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Cold Spray Action Team

Siemens Corporate Technology | June 24, 2015

Neat Cost Prediction Kit for Additive Manufacturing

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Principal Key Experts

Motivation

- Work steps in additive manufacturing (AM)
  - Selection of best manufacturing route
  - Optimization of chosen AM process
    - Quality is subject to specification
      - as much as needed, no advantage from exceeding the spec
      - binary feasibility criteria $\rightarrow$ optimization constraints
    - Costs are the function to be minimized
  - Continuous development of manufacturing equipment

- Proposal
  - Mathematical expressions for process costs
    - allow modeling of given application
    - use minimal complete sets of cost influencing factors
    - cost structures at a glance
  - Analysis and comparison of different AM / coating processes

Outline

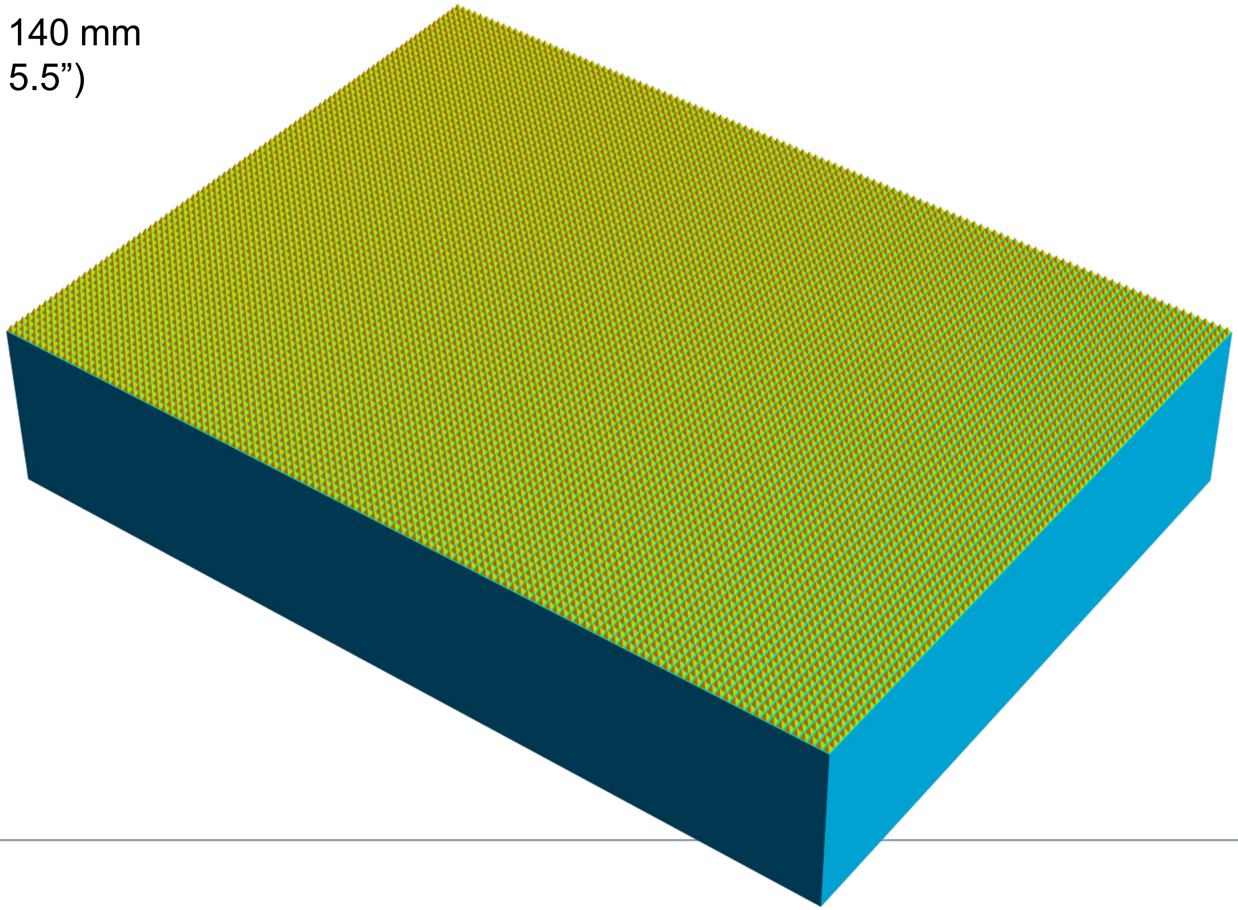
- Model case: Application example (AM of metal)
  - Laser metal deposition (LMD)
  - Selective laser melting (SLM)
  - Cold spray (CS)
  - Comparison by costs and capacity
- Downscaling CS
  - Micro-nozzles
  - Vacuum spraying
  - Aerosol deposition (AD) of ceramic coatings
- Conclusions

Model case

Heat exchanger fins can be added to a casing by CS, SLM, or LMD

Workpiece example for cost comparison

- Power module 190 × 140 mm (7.5” × 5.5”)
- Task:
  Direct deposition of heat exchanger fins on casing
- Fin shape:
  pyramid / cone
- Fin material:
  stainless steel,
  59 g total weight
- Fin size:
  16 fins / inch
  1.5 mm height



Laser metal deposition

LMD process schematic and cost calculation

(nomenclature on next page)

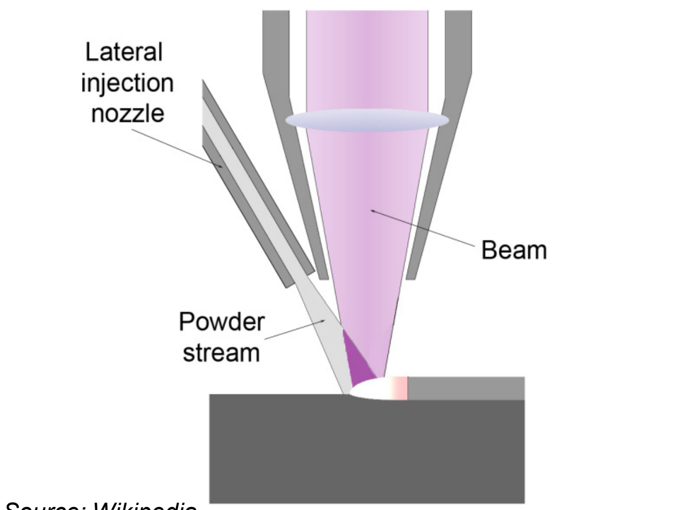
Assumption: Complete reuse of overspray powder

Cost function [€ / kg]:

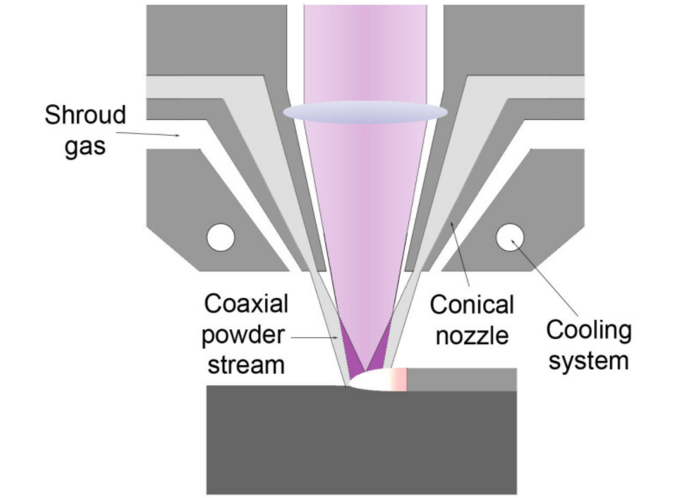
$$C_{tot} = \frac{U_{hr} + \dot{m}_{gas} U_{gas} + S_{tot} U_{elc}}{\dot{m}} + U_{pwd}$$

Approximate cost function [€ / kg]:

$$C_{tot} \approx \frac{U_{hr} + \dot{m}_{gas} U_{gas}}{\dot{m}} + U_{pwd}$$



Source: Wikipedia

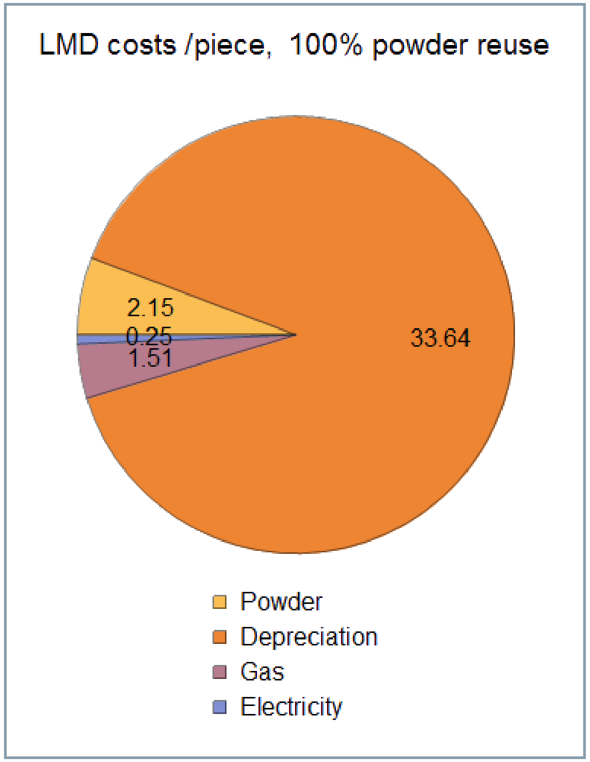


LMD costs governed by material building rate

LMD input and output parameters, and cost breakdown

Parameter	Symbol	Unit	Value
hourly rate	U_{hr}	€ / h	80
powder price	U_{pwd}	€ / kg	37
monetary value of overspray powder	U_{pr}	€ / kg	37
gas price (argon)	U_{gas}	€ / kg	2,80
electrical energy price	U_{elc}	€ / kWh	0,15
total electric power consumption	S_{tot}	kW	4
gas flow rate (argon)	$\dot{m}_{gas}$	kg / h	1,3
effective building rate	$\dot{m}$	kg / h	0,14
total costs of built metal	C_{tot}	€ / kg	641
mass of workpiece (given example)		kg	0,059
total costs per workpiece		€	38
effective building rate		cu in / h	1,1
annual capacity (1500 h)		(pcs.)	3567

