Study of Nozzle Clogging During Cold Spray

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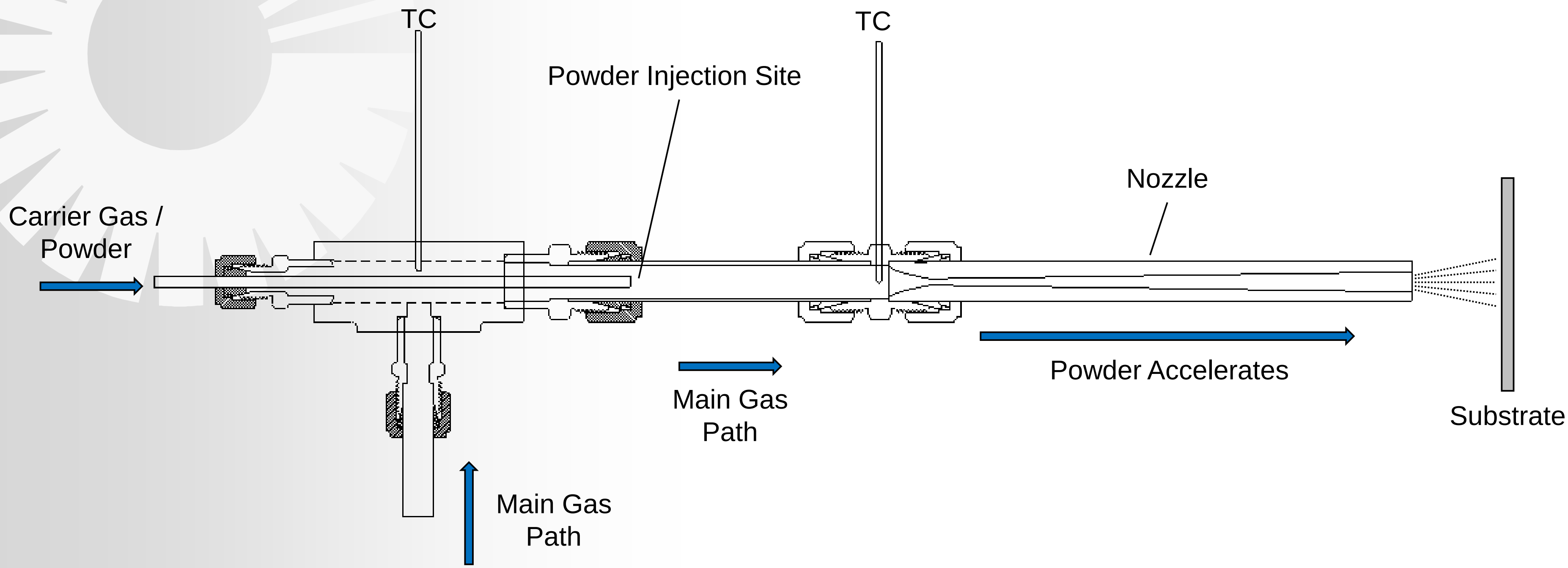
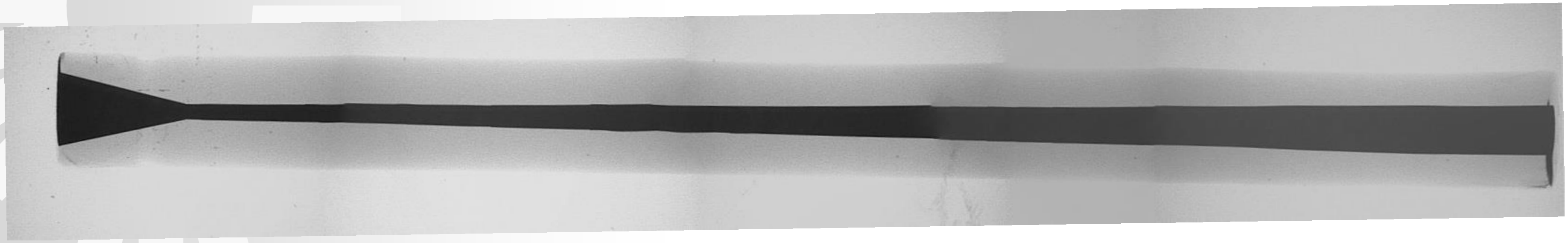
Cold Spray Overview



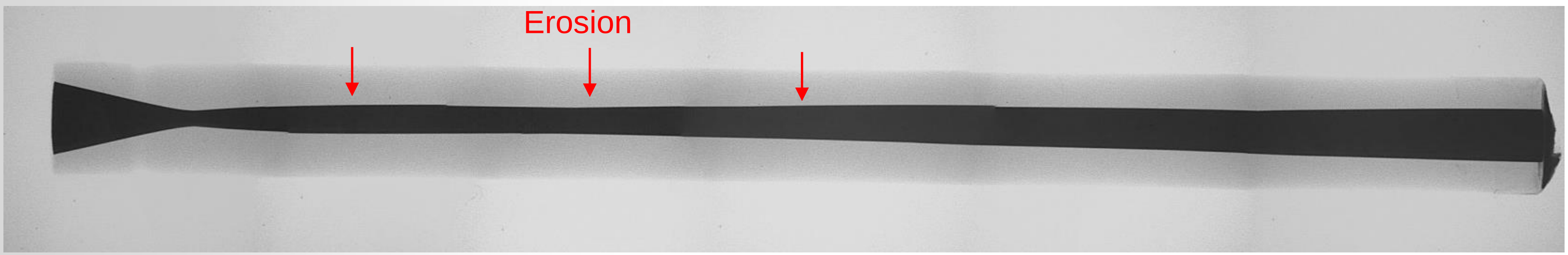
- Pressurize and heat gas (Nitrogen or Helium)
- Inject powder into main gas
- Choke the flow and expand gas (Converging – Diverging Nozzle)
- Accelerate the powder using aerodynamic drag
- Powder velocity will vary depending on the powder particle size and density

