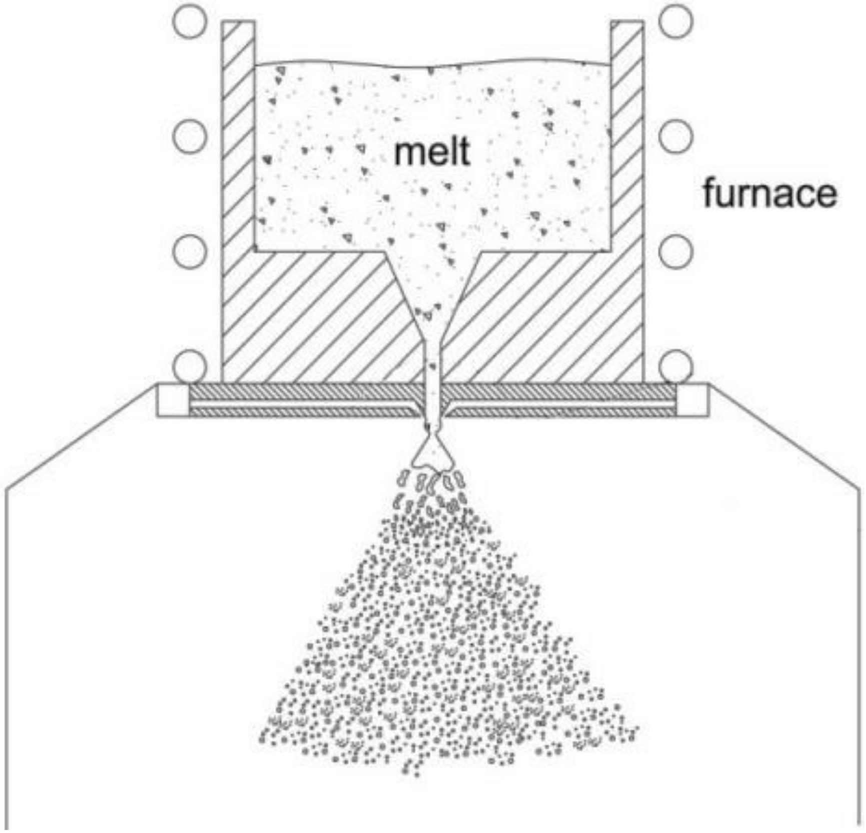
Water atomisation



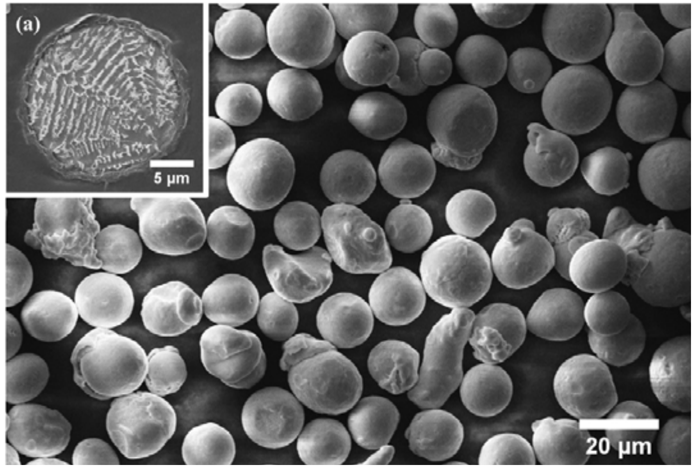
Gas atomisation



Source: German, 1998

LE POLVERI

Table of Powder Manufacturing Processes			
Manufacturing Process	**Particle Size Range**	**Advantages**	**Disadvantages**
Water Atomization	0 - 500 µm	High production rate, Large particle size range, Feedstock in ingot form	Post-processing for water removal, Irregular particle shape, Satellites present, Wide particle size distribution
Gas Atomization	0 - 500 µm	Wide range of alloys available, Suitable for reactive alloys, Feedstock in ingot form, High throughput, Large particle size range, Spherical particles	Satellites present, Wide particle size distribution
Plasma Atomization	0 - 200 µm	Highly spherical particles	Feedstock must be in wire or powder form, High cost
Plasma Rotating Electrode Process	0 - 100 µm	High purity powders, Highly spherical particles	Low productivity, High cost
Centrifugal Atomization	0 - 600 µm	Large particle size range, Narrow particle size	Difficulty in making extremely fine powder
Hydride-dehydride Process	45 - 500 µm	Low cost	Irregular particle shape, Limited to metals which form a brittle hydride



Source

Austin T. Sutton, Caitlin S. Kriewall, Ming C. Leu, Joseph W. Newkirk

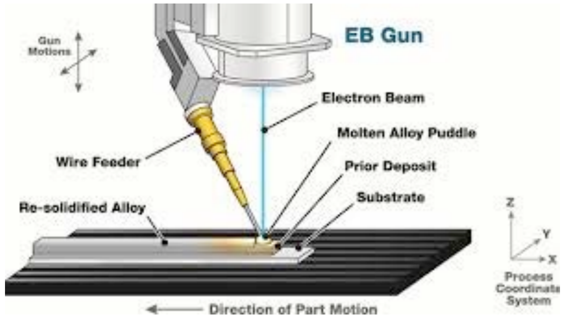
POWDERS FOR ADDITIVE MANUFACTURING PROCESSES: CHARACTERIZATION TECHNIQUES AND EFFECTS ON PART PROPERTIES

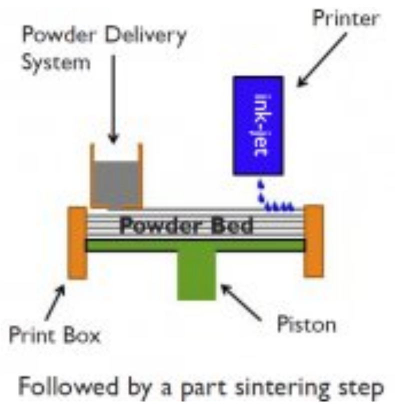
Solid Freeform Fabrication 2016: Proceedings of the 26th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

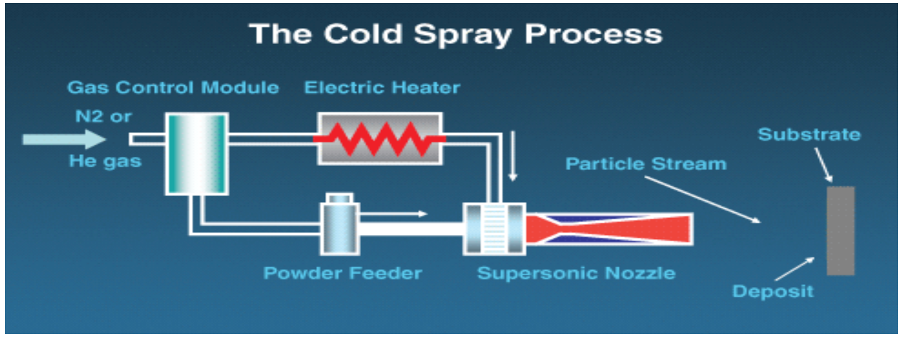
LE TECNOLOGIE

I processi additivi possono essere suddivisi in 3 macro categorie.

- **Processi in cui l'adesione delle polveri è ottenuta con energia termica (Blown powder processes, WAAM, SLM, EBM,…)**
- **Processi in cui l'adesione delle polveri è ottenuta con leganti (Binder Jetting)**
- **Processi in cui l'adesione delle polveri è ottenuta con energia cinetica (Cold Spray)**



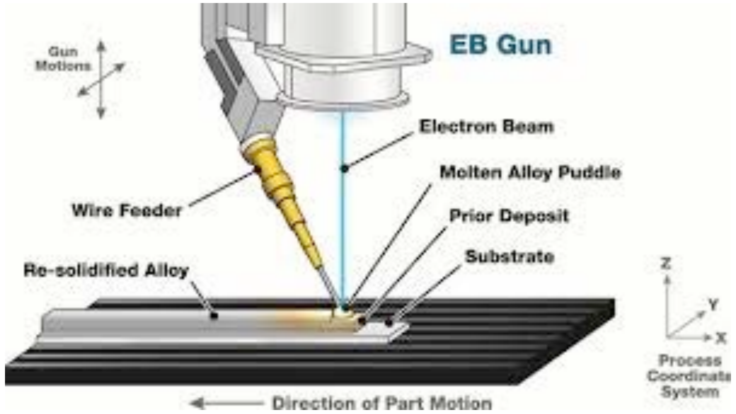


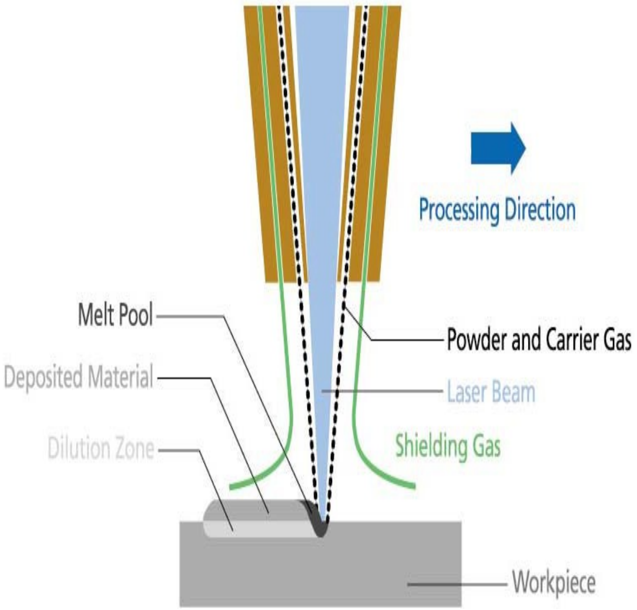


Processi Blown Powder (Laser Cladding)

- La fusione del metallo è ottenuta con laser, fascio elettronico o plasma
- Le polveri o il filo sono guidate nella zona di fusione
- Processi: Direct Metal Deposition (DMD), Laser Engineered Net Shaping (LENS), Wire Arc Additive Manufacturing (WAAM), etc.
- Applicazioni: pezzi nuovi, riparazioni
- Vantaggi: dimensioni pezzi elevate (fino a 10m per il WAAM), maggiori velocità di deposizione (fino a 4 kg/h, tipico 1 kg/h for Ti, WAAM), polveri differenti (graded materials)
- Svantaggi: finitura, risoluzione, complessità

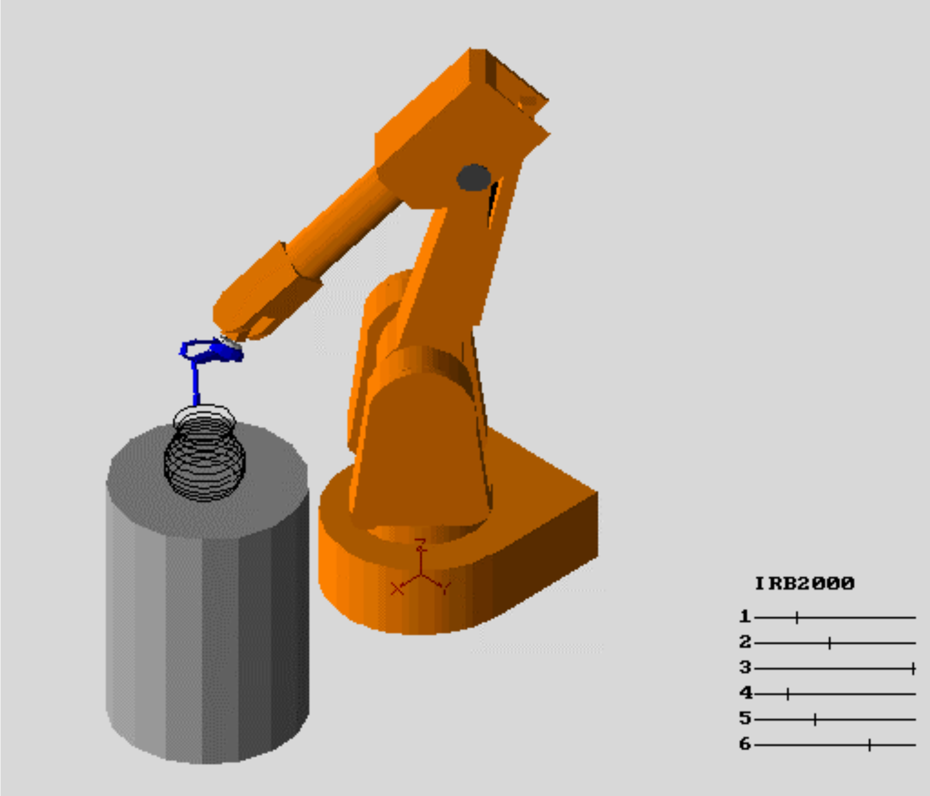
source: www.optomec.com





source: http://www.haydencorp.com/content.php?p=laser_metal_deposition 2014-02-25.

