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Corporate Technology

Economics of Cold Spray – Fundamental Cost Analysis

Oliver Stier

Outline

- Motivation
- Cost types of cold spray
  - Equipment hourly rate
  - Consumable costs
- Total costs of cold spray
  - Gas related costs
- Costs factors of cold spray
  - Cost optimization
- Application example: Gas turbine blade bond coating
- Conclusions

Fundamental cost theorem

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Motivation

Basic requirement to economic CS process

- Equipment amortization (regardless whether at OEM or job shop) requires to create as much CS deposit as possible per time unit
- Required amount of powder is determined by deposition efficiency (DE)
- Required amount of gas is determined by mass flow ratio w

For cost efficient use of CS, both w and DE need to be high

Previously published by H. Gabel, D. Helfritch, and others

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Need for general cost model

Motivation

w and DE not sufficient for cost analysis

		N_2	$He+N_2$ 1:1	He
design M	–	3,17	1,93	2,12
P	bar	50	40	40
T	°C	1000	1000	370
v	m / s	1354	2062	2002
ρ	kg / m³	0,76	0,76	0,76
w	–	5%	20%	20%
DE	–	25%	90%	90%
powder costs	€	520	144	144
gas costs	€	10	181	361
amortization	€	26	4	4
total costs	€	564	331	510

Extend cost model to

- gas composition
- spraying duration

O. Stier, A. Graichen, X.H. Li, *Cost Analysis of Cold-sprayed MCrAlY Coatings for Industrial Power Generation Gas Turbine Blades*, NACSC-2011, 25.-27.10.2011, Windsor ON

Costs of cold spray

Cost types

Costs due to deployment and operation of CS plant

- Process consumables
  - powders
  - propellant gases
  - electrical power
  - masking templates, etc.

Billing by amount of product

- Plant amortization over depreciation period
- Leasing rates
- Labor of operation
- Maintenance and repair

Billing by plant use time

Cost measure for cold spray

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Cost types

Costs for CS deposition of 1 kg material:

$$C_{\mathrm{tot}} = C_{\mathrm{pwd}} + C_{\mathrm{gas}} + C_{\mathrm{elc}} + C_{\mathrm{eqp}}$$

amount of product

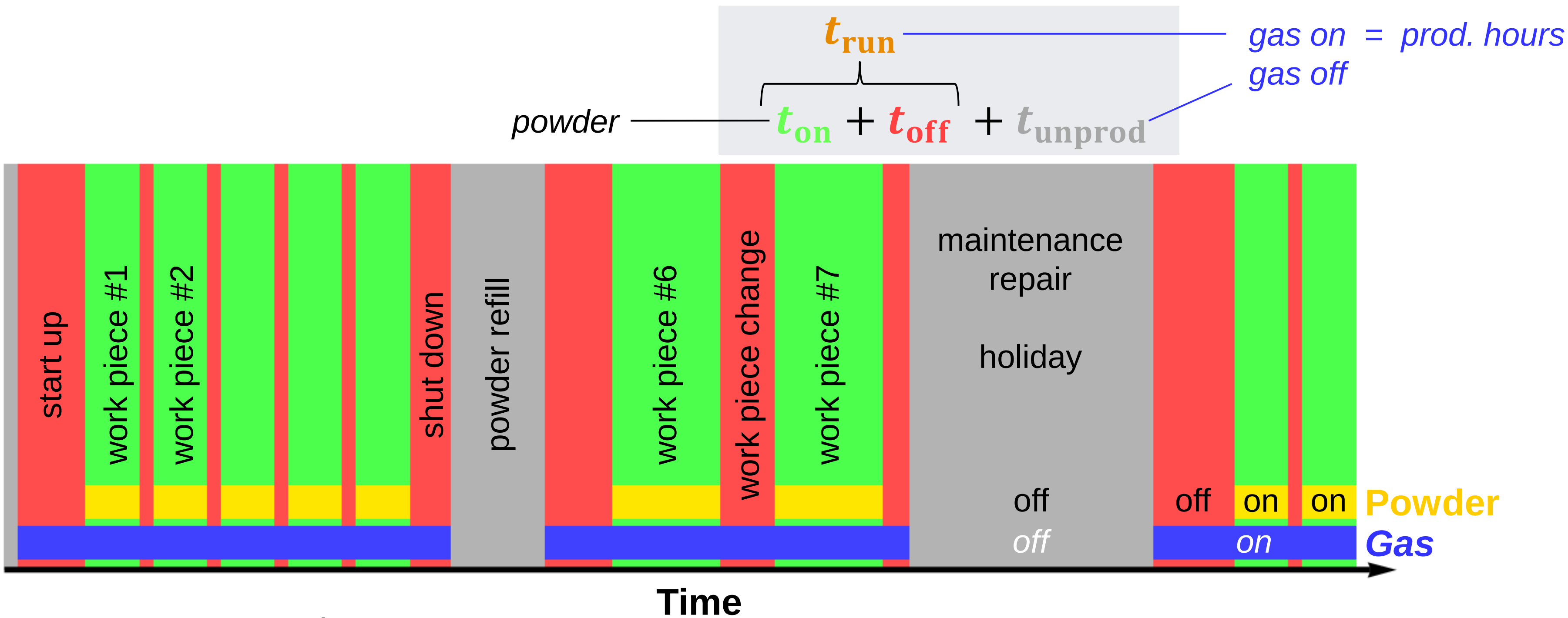
Powder costs	€/kg × kg	$C_{\mathrm{pwd}} = U_{\mathrm{pwd}}\, m_{\mathrm{pwd}}$
Gas costs	€/kg × kg	$C_{\mathrm{gas}} = U_{\mathrm{gas}}\, m_{\mathrm{gas}}$
Energy costs	€/kWh × kWh	$C_{\mathrm{elc}} = U_{\mathrm{elc}}\left(Q_{\mathrm{gas}} + Q_{\mathrm{los}}\right)$

plant use time

Equipment costs	€/h × h	$C_{\mathrm{eqp}} = U_{\mathrm{eqp}}\, t_{\mathrm{run}}$
Labor costs	*neglected*	depend on country and operator skills

Equipment hourly rate

Segmentation of depreciation period



This example: $t_{run}/t_{on} = 1.7$

$t_{unprod} = 26\%$

Equipment cost definition

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Equipment hourly rate

Hourly rate for equipment cost billing

$$\underbrace{t_{\mathrm{on}} + t_{\mathrm{off}}}^{t_{\mathrm{run}}} + t_{\mathrm{unprod}}$$

gas on = prod. hours
gas off

$$\text{productive hours} = \text{depreciation period} - \sum_{\text{gas off}} t_{\mathrm{unprod}}$$

$$U_{\mathrm{eqp}} = \frac{\text{depreciation} + \text{leasing} + \text{maintenance} + \text{repair}}{\text{productive hours}}$$

$$\text{depreciation} = \text{total investment} + \text{capital costs}$$

Equipment cost calculation

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Equipment hourly rate

Example on calculation of hourly rate

1.000.000	invest per unit, €
10	years of usage
8,00%	interest rate
2,16	capital cost factor
1	**unit**
52	weeks / year
6	days / week
3	shift operation
8	hours / shift
0,7	capacity utilization
52.416	max. production hours
5241,6	max. prod. hours / year
2.158.925	investment, €

hours / year	Usage
5000	**95%**

\+ 12000 € / year leasing, maintenance, repair

45,56 hourly rate, €

Equipment costs

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Equipment hourly rate

Assumed hourly rates for stationary high-performance CS systems

Coverage

- Investment
  - actual CS system
  - handling system (robots)
  - peripherals (cabin, collector, filter, etc.)
  - He recovery system
- Capital costs (interest on investment)
- Leasing rates
  - LN_2 supply infrastructure, incl. PRESUS
  - work space
- Maintenance and repair (spare parts)