Powder Particle – Nozzle Interaction

New Nozzle

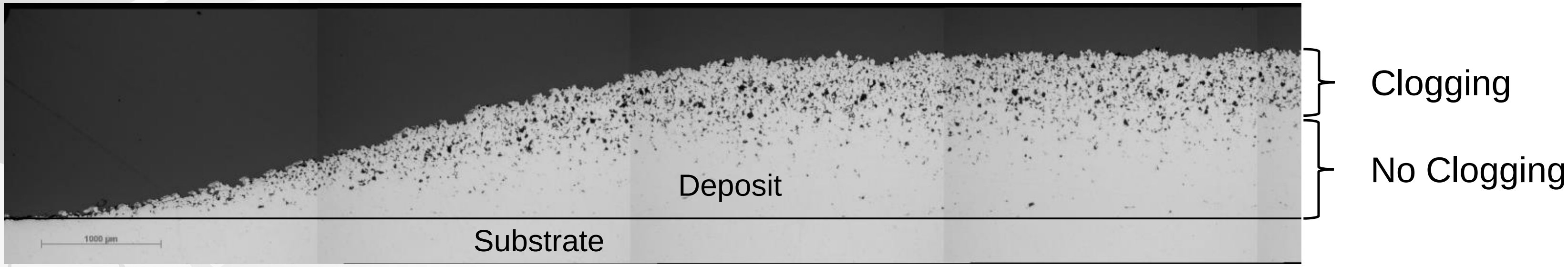


Used Nozzle

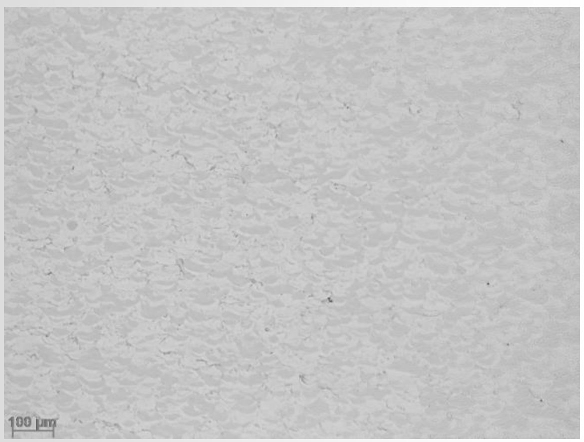


- X-ray images of a polymer nozzle prior to and after use
- Polymer nozzle with relatively hard powder particle
- Nozzle powder interact as indicated by erosion

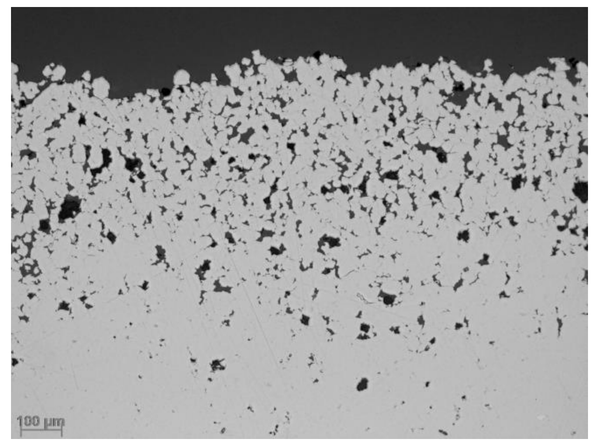
Nozzle Clogging – Deposit Porosity



No Clogging



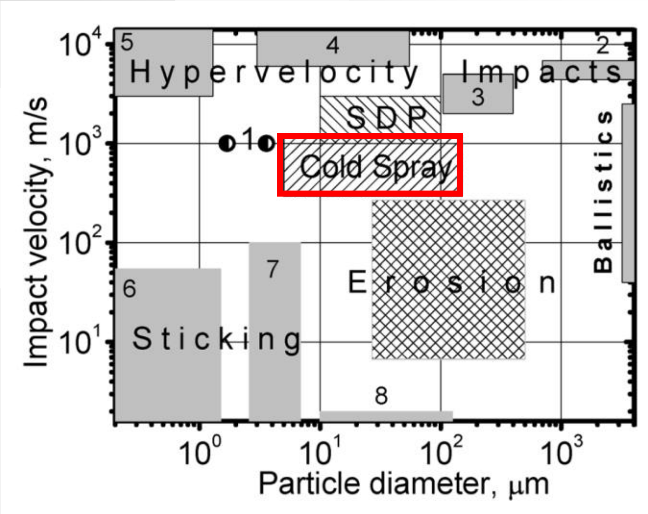
Clogging – High Porosity



- Nozzle clogging results in poor quality deposit
  - High porosity
  - Reduced material properties

Particle Impact Mechanism Map

Influence of Impact Velocity and Particle Size on Particle Impact Phenomena



S. V. Klinkov, V. F. Kosarev, M. Rein, Cold Spray Deposition: Significance of particle impact phenomena, Aerospace Science and Technology 9 (2005) 582-591.

$$V_{crit} = \sqrt{\frac{4F_1\sigma_{uts}\left(1-\frac{T_i}{T_{MP}}\right)}{\rho} + F_2C_p\left(T_{MP}-T_i\right)}$$

T. Schmidt, F. Gartner, H. Assadi, and H. Kreye, Development of a Generalized Parameter Window for Cold Spray Deposition, Acta Mater., 51 (2003) 4379-4394.