Wire Arc Addtive Manufacturing (WAAM)

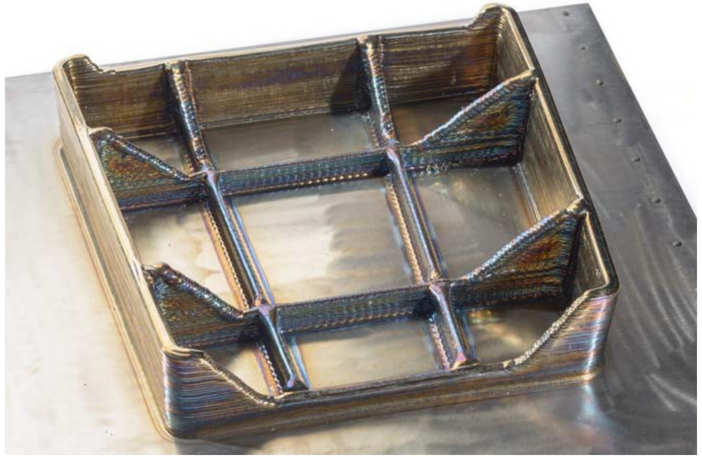


Vantaggi:

- Alte velocità di deposizione (più kg/h)
- Elevata efficienza di deposizione del materiale (
- Bassa difettosità
- Costi contenuti

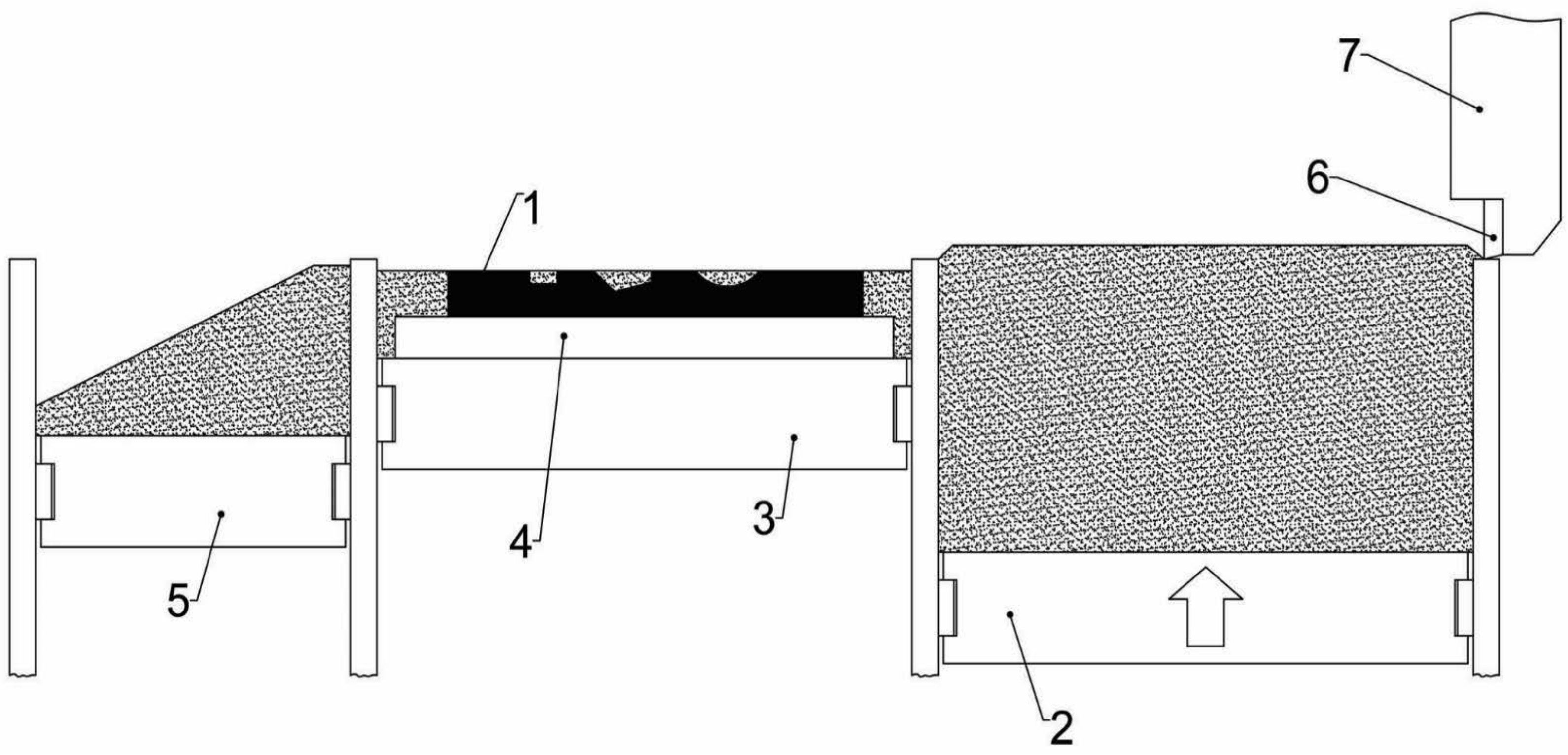
Svantaggi:

- Complessità non elevata



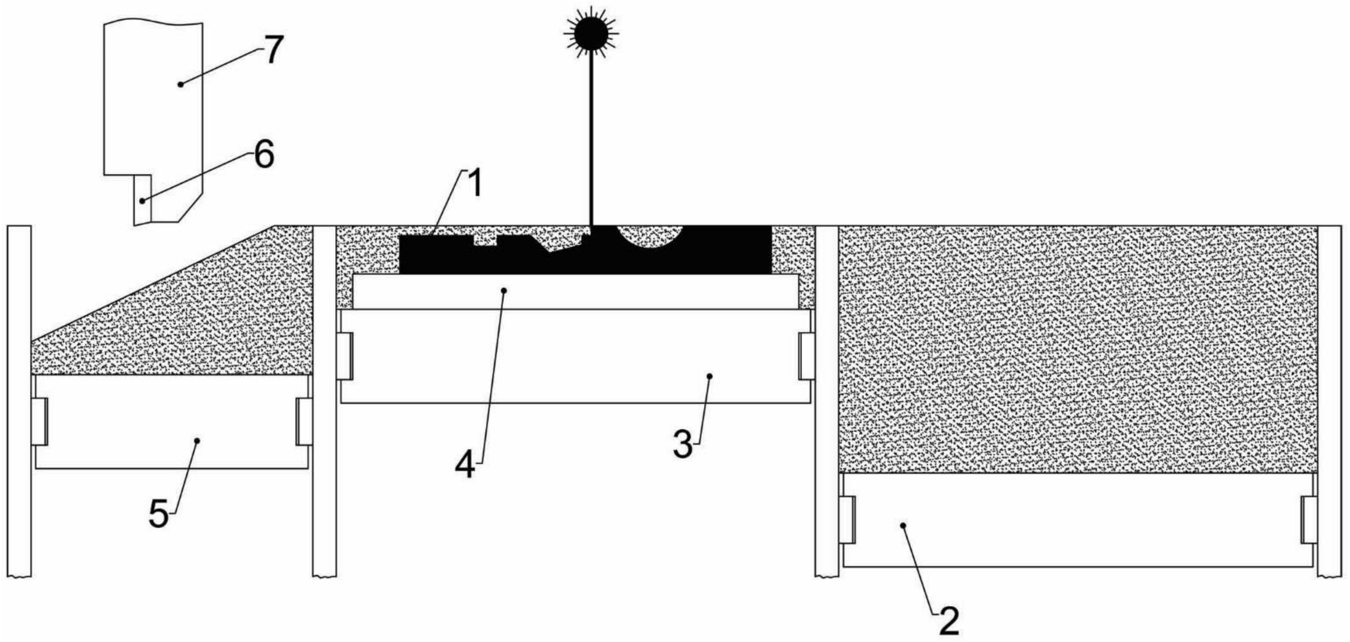
Source: University of Cranfield / WAAMAT http://waammat.com/documents, WAAM 2015 General 2016-06-01

PROCESSI POWDER BED



1 part
2 dispenser platform
3 building platform carrier
4 building platform
5 collector platform
6 recoater blade
7 recoater

PROCESSI POWDER BED



1 part
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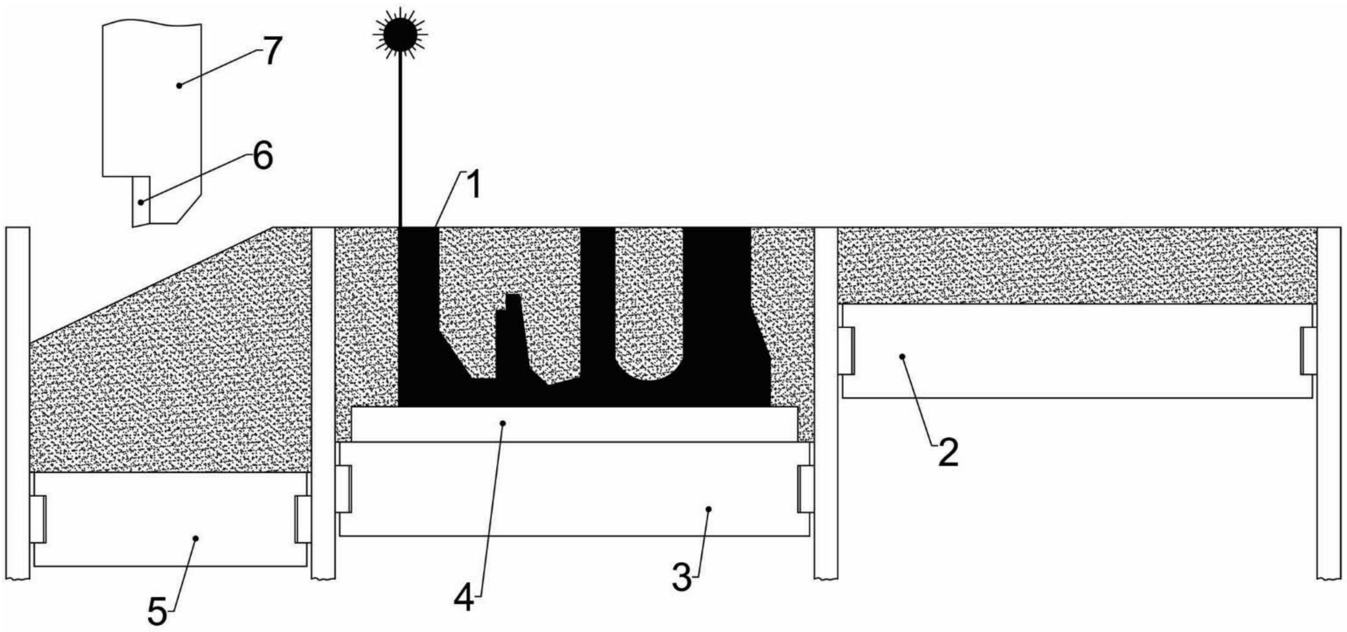
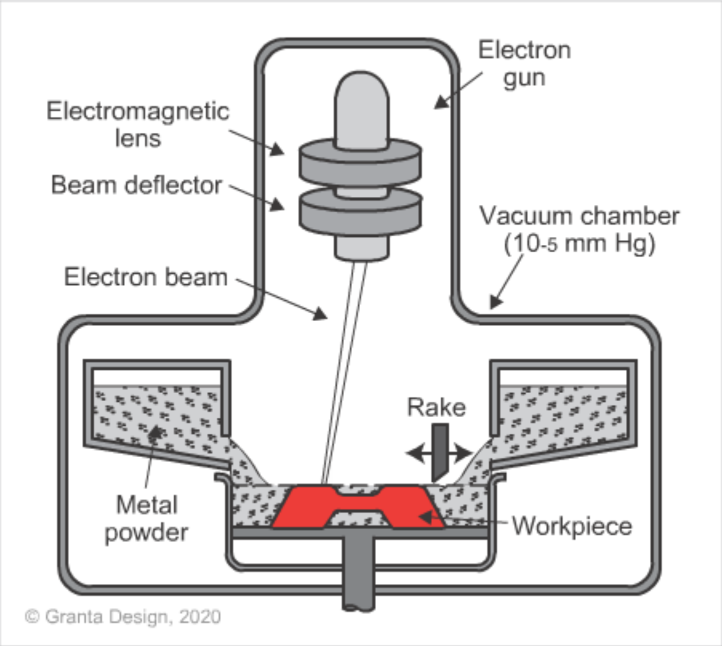
PROCESSI POWDER BED