- without He recovery system

$$U_{\mathrm{eqp}} \approx 50\ €/\mathrm{h}$$

- incl. He recovery system

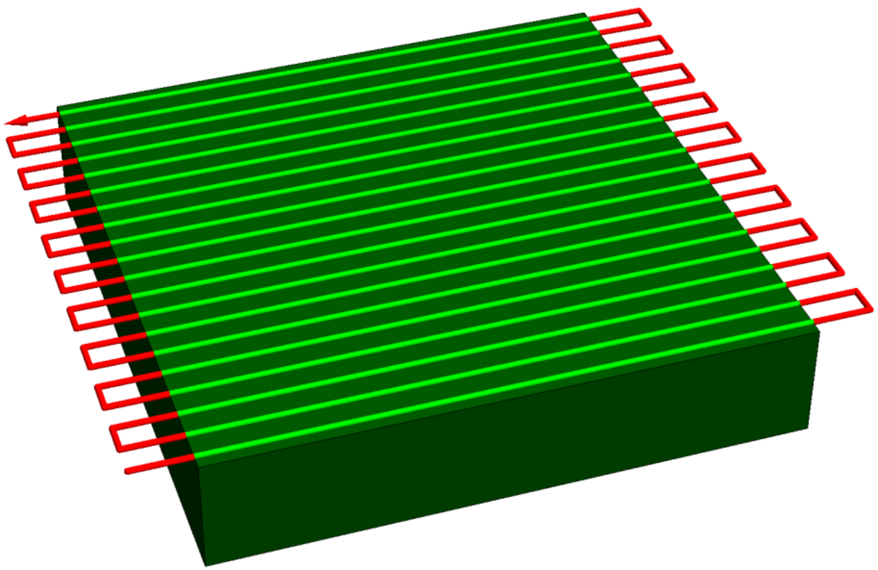
$$U_{\mathrm{eqp}} \approx 100\ €/\mathrm{h}$$

Powder consumption

Consumable costs

Affected by geometric loss GL and deposition efficiency Y_{DE}

$$GL = \left(\sum_{\text{outside}} \text{track length} \right) \Big/ \left(\sum_{\text{inside}} \text{track length} \right)$$



1 kg CS material requires use of

$$m_{\mathrm{pwd}} = \frac{1 + GL}{Y_{\mathrm{DE}}}$$

kg powder at a feeding rate of

$$\dot{m}_{\mathrm{pwd}} = \frac{m_{\mathrm{pwd}}}{t_{\mathrm{on}}}$$

kg/h

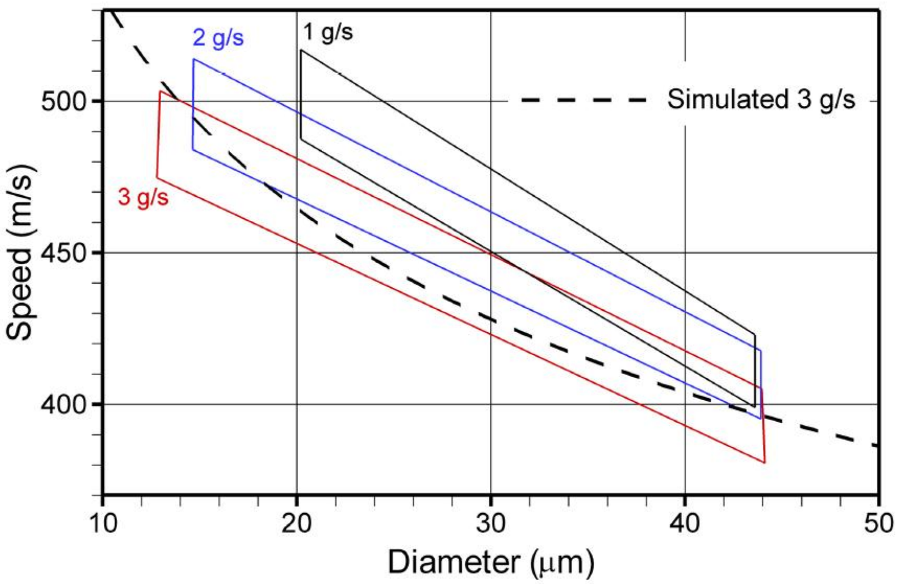
Powder gas mass loading ratio

Consumable costs

Limited by resulting drop of gas and particle velocities

$$w = \frac{\dot{m}_{\mathrm{pwd}}}{\dot{m}_{\mathrm{gas}}}$$

- Energy transfer reduces T
- Injected particles reduce effective value of γ (isentropic exponent)



Ref. B. Samareh, O. Stier, V. Lüthen, A. Dolatabadi, JTST **18**, 934 (2009).
W.Y. Li, C.J. Li, Trans. Nonferrous Met. Soc. China 14 Special 2, 43 (2004).
D.L. Gilmore, R.C. Dykhuizen et al., J. Thermal Spray Technol. 8, 576 (1999).

Other consumptions

Consumable costs

Amounts required to convey m_{pwd} kg powder

Powder feeding time (h): $$t_{\mathrm{on}} = \frac{m_{\mathrm{pwd}}}{\dot{m}_{\mathrm{gas}}\ w}$$

Gas flow time (h): $$t_{\mathrm{run}} = t_{\mathrm{on}} + t_{\mathrm{off}}$$

Gas mass (kg): $$m_{\mathrm{gas}} = \dot{m}_{\mathrm{gas}}\ t_{\mathrm{run}}$$

Energy for gas heating (kWh): $$Q_{\mathrm{gas}} = m_{\mathrm{gas}}\ c_p\ (T - T_{\mathrm{amb}})/3600$$

Thermal loss energy (kWh): $$Q_{\mathrm{los}} = HL\ Q_{\mathrm{gas}}$$

Generic cost function

Total costs

Preceding equations reduce to

$$C_{\text{tot}} = \frac{1+GL}{Y_{\text{DE}}}\left[U_{\text{pwd}} + \frac{1}{w}\,\frac{t_{\text{run}}}{t_{\text{on}}}\left(U_{\text{gas}} + \frac{U_{\text{eqp}}}{\dot{m}_{\text{gas}}} + \frac{1+HL}{3600}\,c_p\,(T - T_{\text{amb}})\,U_{\text{elc}}\right)\right]$$

Gases for cold spray

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Gas related costs

Only air, N_2, He, and their blends feasible gases for CS

$$v = M\,a = M\sqrt{\gamma R t} = M\sqrt{t}\left(\frac{a}{\sqrt{t}} = \sqrt{\gamma R}\right)$$

WANTED!

