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Cold Spray Additive Manufacturing

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Outline

Cold spray technology:
- Principle
- Advantage

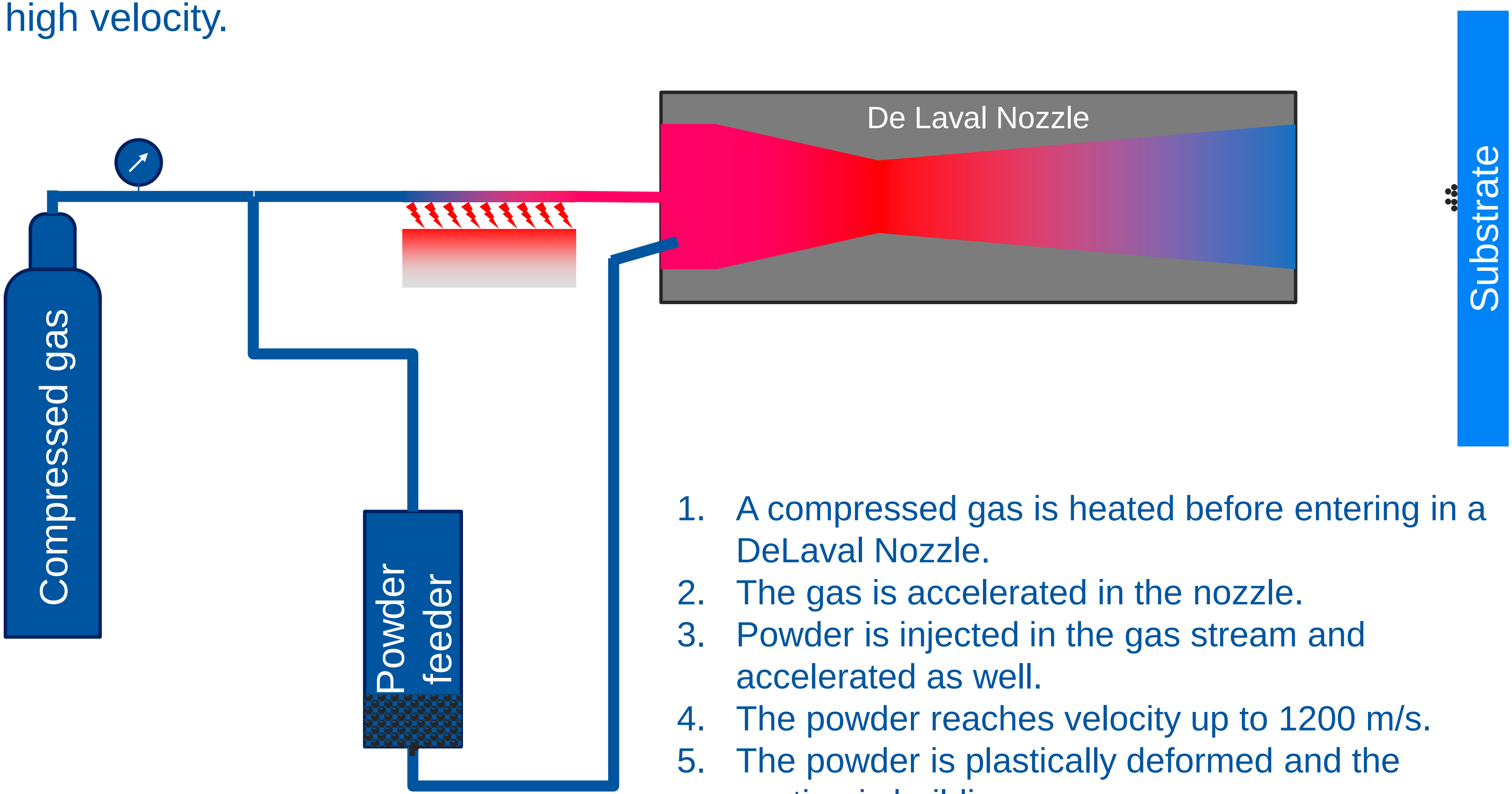
Possible applications in accelerators:
- Local coating
- Additive manufacturing
- New materials

Applications of cold spray to UHV systems
- Thermal outgassing
- Leak tightness

Conclusion

Principle of Cold Spray

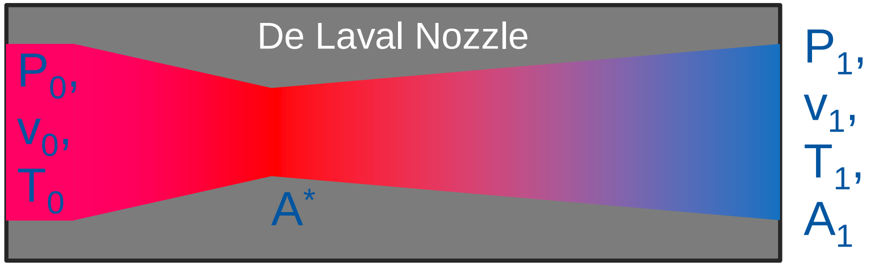
The gas dynamic cold spray coating is based on the projection of solid powder at high velocity.



1. A compressed gas is heated before entering in a DeLaval Nozzle.
2. The gas is accelerated in the nozzle.
3. Powder is injected in the gas stream and accelerated as well.
4. The powder reaches velocity up to 1200 m/s.
5. The powder is plastically deformed and the coating is building up.