(reusing overspray powder)

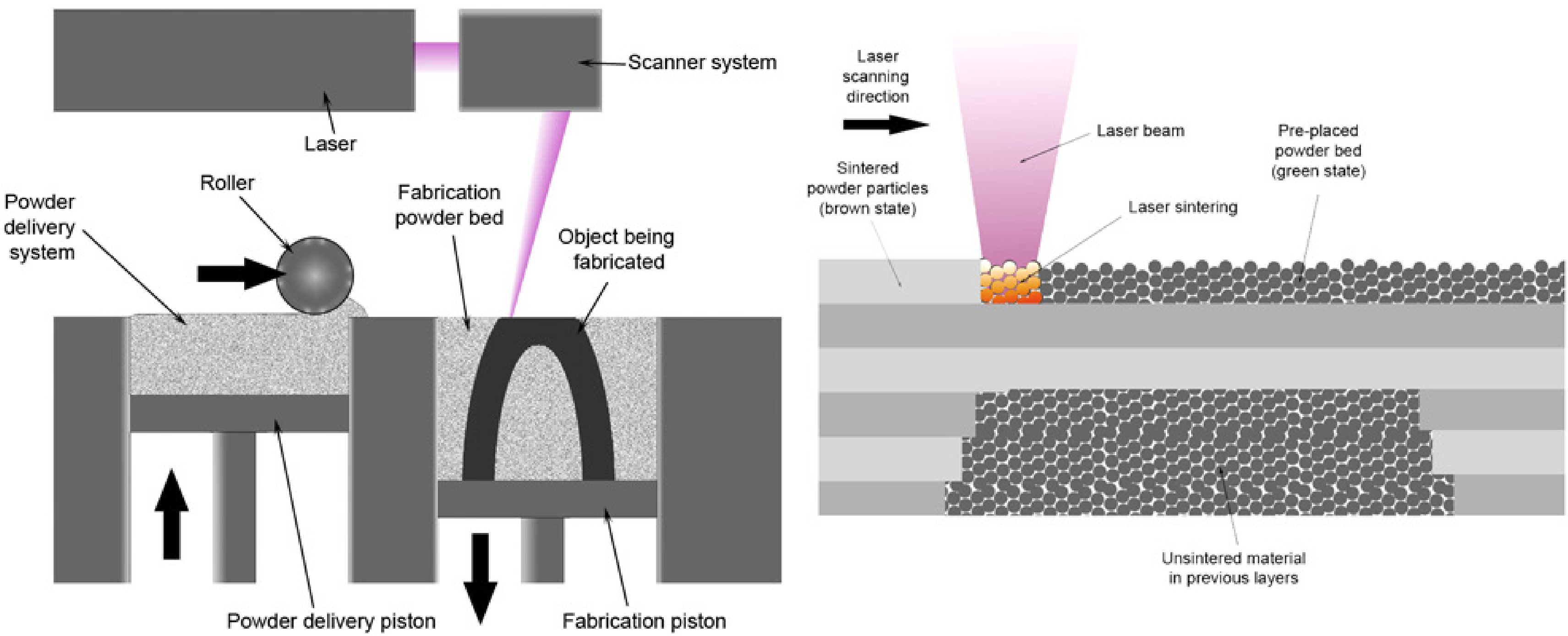


Selective laser melting

SLM yields higher spatial resolution than LMD and CS

Schematic of selective laser melting (SLM)

Source: Wikipedia

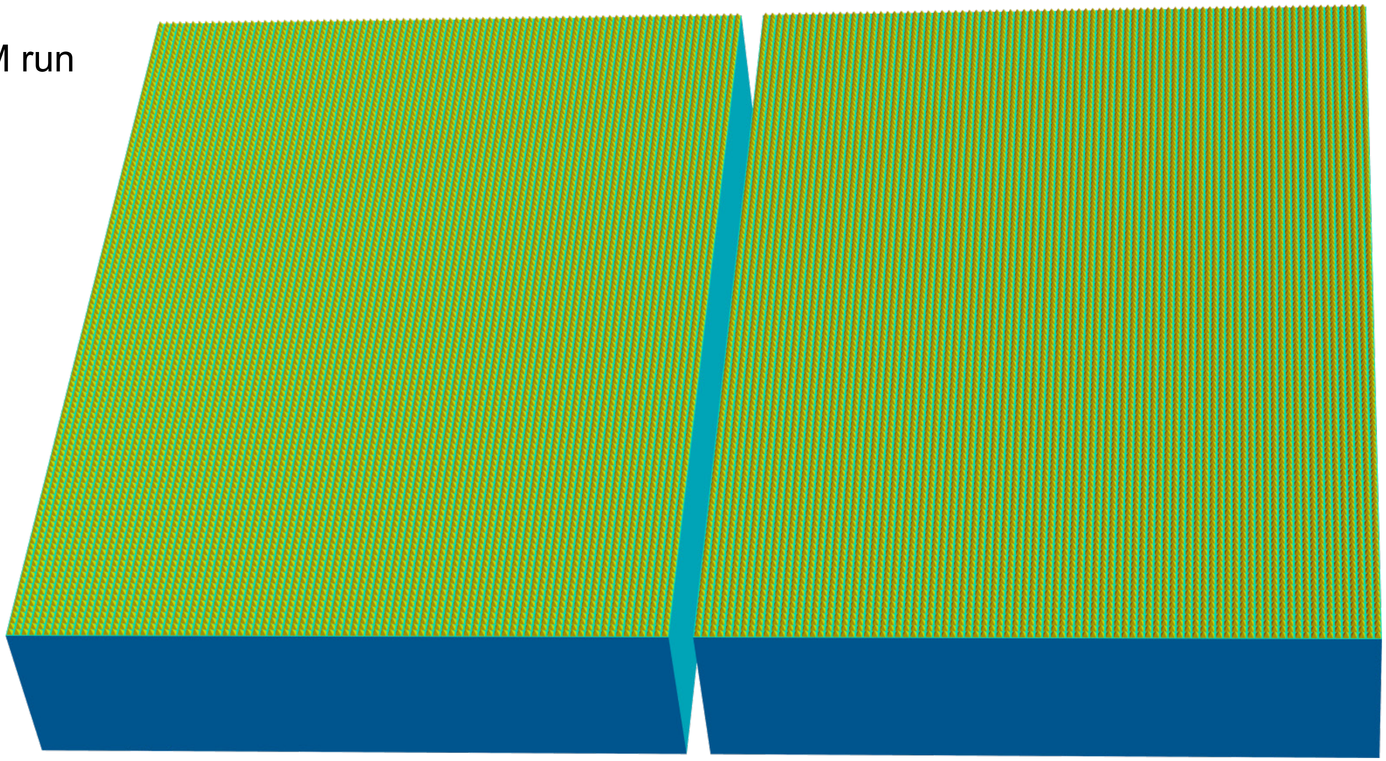


SLM batch size limited by building chamber size

Module casings have to be arranged co-planar for addition of fins

Manufacturing configuration for selective laser melting (SLM)