$$\text{CVR}= \frac{V_{impact}}{V_{critical}}$$

- Impact Velocity
  - Process Gas
  - Gas Pressure
  - Gas Temperature
  - Nozzle Geometry
  - Powder size
  - Powder shape

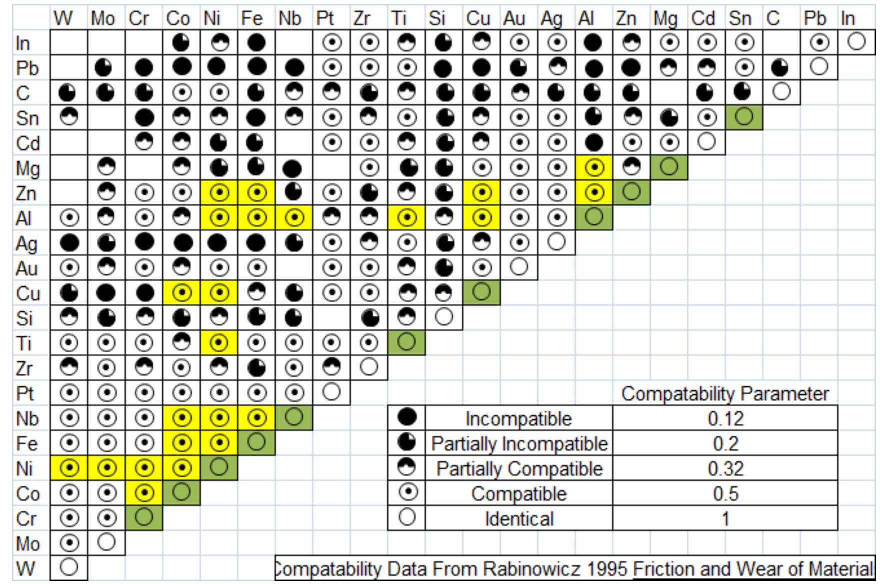
- Critical Velocity Ratio
  - >1.0
- Substrate / Solid Surface
  - Angle of Impact
  - Hardness
  - Material Compatibility
  - Temperature (Preheat)

Material Compatibility

- Adhesion in tribo-contact is when two metallic surfaces come into contact and create metallic bonds at the asperity level

$$W_{ad}=C_m(\gamma_1 + \gamma_2)$$

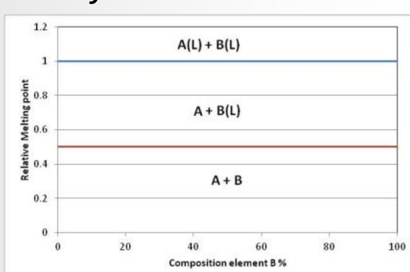
W_{ad}= Work of Adhesion
γ_1= Surface energy material 1
γ_2= Surface energy material 2
C_m= Compatibility Parameter

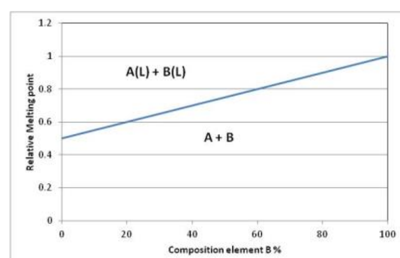


		Compatability Parameter
●	Incompatible	0.12
◕	Partially Incompatible	0.2
◓	Partially Compatible	0.32
⊙	Compatible	0.5
○	Identical	1

Compatability Data From Rabinowicz 1995 Friction and Wear of Material

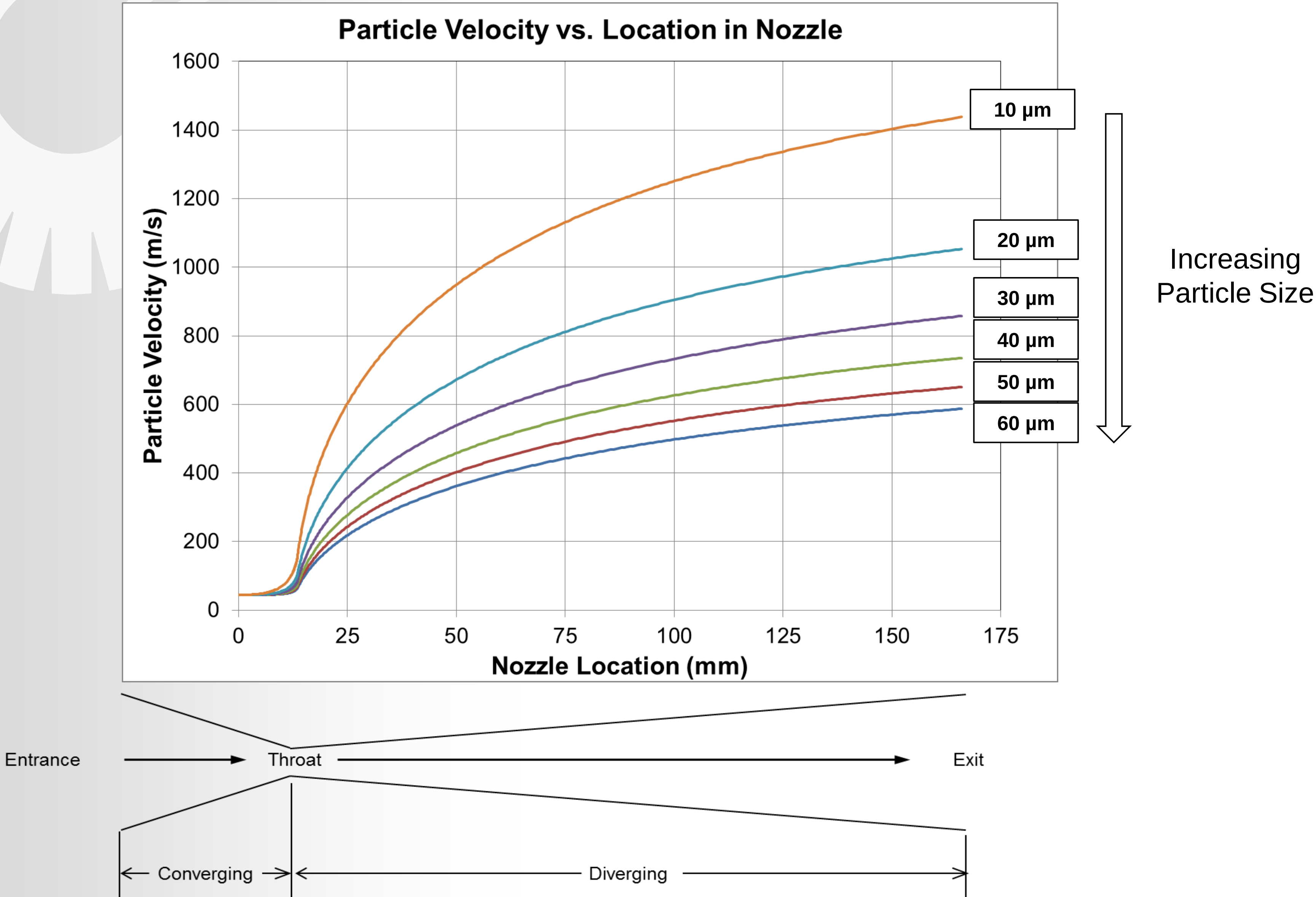
- Surface energy affected by surface condition
  - Oxides
  - Chemisorbed layers
  - Greases



