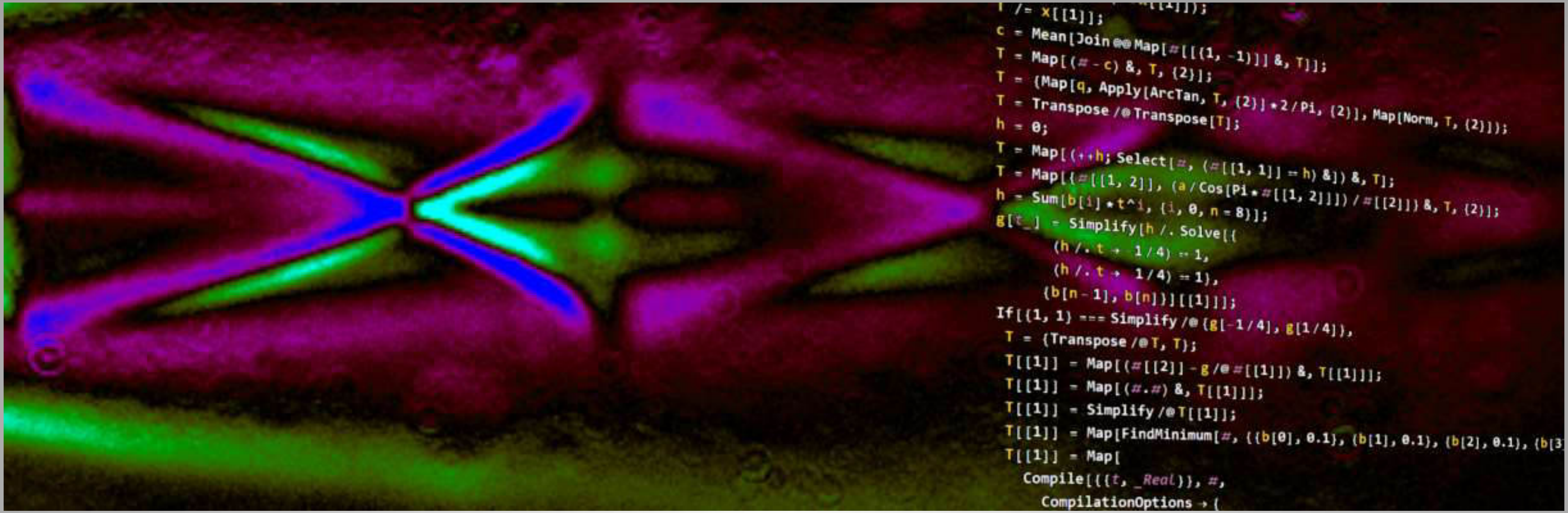


Qualification requirements to process monitoring for industrial cold spray

To watch the videos originally shown in this presentation please visit www.volinesystems.com

Oliver Stier & Aline Creuz

Cold Club Spray | VOLINE >< systems

Outline

Process key characteristics: Figures of merit for quality of deposited material
1. Particle velocities – η

Factors influencing partice velocities

Indirect monitoring of particle velocities constancy

Schlieren monitoring of nozzle performance

Process key characteristics:
2. Impact angle

Monitoring particle impact by spray spot imaging
Deposition intensity

Comparison of monitoring methods

Recommendations

Process key characteristics

Strength and particle velocity

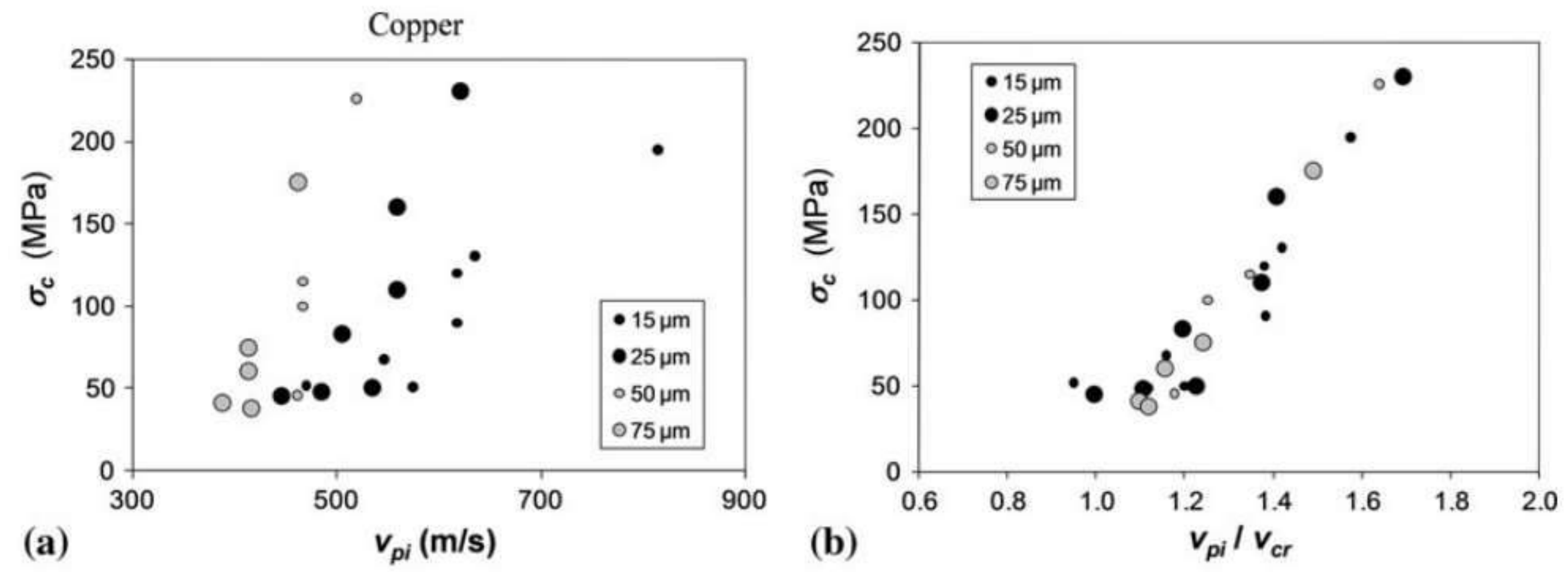


Fig. 8 Measured values of the cohesive strength of cold-sprayed copper coatings, as plotted against (a) particle impact velocity, and (b) the ratio of particle impact velocity to critical velocity