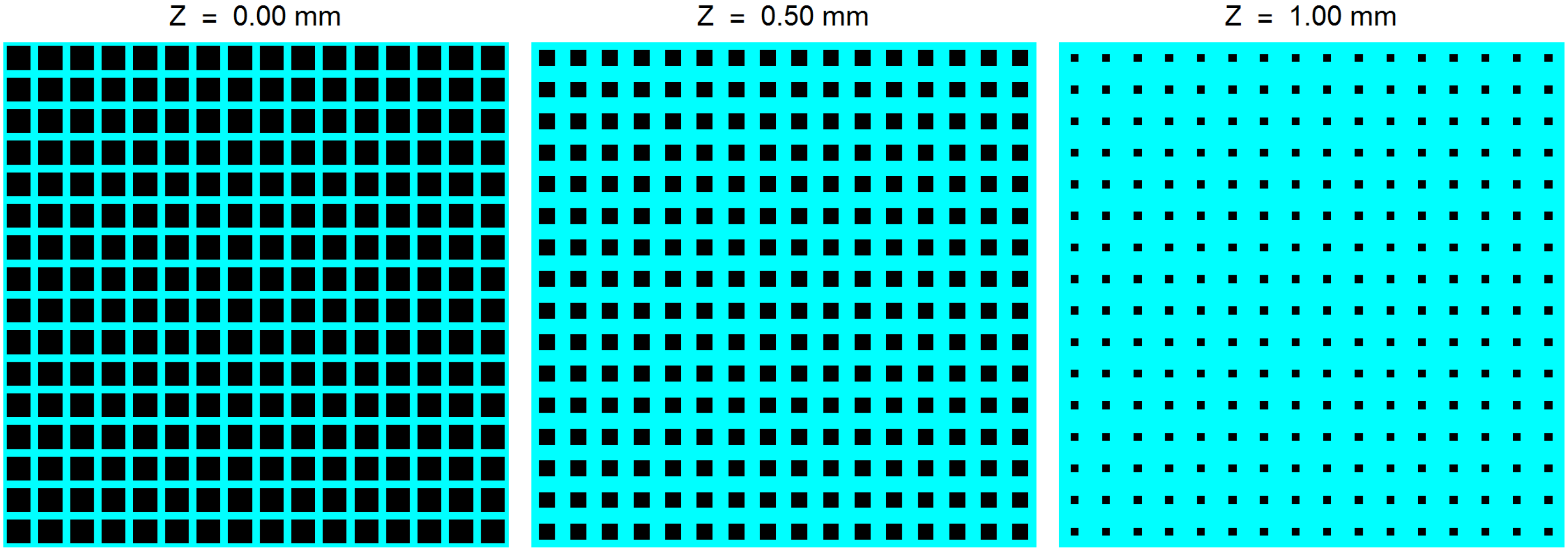
2 modules / SLM run



SLM laser duty cycle varies from layer to layer

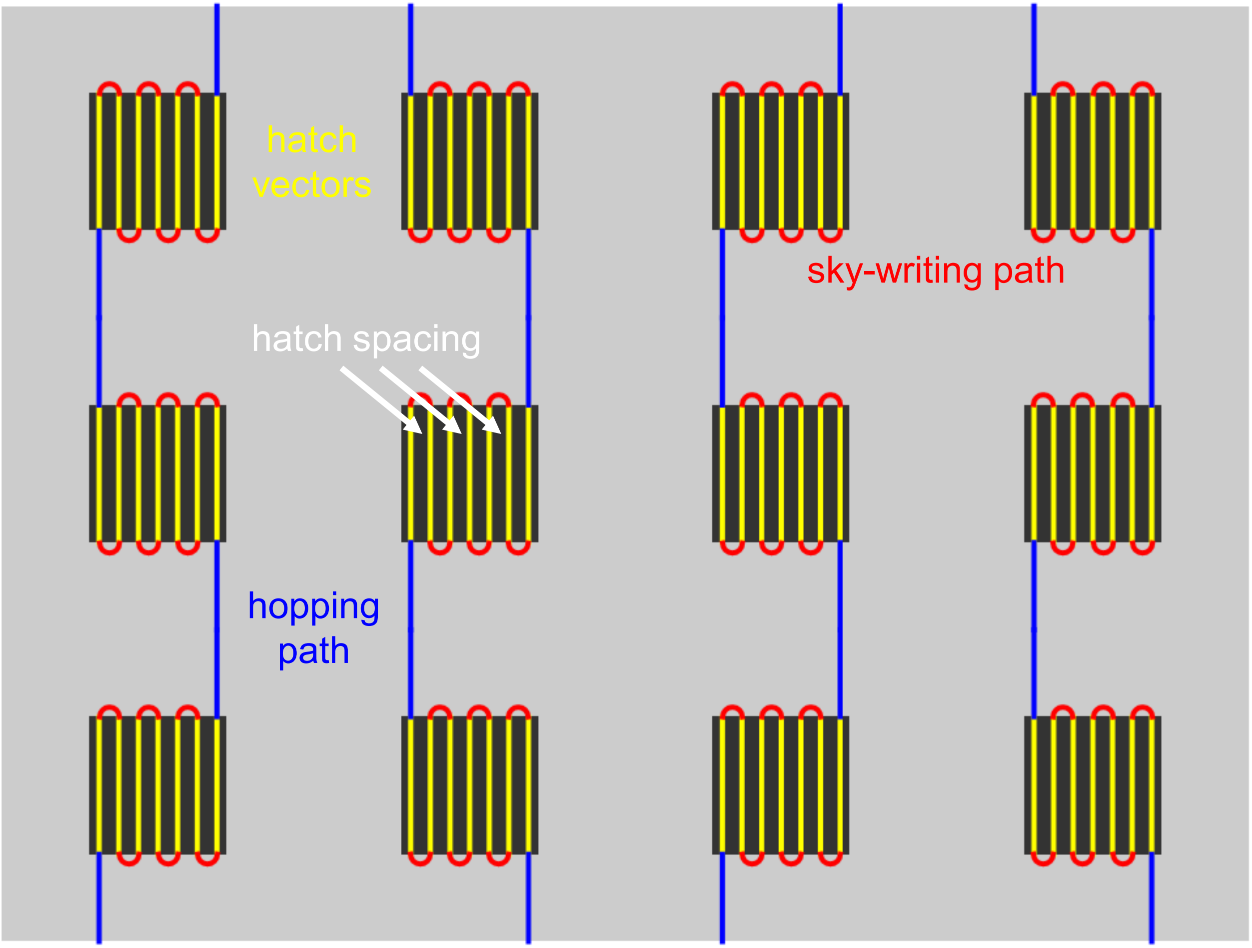
Layer-wise generation of pyramid arrays by SLM

Laser writes in XY plane, layer stacking in Z direction



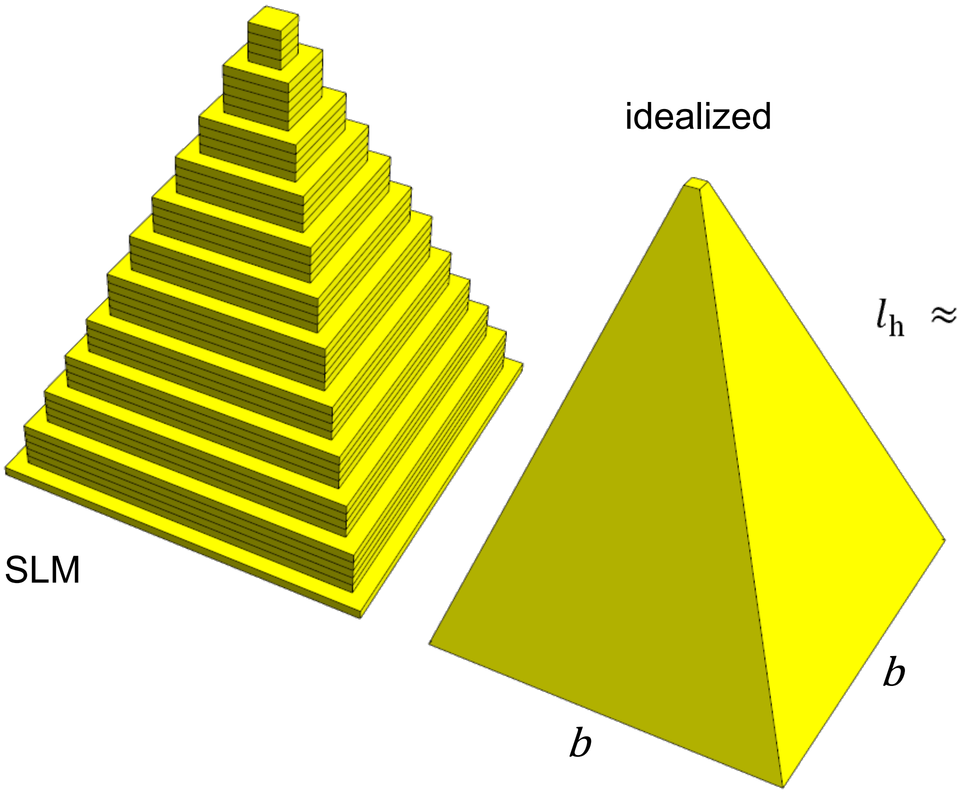
SLM: Time loss types

Partitioning of laser spot trajectory into productive writing segments and connecting paths



SLM: Geometry governs time loss

Analytical estimates for productive and unproductive path lengths in pyramid arrays



Truncated pyramid missing tip height fraction:

$$q = 0.04$$

Average hopping path length per SLM layer:

$$l_{\mathrm{h}} \approx 2\,(7.5 \times 16)(5.5 \times 16)\left[\frac{25.4}{16} - \frac{1}{2} b(1+q)\right]$$

Average hatch vector length:

$$d_x \approx \frac{2}{3}\frac{1-q^3}{1-q^2} b \approx \frac{2}{3}\, b$$

SLM cost influencing factors

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SLM input parameters

Parameter	Symbol	Unit	Value
hourly rate	U_{hr}	€ / h	60
powder price	U_{pwd}	€ / kg	37
gas price (argon)	U_{gas}	€ / kg	2,80
electrical energy price	U_{elc}	€ / kWh	0,15
cost of pre-/post-processing, per run	C_{ppp}	€	15
total electric power consumption	S_{tot}	kW	4
gas flow rate (argon)	$\dot{m}_{gas}$	kg / h	0,3
re-coating time, per layer	t_{rc}	s	9
evaporation loss factor	EL	–	0,05
built material density	ρ	g / cm³	7,9
payload, per run	m_{pl}	kg	0,12
characteristic height of workpiece	h	mm	1,44
average hopping path length, per layer	l_{h}	mm	20504
scanning speed	v_x	mm / s	1300
hopping speed	v_{h}	mm / s	1300
average hatch vector length	d_x	mm	0,79
hatch spacing	d_y	mm	0,10
layer thickness	d_z	mm	0,03