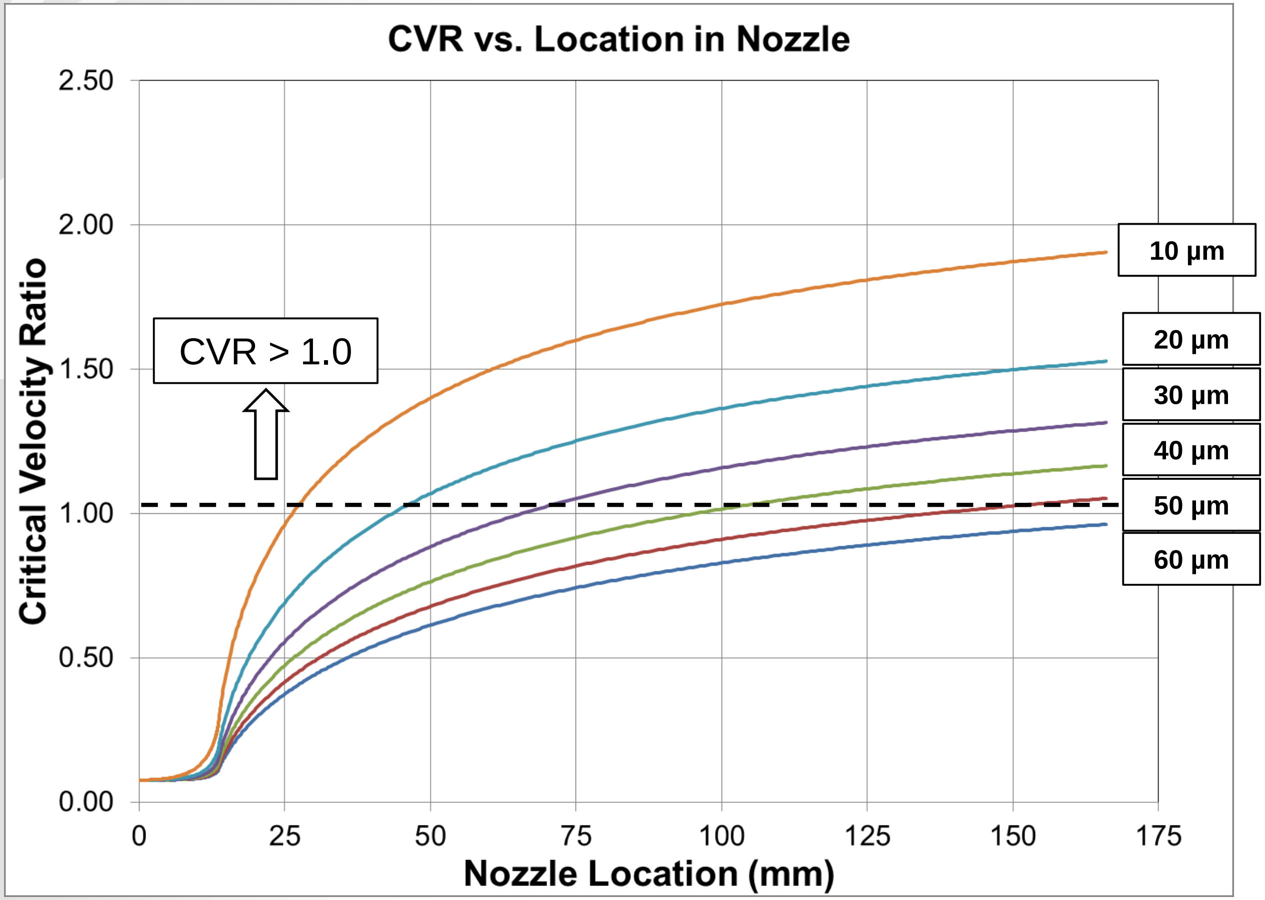


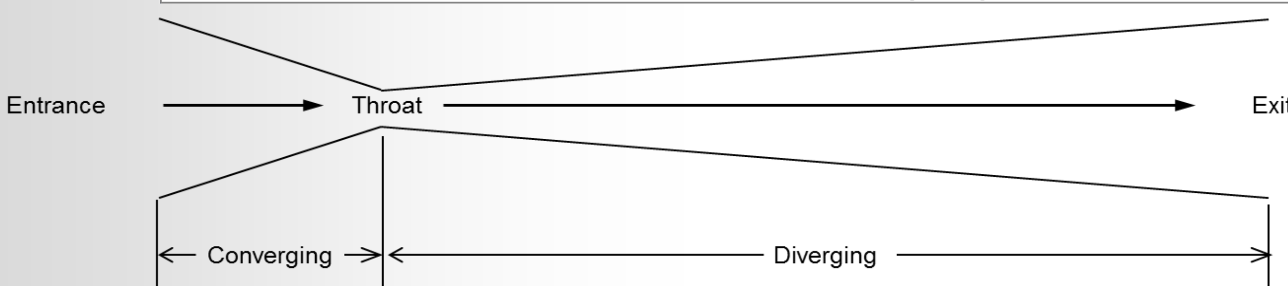
Derived from phase diagrams of pure metals

Particle Impact Velocity in Nozzle



Particle CVR in Nozzle





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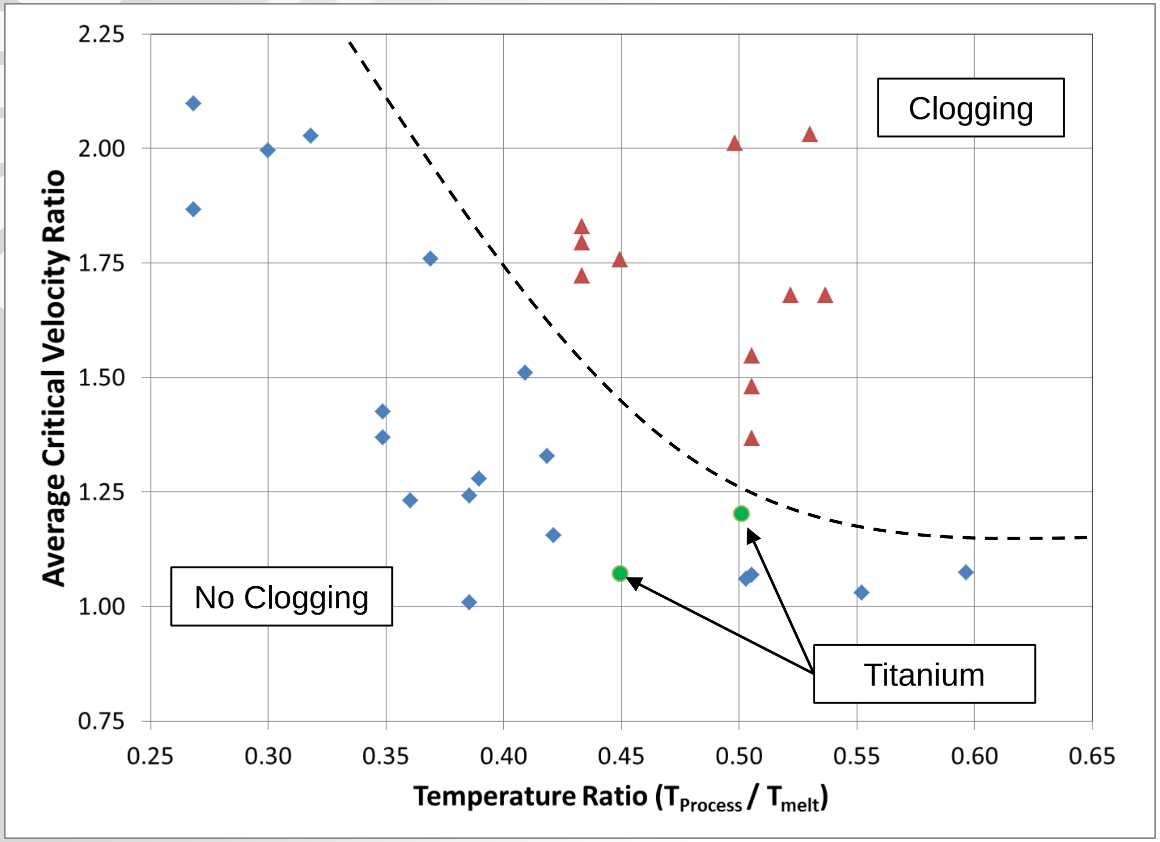
Nozzle Clogging Data



- Clogs occurred within 5 minutes of spraying