JTTEE5 20:1161–1176
DOI: 10.1007/s11666-011-9662-9
1059-9630/$19.00 © ASM International

On Parameter Selection in Cold Spraying

H. Assadi, T. Schmidt, H. Richter, J.-O. Kliemann, K. Binder, F. Gärtner, T. Klassen, and H. Kreye

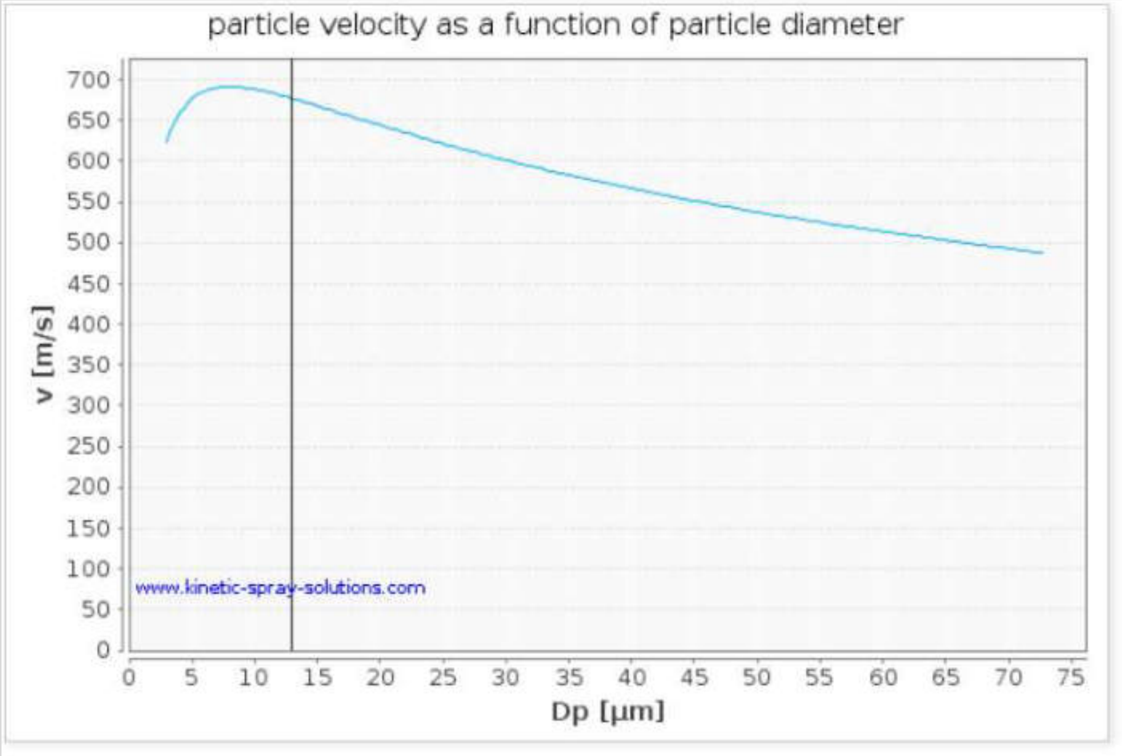
(Submitted December 30, 2010; in revised form April 19, 2011)