Principle of Cold Spray

1D isentropic flow equations:



$$\frac{P_0}{P_1} = \left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma}{\gamma - 1}} \qquad \frac{T_0}{T_1} = 1 + \frac{\gamma - 1}{2} M_1^2 \qquad M_1 = \frac{v_1}{c_1} = \frac{v_1}{\sqrt{\gamma R_s T_1}}$$

$$\frac{A_1}{A^*} = \frac{1}{M_1}\left[\frac{2}{\gamma + 1}\left(1 + \frac{\gamma - 1}{2} M_1^2\right)\right]^{\frac{\gamma + 1}{2(\gamma - 1)}}$$

$$\gamma = \frac{c_p}{c_v}$$

γ=5/3 (1.67) for monoatomic perfect gas
γ=7/5 (1.4) for diatomic perfect gas and
γ=1,33 for polyatomic perfect gas

R_s is the specific gas constant given by R/M_{molar}

Nitrogen is commonly used. Helium is used to reach higher velocity.

Cold Spray Advantages and Limitations

Advantages:

- No powder melting.
  - → No phase change.
  - → No grain growth.
  - → Low heating of the substrate.
- No significant impact on the oxide content w.r.t. initial material.
- Powder mixture possible.
- Compressive residual stress (fatigue life increase).
- Nozzle geometry can be tuned for a given jet size.
- Thick coating.
- High deposition rate.

Limitations:

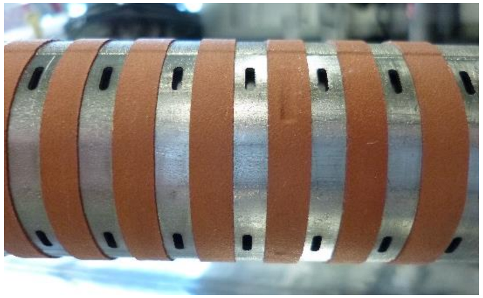
- One constituent has to be ductile.
- Accessibility to the surface to be coated.

Possible Applications in Accelerators

Local coating:

Heat transfer:

Copper trips on FCC-hh beam screen prototype.



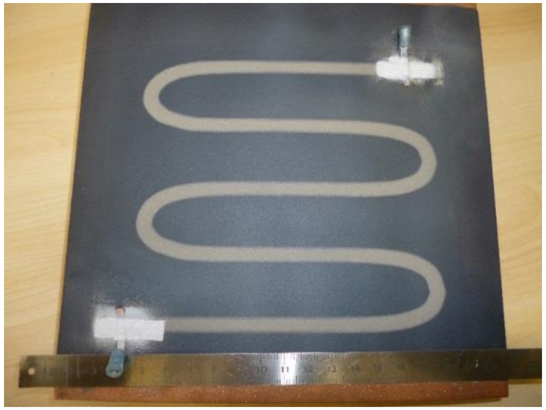
Electrode:

- Measurement of electrons for the FCC-hh beam screen prototype experiment at ANKA.
- Clearing electrode (optimisation of ceramic layer required for non-baked system).

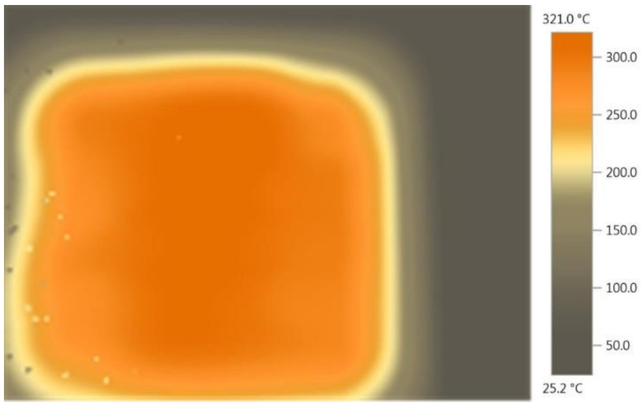
Copper and aluminium cold spray coating on ceramic insulated copper coated stainless steel sheet

Possible Applications in Accelerators

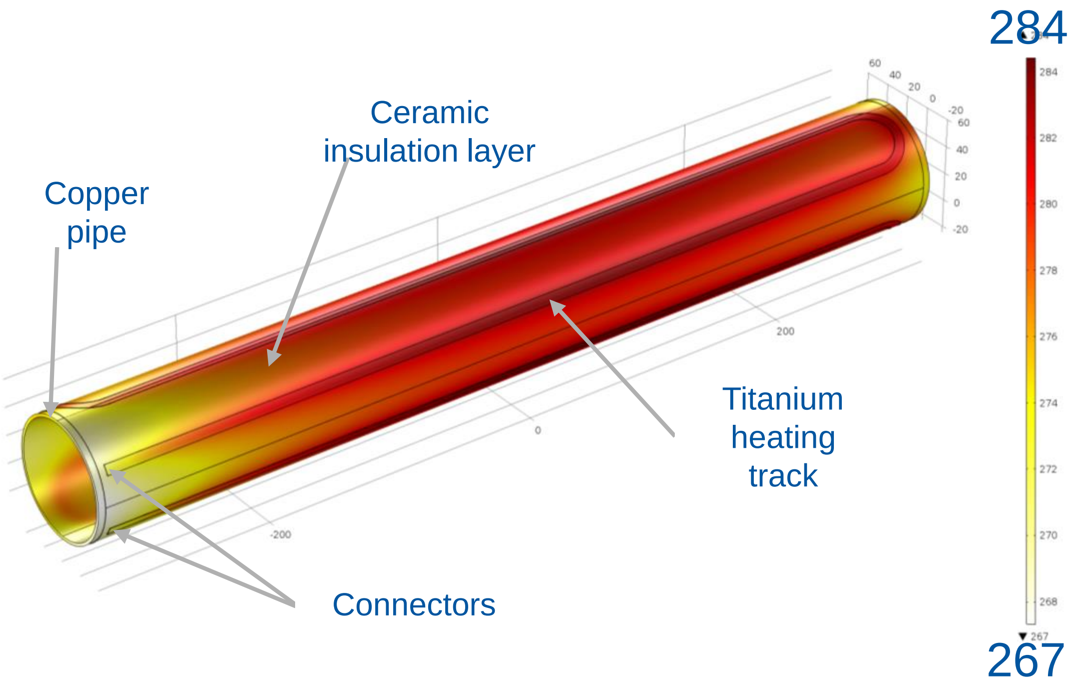
<u>Local coating:</u> Heating element for bake out in or outside vacuum