- Nozzle material
  - High hardness
  - High temperature
- Powder Materials
  - Copper & alloys
  - Nickel & alloys
  - Tantalum
  - Niobium
  - Chromium
  - Stainless Steel
  - Cobalt alloy
  - Titanium
- Titanium is an exception

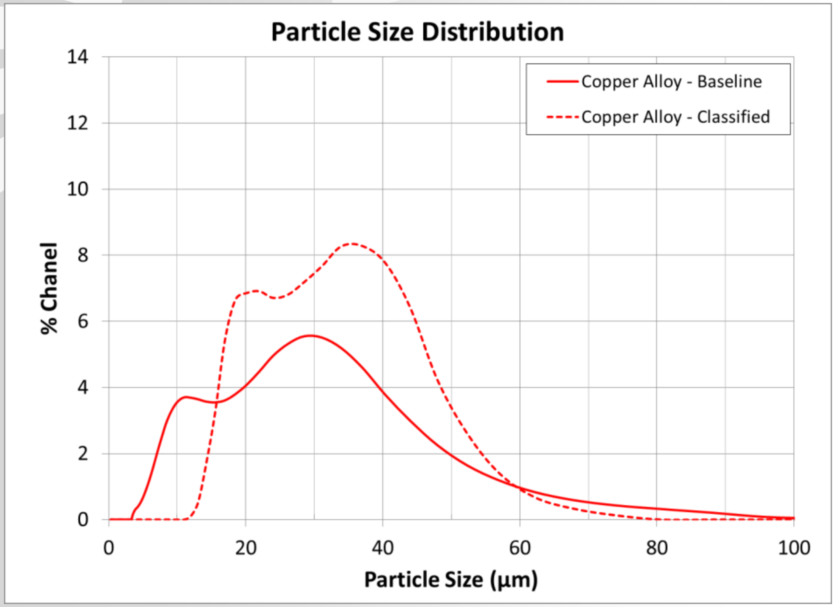
$$CVR = \frac{V_{impact}}{V_{critical}}$$