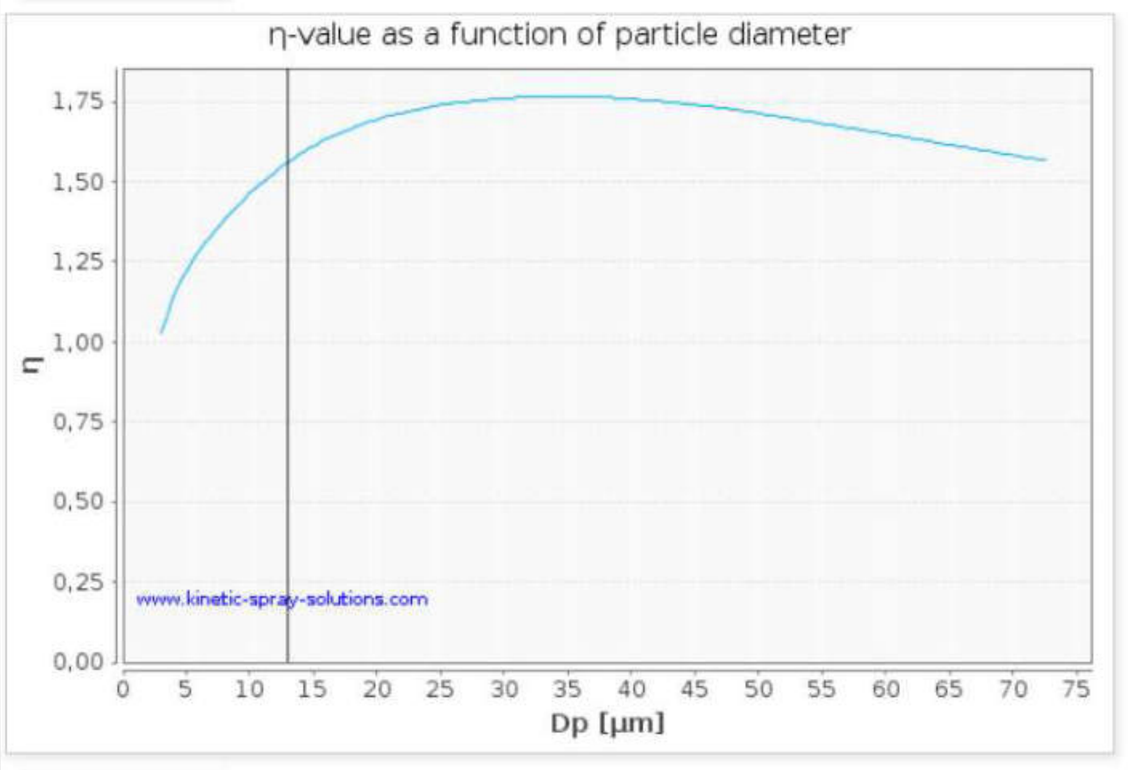
Process key characteristics

Critical velocity

Process key characteristics

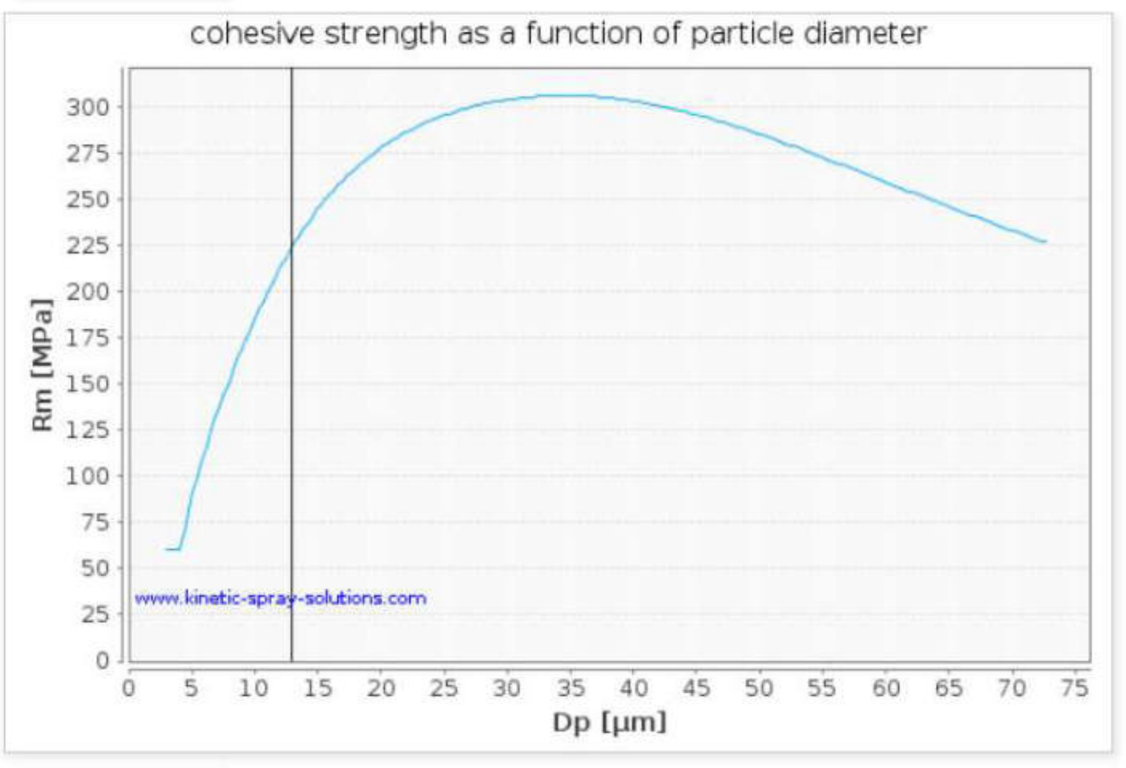
Eta ratio

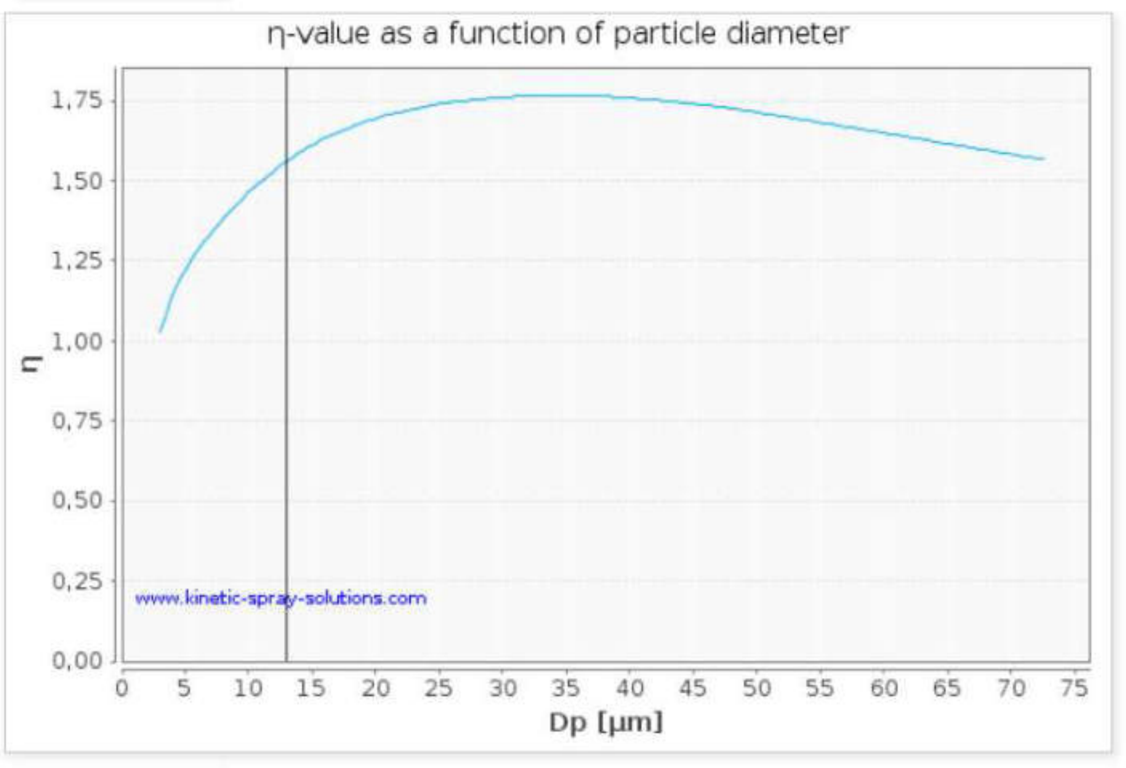




Strength prediction