Copper plate with plasma sprayed ceramic and 0.2 mm thick cold sprayed titanium heating track



Measurement of the temperature field



Expected temperature profile on a copper tube, ID 80 mm

A prototype of a copper tube with permanent radiation tolerant bake out system is in fabrication.
A study will be carried out for heating system in a vacuum vessel (low outgassing of ceramic coating).

New Manufacturing Process

<u>Additive manufacturing </u>for:
- Joining of dissimilar materials
- New feature
- Repair
- Local reinforcement of thin walled structure

Titanium on glassy carbon

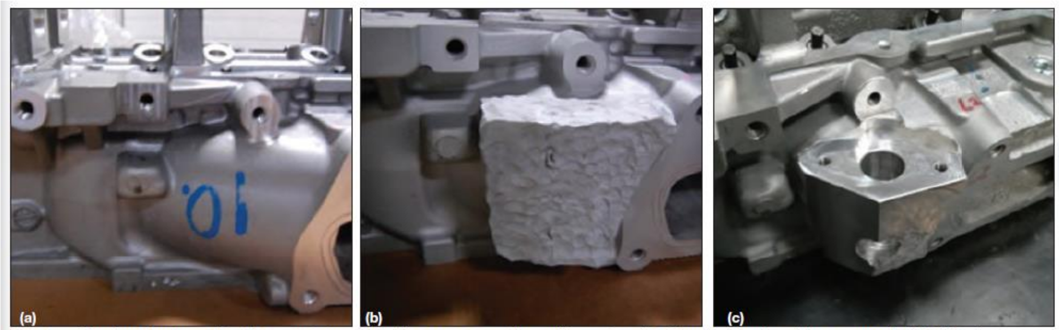
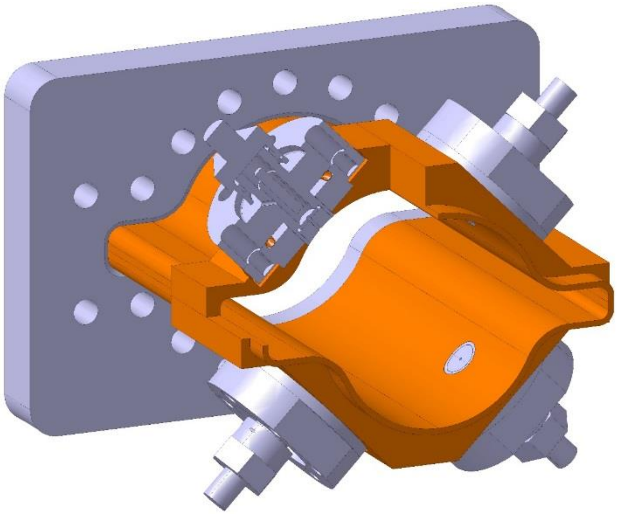


Fig. 3 — *Freeform feature added to a prototype machine component by cold spraying. (a) Prior to spraying, (b) as sprayed, (c) finished.*

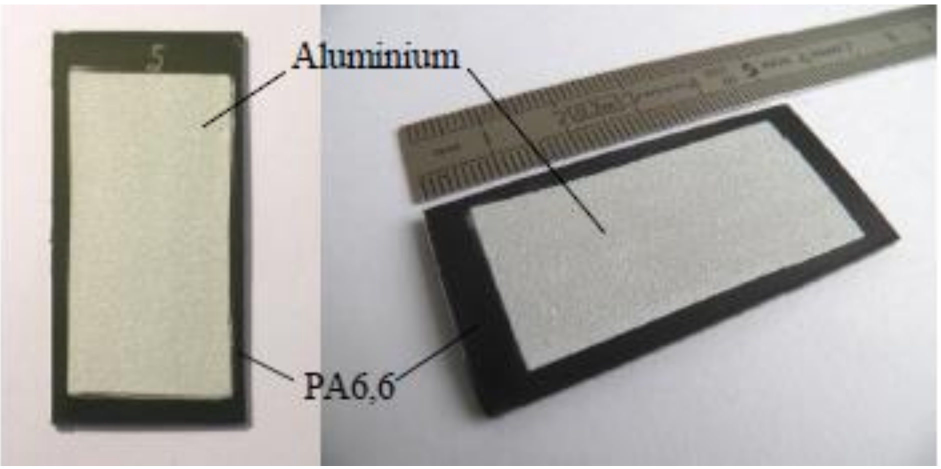
J. Villafuerte, ADVANCED MATERIALS & PROCESSES, 2014



FCC-ee quadrupole chamber with BPM

New Materials

Metallization of polymer



D. Giraud, Etude des composantes mécanique et métallurgique dans la liaison revêtement-substrat par projection dynamique pas gaz froid pour les systèmes aluminium/Polyamide6,6 et titane/TA6V, Mines ParisTech, 2014

Could it be a candidate for experimental vacuum chamber?