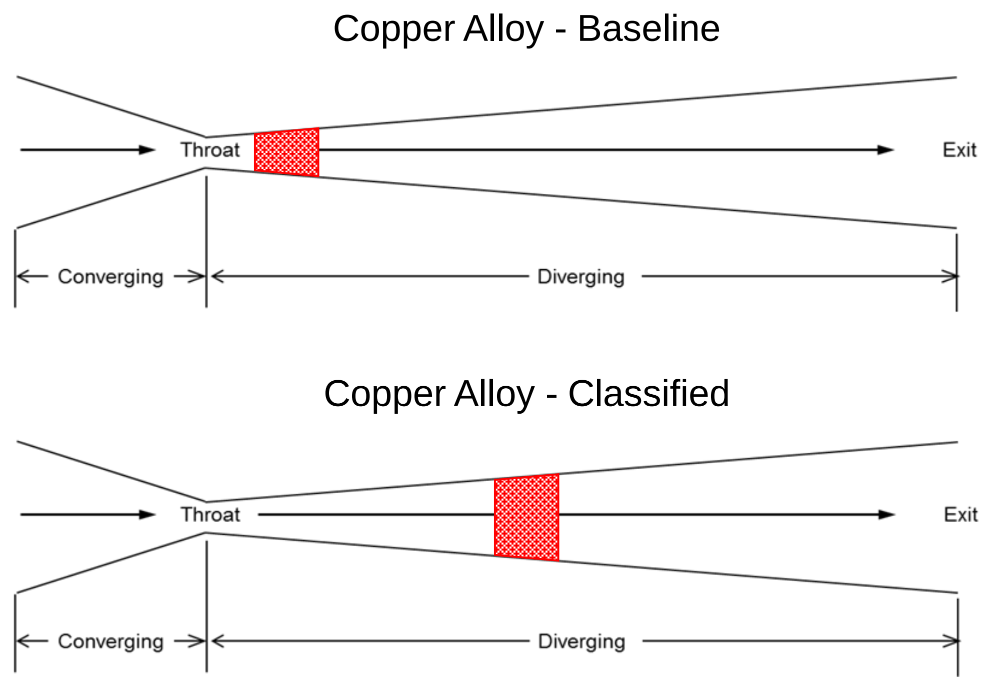
- CVR >1.0
- Averaged for particle size distribution
- CVR at nozzle exit (upper bound)

$$T_{Ratio} = \frac{T_{process}}{T_{melt}}$$

- Gas process temperature (T process)
- Powder melt temperature (T melt)
- Units are in Kelvin

Nozzle Clogging – Powder Size





- Cold sprayed copper alloy
  - Fixed spray process parameters using helium
  - Powder as received (solid line)
  - Powder classified to remove fines (dashed line)

- Powder velocity varies with location and particle size
  - Fine powders achieve higher velocities

Nozzle Clogging – Morphology & Blends

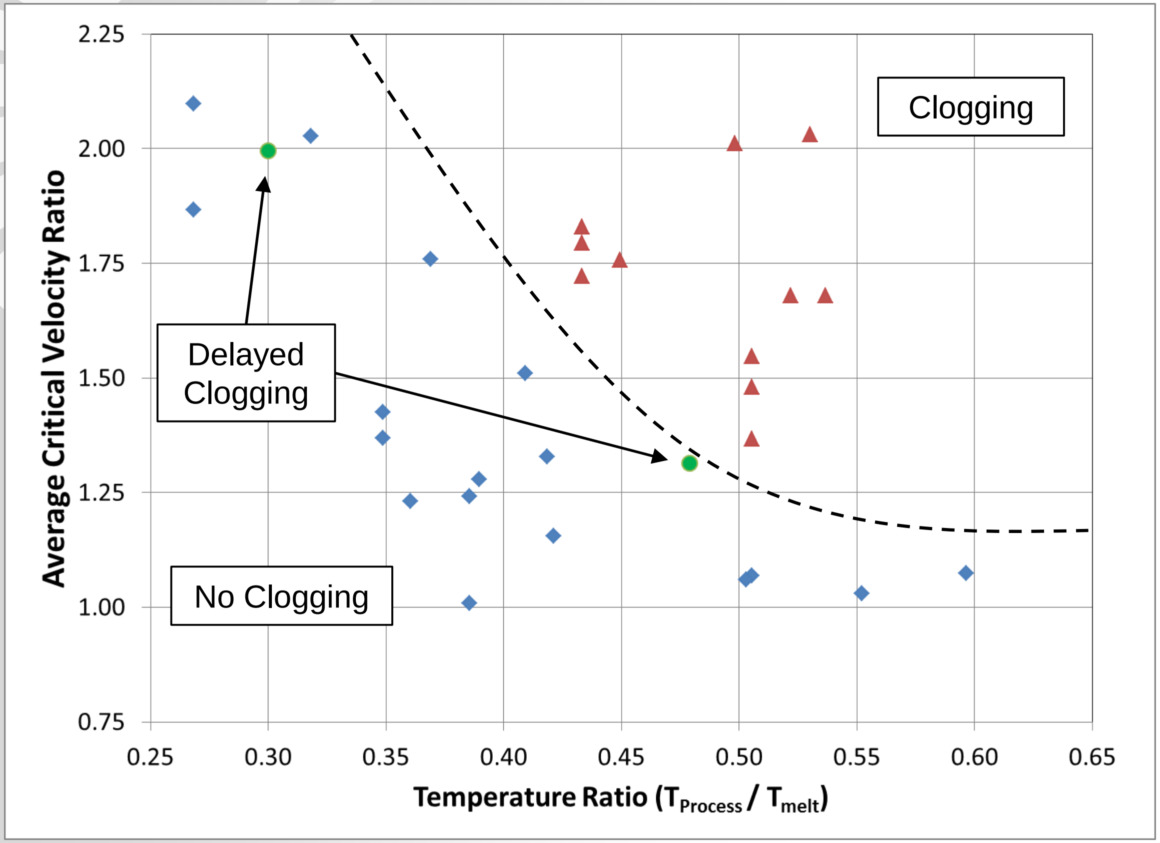
- Cold sprayed five different powders
  - Fixed spray process parameters using helium