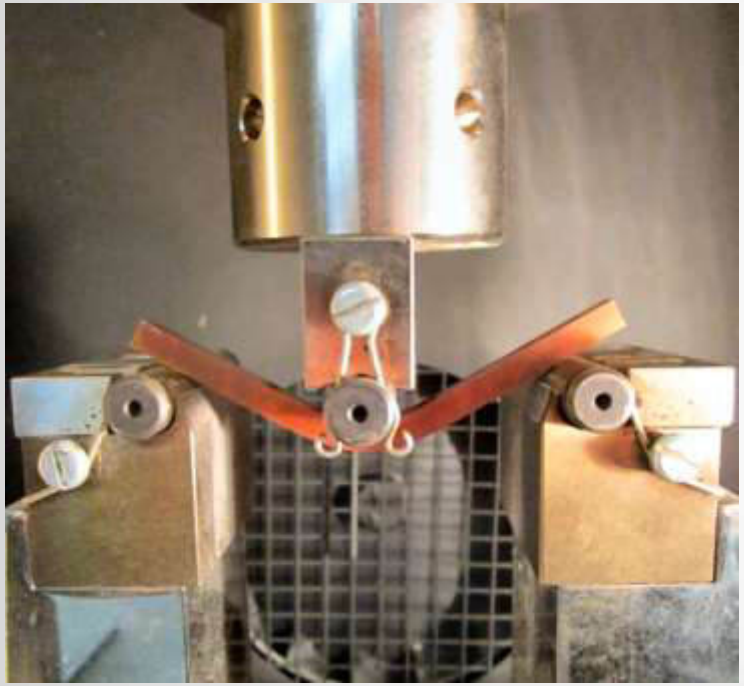
Process key characteristics





Process key characteristics

Material quality



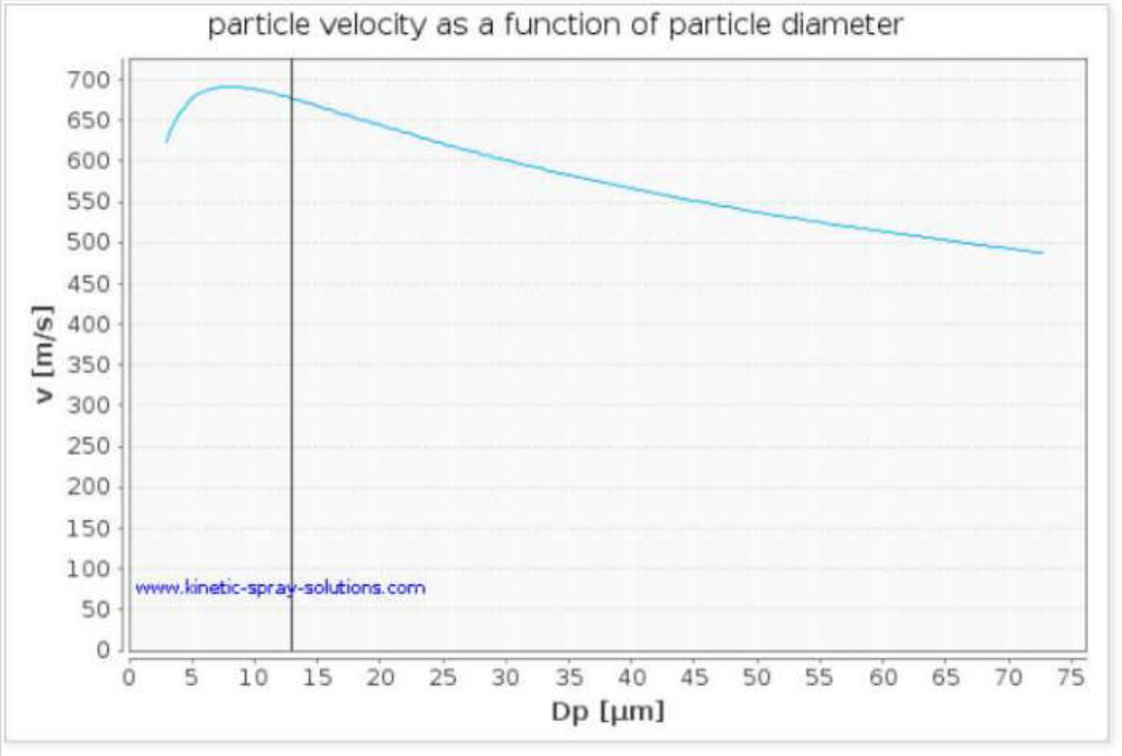
	(MS/m)
1	56,30
2	56,16
3	56,29
4	56,42
5	56,43
6	56,29
7	56,40
8	56,44
9	56,43