Composite material:
Example of diamond copper composite

Shuo Yin, Barry Aldwell and Rocco Lupoi, Advanced diamond-reinforced copper composite coatings via cold spray and material characterization, Trinity College Dublin

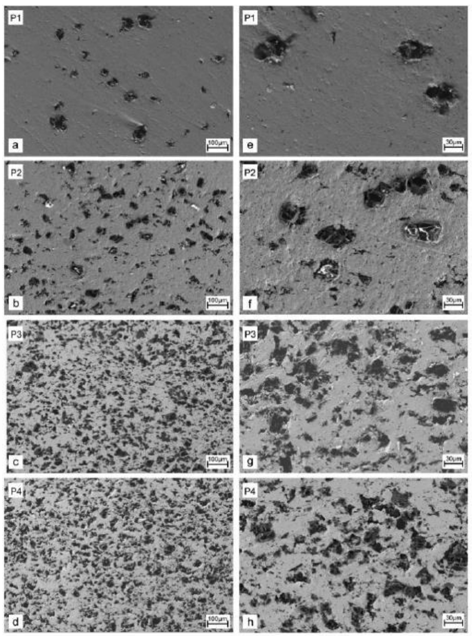


Fig. 6. Cross-sectional SEM images of MMC coatings fabricated with different powders and working conditions

Could it be a candidate for collimator material?

Application of Cold Spray for UHV system

Requirements for UHV applications:

- Outside vacuum chamber: not relevant.
- In vacuum applications: low outgassing rate.
- Vacuum barrier:
  - Low outgassing rate.
  - Leak tightness.

Ceramic plasma spray underlayer might be applied for some applications. Same requirements apply.

Vacuum Performance

Thermal outgassing

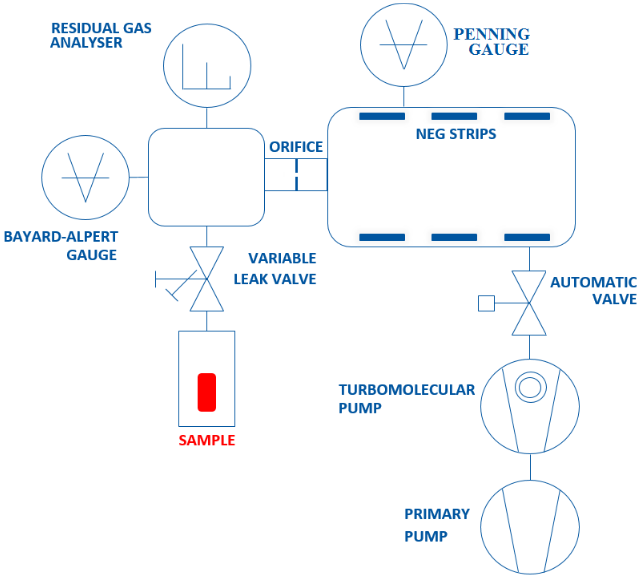
Samples:
- Substrate: 3 stainless steel tubes, vacuum fired
- Titanium coating, grade 2, 0.5 mm thick
- Copper, 99.95%, 0.5 mm thick

Substrates

Titanium coated samples

Copper coated samples

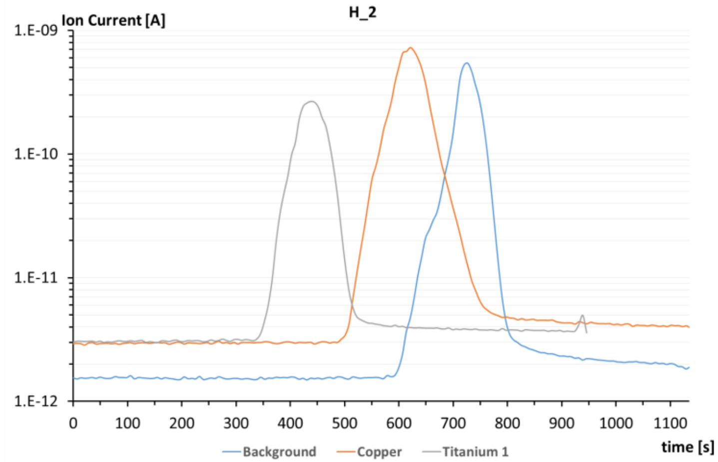
Measurements by accumulation method:



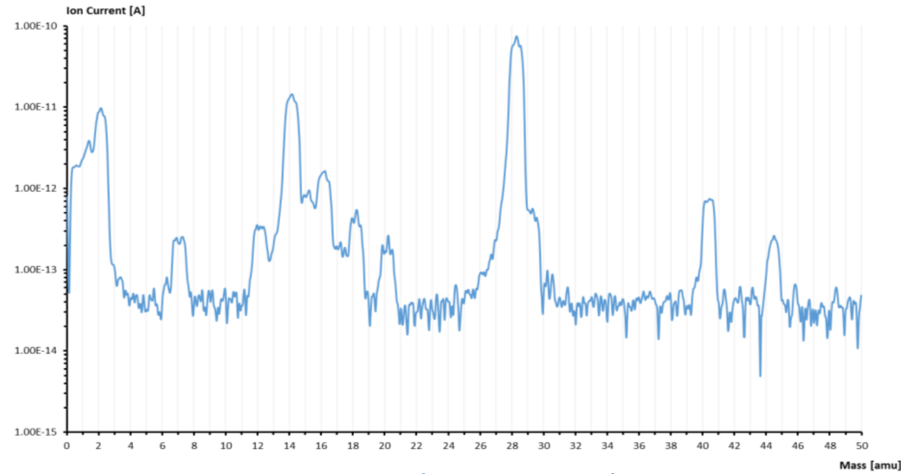
Set-up principle for thermal outgassing measurement by accumulation

Vacuum Performance

Thermal outgassing



Typical current (pressure) curves accumulation time and valve opening



RGA scan for copper samples

	Total Outgassing [mbar·l·s^{-1}]	Specific Outgassing (H2) [mbar·l·s^{-1}·cm^{-2}]
Background	3.9e-11	
Stainless steel substrate	6.37e-11	4.5e-14
Copper	6.24e-11	3.9e-14
Titanium #1	1.73e-11	

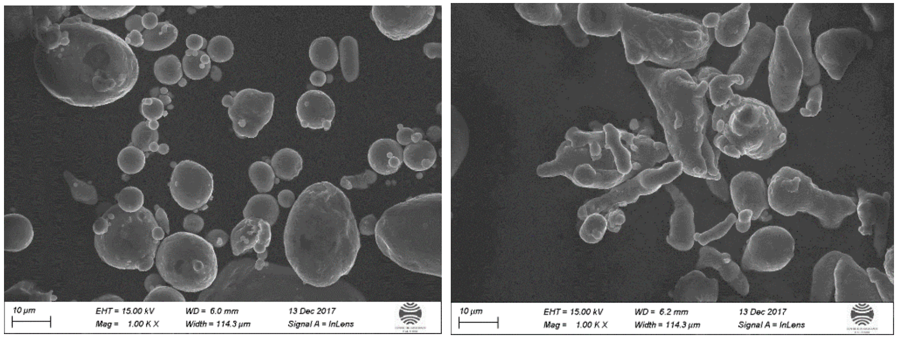
- Outgassing of H2 for copper is similar to bulk material.
- Titanium outgassing is surprisingly low. Measurement to be redone.
- Inert gas used during the powder fabrication may have a significant impact (high outgassing of N2 and Ar observed, for copper).

Vacuum Performance

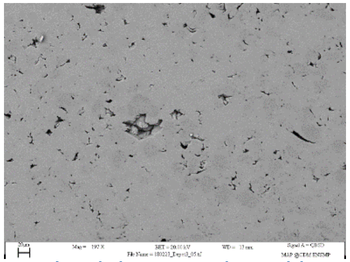
Leak tightness

Present study program on aluminium coatings (in collaboration with Mines ParisTech):

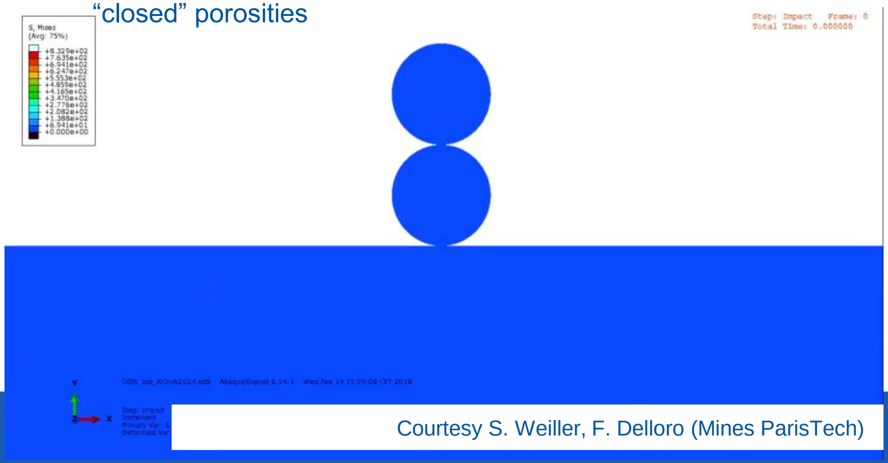
- Powder :
  - Morphology, metallurgical characteristics, mechanical properties.
  - Pre-treatment.
- Processing parameters:
  - Cold spray: gas pressure and temperature.
  - Post-treatment.
- Coating microstructure.
- Vacuum performance.
- Mechanical testing.
- Modeling and numerical simulations.



Powder morphology



Aluminium Coating with “closed” porosities



Courtesy S. Weiller, F. Delloro (Mines ParisTech)

Conclusions

Gas dynamic cold spray is a coating method based on supersonic jet of powders, heavily plastically deformed during the impact.

Ductile materials are well suitable for this manufacturing process.