SLM has same cost structure as LMD

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SLM cost calculation

Cost function [€ / kg]:

$$C_{\mathrm{tot}} = \frac{U_{\mathrm{hr}} + \dot{m}_{\mathrm{gas}}\, U_{\mathrm{gas}} + S_{\mathrm{tot}}\, U_{\mathrm{elc}}}{\dot{m}} + \frac{C_{\mathrm{ppp}}}{m_{\mathrm{pl}}} + (1 + EL)\, U_{\mathrm{pwd}}$$

Building rate [kg / h]:

$$\dot{m} = \frac{3600\, d_z}{\frac{h}{m_{\mathrm{pl}}}\left(\frac{l_{\mathrm{h}}}{v_{\mathrm{h}}} + t_{\mathrm{rc}}\right) + \frac{10^6}{\rho\, v_x}\left(\frac{1}{d_y} + \frac{\pi/2}{d_x}\right)}$$

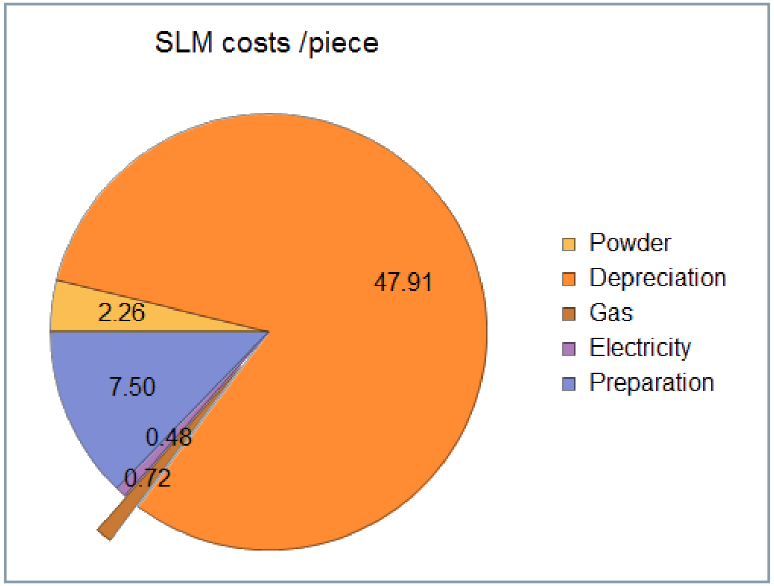
Approximate cost function [€ / kg]:

$$C_{\mathrm{tot}} \approx \frac{U_{\mathrm{hr}}}{3600}\,\frac{1}{d_z}\left[\frac{h}{m_{\mathrm{pl}}}\left(\frac{l_{\mathrm{h}}}{v_{\mathrm{h}}} + t_{\mathrm{rc}}\right) + \frac{10^6}{\rho\, v_x}\left(\frac{1}{d_y} + \frac{\pi/2}{d_x}\right)\right] + \frac{C_{\mathrm{ppp}}}{m_{\mathrm{pl}}} + U_{\mathrm{pwd}}$$

SLM costs governed by material building rate

SLM output parameters and cost breakdown

Parameter	Symbol	Unit	Value
total costs of built metal	C_{tot}	€ / kg	1004
mass of workpiece (given example)		kg	0,059
total costs per workpiece		€	59
effective building rate	$\dot{m}$	kg / h	0,07
		cu in / h	0,57
annual capacity (1500 h)		(pcs.)	1878



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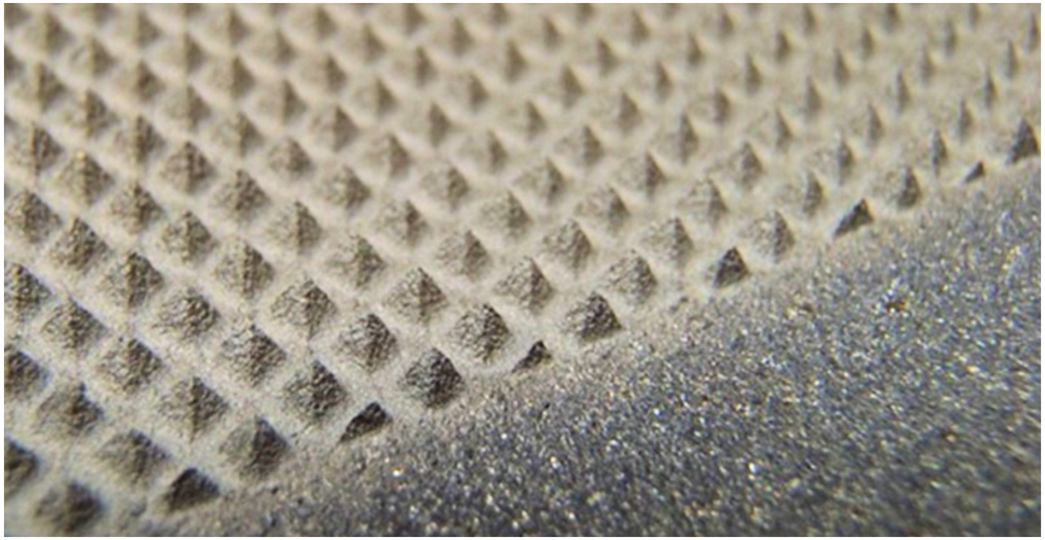
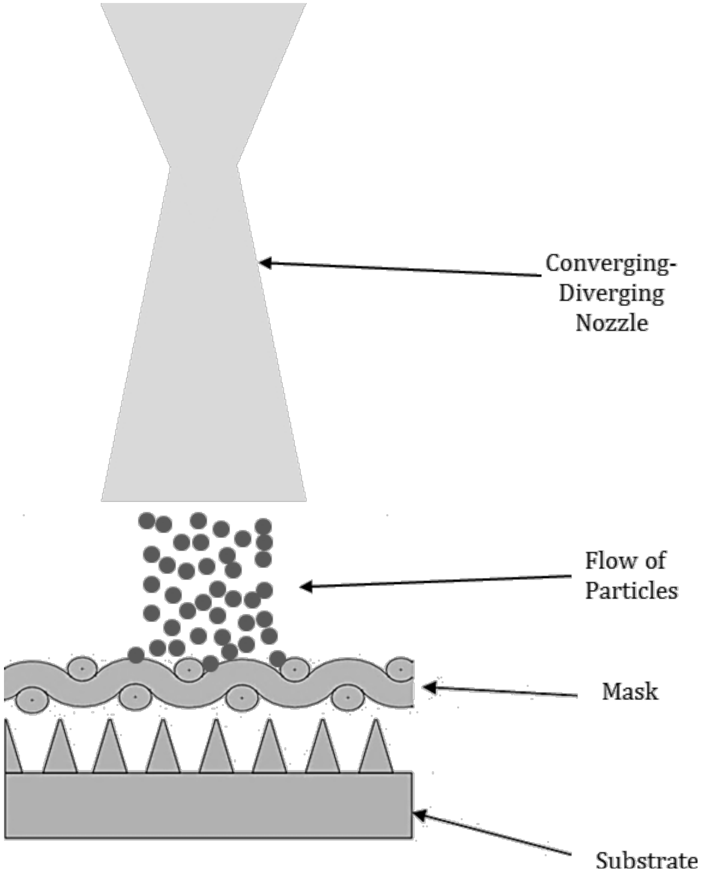
Cold spray is a (up)scalable deposition process

Cold spray production of pyramid arrays (University of Ottawa / Brayton Energy Canada)

Y. Cormier, P. Dupuis, B. Jodoin, A. Corbeil, *Net Shape Fins for Compact Heat Exchanger Produced by Cold Spray*, J. Thermal Spray Technol. **22** (2013) p. 1210