- Powder Forms
  1) *High Purity*
     Single material
  2) *Alloyed*
     Two or more materials in solid solution
  3) *Agglomerate*
     Two high purity powders sintered together
  4) *Blended*
     Two high purity powders mixed together

Material	Form	Nozzle Clog
Cu-Ni	Alloy	Yes
Cu-Ni	Agglomerate	No
Cu-Ni	Blend	No
Ni	High Purity	Yes
Ni + Hard phase	Blend	No

Nozzle clogging can be managed through blends

Nozzle Clogging – Extended Use



- Nozzle clogging can occur during extended use
  - 15 - 60 minutes
- Working Theory:
  - Compatibility of powder particle and nozzle material
  - Time at temperature changes surface chemistry
  - Compatibility can be evaluated by through wettability
  - Nozzle cooling would delay / slow this process

Nozzle Clogging – Wettability

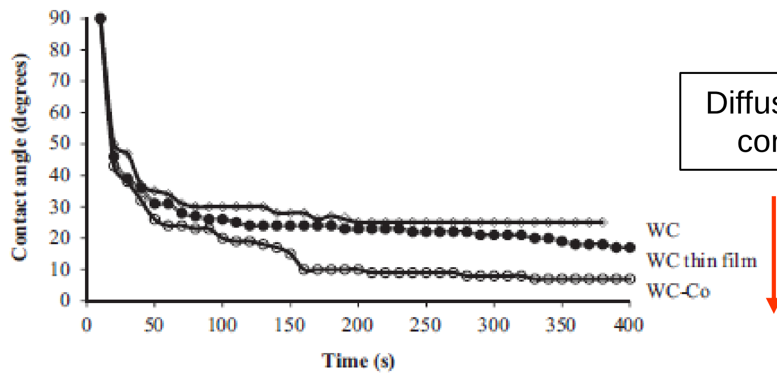
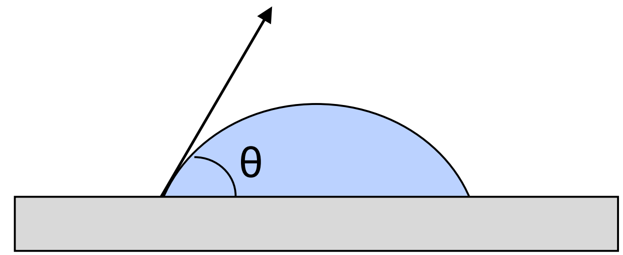


Fig. 5. Contact angle vs. time of Cu melted on the WC based surfaces at 1080 °C.

Diffusion changes contact angle

V.L. Silva, C.M. Fernades, A.M.R. Senos Copper Wettability on Tungsten Carbide Surfaces, Ceramics International 42 (2016) 1191-1196.

Wetting Contact Angle



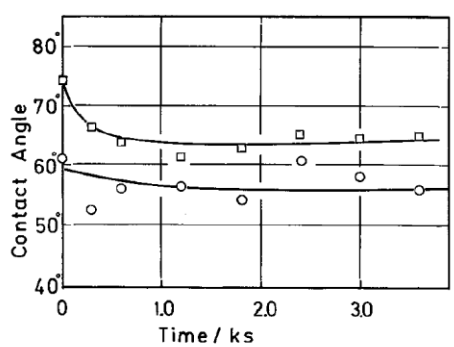


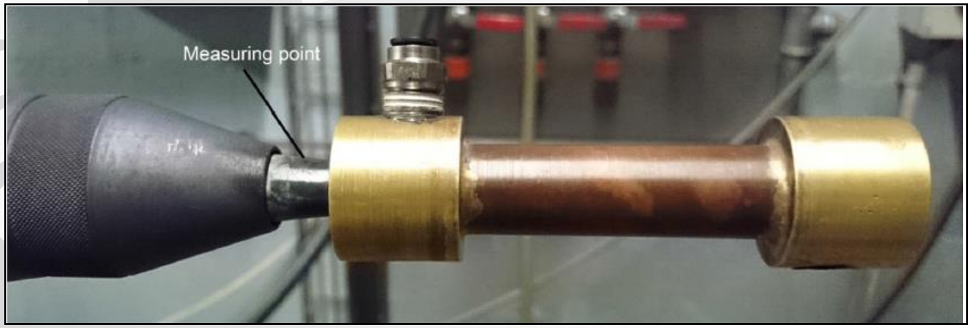
Fig. 9 Time dependence of contact angle of liquid pure Co on SiC at 1803 K. ○ : Reaction-bonded SiC, □ : Hot-pressed SiC.

K. Nogi, K. Ogino, Wettability of SiC by Liquid Pure Metals, Transactions of the Japan Institute of Metals 29 (1988) 742-747.