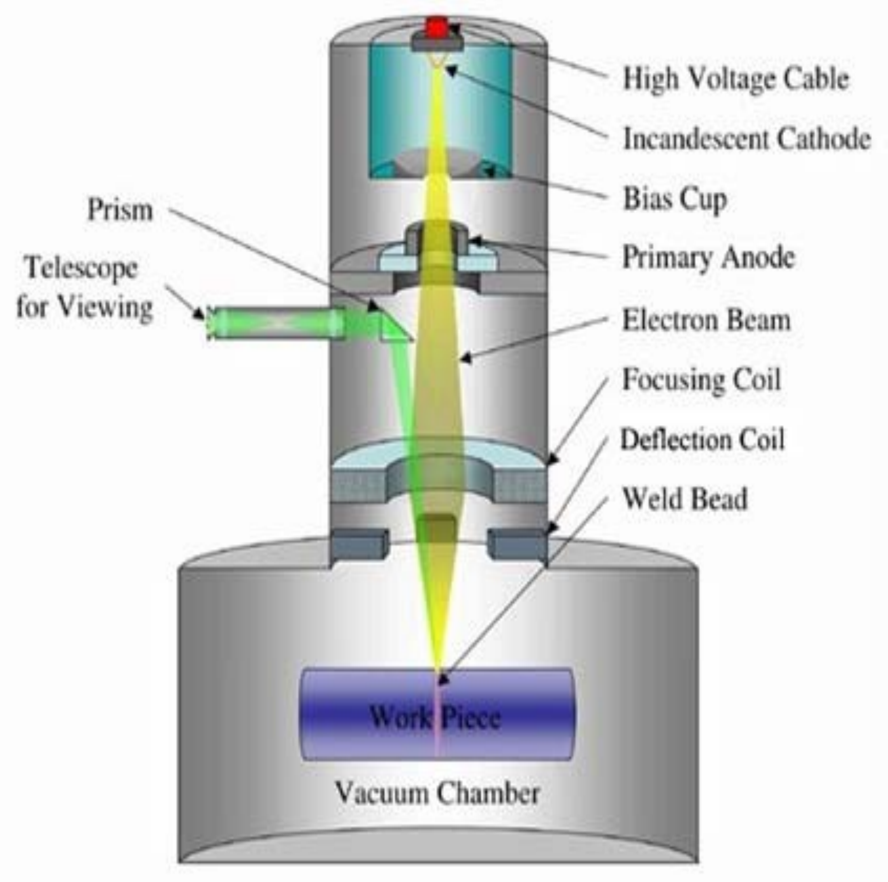


1 part
2 dispenser platform
3 building platform carrier
4 building platform
5 collector platform
6 recoater blade
7 recoater

Electron Beam Melting (EBM)

- La fusione è indotta da un fascio elettronico ad alta energia sotto vuoto.
- Le poveri sono depositate strato per strato
- Applicazioni: Biomed, Aerospace,..
- Vantaggi: Si possono utilizzare più punti di fusione, velocità di deposizione elevata
- Svantaggi: finitura, risoluzione, complessità geometrica

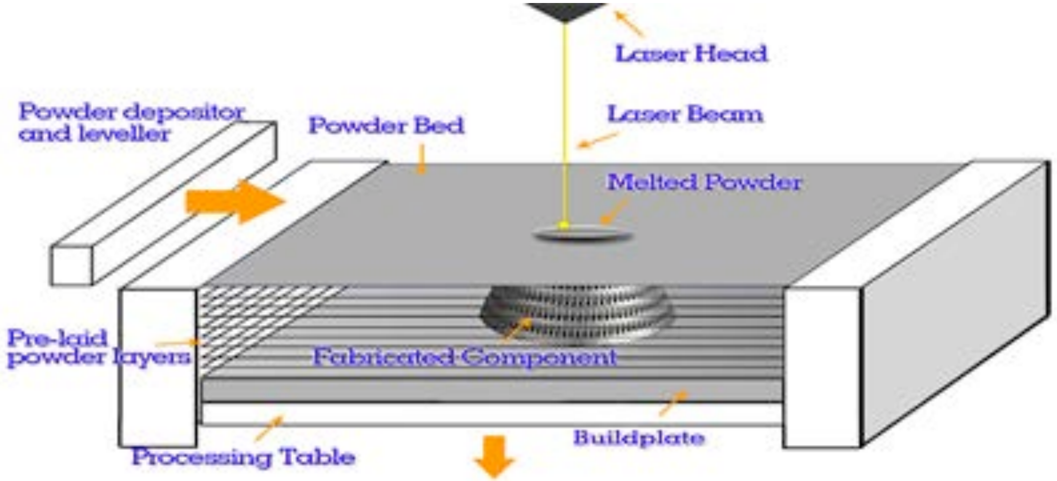




source:
http://www.popular3dprinters.com/electr_on-beam-melting-ebm/

Selective Laser Melting

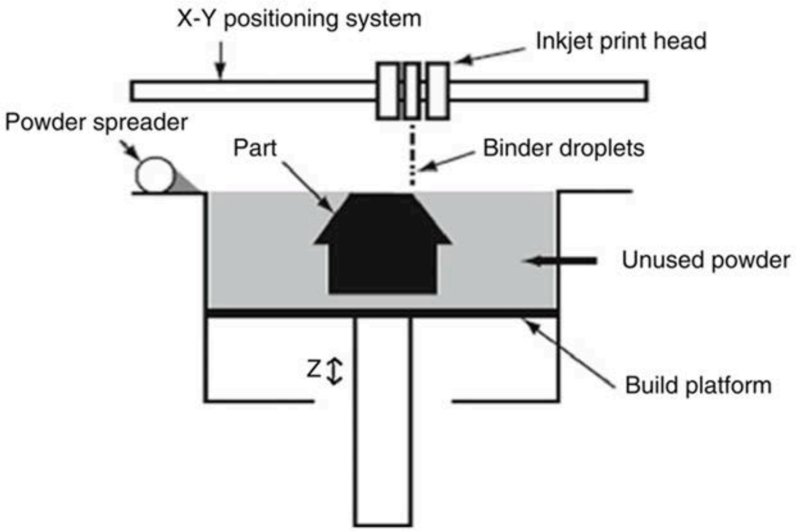
– La fusione è creata via fascio Laser in atmosfera inerte.
– Altre denominazioni: Direct Metal Laser Sintering, LaserCusing, Laser Beam Melting,
– Le poveri sono depositate strato per strato
– Applicazioni: Biomed, aerospace, automotive, tooling
– Vantaggi: alta versatilità e libertà geometrica (lattice structures)
– Svantaggi: bassi tassi di deposizione
– Costi (approx): 200000-400000€



SLM® 280HL (SLM Solution Group AG) system equipped with 2x400W Yttrium fiber lasers

Binder jetting

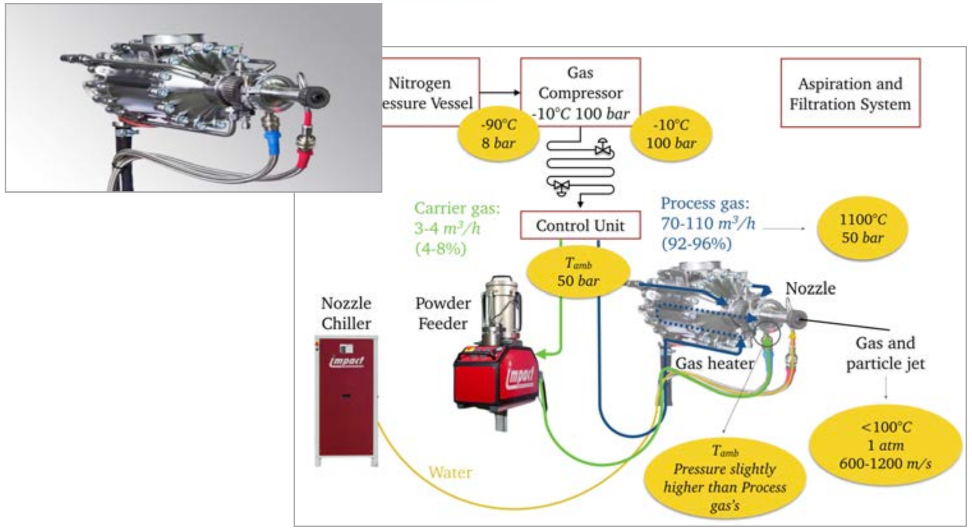
- La polvere è miscelata a un legante. Dopo la stampa la parte viene consolidata con sinterizzazione. Non è un processo termico
- Le poveri sono depositate strato per strato
- Applicazioni: piccole dimensioni,
- Vantaggi: buone tolleranze e finitura, alta risoluzione. Volume camera elevato. NO struttura di supporto. No distorsioni termiche.
- Svantaggi: Sinterizzazione, proprietà meccaniche.