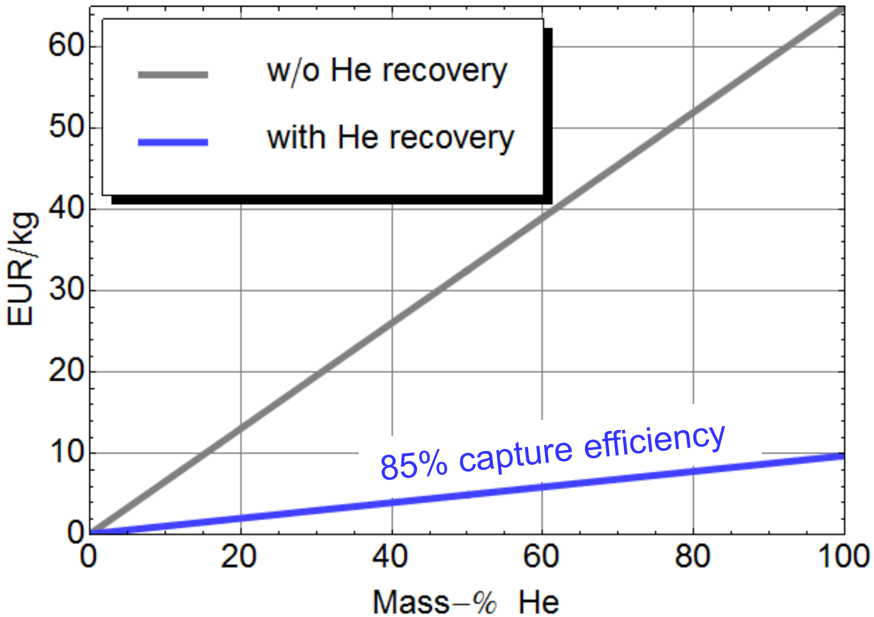
- low molecular weight
- few degrees of freedom
- non-explosive
- non-inflammable
- non-toxic
- non-oxidizing
- affordable

Property	R	γ	ρ_{standard}	$\sqrt{\gamma R}$	U_{gas}	Problem
Unit	J / (kg K)	–	kg / m³	m / (s √K)	€ / kg	–
H_2	4124	1,41	0,08	76		explosive
He	2077	1,67	0,17	59	20 … 65	
Ne	412	1,67	0,84	26	> 60	
CH_4	517	1,17	0,67	25		explosive
NH_3	488	1,22	0,71	24		toxic
steam	460	1,24	–	24		generation
N_2	303	1,37	1,14	20	0,13	
air	293	1,36	1,18	20	≈ 0	
Ar	211	1,68	1,64	19		
CO_2	189	1,19	1,83	15		

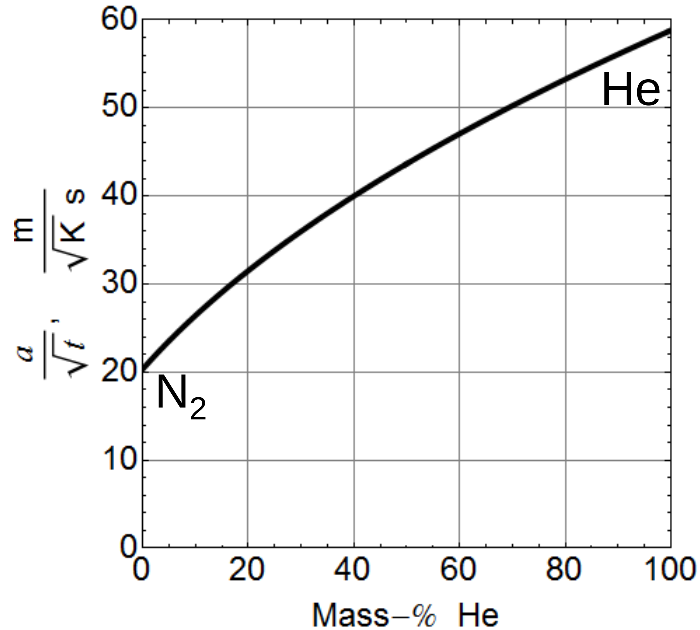
He-N_2 blends

Gas related costs

Price U_{gas} (€/kg) of He-N_2 blends linear in He <u>mass</u> concentration c



$$\frac{a}{\sqrt{t}} = \sqrt{\gamma R}$$



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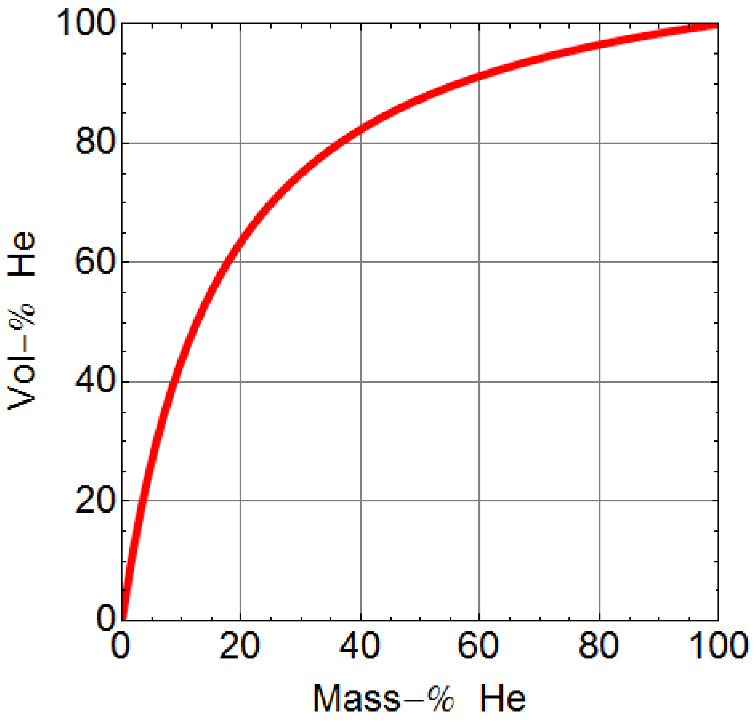
Gas related costs

Non-linear relation between mass and volume (mole) concentrations

- w refers to mass flow rates
- mass fraction c preferred over volume fraction or (isobaric) volume flow ratio



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Electricity costs

Gas related costs

Comparing powder and gas heating power costs

$$C_{\text{tot}} = C_{\text{pwd}} + C_{\text{gas}} + C_{\text{elc}} + C_{\text{eqp}}$$

$$\frac{C_{\text{elc}}}{C_{\text{pwd}}} = \frac{U_{\text{elc}}}{U_{\text{pwd}}} \frac{t_{\text{run}}}{t_{\text{on}}} \frac{1 + HL}{w} \frac{T - T_{\text{amb}}}{3600} c_p$$

$$\approx \frac{0.11\, c_p}{U_{\text{pwd}}\, w}$$

$$\approx \frac{2.5}{U_{\text{pwd}}}$$

$\ll 1$, for expensive powders ($U_{\text{pwd}} \geq 100$ €/kg)