Figures courtesy of Prof. Bertrand Jodoin
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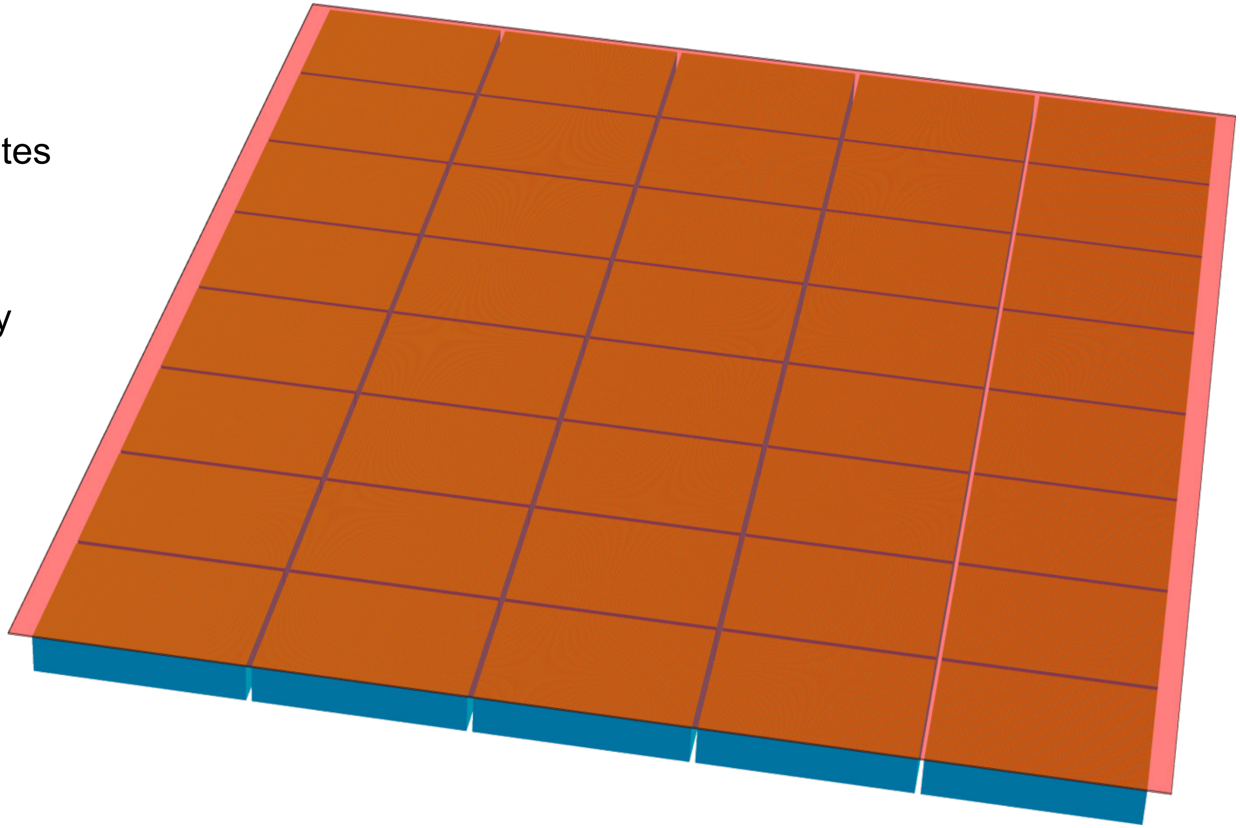
CS at high building rates

High pressure CS allows processing of 20 kg steel / hour

Manufacturing configuration for cold spray (CS)

- 40 modules / CS run
- Accomplished in 20 minutes
- Wire mesh masking to produce fin structure
- 10% geometric overspray
- Consumption:
  - 6 kg steel powder
  - 30 kg N_2 gas
  - 17 kWh



CS cost influencing factors

CS input parameters

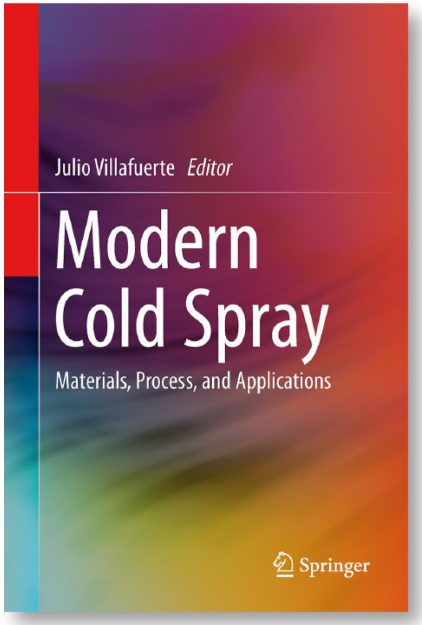
Parameter	Symbol	Unit	Value	
hourly rate	U_{hr}	€ / h	100	(simultaneous preparation work)
powder price	U_{pwd}	€ / kg	37	
monetary value of overspray powder	U_{pr}	€ / kg	0	(dropping overspray powder)
gas price (nitrogen)	U_{gas}	€ / kg	0,15	
electrical energy price	U_{elc}	€ / kWh	0,15	
ancillary electric power consumption	S_{tot}	kW	18	
powder-to-gas flow duration ratio	r	–	0,90	
geometric loss factor	GL	–	0,10	
isobaric specific heat (nitrogen)	c_p	kJ / (kg K)	1,13	
inverse gas flow factor (nitrogen)	F_{gas}	3600 m $K^{-1/2}$ / s	0,00705	
ambient temperature	T_{amb}	K	288	
nozzle throat cross section area	A_{thr}	mm^2	7,1	
gas stagnation pressure	P	MPa	3,1	
gas stagnation temperature	T	K	1173	
heat loss factor	HL	–	0,35	
powder-to-gas mass loading ratio	w	–	0,2	
deposition efficiency	Y_{DE}	–	0,4	

CS cost structure more complex than SLM, LMD

Cost calculation function for CS has been derived previously

Connection to prevailing nomenclature

$$
\begin{aligned}
C_{\text{pwd}} &\rightarrow C_{\text{pwd}} - \left(m_{\text{pwd}} - 1\right) U_{\text{pr}} \\
t_{\text{on}} / t_{\text{run}} &\rightarrow r \\
t_{\text{run}} &\rightarrow 1/\dot{m} \\
S_{\text{anc}} &\rightarrow S_{\text{tot}} \\
U_{\text{eqp}} &\rightarrow U_{\text{hr}}
\end{aligned}
$$



- D. Helfritch, O. Stier, J. Villafuerte, *Cold Spray Economics*, in: J. Villafuerte, Ed., *Modern Cold Spray*, Springer, 2015
- O. Stier, *Fundamental Cost Analysis of Cold Spray*, J. Thermal Spray Technol. **23** (2014) p. 131
- O. Stier, *Economics of Cold Spray – Fundamental Cost Analysis*, 2012 CSAT Meeting http://www.coldsprayteam.com/files/Oliver%20Stier%20-%20Siemens.pdf

CS costs depend on operating conditions and gas

CS cost calculation

Cost function [€ / kg]:

$$C_{\mathrm{tot}} = \frac{1+GL}{Y_{\mathrm{DE}}} \left\{ \frac{1}{r\,w} \left[\frac{F_{\mathrm{gas}}\,\sqrt{T}}{A_{\mathrm{thr}}\,P} \left(U_{\mathrm{hr}} + S_{\mathrm{tot}}\,U_{\mathrm{elc}} \right) + \frac{1+HL}{3600}\, c_p \left(T - T_{\mathrm{amb}} \right) U_{\mathrm{elc}} + U_{\mathrm{gas}} \right] + U_{\mathrm{pwd}} - U_{\mathrm{pr}} \right\} + U_{\mathrm{pr}}$$

Building rate [kg / h]:

$$\dot{m} = \frac{A_{\mathrm{thr}}\,P\,r\,w\,Y_{\mathrm{DE}}}{(1+GL)\,F_{\mathrm{gas}}\,\sqrt{T}}$$

Note:
Laser assisted cold spray uses an additional energy source to increase Y_{DE} which may allow reduction of T or substitution of He by N_2 (change in F_{gas})

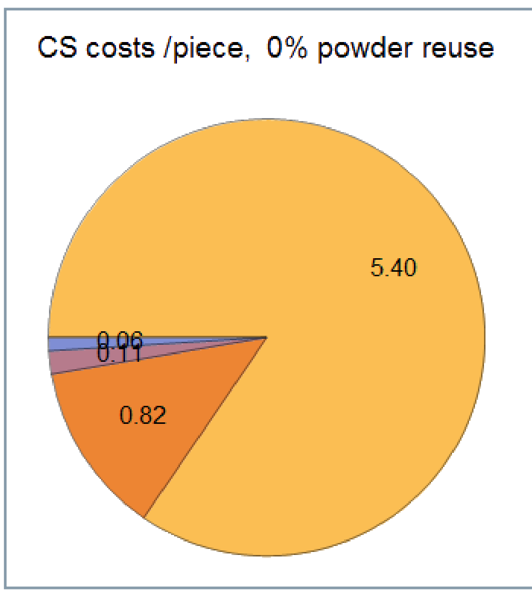
Approximate cost function [€ / kg]:

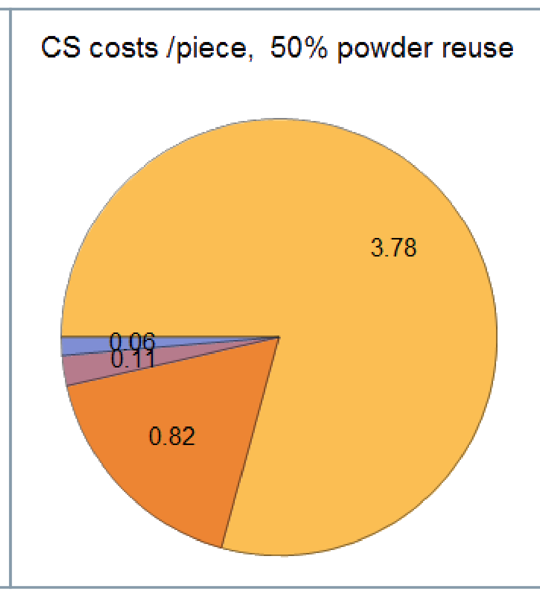
$$C_{\mathrm{tot}} \approx \frac{1+GL}{Y_{\mathrm{DE}}} \left[\frac{1}{r\,w} \left(\frac{F_{\mathrm{gas}}\,\sqrt{T}}{A_{\mathrm{thr}}\,P}\, U_{\mathrm{hr}} + U_{\mathrm{gas}} \right) + U_{\mathrm{pwd}} - U_{\mathrm{pr}} \right] + U_{\mathrm{pr}}$$