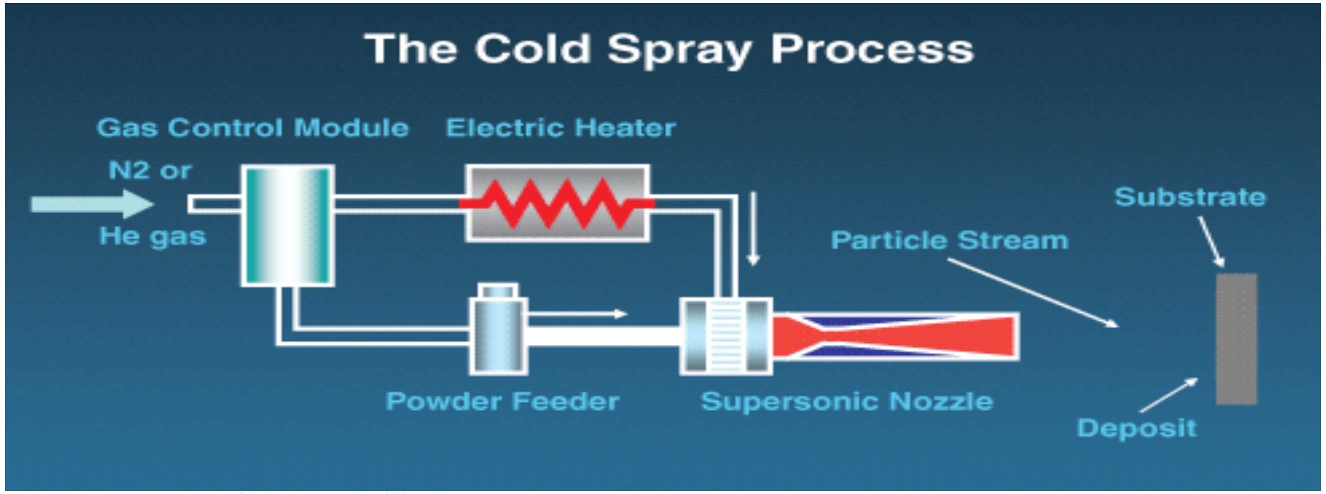


Multi-part sand casting assembly used to cast an engine block. Source: ExOne

Cold Gas Dynamic Spray

- La polvere è lanciata a velocità supersonica contro un bersaglio, l'adesione avviene allo stato solido grazie alla elevata deformazione plastica e all'elevato strain rate.
- Utilizza energia cinetica, non termica.
- Necessita post-trattamenti.
- Applicazioni: biomed, aerospace, automotive, repair, coatings,
- Vantaggi: elevata velocità di deposizione (10-15 volte SLM), non c'è bisogno di atmosfera controllata, grandi dimensioni, tensioni residue compressione.
- Svantaggi: risoluzione e tolleranze.
- Costi (approx): da 70000€ a 300000€





Cold Gas Dynamic Spray

Cold Gas Dynamic Spray, un processo versatile

I COSTI

- **SLM, SLS,..** — **Max. build size: 100x100x100mm^3: > 250k€**
- **SLM** — **Max. build size: 250x250x350mm^3: > 350k€**
- **Blown powder** — **Max. build size: 160x120x450 mm^3: 100k€**
- **Cold spray** — **Max build size 500x500x500 mm^3: 100k€ (LP) – 300 k€ (HP)**
- **Binder jetting** — **Max build size 800x500x400 mm^3: >250k€**

https://www.aniwaa.com/buyers-guide/3d-printers/best-metal-3d-printer/

1. Introduzione

2. Le tecnologie additive

3. Design for Additive Manufacturing (DfAM)

4. Problematiche

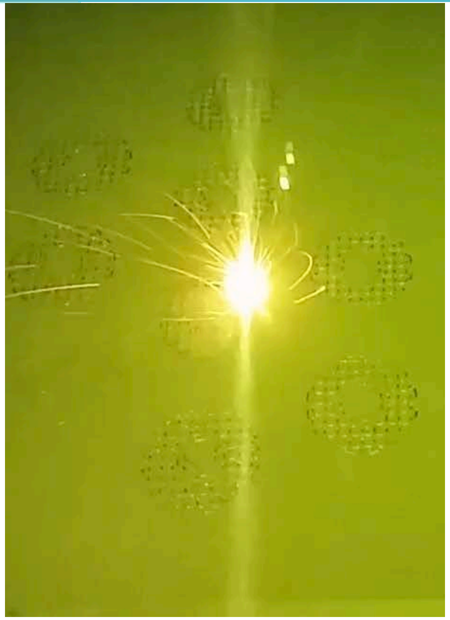
5. Alcuni esempi

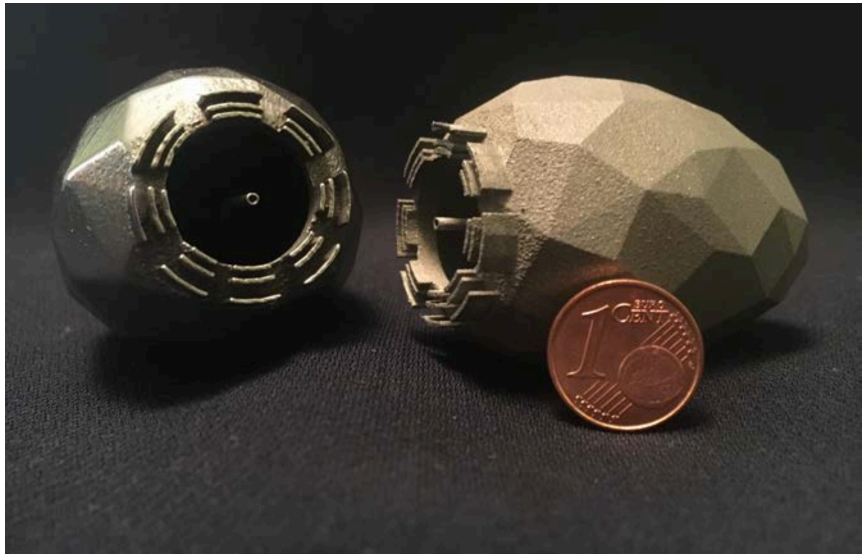
DESIGN FOR ADDITIVE MANUFACTURING

L'utilizzo delle tecnologie additive richiede uno sforzo di progettazione relativo…:

1. …alle peculiarità della tecnologia utilizzata, con relativi vincoli e limiti

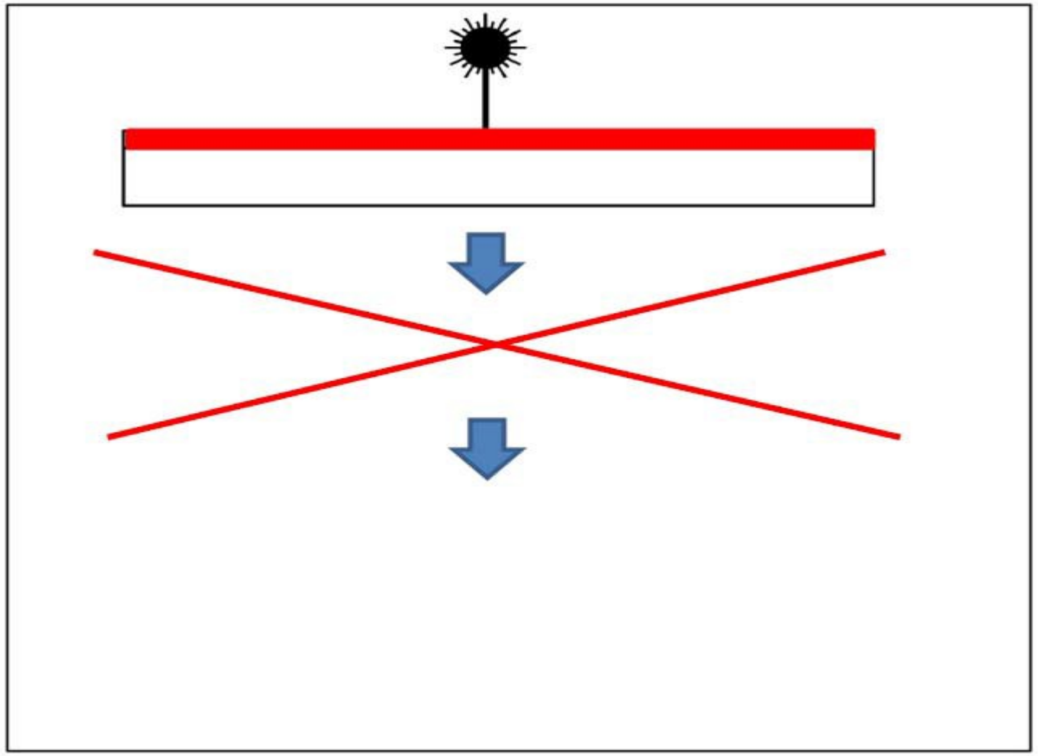
2. ..all'applicazione della parte da produrre, considerando i gradi di liberà offerti da queste tecnologie.





Giorgia Galimberti, PhD
From metallic powder to the object
supervisors
Mario Guagliano, Barbara Previtali

Theoretical background

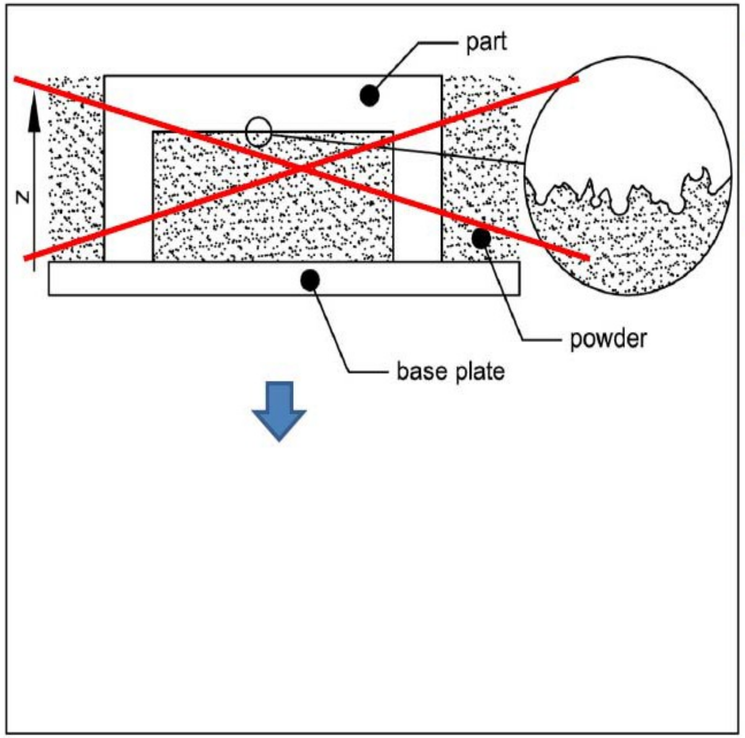


Key:
z … building direction

- Due to induced thermal stresses resulting from reduction in temperature from the melting point: metal would bend!
- => supporting structure keeps part in its position
- => thermal stresses
- => will be partially relieved when cutting the part off the base plate and when supporting structure is removed
- Different (elastic) deformation for different materials!

DESIGN FOR ADDITIVE MANUFACTURING

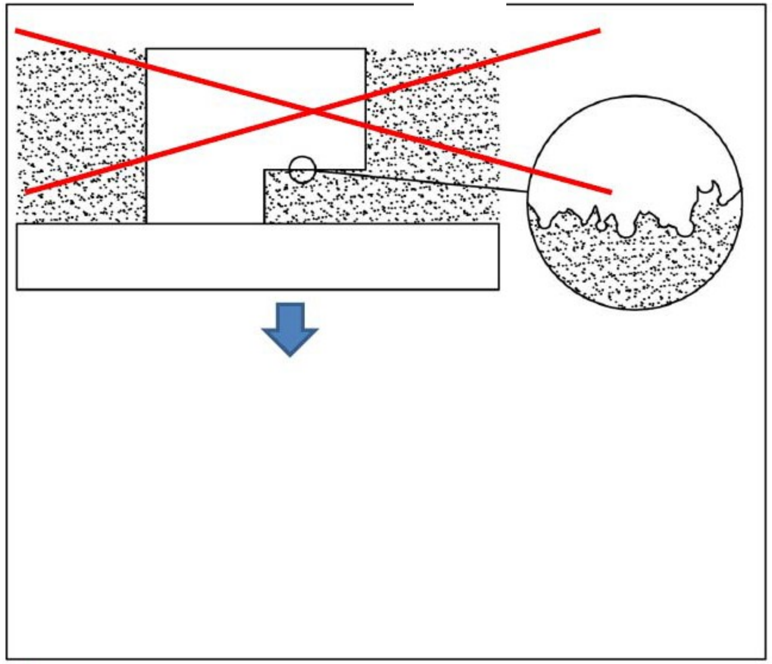
Design Rules



Key:
z … building direction

- Design would most likely result in a building error
- Surface quality is very poor!
- Flat, down-facing areas shall be designed as arch

Design Rules

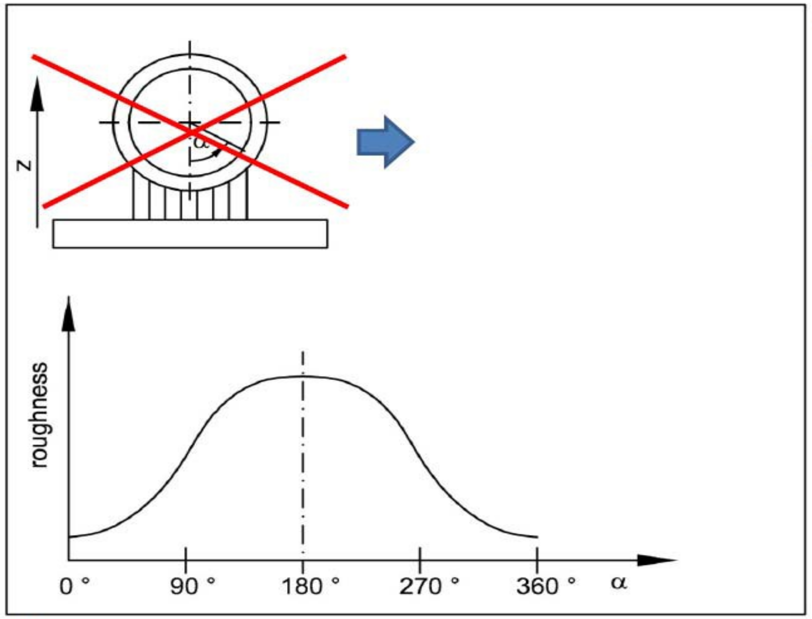


Key:
z … building direction

- Flat down-facing surfaces shall show an angle $\alpha > 45°$
- The steeper the angle, the better it is!