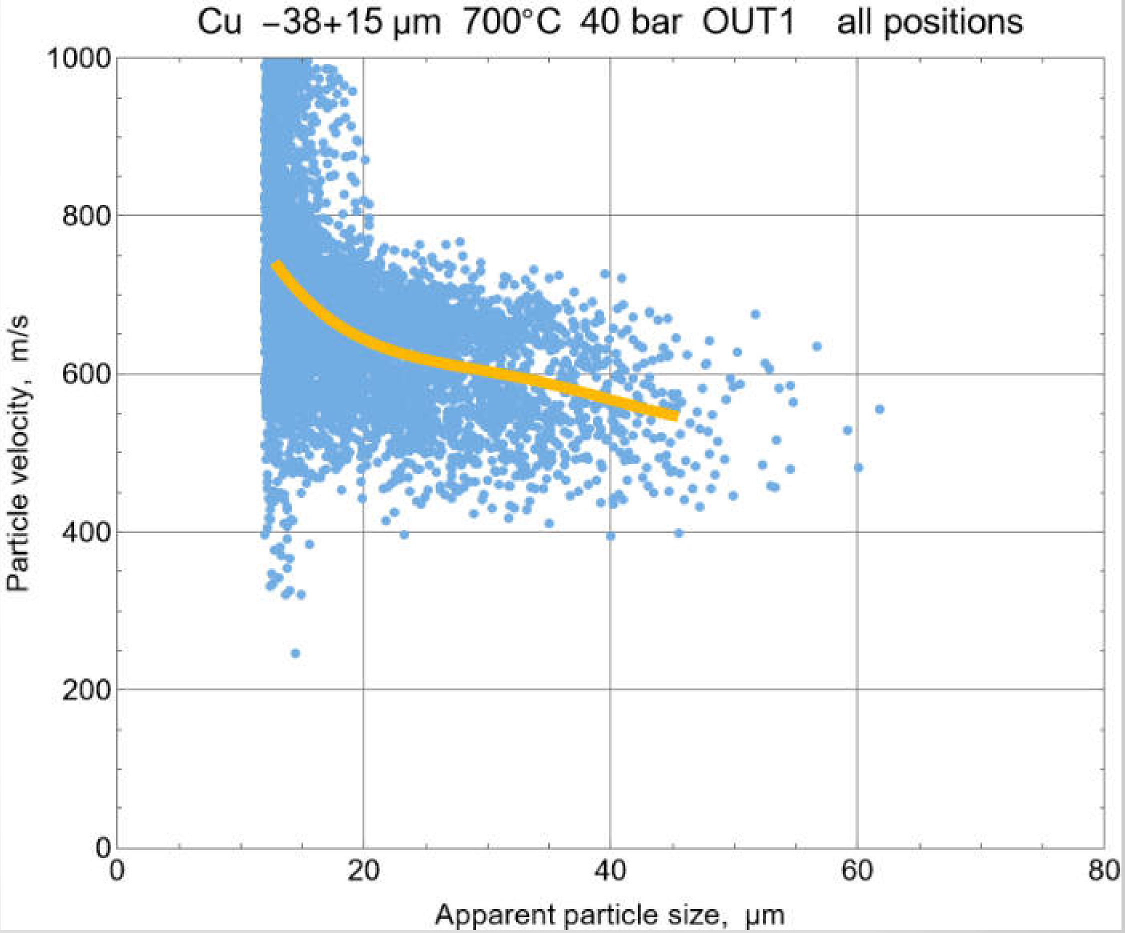
Particle acceleration

Particle velocity calculation vs. measurement

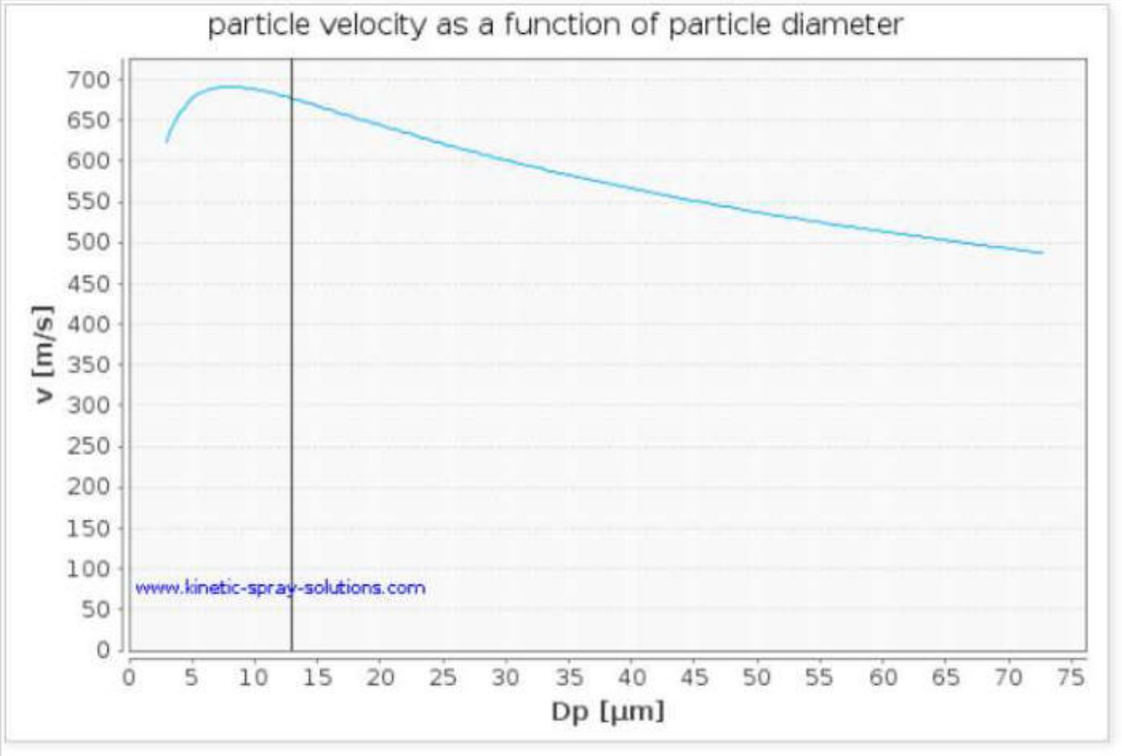