Generic cost function

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Costs factors

Simplified by neglecting electricity costs in case of expensive powders

$$C_{\mathrm{tot}} \approx \frac{1+GL}{Y_{\mathrm{DE}}}\left[U_{\mathrm{pwd}} + \frac{t_{\mathrm{run}}}{t_{\mathrm{on}}}\left(\frac{U_{\mathrm{gas}}}{w} + \frac{U_{\mathrm{eqp}}}{\dot{m}_{\mathrm{pwd}}}\right)\right]$$

$$\frac{1+GL}{Y_{\mathrm{DE}}}\left[U_{\mathrm{pwd}} + \frac{1}{w}\,\frac{t_{\mathrm{run}}}{t_{\mathrm{on}}}\left(U_{\mathrm{gas}} + \frac{1}{\dot{m}_{\mathrm{gas}}}U_{\mathrm{eqp}}\right)\right]$$

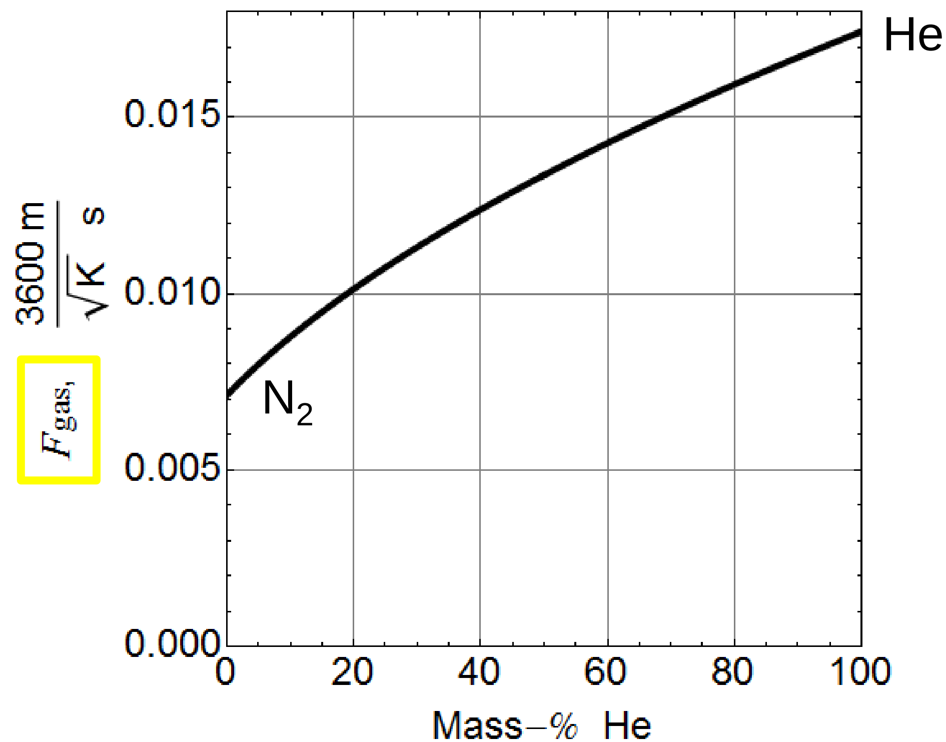
$$\frac{1+GL}{Y_{\mathrm{DE}}}\left[U_{\mathrm{pwd}} + \frac{1}{w}\left(1+\frac{t_{\mathrm{off}}}{t_{\mathrm{on}}}\right)\left(U_{\mathrm{gas}} + F_{\mathrm{gas}}\frac{\sqrt{T}}{A_{\mathrm{thr}}\,P}U_{\mathrm{eqp}}\right)\right]$$

Gas flow rate depends on composition

Costs factors

"Inverse flow factor" F_{gas} affects gas flow rate

$$\frac{1}{\dot{m}_{\text{gas}}} = F_{\text{gas}} \frac{\sqrt{T}}{A_{\text{thr}}\, P}$$



Cost factors of cold spray

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Costs factors

(neglecting electricity costs in case of expensive powders)

$$C_{\mathrm{tot}} \approx \frac{1+GL}{Y_{\mathrm{DE}}}\left[U_{\mathrm{pwd}} + \frac{1}{w}\left(1+\frac{t_{\mathrm{off}}}{t_{\mathrm{on}}}\right)\left(U_{\mathrm{gas}} + F_{\mathrm{gas}}\frac{\sqrt{T}}{A_{\mathrm{thr}}\,P}U_{\mathrm{eqp}}\right)\right]$$

- application specific process parameters GL and t_{off}
- flow parameters P, T, w
- propellant gas property F_{gas}
- particle bonding characteristic Y_{DE} (depends on P, T, w, c, nozzle shape)
- equipment parameter A_{thr}

Deposition efficiency

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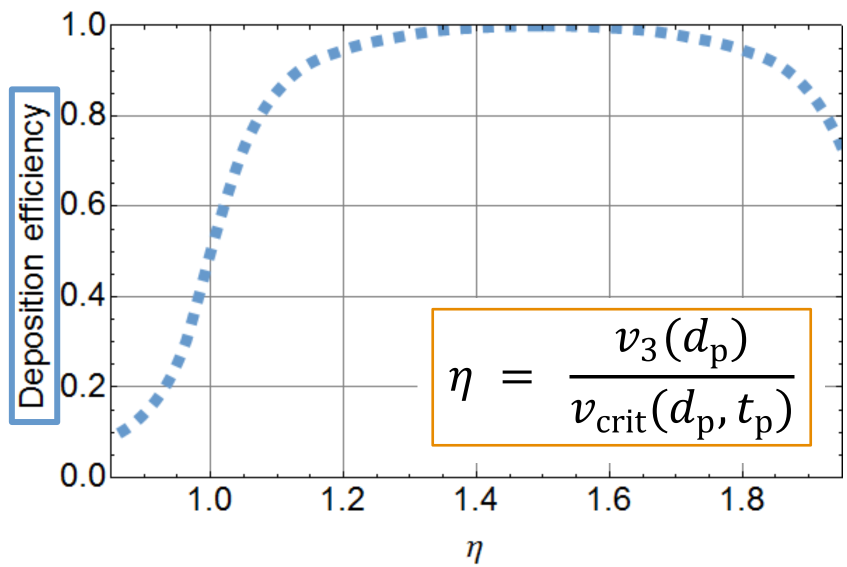
Costs factors

Empirical relation between Y_{DE} and particle impact velocity v_3

Blend of different particle sizes d_{p}:

$$Y_{\mathrm{DE}} = \int_0^\infty \mu(d_{\mathrm{p}}) \boxed{DE} \left(\boxed{\frac{v_3(d_{\mathrm{p}})}{v_{\mathrm{crit}}(d_{\mathrm{p}}, t_{\mathrm{p}}(d_{\mathrm{p}}))}} \right) \mathrm{d}d_{\mathrm{p}}$$



Prediction of v_{crit} is utterly difficult

➢ empirical black-box function

Ref.