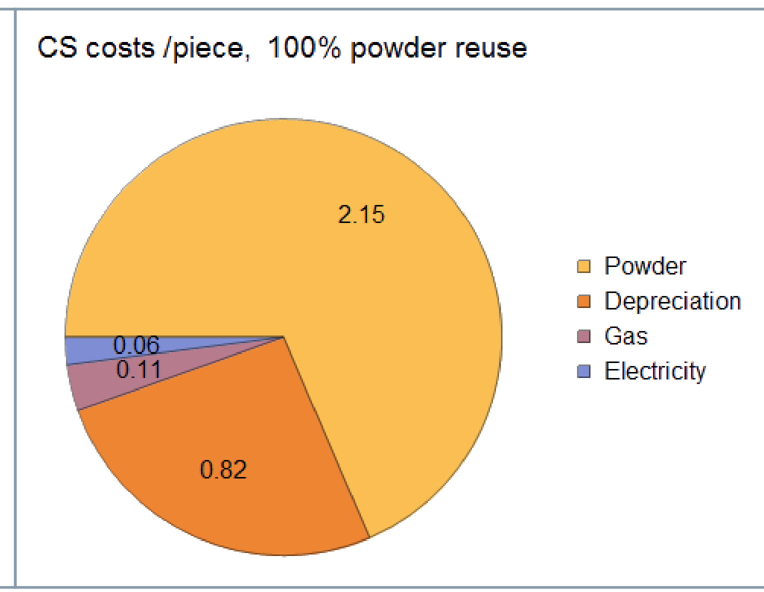
CS costs governed by powder, for high pressure N_2

CS output parameters and cost breakdown

Parameter	Symbol	Unit	Value	
total costs of built metal	C_{tot}	€ / kg	109	
mass of workpiece (given example)		kg	0,059	
total costs per workpiece		€	6,39	(dropping overspray powder)
effective building rate	$\dot{m}$	kg / h	7,2	
		cu in / h	55	
annual capacity (1500 h)		(pcs.)	183691	