DESIGN FOR ADDITIVE MANUFACTURING

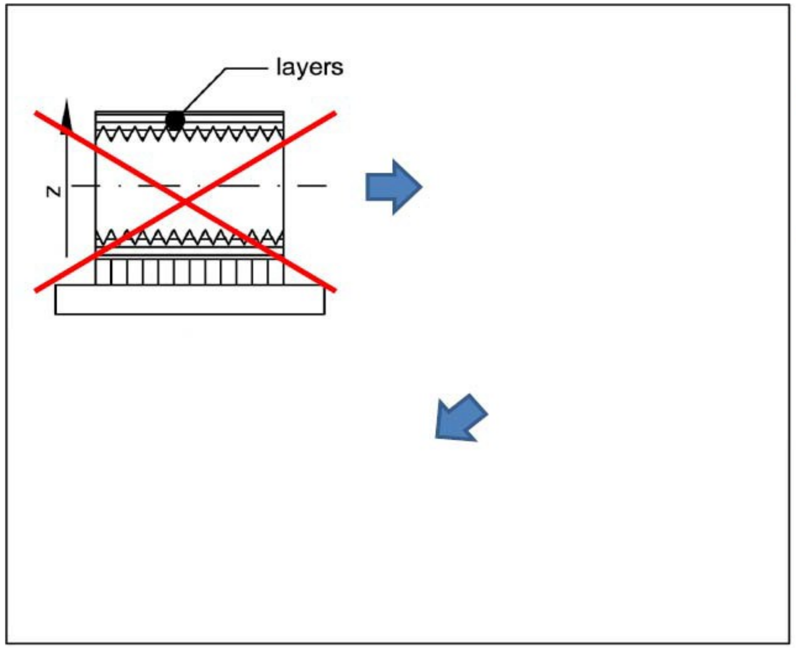
Design Rules



Key:
z … building direction

- Anisotropic surface roughness / quality when building circular shapes in horizontal direction
- => whenever possible: build circular shapes vertically!

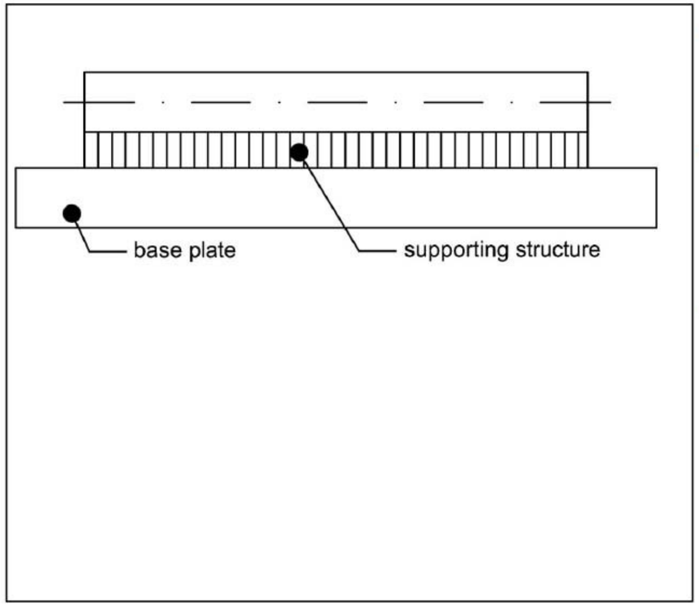
Design Rules



Key:
z … building direction

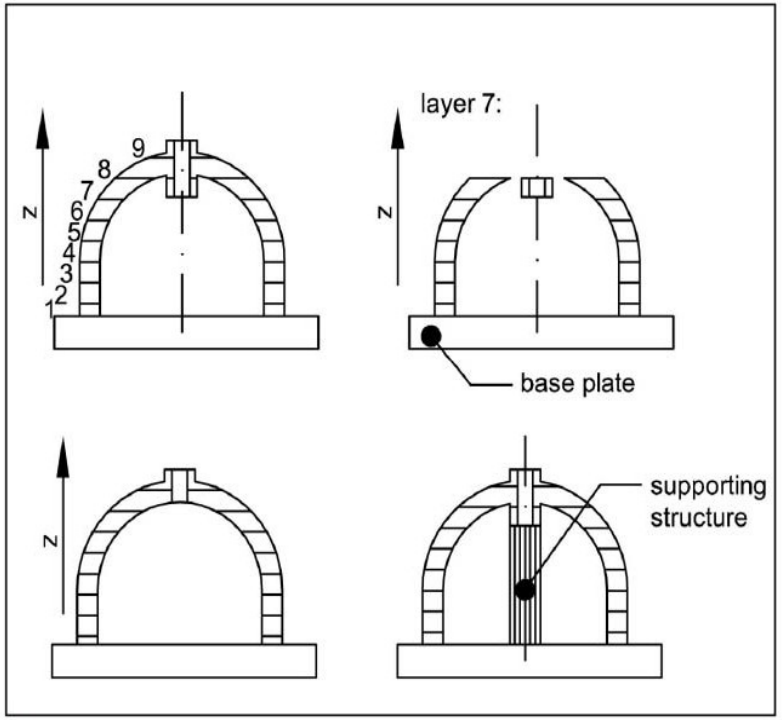
- Threads can readily be built
- Dependent on achieveable surface roughness of the certain material
- Threads (i.e. circular shapes) shall be built vertically

Design Rules



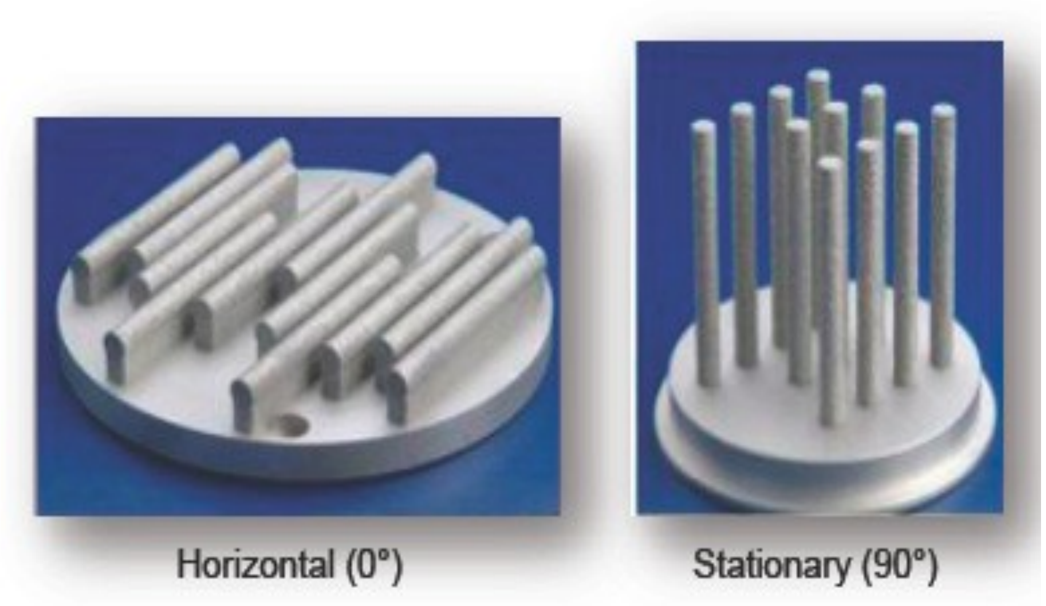
- Flat, long parts, built horizontally will bend after being removed from the base plate
- Dependent on the material (modulus of elasticity)
  - especially important for titanium or aluminium
- => stress relief annealing of the whole base plate with parts

Design Rules



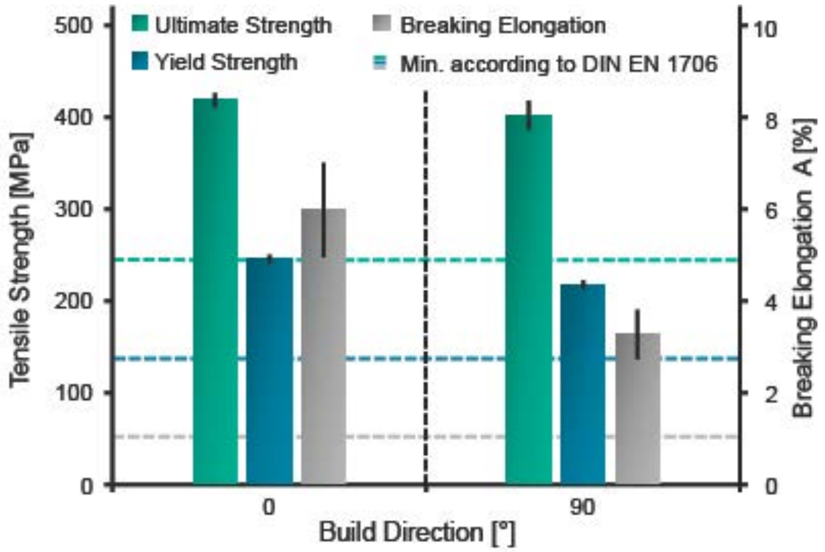
Key:
z … building direction

- Any welded area must be connected to the base plate ANY time!
- Otherwise: building error



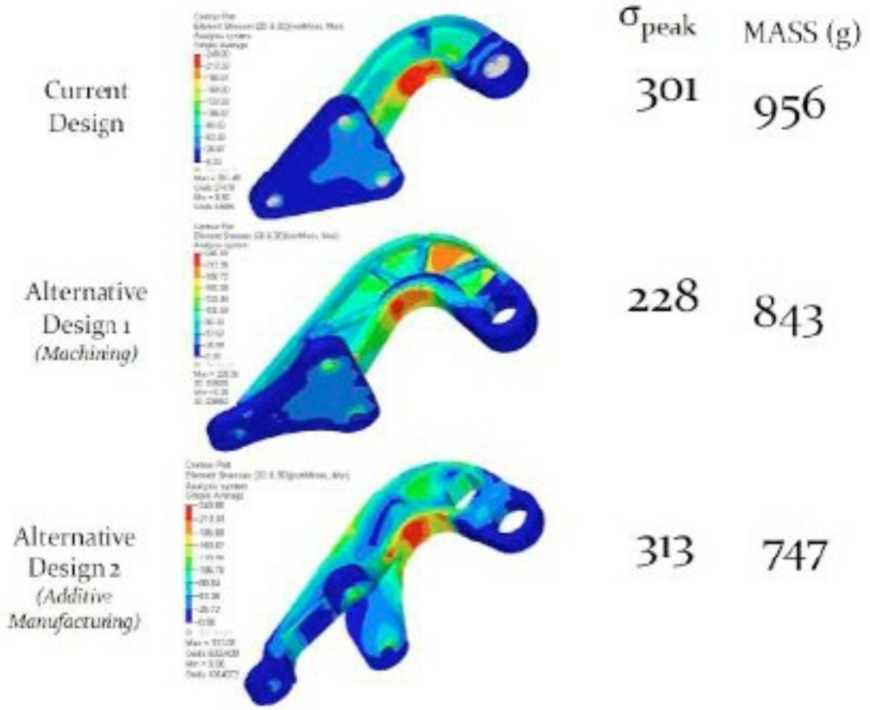
L’orientamento dell’oggetto all’interno dell’area di stampa genera caratteristiche differenti, sia per il posizionamento dei supporti, sia per le proprietà meccaniche che ne risultano.