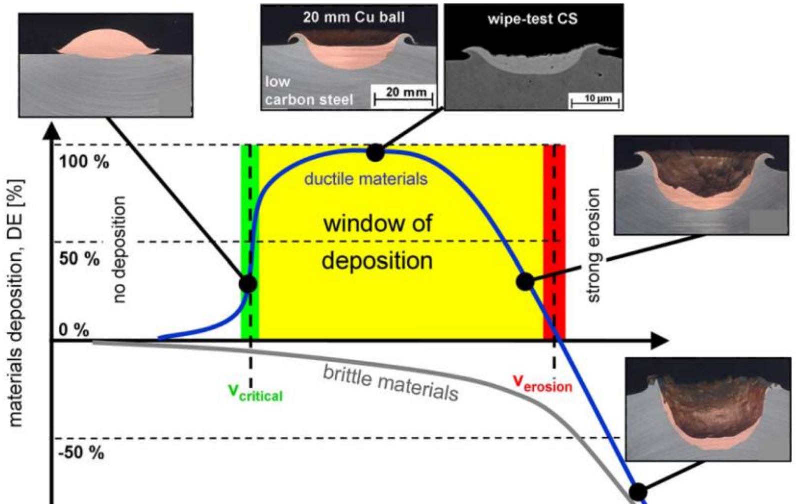
Cold sprayed copper coating has been successfully been applied on a first FCC-hh beam screen prototype.

Other applications have been identified in different field of high energy particle accelerators. First tests are ongoing.

A study is carried out at CERN to assess the vacuum performance of cold sprayed materials.

www.cern.ch

Bounding mechanism

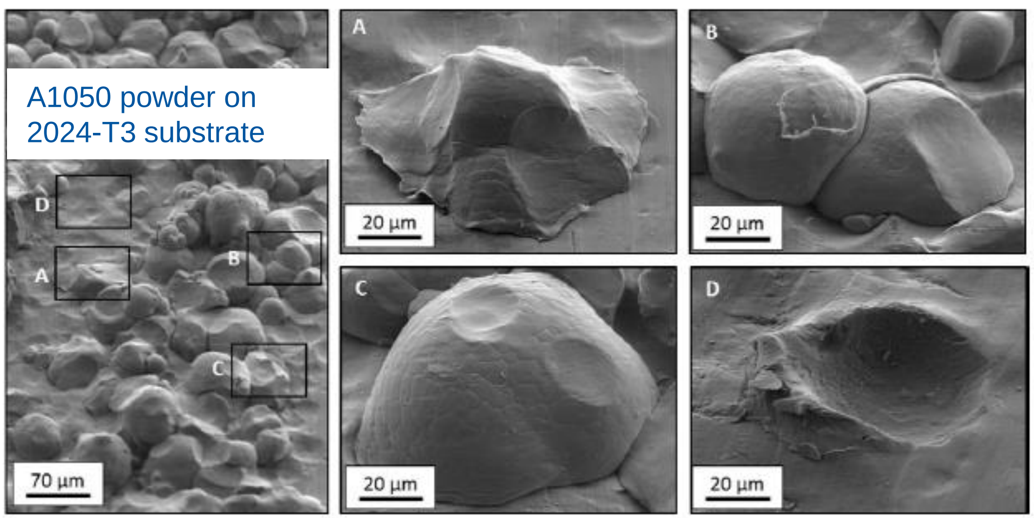


T. Schmidt et al., From Particle Acceleration to Impact and Bonding in Cold Spraying, Journal of Thermal Spray Technology, 18, 5-6, 794-808, 2009

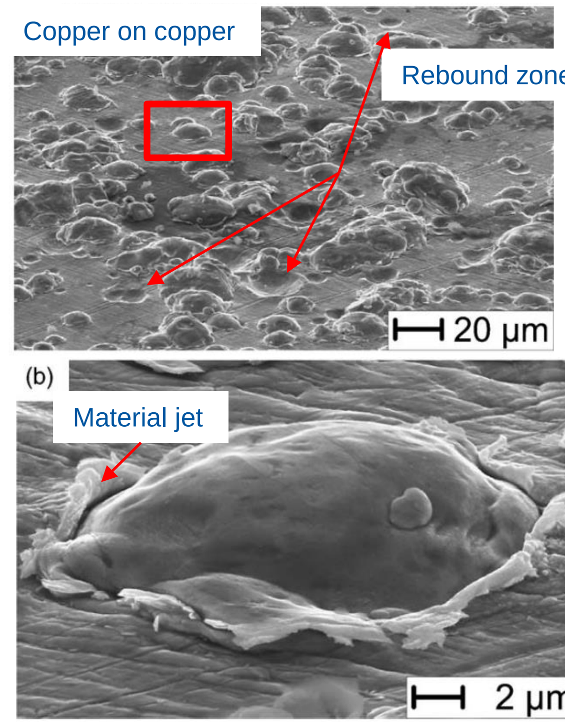
Table 1 Values of critical velocity for bonding assuming a particle size of 20 µm

Material	Melting point, °C	Critical velocity, m/s
Aluminium	660	620-660
Titanium	1670	700-890
Tin	232	160-180
Zinc	420	360-380
Stainless steel (316L)	1400	700-750
Copper	1084	460-500
Nickel	1455	610-680
Tantalum	2996	490-650