- Delayed nozzle clogged
  - Copper alloy with WC-Co Nozzle
  - Cobalt alloy with SiC Nozzle
- Trace amounts of material left on nozzle ID
- Time at temperature can cause diffusion of elements
- Effective “sintering” can occur resulting in an initiation site for clogging to occur

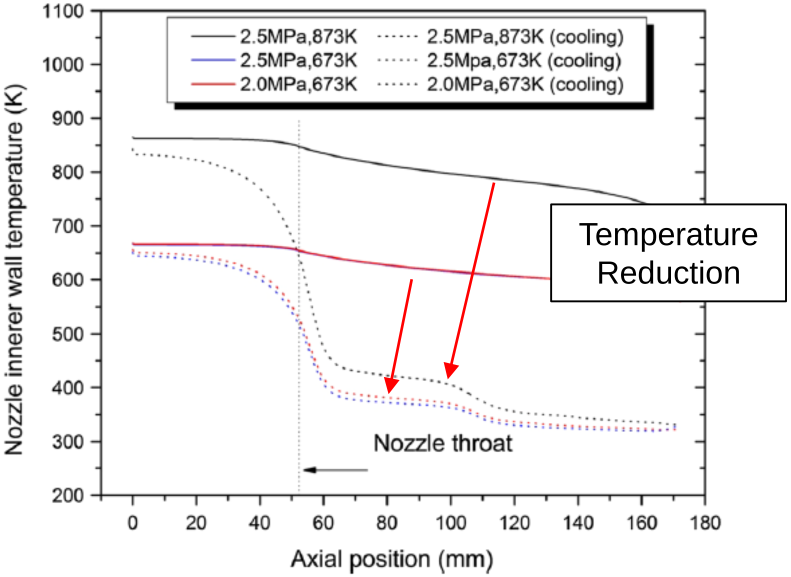
Nozzle Cooling

Nozzle Cooling Device



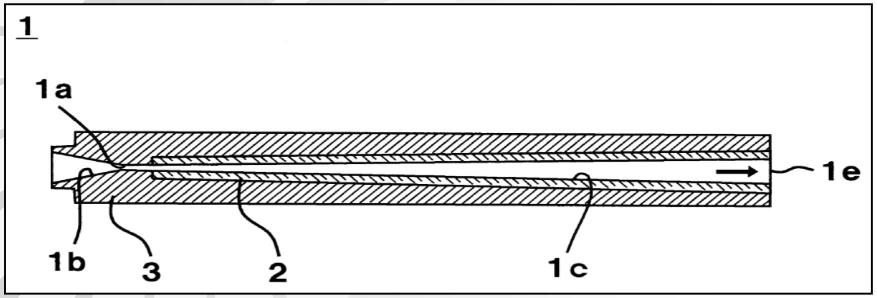
X. Wang, B. Zhang, J. Lv, S. Yin Investigation on the Clogging Behavior and Additional Wall Cooling for the Axial-Injection Cold Spray Nozzle, Journal of Thermal Spray Technology 24 (2015) 697-701.

Nozzle Wall Temperature



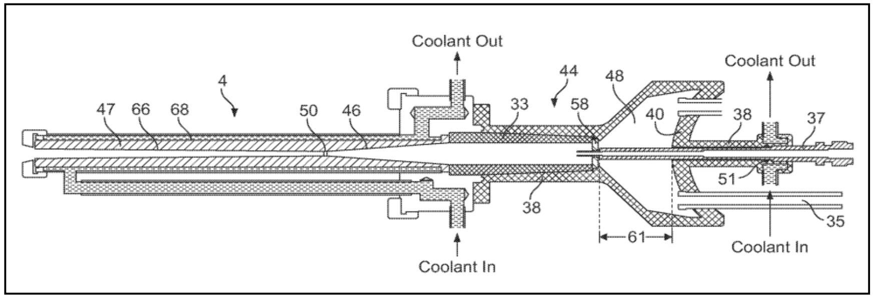
- Sleeve type nozzle cooling device
    - Cooling Fluid: Water
- Lowers nozzle wall temperature
- Observed delayed nozzle clogging when using

Nozzle Clogging – Patents



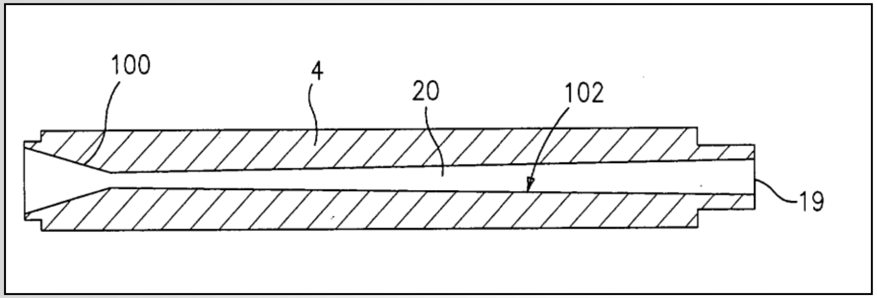
Patent: US20130327856 A1
Nozzle for cold spray allowing for greatly improved long-term sustained usage over the prior art, without the occurrence of nozzle clogging.

Glass: Quartz or Borosilicate



Patent: US20130087633 A1
An improved cold spray gun apparatus and system, which prevents nozzle clogging and erosion of the nozzle material.

Biphenyl tetracarboxilic dianhydride (BPDA), low expansion glass, or silicon nitride.



Patent: US 20040191449 A1
Clogging of the passageway in the supersonic nozzle (4) is prevented by forming at least the diverging section (102) from polybenzimidazole.

Polybenzimidazole (PBI)

Thanks!

Any Questions?