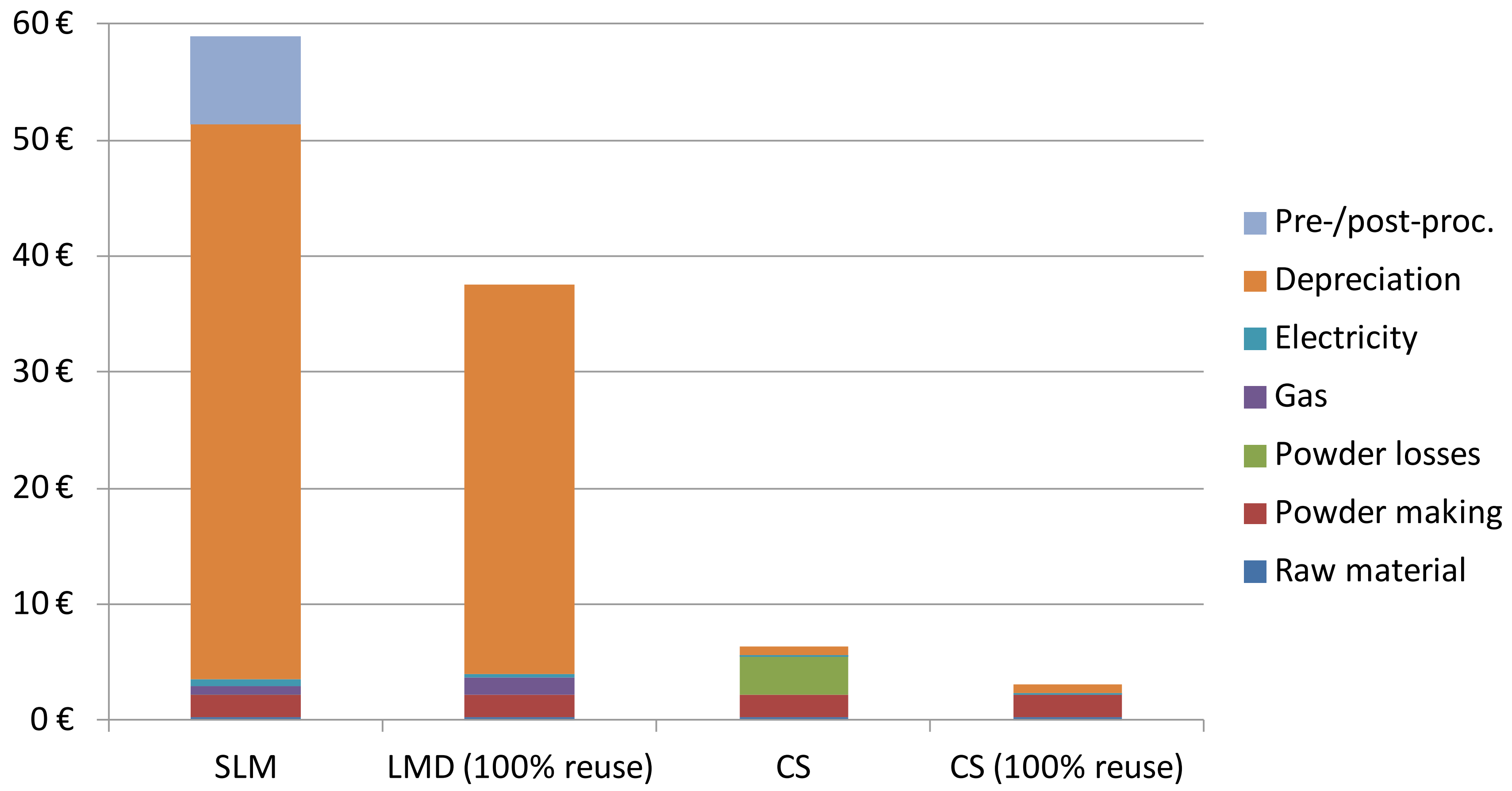






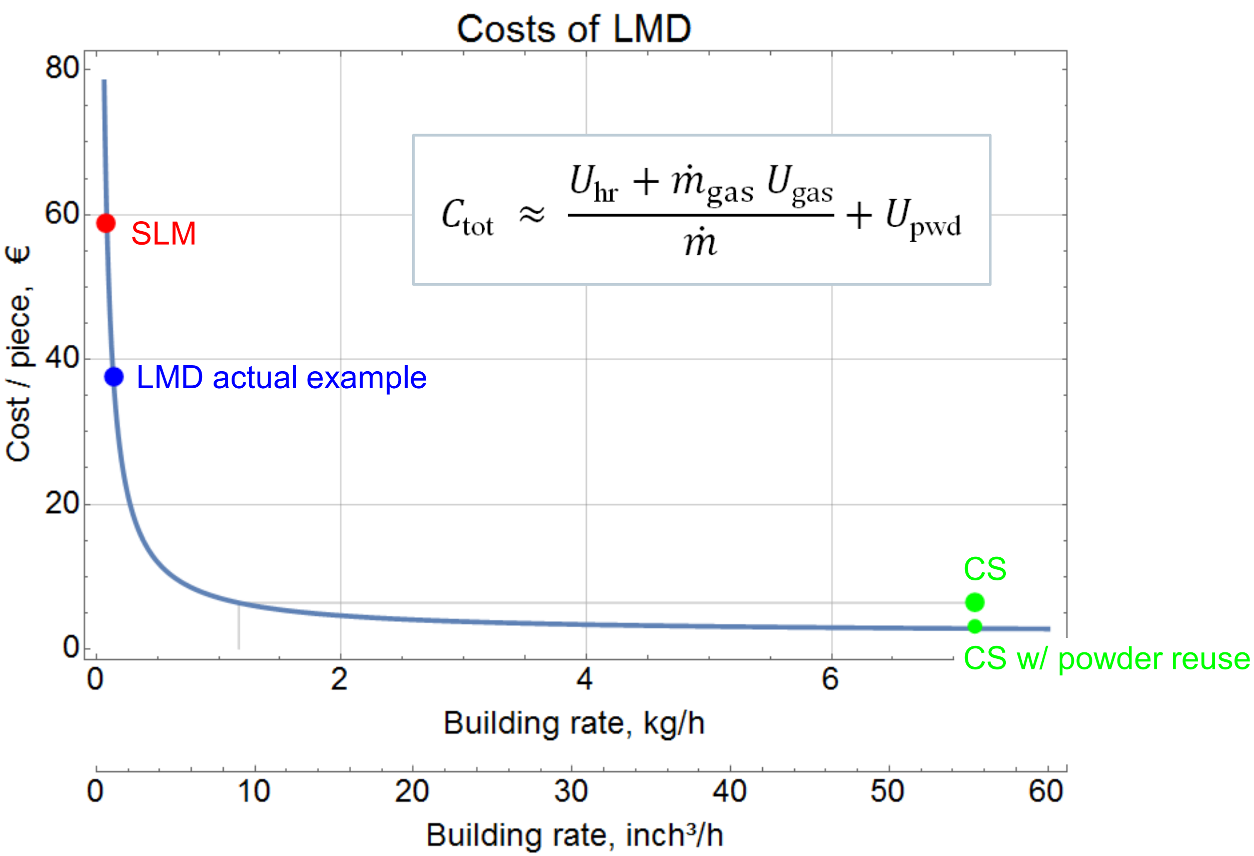
Depreciation makes the difference

Cost breakdown comparison of SLM, LMD, and CS for heat exchanger example



Building rate is key for costs

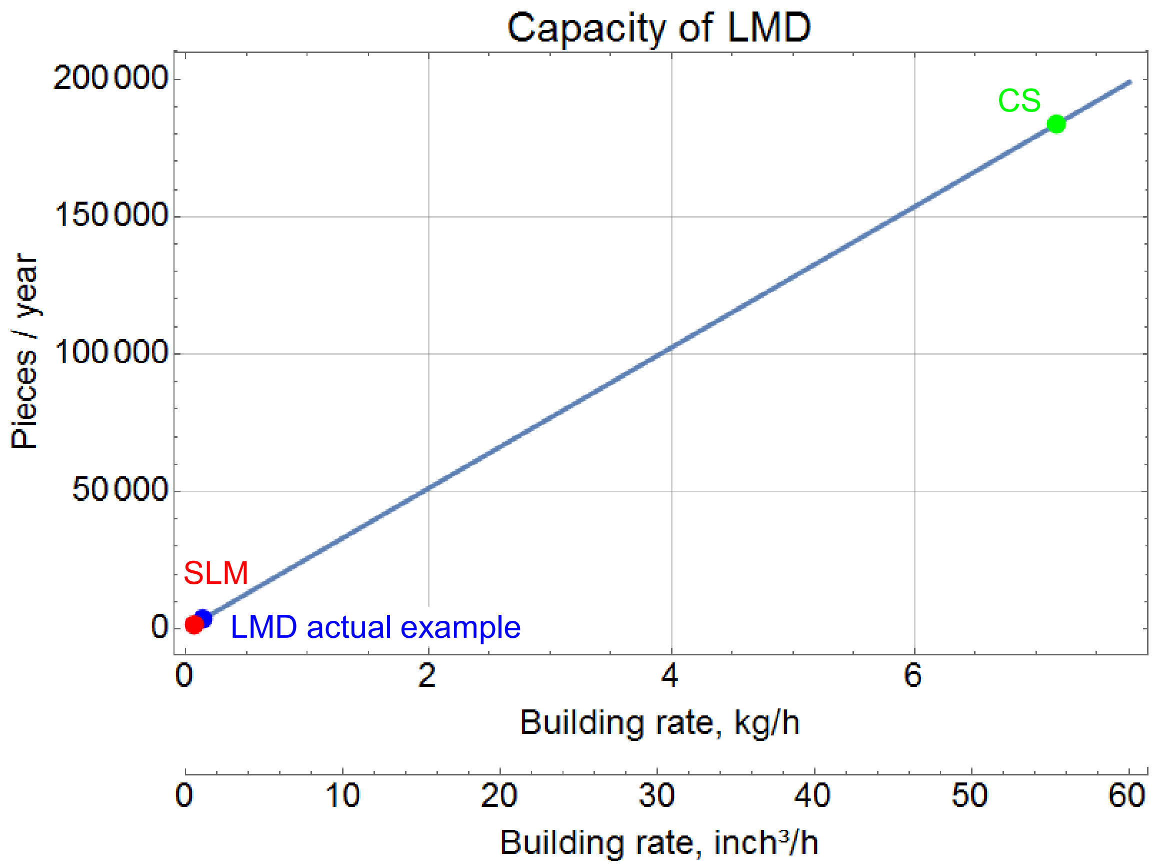
Comparison of total costs by SLM, LMD, and CS for heat exchanger example



$$C_{\mathrm{tot}} \approx \frac{U_{\mathrm{hr}} + \dot{m}_{\mathrm{gas}} U_{\mathrm{gas}}}{\dot{m}} + U_{\mathrm{pwd}}$$

CS has 100 × production capacity of SLM

Comparison of annual capacity of SLM, LMD, and CS for heat exchanger example

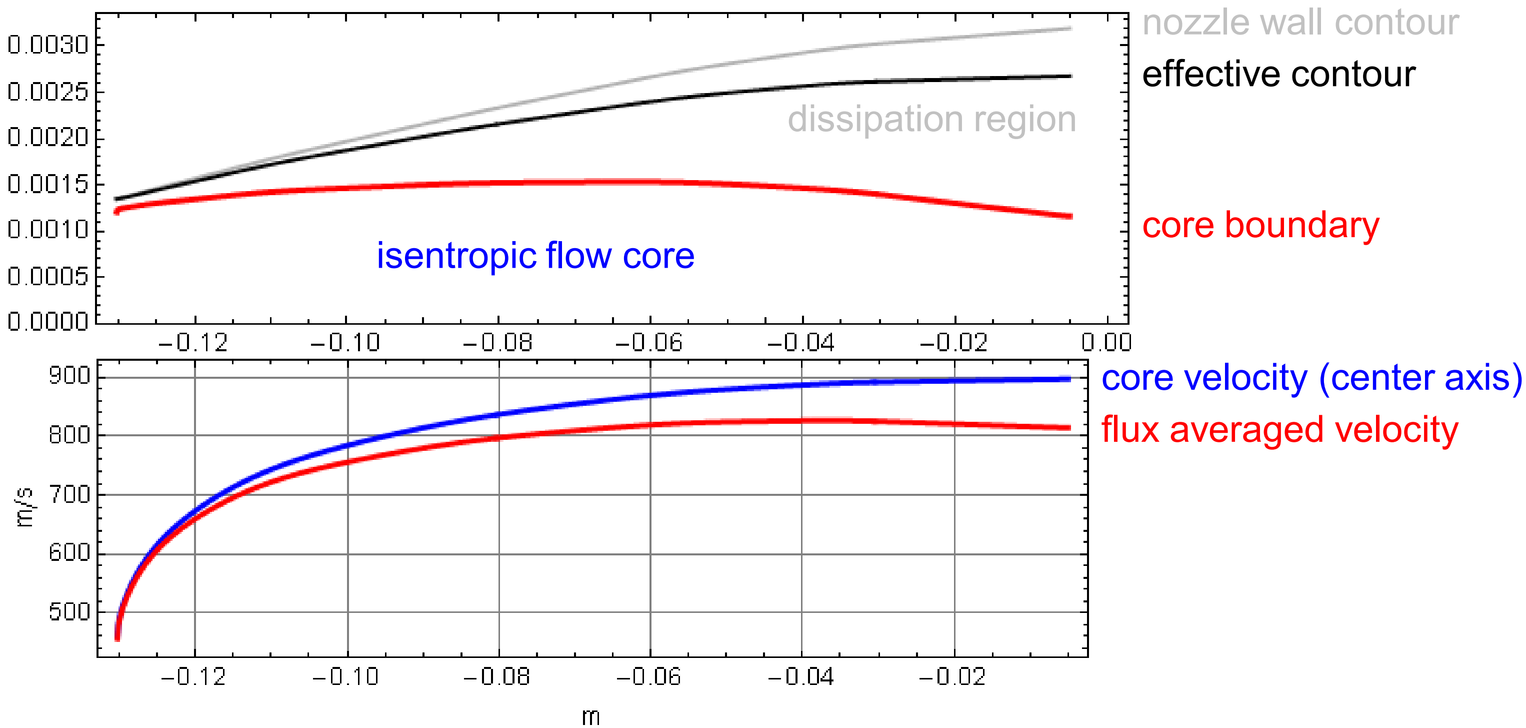


CS downscaling (miniaturization)

Reduction of spray spot diameter to ≤1 mm

Problem with downscaling the nozzle diameter

Internal boundary layer will transform supersonic flow to self-similar pipe flow



CS micro-nozzles

Shrinkage of nozzle dimensions causes cost increase

Mitigation of the boundary layer problem

Decrease of effective building rate (e.g., 0.05 kg/h)

→ increase of depreciation costs

- Use of inexpensive equipment
- Use of helium
  - waive He recovery system (low depreciation)
    - high gas costs (e.g., 60...90% of total costs)
  - CCS [1] ≈ miniaturization of KM™ (Inovati)
  - reduction of nozzle length (divergent section)
    - decrease of particle velocities
      - decrease of DE (e.g., 50%) and deposit quality
- Use of extra-fine powders
  - more expensive than standard powder
  - bow shock in front of substrate reduces DE

$$C_{\mathrm{hr}} = \frac{U_{\mathrm{hr}}}{\dot{m}} = \frac{(1 + GL)\, F_{\mathrm{gas}} \sqrt{T}}{A_{\mathrm{thr}}\, P\, r\, w\, Y_{\mathrm{DE}}}\, U_{\mathrm{hr}}$$

CS depreciation

[1] B. Barnett, D. Helfritch, E. Weinhold, J. DeHaven, *The Development of a Capillary Cold Spray System*, 2013 CSAT Meeting
http://www.coldsprayteam.com/files/CSAT_2013_Barnett.pdf

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CS at low building rates

CS more expensive than SLM due to helium usage

Cost effect of the boundary layer problem

- Spraying extra-fine powders with micro-nozzles using helium results in
  - costs: e.g., 1500...3000 €/kg (Al with μ-nozzle) or 400...1000 €/kg (Cu by CCS)
  - annual capacity: <100 kg (1500 hours/year) (≈ 50 miles spray track)
  - effective building rate is similar to SLM
    - SLM does not use helium and causes marginal powder loss
      - SLM is potentially less expensive
    - SLM allows higher dimensional accuracy
    - SLM has more potential for complex net shapes
- CS is better suited than SLM to
  - large workpieces
  - thermally sensitive substrates
  - AM of copper