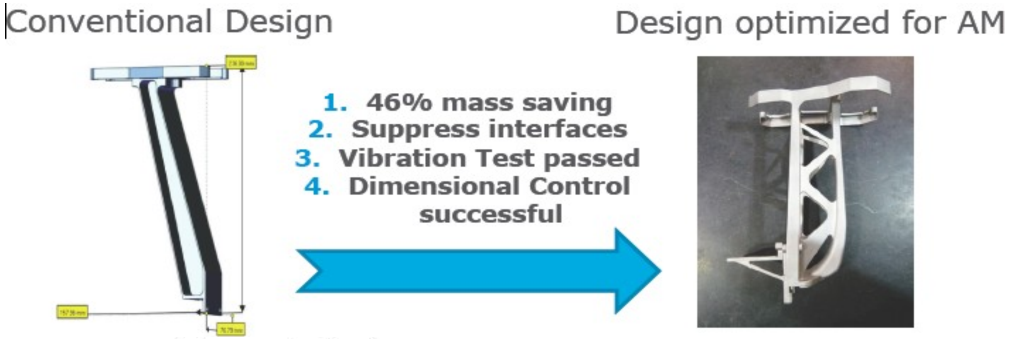
Esempio: AlSi10Mg



DESIGN FOR ADDITIVE MANUFACTURING

La libertà offerta dalle tecnologie additive permette la realizzazione di pezzi ottimizzati topologicamente, con grande risparmio di materiale e notevole riduzione del peso.





AM benefits: Weight reduction

TRADITIONAL DESIGN

Source: SAVING project

- A conventional steel buckle weights 155 g[1)]
- Weight should be reduced on a like-for-like basis within the SAVING project
- Project partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter

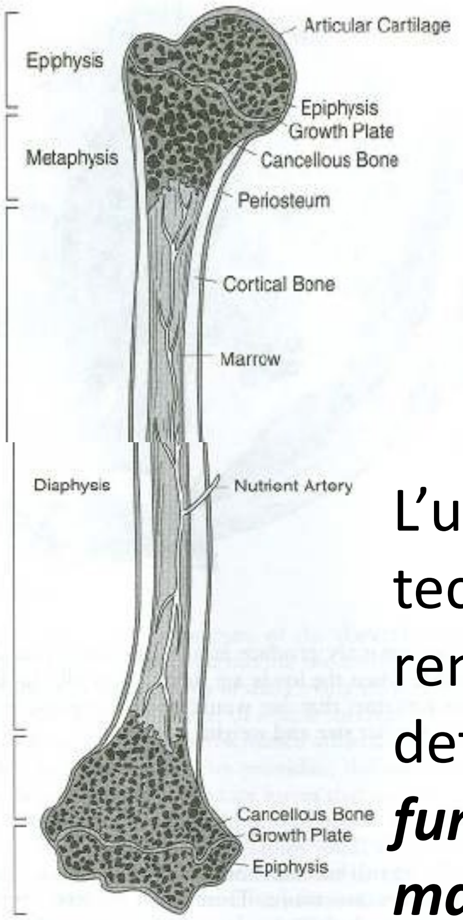
AM OPTIMIZED DESIGN

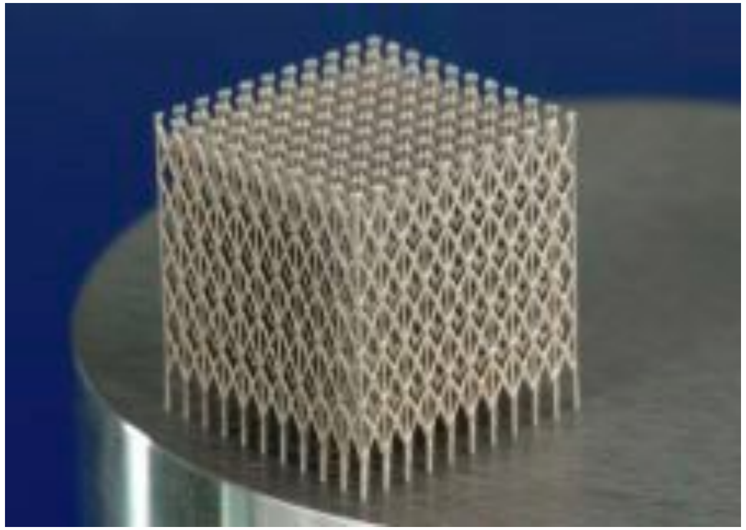
Source: SAVING project

- Titanium buckle designed with AM weighs 70 g – reduction of 55%
- For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 72.5 kg
- Over the airplane's lifetime, 3.3 million liters of fuel or approx. EUR 2 m could be saved, assuming a saving of 45,000 liters per kg and airplane lifetime

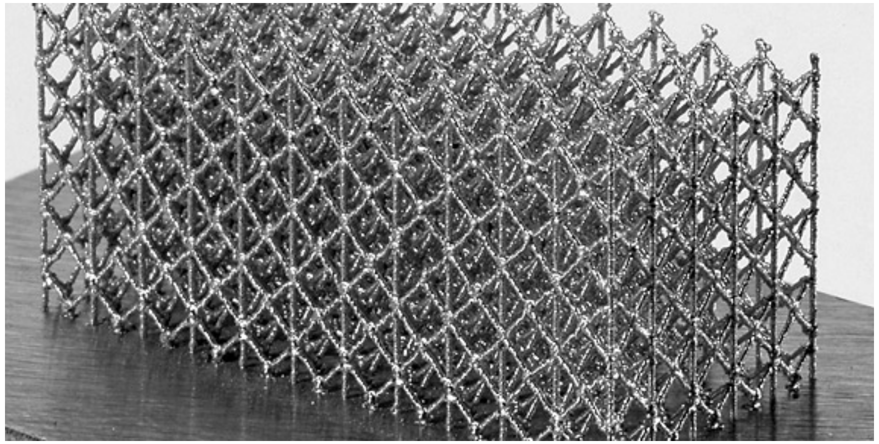
1) 120 g when made of aluminum

DESIGN FOR ADDITIVE MANUFACTURING



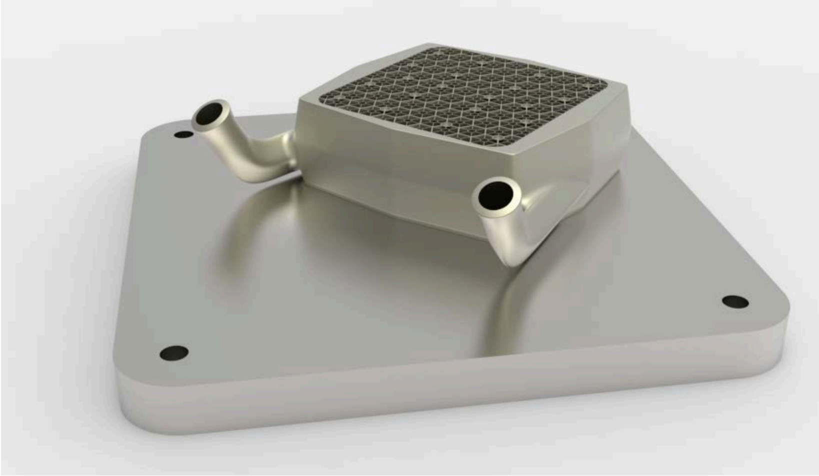


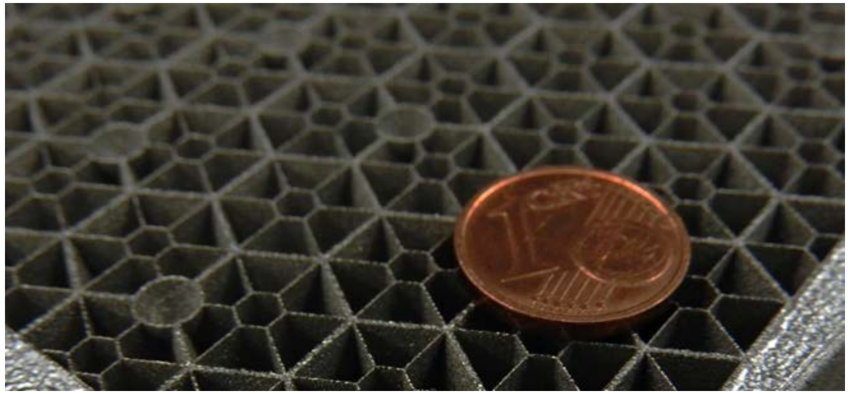
L'utilizzo delle tecnologie additive rende possibile la definizione di ***functonally graded materials***, con struttura cellulare progettata ad hoc.



Radiatore pr motociclo realizzato con tecnologia SLM.

(tesi, D. Raffaelli, Supervisors: B. Previtali, M. Guagliano, D. Gökhan)





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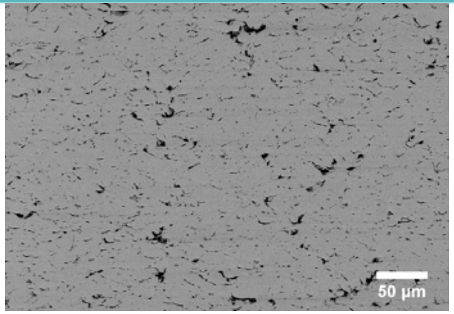
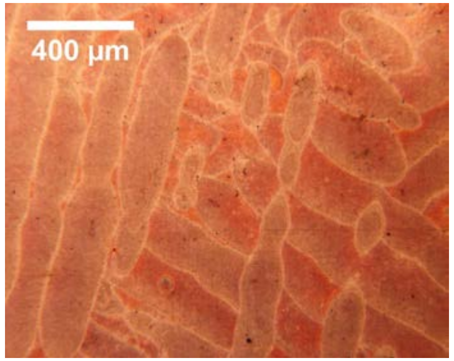
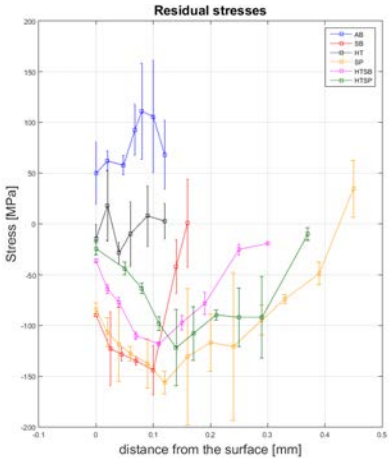
PROBLEMATICHE (PROCESSI TERMICI)

- ✓ Pre e post trattamenti
- ✓ Finitura superficiale
- ✓ Proprietà meccaniche (fatica)
- ✓ Difettosità, interna e superficiale
- ✓ Limitato numero di materiali
- ✓ Materiali sensibili alla temperatura
- ✓ Dimensioni limitate
- ✓ Costo d'impianto elevato
- ✓ Produttività bassa
- ✓ Mancanza di standard







Sample series	Fatigue limit [MPa]	Improvement [%]
As Built	50 ± 4.5	-
Heat Treated	75 ± 6.9	33.3
Shot Peened	185 ± 13.4	73
Heat Treated + Sand Blasted	172.5 ± 3.5	71
Heat Treated + Shot Peened	102 ± 4.1	51
Wrought and machined Al6061	120	

Bagherifard, S., Beretta, N., Monti, S., Riccio, M., Bandini, M., Guagliano, M. (2018) On the fatigue strength enhancement of additive manufactured AlSi10Mg parts by mechanical and thermal post-processing, MATERIALS AND DESIGN, Vol. 145, pp. 28-41.