VOLINE systems

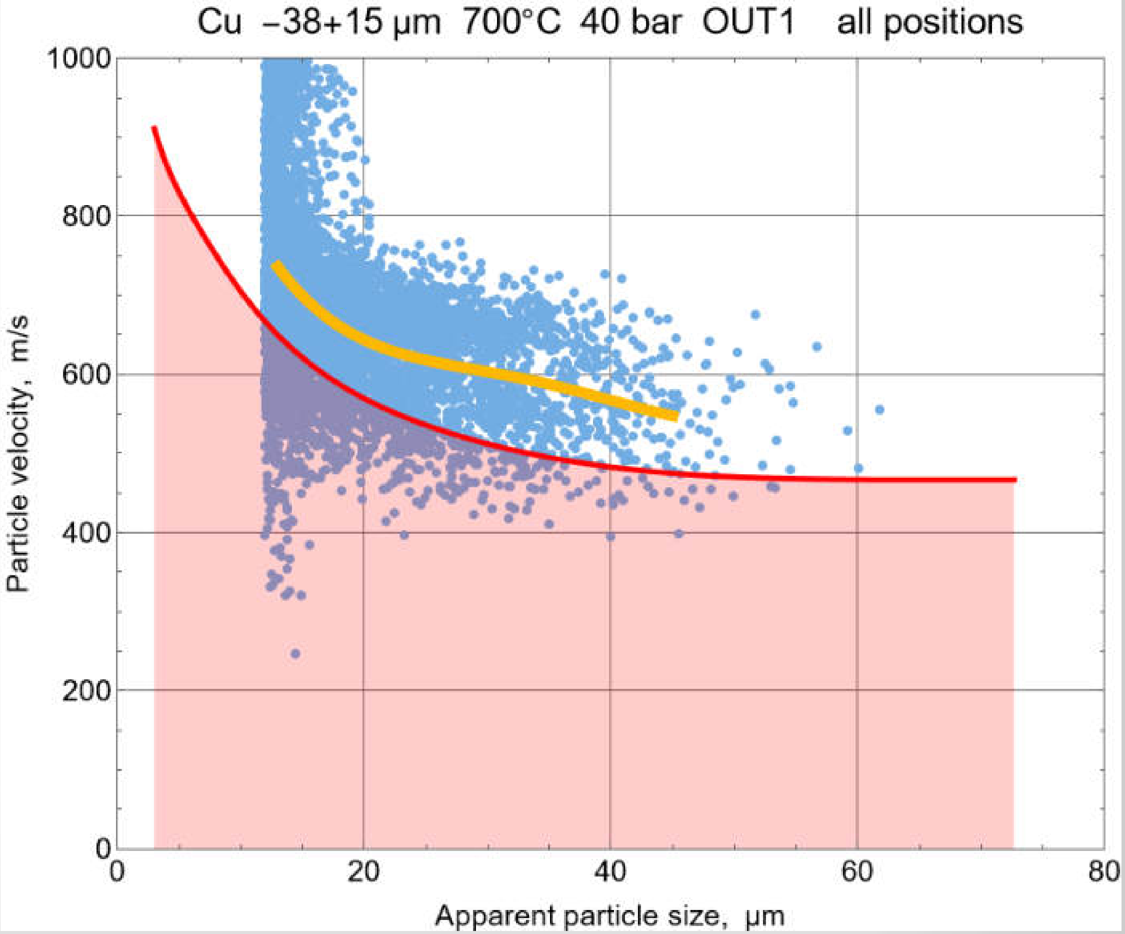
Single particle properties statistically distributed with large scatter