Vacuum spraying

Particle acceleration shifted from nozzle to discharging free jet

Bypassing the boundary layer problem

- Reduce back pressure to solve bow shock problem: CS → Vacuum CS, KM™ → Vacuum KS
  - very high pressure ratios (e.g., 500)
    - high Mach numbers (>3) at low stagnation pressures (<< 1 atm)
      - need for very fine powder (e.g., d_{50} = 1 µm)
      - simplification of nozzle design
      - elimination of gas heating unit
        - union of main gas flow and powder feeding flow
          - high pressure drop in powder feeder (aerosol chamber)
            - very low flow rates and effective building rates
              - very high total costs per kg coating

→ Aerosol deposition (AD)

- particles <1 µm may contain low dislocation density allowing plastic deformation by nucleation and glide of dislocations [1] → suited to ceramics (advantage over SLM)
  - AD feed stock preparation by ball milling particles <1 µm may lead to increased DE [1]

[1] P. Sarobol, M. Chandross, J.D. Carroll, W.M. Mook, D.C. Bufford, P.G. Kotula, B.B. McKenzie, B.L. Boyce, K. Hattar, A.C. Hall, *Deformation Behavior of Alumina Particles in Compression for Room Temperature Solid-State Deposition*, Proc. Int. Thermal Spray Conference, May 11–14, 2015, Long Beach, California, USA. ASM International (2015)

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Aerosol deposition

AD parameters for two different materials (from literature)

Parameter	Symbol	Unit	Value #1	Value #2
coating material			SiC-$MoSi_2$ [1]	AlN [2]
coating density	ρ	g / cm³	3,3	3,1
hourly rate	U_{hr}	€ / h	7	7
powder price	U_{pwd}	€ / kg	300	300
monetary value of overspray powder	U_{pr}	€ / kg	0	0
gas price (helium)	U_{gas}	€ / kg	65	65
electrical energy price	U_{elc}	€ / kWh	0,15	0,15
total electric power consumption	S_{tot}	kW	6	6
geometric loss factor	GL	–	0	0
gas flow rate (helium)	$\dot{m}_{gas}$	kg / h	0,06	0,06
powder-to-gas mass loading ratio	w	–	0,05	0,23
deposition efficiency	Y_{DE}	–	0,18	0,06
effective building rate	$\dot{m}$	kg / h	0,0005	0,0009
total costs of coating per unit mass	C_{tot}	€ / kg	24639	19278
total costs of coating per unit volume	C_{ccm}	€ / (m² µm)	81	60
effective building rate		cu in / h	0,010	0,017
annual capacity (1500 h)		€ / (m² µm)	241	414

(dropping overspray powder)

[1] Y.-Y. Wang, Y. Liu, C.-J. Li, G.-J. Yang, J.-J. Feng, K. Kusumoto, *Investigation on the Electrical Properties of Vacuum Cold Sprayed SiC-$MoSi_2$ Coatings at Elevated Temperatures*, J. Thermal Spray Technol. **20** (2011) p. 892

[2] H. Park, J. Heo, F. Cao, J. Kwon, K. Kang, G. Bae, C. Lee, *Deposition Behavior and Microstructural Features of Vacuum Kinetic Sprayed Aluminum Nitride*, J. Thermal Spray Technol. **22** (2013) p. 882

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AD costs not dominated by single factor

AD cost calculation

Cost function [€ / kg]:

$$C_{\mathrm{tot}} = \frac{U_{\mathrm{hr}} + \dot{m}_{\mathrm{gas}} U_{\mathrm{gas}} + S_{\mathrm{tot}} U_{\mathrm{elc}}}{\dot{m}} + \frac{1 + GL}{Y_{\mathrm{DE}}} \left(U_{\mathrm{pwd}} - U_{\mathrm{pr}} \right) + U_{\mathrm{pr}}$$

Cost function [€ / cm³] = [€ / (m² µm)]:

$$C_{\mathrm{ccm}} = \frac{\rho}{1000} C_{\mathrm{tot}}$$

Note:
The AD cost function is a particular case of the CS cost function

AD costs per sq m coating (1 µm)

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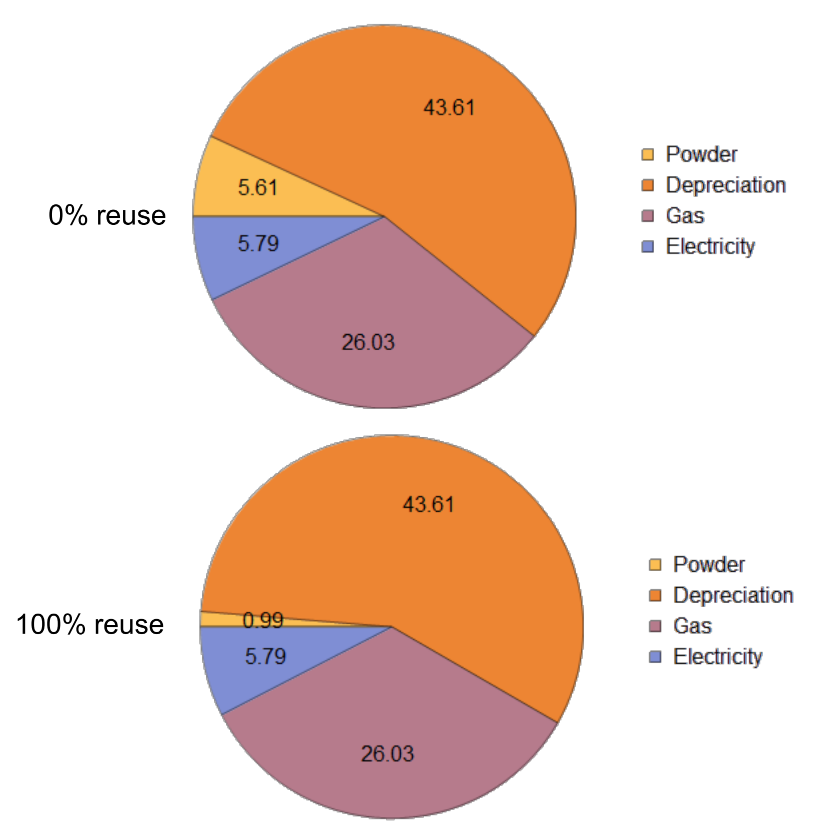
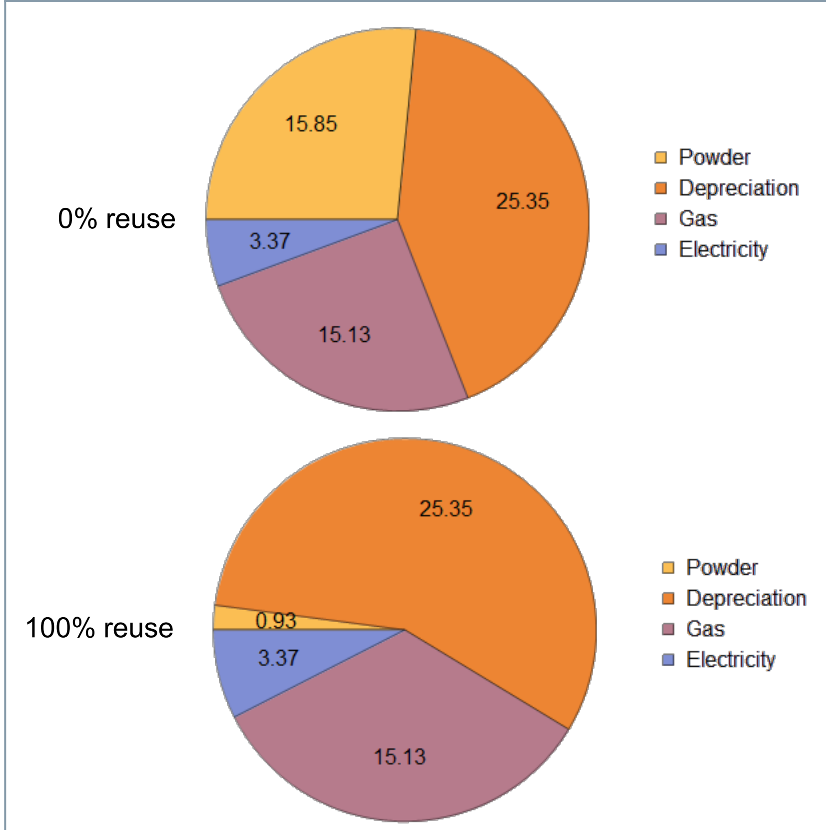
AD cost breakdown for two materials

$SiC\text{-}MoSi_2$ AD costs /(m² µm)



AlN AD costs /(m² µm)



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Conclusions

- Easy to use cost models available for CS, AD, LMD, and SLM
- Costs of SLM and LMD largely consist of depreciation,
    - governed by low effective material building rate
- Costs of CS and AD depend on several parameters in more complex way
- High stagnation pressures generally beneficial to costs
- Costs of CS with high pressure nitrogen arise mainly from powder
    - high building rates (>5 kg/h) suppress depreciation effect on costs
    - powder reuse/recycling may bring down costs to theoretical limit (LMD curve)
- Upscaling of CS is technically possible and beneficial to costs
- Downscaling of CS is not beneficial to costs (need for helium)
    - vacuum spraying (AD, VCS, VKS, NPDS) works with ceramic feedstock
    - suited for thin coatings, not for 3D net shapes

Questions?

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siemens.com/innovation/en/technology-focus/materials.php