COLD SPRAY (CS) DEPOSITION VS. SELECTED LASER MELTING (SLM)

Why Cold Spray deposition for additive manufacturing?

S. Bagherifard, G. Roscioli, M.V. Zuccoli, J. Kondás, M. Guagliano (2017) Cold Spray Deposition of Freestanding Inconel Samples and Comparative Analysis with Selective Laser Melting. JOURNAL OF THERMAL SPRAY TECNOLOGY, Vol. 26, pp. 517-526. SSN:1059-9630.

Selective Laser Melting (SLM)

- ⊙ High processing temperature
- ⊙ Build area limitations
- ⊙ Low deposition rate
- ✓ Ideal for small components of intricate geometries with lattice structures.

Cold Spray

- ✓ No theoretical thickness limit
- ✓ High density, homogeneity and cohesive strength
- ✓ High production rate
- ✓ Low temperature
- ✓ Depositing functionally graded/multi-material components
- ⊙ Low resolution and geometrical accuracy
- ⊙ Difficulty of spraying materials with low plasticity.

....The properties we can get by using these processes are the real challange.

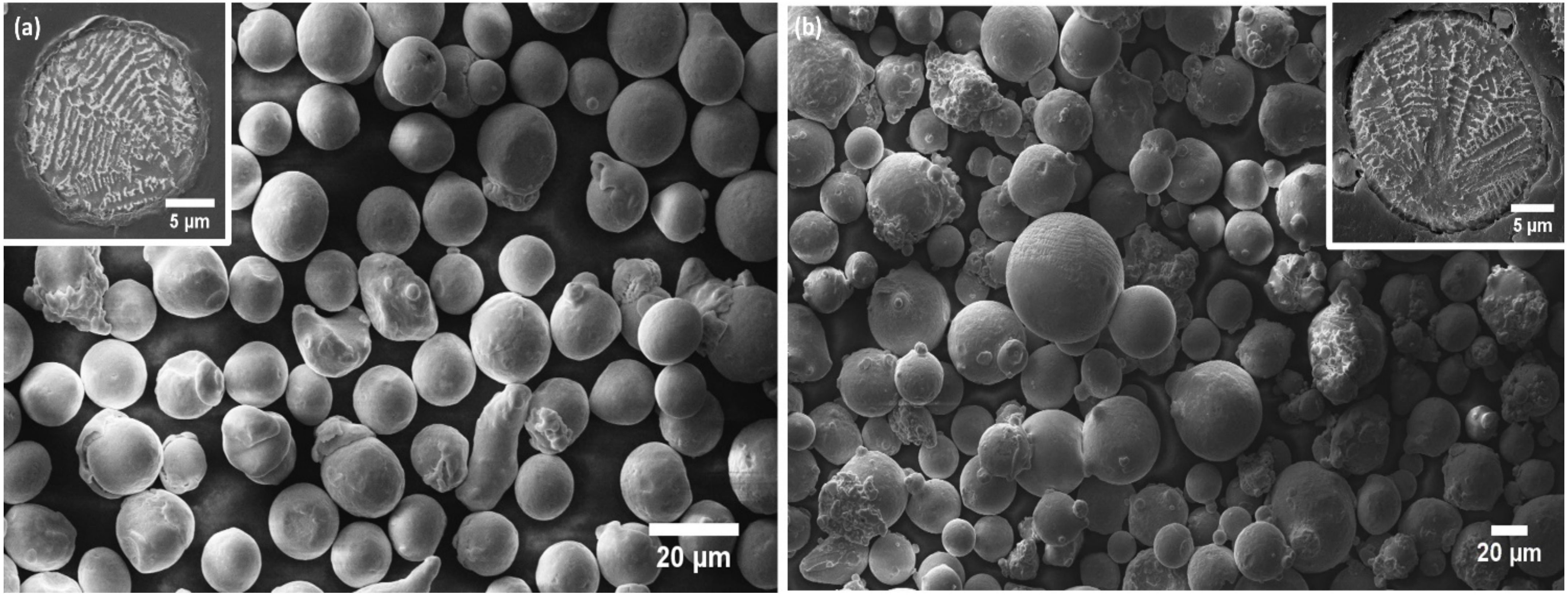
COLD SPRAY (CS) DEPOSITION VS. SELECTED LASER MELTING (SLM)

- ✓ A wide experimental activity was done to compare the properties of free-standing samples obtained by SLM and CS.
- ✓ **Material: Inconel 718** (widely used in aeronautics gas turbines and and industrial plants for its high strength and resistance to corrosion even at high temperature).
- ✓ The process parameters used were the ones that are usually utilized for powder of this material in practical applications.
- ✓ The characterization included:

- Powder characteristics
- Microstructure
- Porosity
- Hardness and residual stresses
- Tensile and fatigue strength at room temperature.

S. Bagherifard, G. Roscioli, M.V. Zuccoli, J. Kondás, M. Guagliano (2017) Cold Spray Deposition of Freestanding Inconel Samples and Comparative Analysis with Selective Laser Melting. JOURNAL OF THERMAL SPRAY TECNOLOGY, Vol. 26, pp. 517-526. SSN:1059-9630.

COLD SPRAY?



PSD (10 µm - 32 µm)

PSD (15 µm - 45 µm)

Micrografie SEM delle polveri di Inconel 718, (a) CS (b) SLM

S. Bagherifard, G. Roscioli, M.V. Zuccoli, J. Kondás, M. Guagliano (2017) Cold Spray Deposition of Freestanding Inconel Samples and Comparative Analysis with Selective Laser Melting. JOURNAL OF THERMAL SPRAY TECNOLOGY, Vol. 26, pp. 517-526. SSN:1059-9630.

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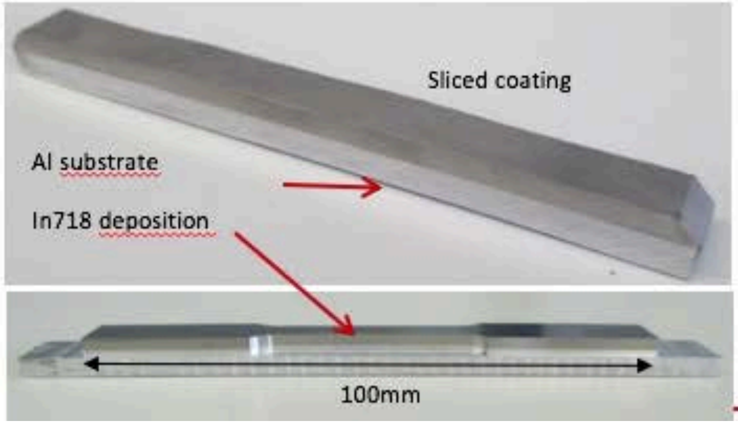

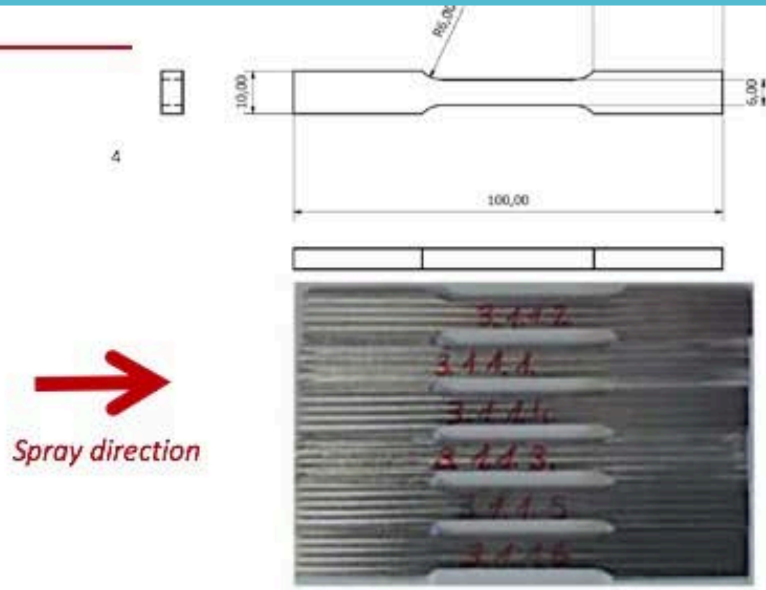

CS dog bone Samples (ASTM E8/E8M–15a)

Impact innovation Spray System 5/11 (60 bar upgrade)

Substrate	Spray parameters	
Aluminum	Gas temperature (ºC)	1000
	Gas	N_2
	Gas pressure (bar)	55
	Traverse velocity (mm/s)	500
	Track spacing (mm)	1
	Stand off distance (mm)	25

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SLM SAMPLES PREPARATION

SLM parameters	
Build chamber size (mm^3)	280x280x350
Gas	Ar
Laser fluence (J/mm^3)	61.3
Layer thickness (µm)	50
Hatch distance (mm)	0.17
Scan path orientation (º)	33
Platform temperature (ºC)	200
Scan strategy	Stripe
Building direction (º)	90 (along Z)

SLM® 280HL (SLM Solution Group AG) system equipped with 2x400W Yttrium fiber lasers

S. Bagherifard, G. Roscioli, M.V. Zuccoli, J. Kondás, M. Guagliano (2017) Cold Spray Deposition of Freestanding Inconel Samples and Comparative Analysis with Selective Laser Melting. JOURNAL OF THERMAL SPRAY TECNOLOGY, Vol. 26, pp. 517-526. SSN:1059-9630.

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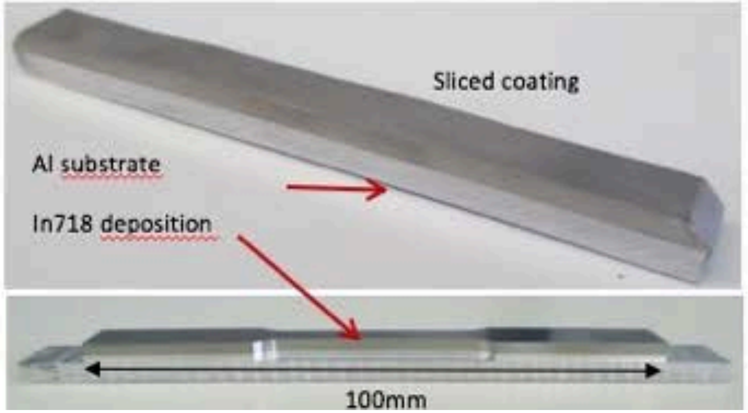