Typical surface around the critical velocity



Q. Blochet, Influence of substrate surface roughness on cold-sprayed coating-substrate bond strength in aluminum-based systems, PhD Thesis, Mines ParisTech, 2015



Assadi et al., Bonding mechanism in cold gas spraying, Acta Materialia, 51, 4379-4394, 2003

Some properties: example of copper

Electrical conductivity

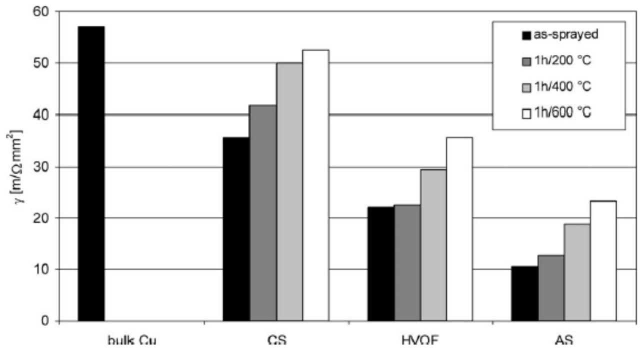


Fig. 9. Conductivity of Cu-coatings processed by cold spraying, HVOF spraying and arc spraying in the as-sprayed state and after different annealing conditions. Annealed bulk Cu serves as reference material.

T. Stoltenhoff et al., Microstructures and key properties of cold-prayed and thermally sprayed copper coatings, Surface & coatings Technology, 200, 2006

Bounding strength

With helium

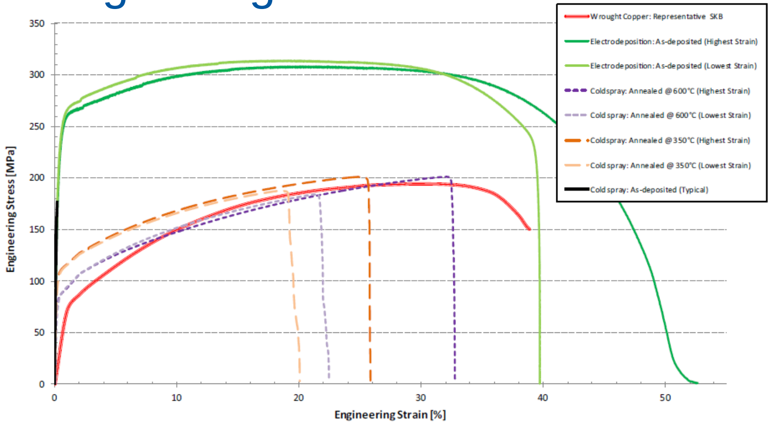
Coating material	Substrate material	Substrate preparation	Bond strength		Reference
Cu	Aluminum	Grit blasting	30–35	ASTM C-633	Taylor et al. (2006)
Cu	Copper, AA5052, AA6063		> 150	Modified tensile test	Huang and Fukanuma (2012)

With nitrogen

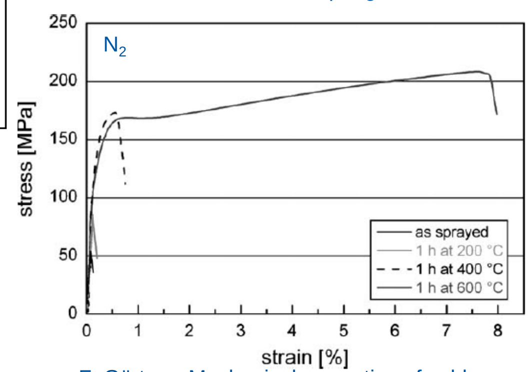
Cu	Copper	Grit blasting	17	JIS H 8664	Fukanuma and Ohno (2004)
Cu	Aluminum	Grit blasting	24	JIS H 8664	Fukanuma and Ohno (2004)
Cu	Aluminum	Grit blasting	> 40	ASTM C-633	Gärtner et al. (2006)
Cu	Steel	Grit blasting	10–20	ASTM C-633	Gärtner et al. (2006)
Cu	Aluminum, Copper	Grit blasting	40	EN 582	Stoltenhoff et al. (2006)
Cu	Steel	Grit blasting	10	EN 582	Stoltenhoff et al. (2006)
Cu	Copper, AA5052, AA6063		> 100	Modified tensile test	Huang and Fukanuma (2012)
Cu+Al_2O_3	Copper, steel	Grit blasting	20–23	EN582	Koivuluoto et al. (2008a, b)

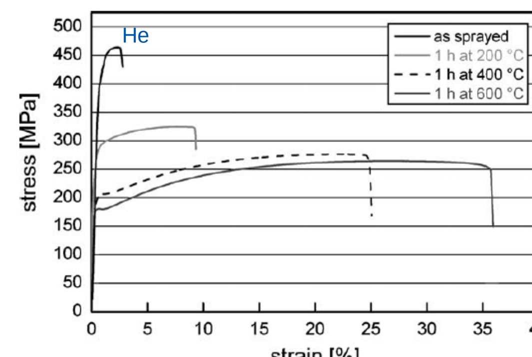
After Jeandin et al., Coating properties in Modern cold spray, Ed. J. Villafuerte, Springer, 2015

Coating strength



C.H. Boyle, Mechanical performance of integrally bounded copper coatings for the long term disposal of used nuclear fuel, Nuclear Engineering and design, 293, 2015