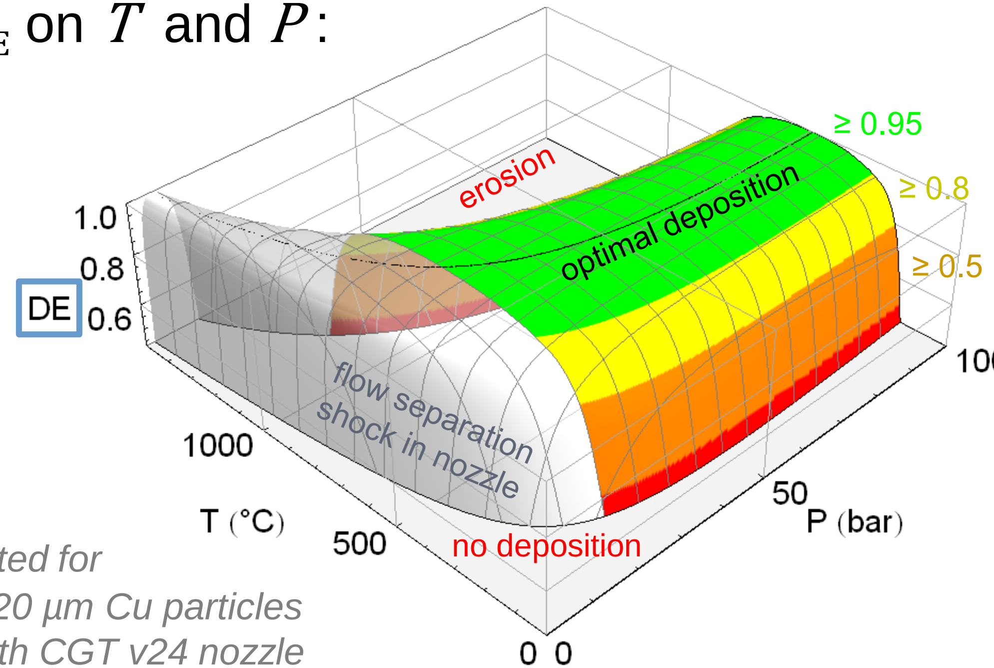
H. Assadi, T. Schmidt, H. Richter, J.O. Kliemann et al., JTST **20**, 1161 (2011).
H. Assadi, H. Richter, F. Gärtner, T. Schmidt, J.O. Kliemann, K. Binder, T. Klassen, H. Kreye, *Application of parameter selection maps in cold spraying*, ITSC-2011.

Deposition efficiency

Costs factors

Qualitative dependence of Y_{DE} on T and P:

Deposition efficiencies Y_{DE} of given powders need to be determined experimentally



Calculated for

- *d_p = 20 µm Cu particles*
- *N_2 with CGT v24 nozzle*

Model: H. Assadi, T. Schmidt, H. Richter, J.O. Kliemann et al., JTST **20**, 1161 (2011).
H. Assadi, H. Richter, F. Gärtner, T. Schmidt, J.O. Kliemann, K. Binder, T. Klassen, H. Kreye, *Application of parameter selection maps in cold spraying*, ITSC-2011.

Advantage of high stagnation pressure

Costs factors

Acceleration force on particles proportional to $\rho_{\mathrm{gas}}(v_{\mathrm{gas}} - v_{\mathrm{p}})|v_{\mathrm{gas}} - v_{\mathrm{p}}|$

- v_{gas} originates from T
- v_{gas} independent of P
- ρ_{gas} proportional to P
- higher M increase v_{gas} and decrease ρ_{gas} $\Longrightarrow$

Existence of optimal nozzle Mach number M (given gas and powder)

Higher P
- ➢ improved particle acceleration
  - ➢ higher Y_{DE} (below erosion T)
    - ➢ **lower C_{tot}**

Economic use of cold spray

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Cost optimization

General recommendations

$$C_{\mathrm{tot}} \approx \frac{1+GL}{Y_{\mathrm{DE}}}\left[U_{\mathrm{pwd}} + \frac{1}{w}\left(1+\frac{t_{\mathrm{off}}}{t_{\mathrm{on}}}\right)\left(U_{\mathrm{gas}} + F_{\mathrm{gas}}\frac{\sqrt{T}}{A_{\mathrm{thr}}\,P}U_{\mathrm{eqp}}\right)\right]$$

- GL, t_{off} : Minimize by accurate contour tracking and fast work piece changing
- $Y_{\mathrm{DE}}\,(M, P, T, w, c)$: Maximize by
  - using nozzle with optimal M
  - setting P as high as possible
  - setting T as high as necessary
- If necessary, limit powder feeding rate by A_{thr}, rather than by P

Costs of cold sprayed MCrAlY

Cost optimization

Case study

$$C_{\mathrm{tot}}(c,w) \approx \frac{1+GL}{Y_{\mathrm{DE}}(c,w)}\left[U_{\mathrm{pwd}} + \frac{t_{\mathrm{run}}}{t_{\mathrm{on}}}\left(\frac{c\,U_{\mathrm{He}}}{w} + \frac{U_{\mathrm{eqp}}}{\dot{m}_{\mathrm{pwd}}}\right)\right]$$

fixed parameters

- $Y_{\mathrm{DE}}\,(M, P, T, w, c)$ assuming
  - measured properties $\mu(d_{\mathrm{p}})$, … of proprietary MCrAlY powder
    - $v_{\mathrm{crit}}(d_{\mathrm{p}}, t_{\mathrm{p}})$ empirical black-box function
  - commercial nozzle: $M(c)$
  - commercial system at maximum pressure P
  - and necessary temperature T
  - $v_3(c, w, d_{\mathrm{p}})$ particle impact velocity model