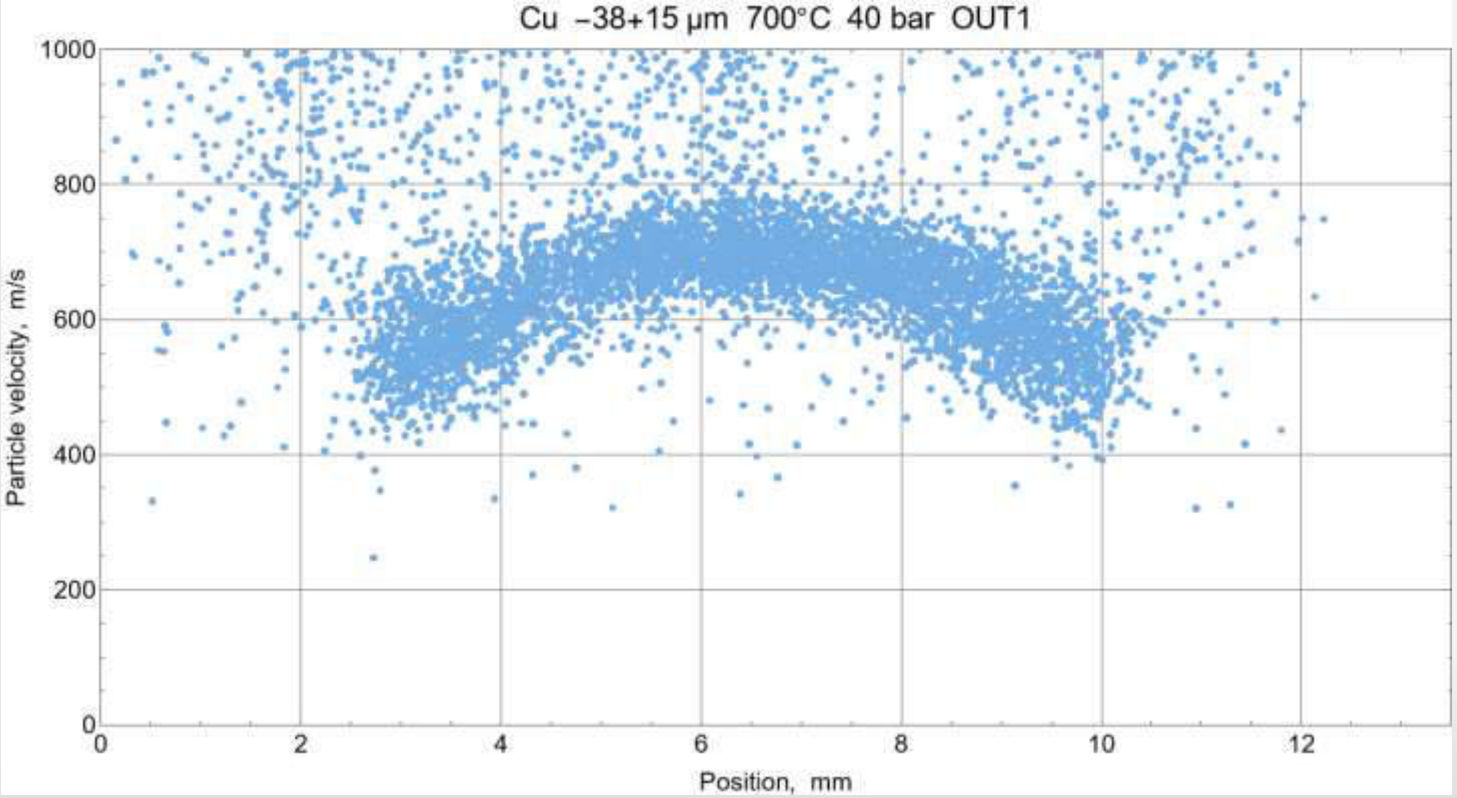
Acceptance range of particle velocities





Position dependence of particle velocities

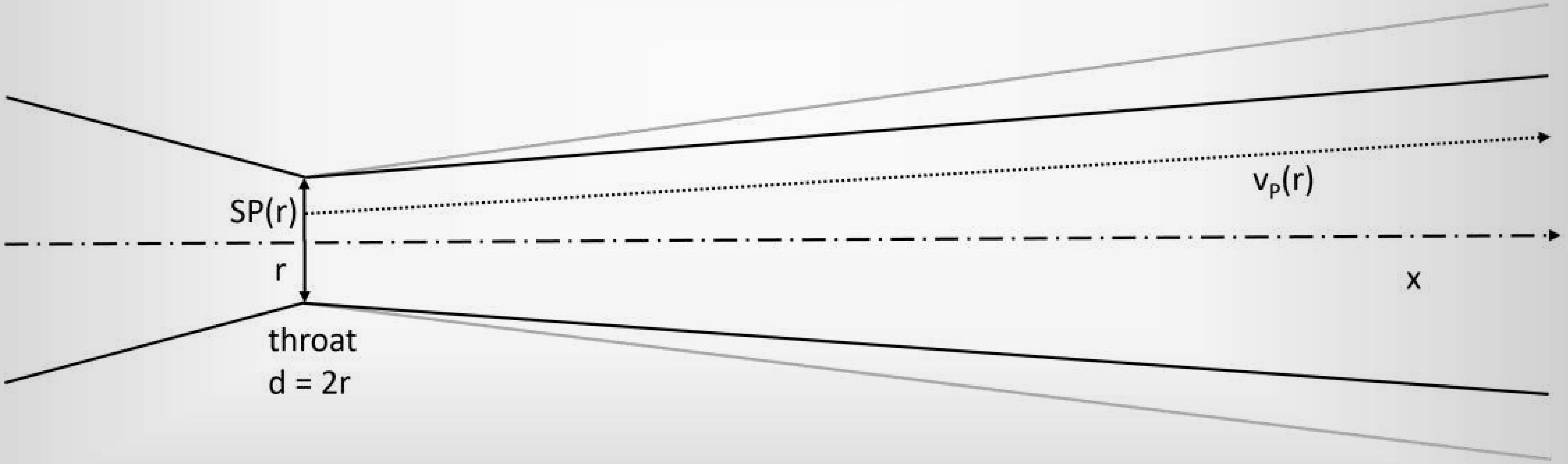
When we measure particle velocities, we have to pay attention where in the jet they are measured.