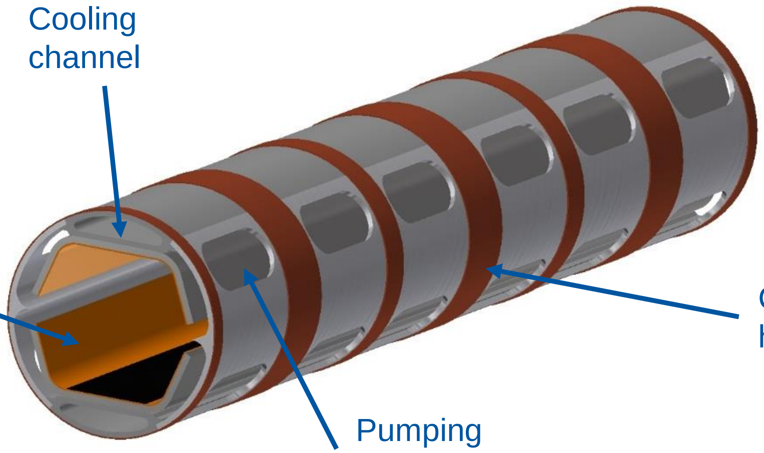


F. Gärtner, Mechanical properties of cold-sprayed and thermally sprayed copper coatings, Surface & Coatings Technology 200, 2006

→ Material properties are affected by the cold spray process but they can significantly be recovered by dedicated post treatment.

Application to FCC

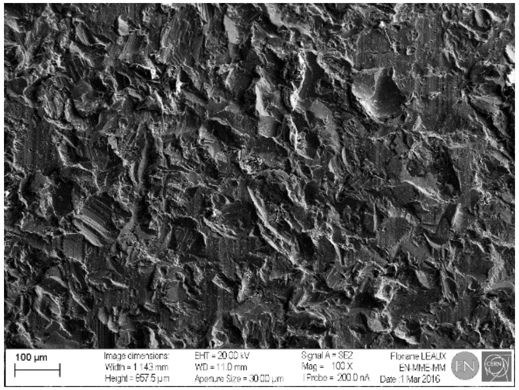
FCC-hh beam screen



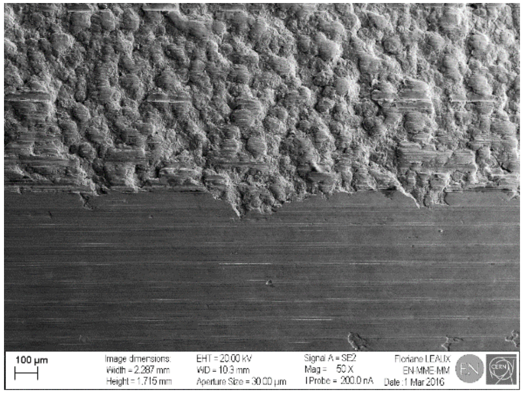
Requirements:

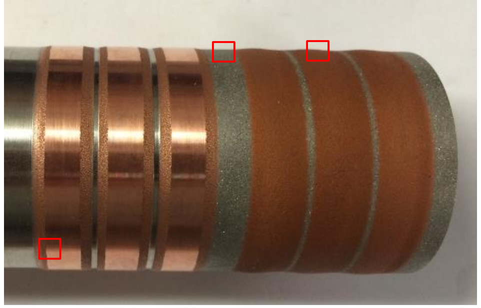
- Copper material (thermal conductivity)
- Stainless steel substrate
- Discountinuous (longitudinally → reduced Lorentz forces during a magnet quench)
- Continuous as close as possible to the cooling channel (better cooling and temperature control)
- Done after beam screen assembly (welds)
- No spray or coating contamination inside the beam screen
- Industrial process

Application to FCC beam screen

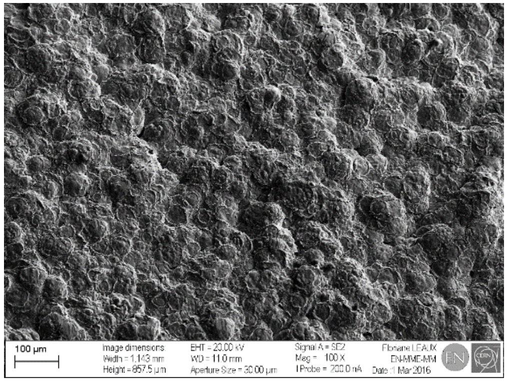


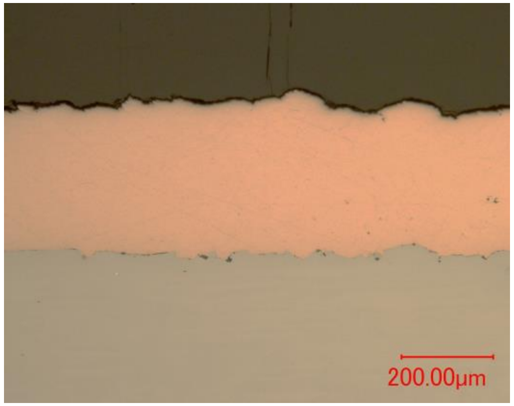
Surface preparation by blasting (Al2O3)





Cold sprayed copper on austenitic stainless steel.





Possible improvements:

- Surface preparation: laser treatment
- Nozzle geometry: correct width
- Process parameters