Costs of cold sprayed MCrAlY

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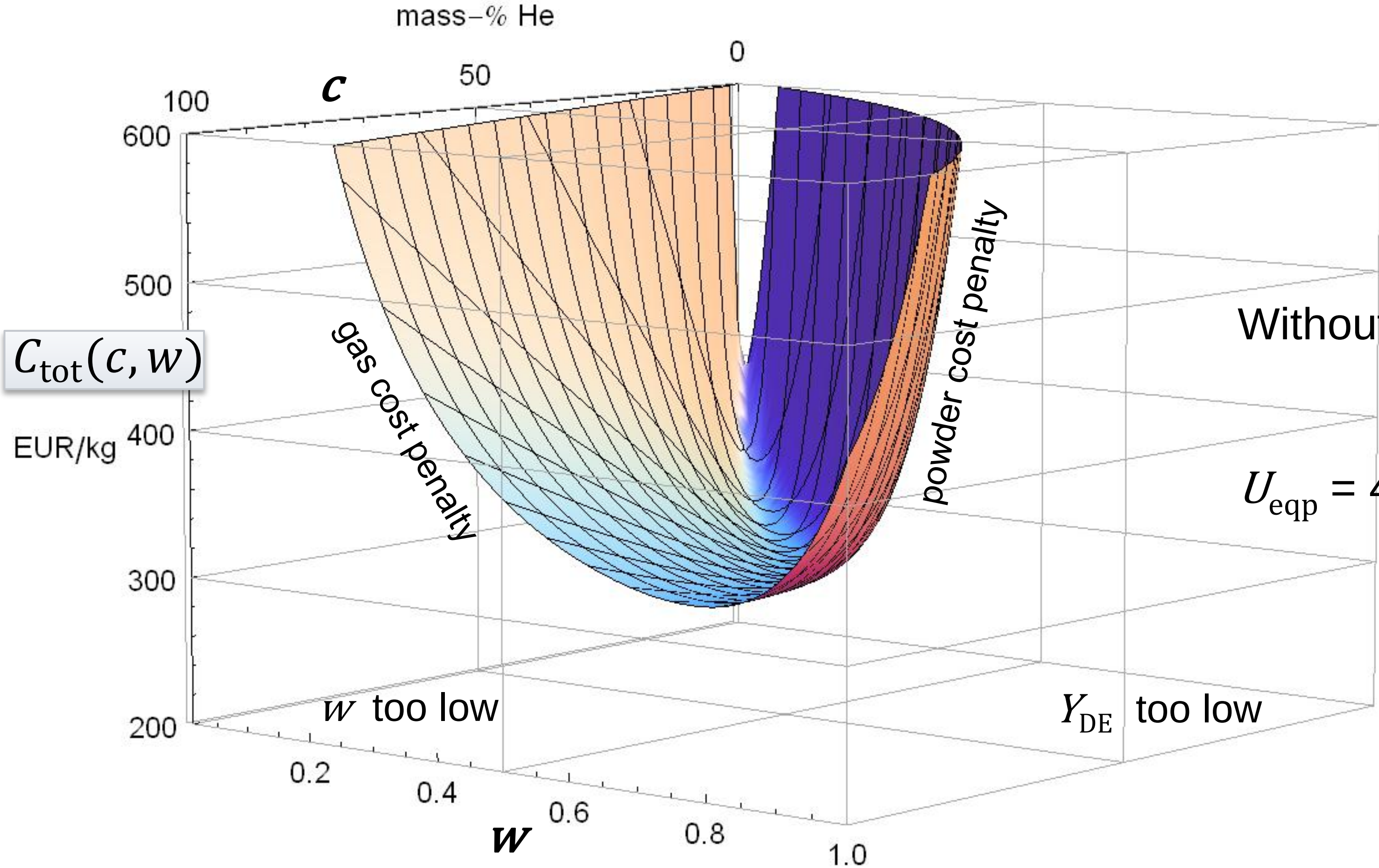
Cost optimization

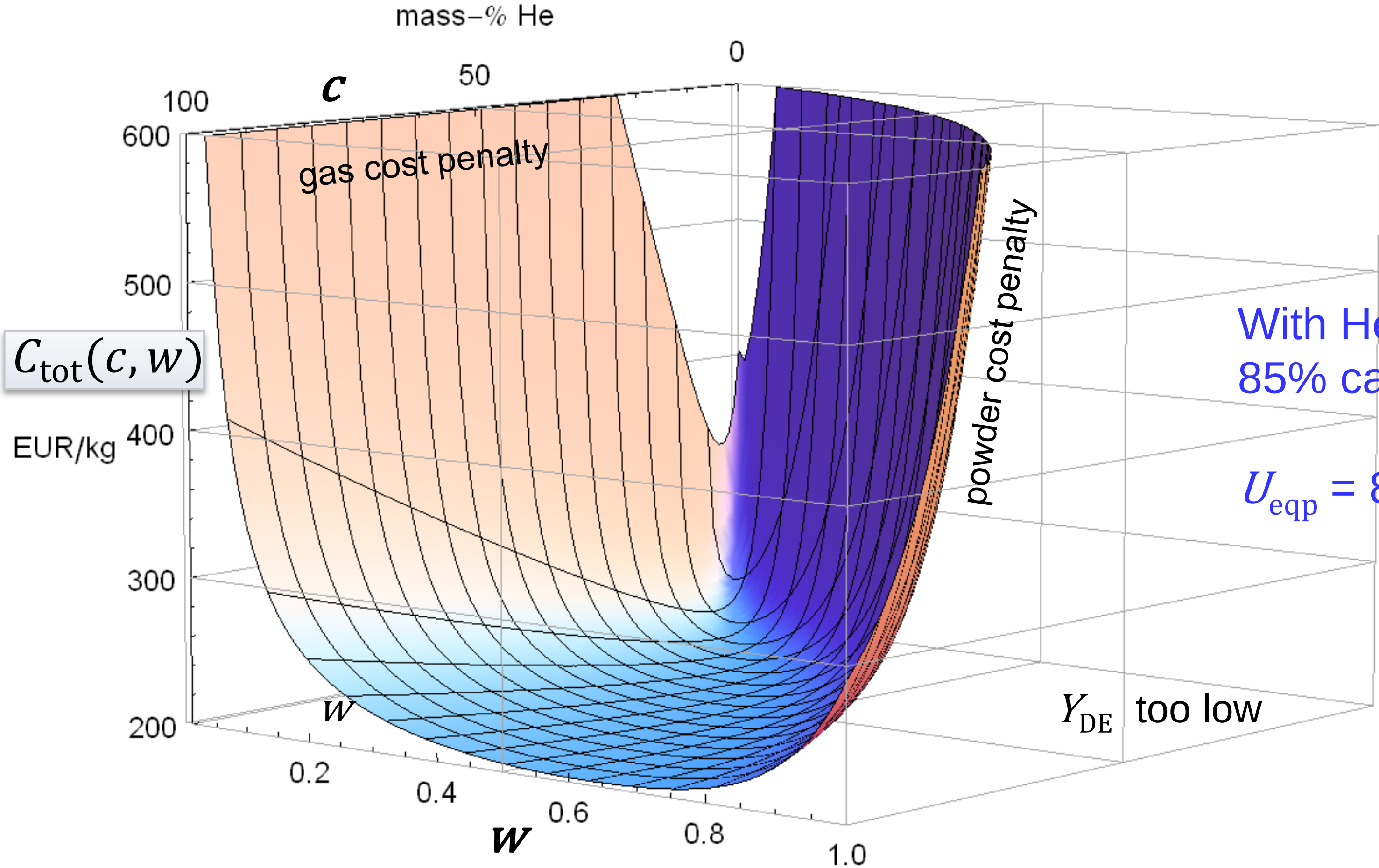


Without He recovery

U_{eqp} = 46 €/kg

Costs of cold sprayed MCrAlY

Cost optimization



With He recovery
85% capture efficiency

U_{eqp} = 89 €/kg

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Cold spray of gas turbine blade bond coating

Application example

Specific requirements:

- Geometric and motion parameters (stand-off distance, spray angle, traversing speed, track pitch) and their tolerances are usually optimized using planar or cylindrical samples
- Turbine blade surface areas to be coated are topologically homeomorphic to cylinders or half spheres, but not geometrically conformal
- Translation of motion parameters requires differential geometry computation based on CAD model of turbine blade
- Small curvature radii lead to rapid rotations around some robot axes