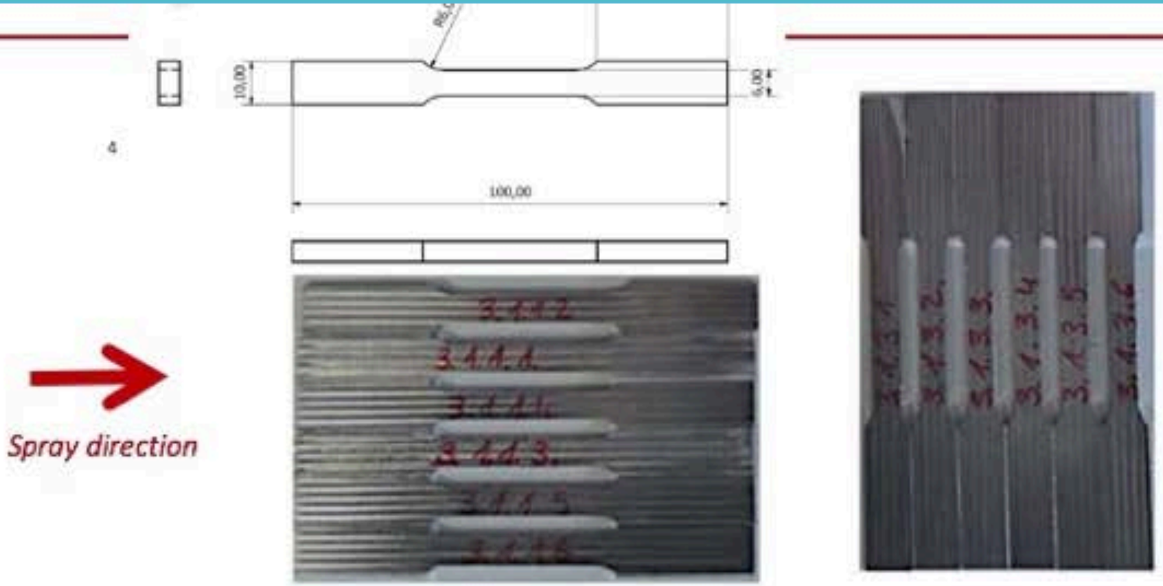

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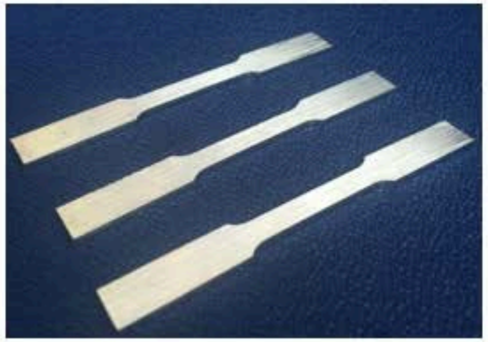
HEAT TREATMENTS

HTA	1050°C for 3h under Argon atmosphere
HTB	1200°C for 1h under Rrgon atmosphere
HTC	Heating and cooling cycles with max temperature of 980°C for a total cycle length of 23 h under Argon atmosphere
HTD	980°C for 5h under Argon atmosphere



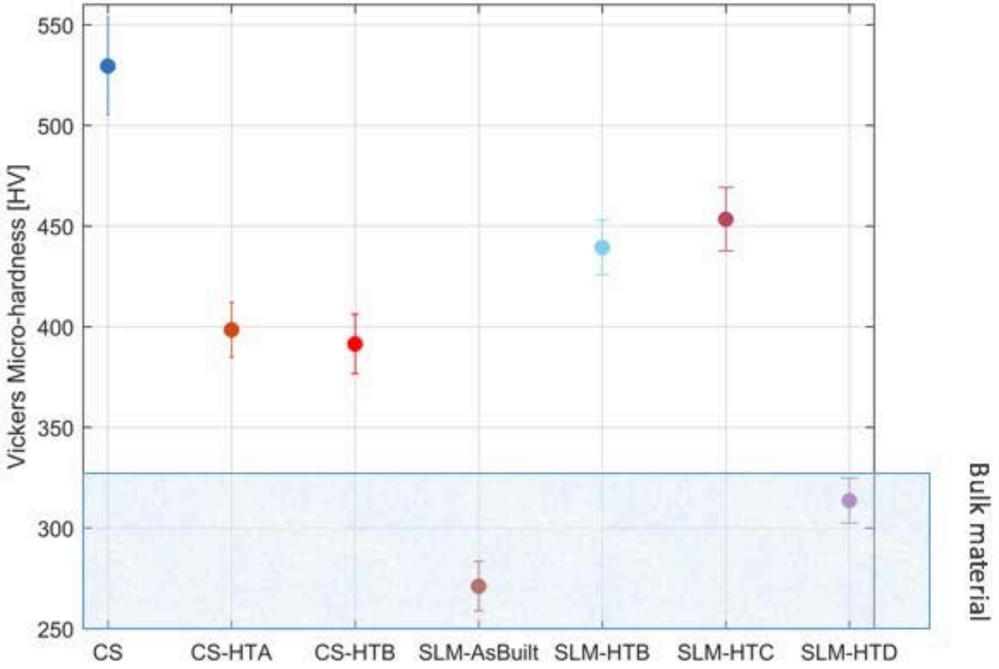
Samples separated with Rockwool from chamber

Carbolite Furnace

S. Bagherifard, G. Roscioli, M.V. Zuccoli, J. Kondás, M. Guagliano (2017) Cold Spray Deposition of Freestanding Inconel Samples and Comparative Analysis with Selective Laser Melting. JOURNAL OF THERMAL SPRAY TECNOLOGY, Vol. 26, pp. 517-526. SSN:1059-9630.

MICROHARDNESS MEASUREMENTS

Microhardness tester
Future-Tech FM-700



Measured across lateral cross sections of CS and SLM samples perpendicular to the spray and the build direction

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COLD SPRAY?

TENSILE TEST RESULTS

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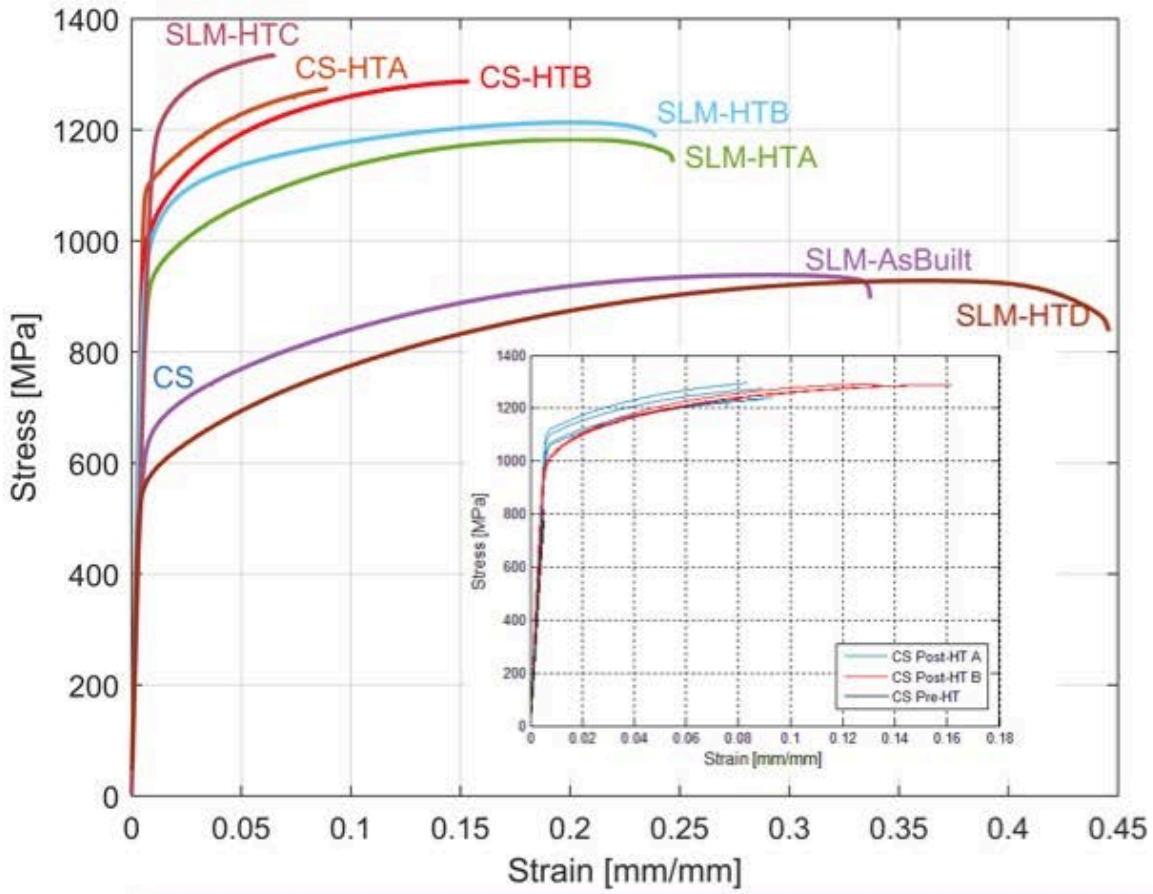

	E (MPa)	Yield Stress (MPa)	UTS (MPa)	Strain at break (%)
CS-As sprayed	167±7	-	713±11	0.45±0.1
CS-HTA	191±9	1087±24	1260±26	8.85±0.36
CS-HTB	202±2	1004±7	1289±2	15±1
SLM-As Built	170±9	596±30	943±8	35±1
SLM-HTA	158±17	924±11	1186±2	25±5
SLM-HTB	195±2	951±3	1210±23	23±1
SLM-HTC	138±6	158±14	1339±30	7±1
SLM-HTD	170±7	558±7	933±3	43±1
Bulk Material	200-480	760-1050	860-1400	12-40

FORCE CONTROLLED CONSTANT AMPLITUDE AXIAL FATIGUE TESTS

ASTM E466 – 15: Force Controlled Constant Amplitude Axial Fatigue
Staircase approach Hodge-Rosenblatt fatigue strength assessment Method

Number of cycles to Run out: 2 million
Temperature: Room temperature
Stress ratio: R = 0.1
Test frequency: 30 Hz

	Fatigue Strength (MPa)	
	Hodge Rosenblatt	ISO 12107:2012
SLM-HTB	481	481±9
SLM-HTC	377	373±62
CS-HTA	361	363±35
CS-HTB	467	465±26
Bulk Material	235*-275**-184***	

*Fatigue limit under rotating bending on rolled round bar, solid solution treated.

**Cantilever-type rotary bending fatigue tests at room temperature under the load ratio of R=−1.

***Hot rolled plates with comparable thickness annealed at 1000 C /1hr and aged at 700 C/8hr.

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COLD SPRAY?

- Con il Cold Spray è possibile costruire provini 3D con buona accuratezza e lavorabilità.
- Le strutture ottenute mostrano alta densità, sia per il CS che per SLM.
- Dopo adeguato trattamento termico, nei provini CS la porosità è stata sensibilmente ridotta mentre la duttilità è risultata in linea con i provini SLM e comparabile con il materiale base.
- I provini CS sono privi di apprezzabili sforzi residui prima del trattamento termico e delle lavorazioni, i provini SLM sono caratterizzati da sforzi residui di trazione.
- I risultati delle prove meccaniche statiche e a fatica, mostrano risultati comparabili e in linea con il materiale base.

INDICE

1. Introduzione

2. Le tecnologie additive

3. Design for Additive Manufacturing (DfAM)

4. Problematiche

5. Conclusioni

CONCLUSIONI

1. Le tecnologie additive sono destinate ad acquisire uno spazio sempre più rilevante nel panorama della produzione industriale.

2. L'applicazione di processi AM permette di definire soluzioni progettuali ottimizzate, altrimenti impossibili ed in grado di garantire nuove funzionalità e leggerezza.

3. Al di là delle aspettative tecniche ed economiche, ad oggi numerosi vincoli devono essere rimossi per una profonda penetrazione dell'AM in molti settori industriali.

4. Lo sviluppo e l'impiego di tecnologie di deposizione allo stato solido (CS) può aiutare a superare tali ostacoli.

Grazie!

(colori di testo)

blue

#164194
CMYK 100, 80, 0, 0
RGB 22, 65, 148

black

#000000
CMYK 100, 100, 100, 100
RGB 0, 0, 0

(dimensioni testo)

Titolo / open sans bold 18 pt, blue

Testo principale / open sans regular 16 pt, black

Testo generale, elenco puntato / open sans regular 14 pt, black

Testo secondario / open sand italic 14 pt, black

Didascalie e fonti / open sans regular 8 pt, black