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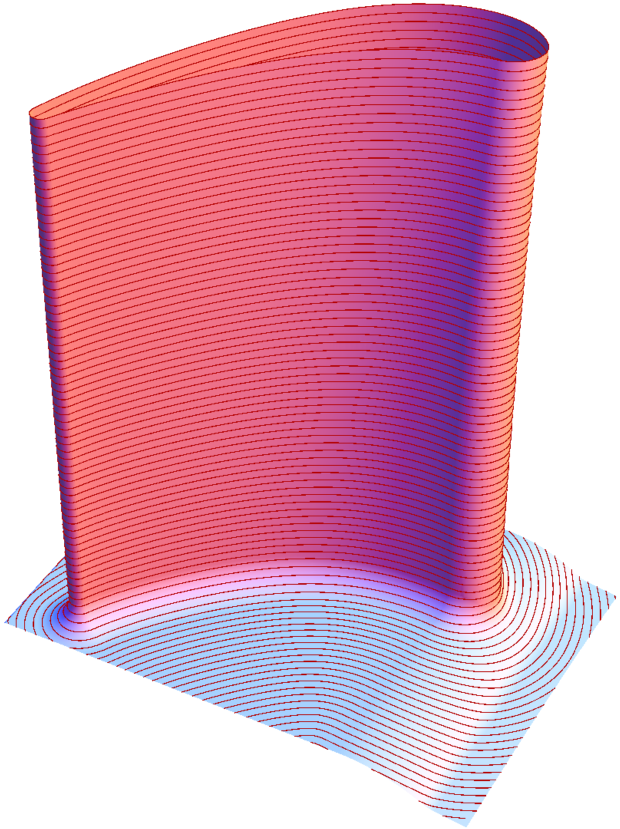
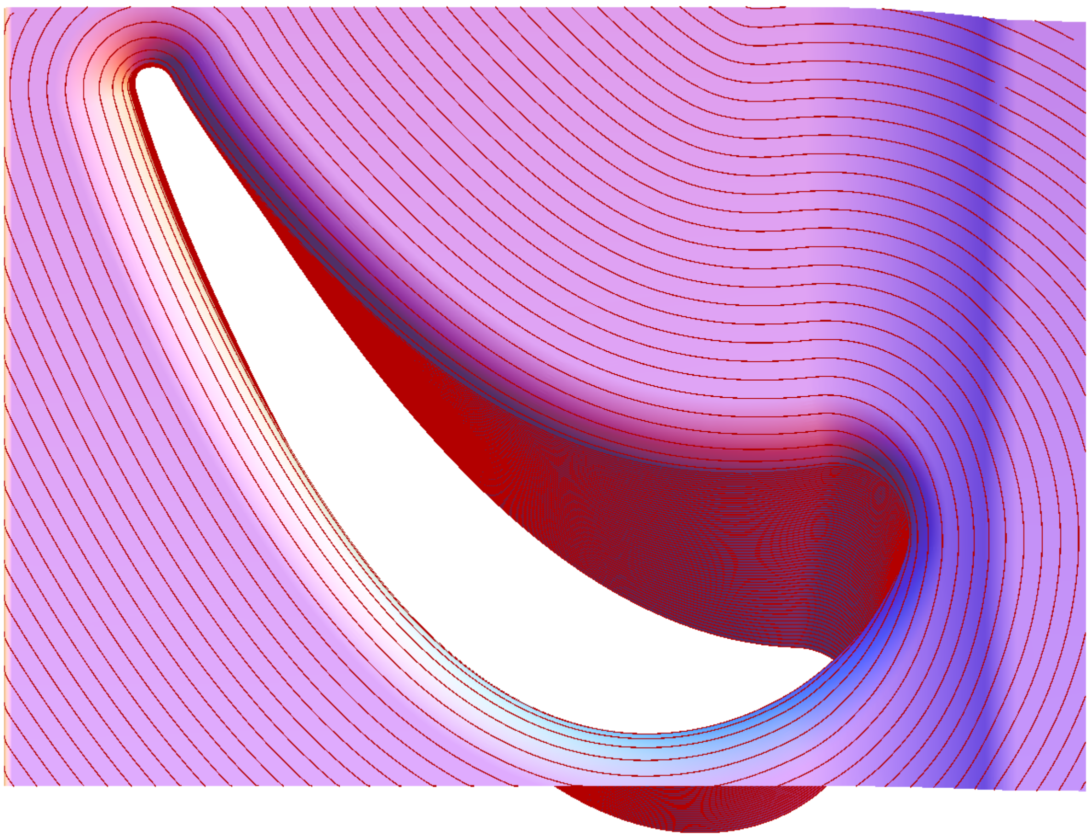
Complete blade and platform in one run

Application example

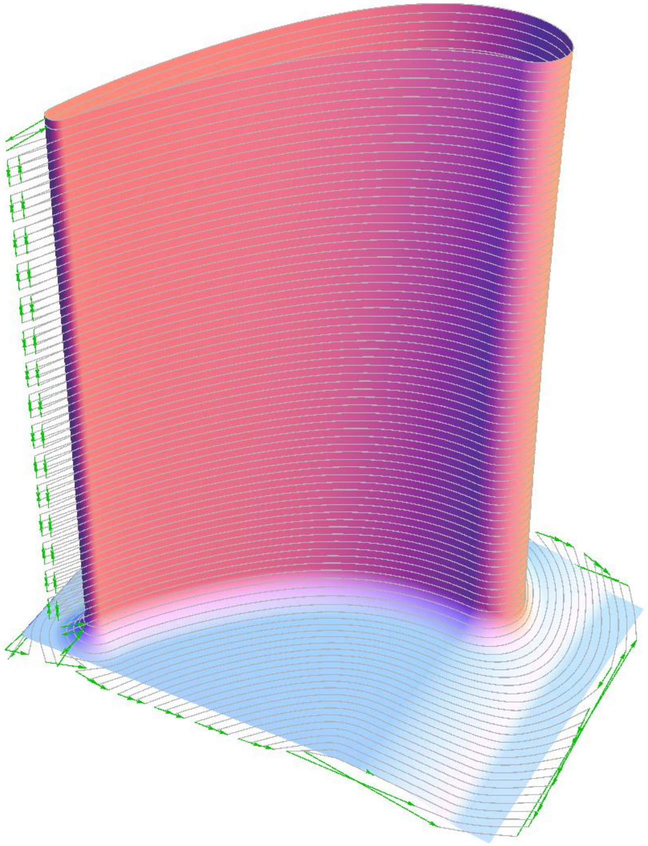
Spray tracks arranged as circumferential geodesic parallel curves

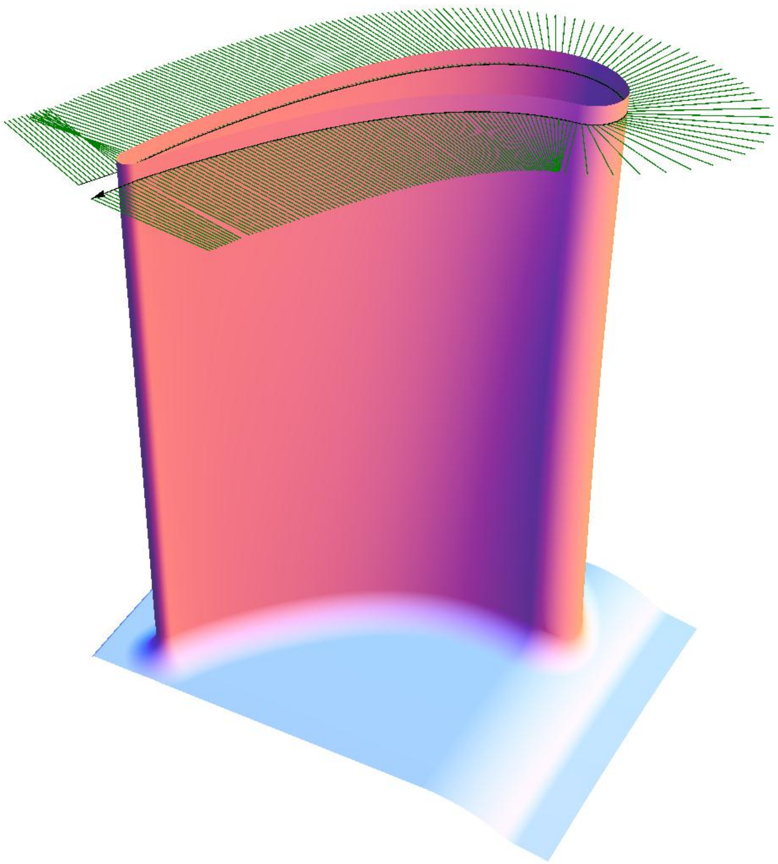




Low geometric loss and open cooling duct

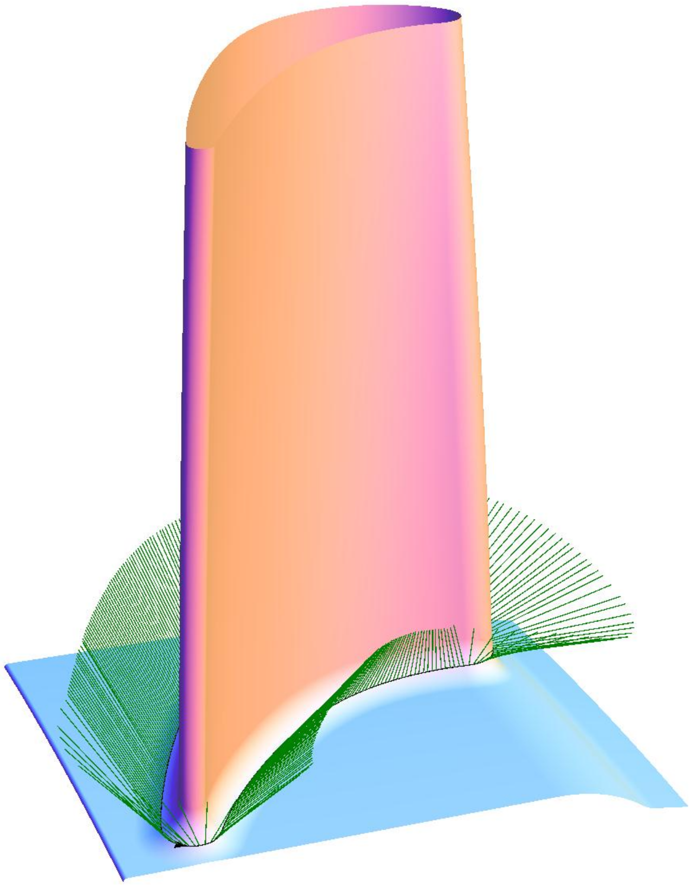
Application example

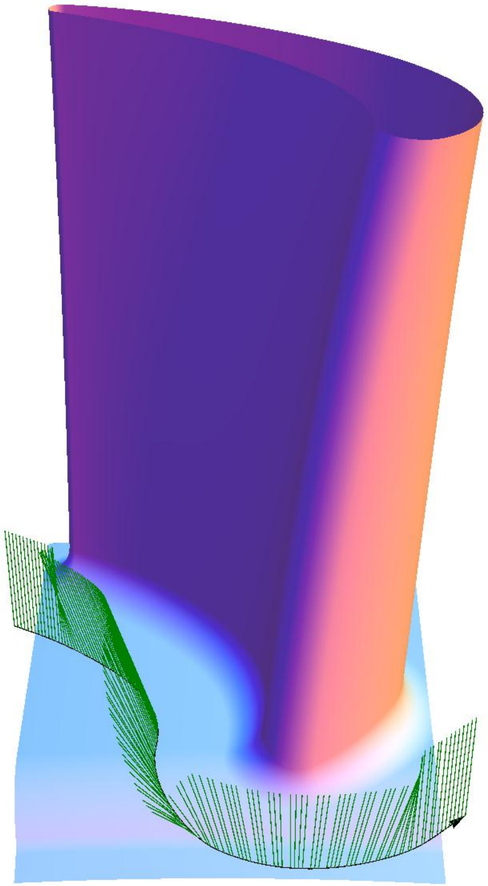




Adaptive spray angle

Application example

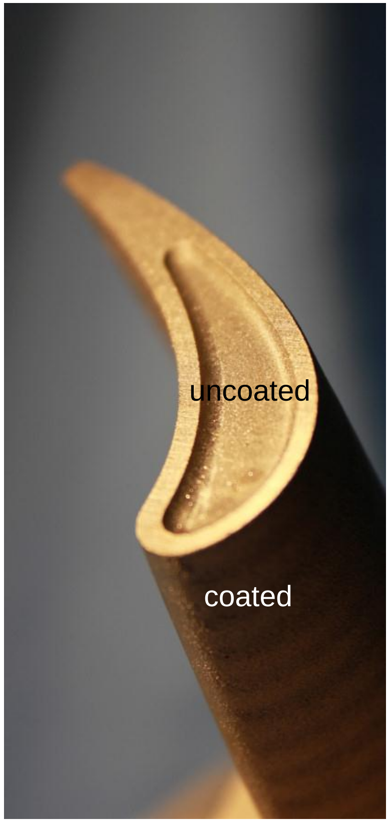




Cold spray coated gas turbine blade

Application example

Horizontal stripes are texture, not undulation



Cold spray coated gas turbine blade

Application example

CS of Amperit™ 429.090 on Inconel™ 792 gas turbine blade

- No masking, no surface preparation
- GL limited to 15%, even for small blades
- Cooling ducts at trailing edge remain open
- Homogeneous coating thickness
- Adhesion strength >60 MPa
- Roughness R_a = 17 µm suited to TBC deposition

Conclusions

- Generic cost function applies to all
  - present types of CS systems (“HP”, “LP”, KM™, “kinetic spraying”, etc.)
  - relevant kinds of application (coating, restoration, additive manufacturing)

  and is useful for cost estimation and optimization
- High pressure is generally favorable
- He-N_2 blends possess highest commercial potential
- He recovery saves costs in high volume production, even with He-N_2 blends
- CS particularly suited to gas turbine blade bond coatings, offers cost savings