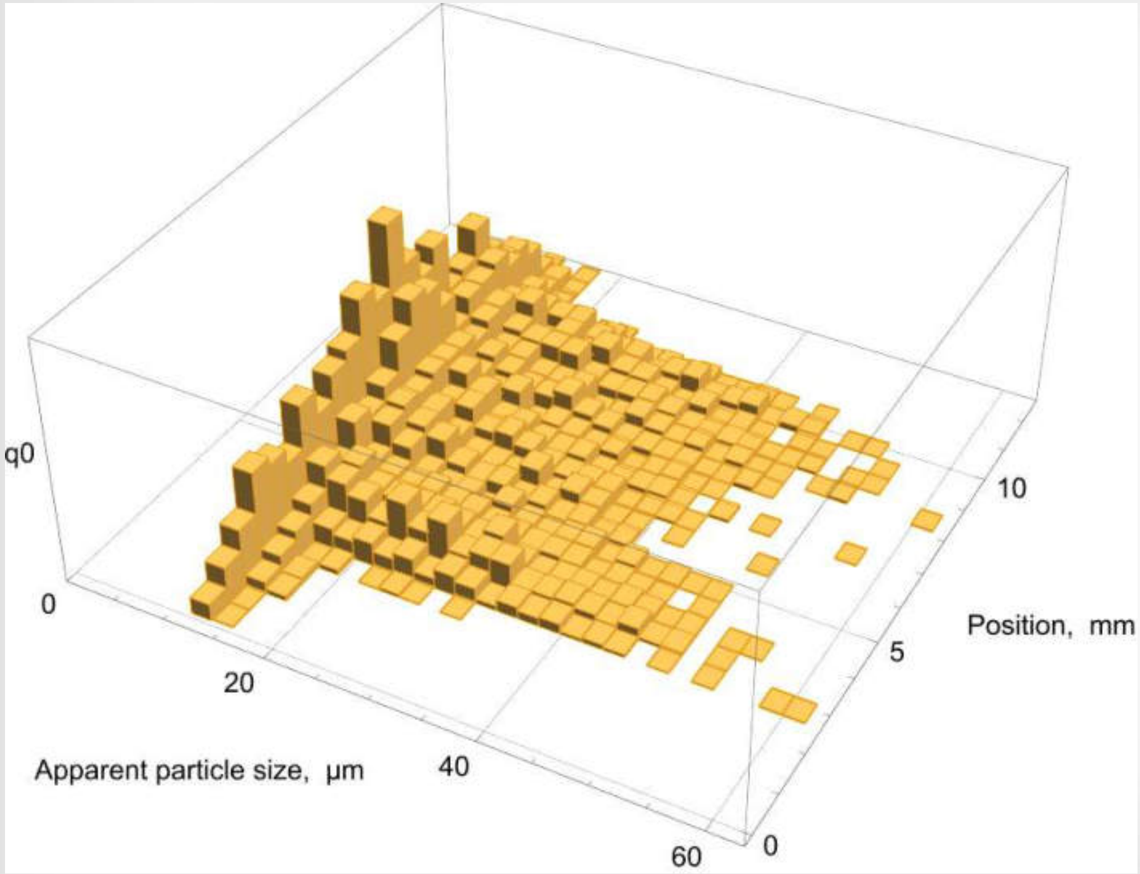
Particle acceleration

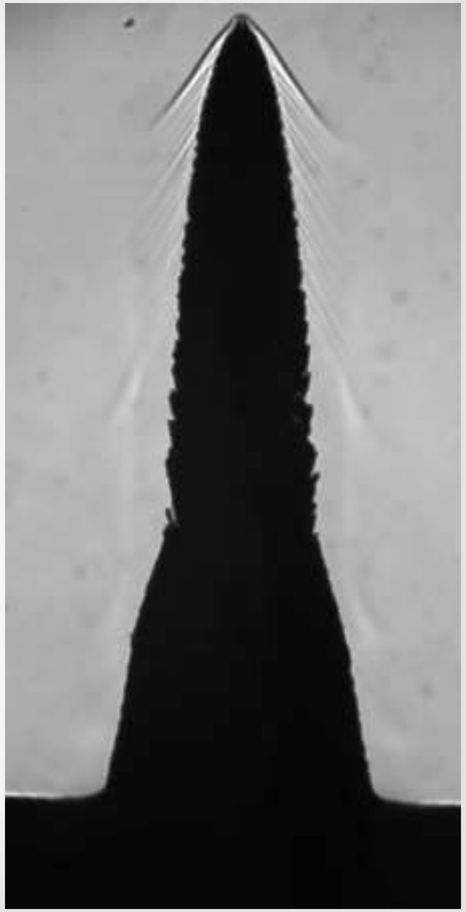
Factors influencing particle velocity: Injection

The particle trajectories depend on the injection in the stagnation chamber.

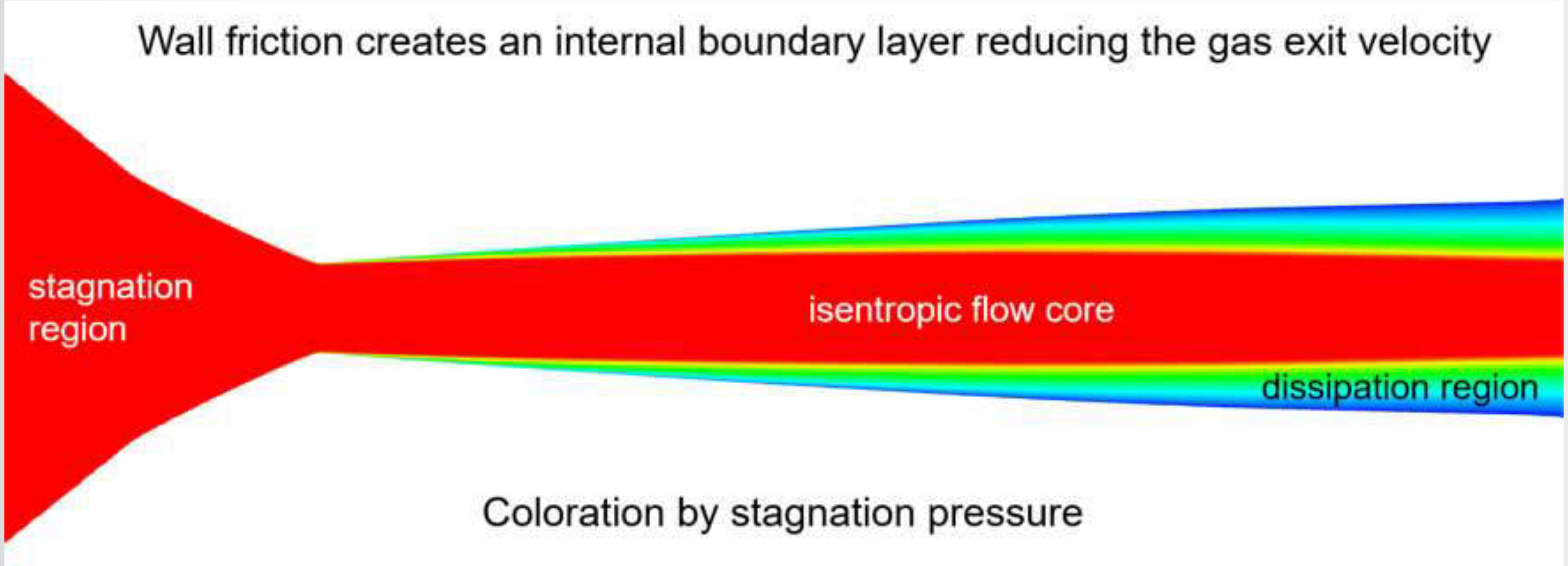


Resulting particle distribution



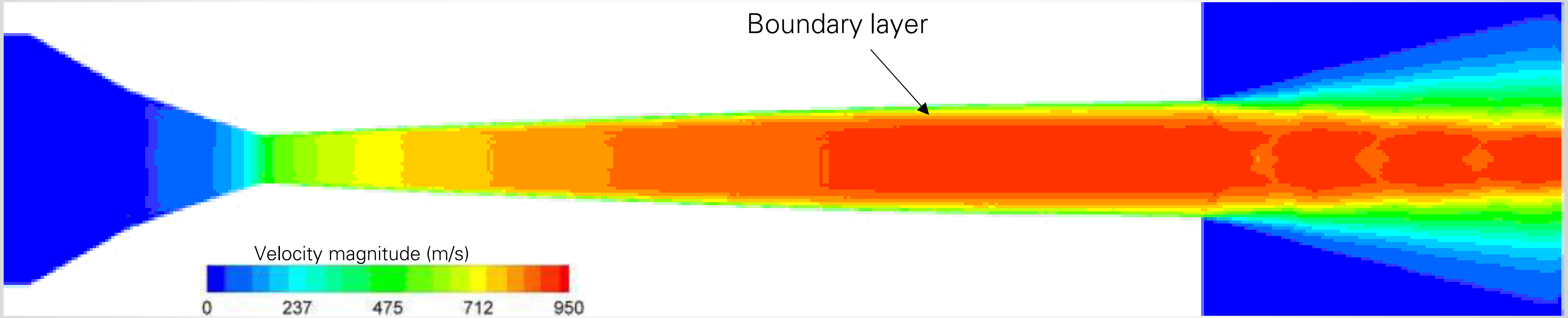


Factors influencing particle velocity: Internal boundary layer



O. Stier, A. Graichen, X.-H. Li. Cost Analysis of Cold Sprayed MCrAlY Coatings for Industrial Power Generation Gas Turbine Blades. NACSC 2011

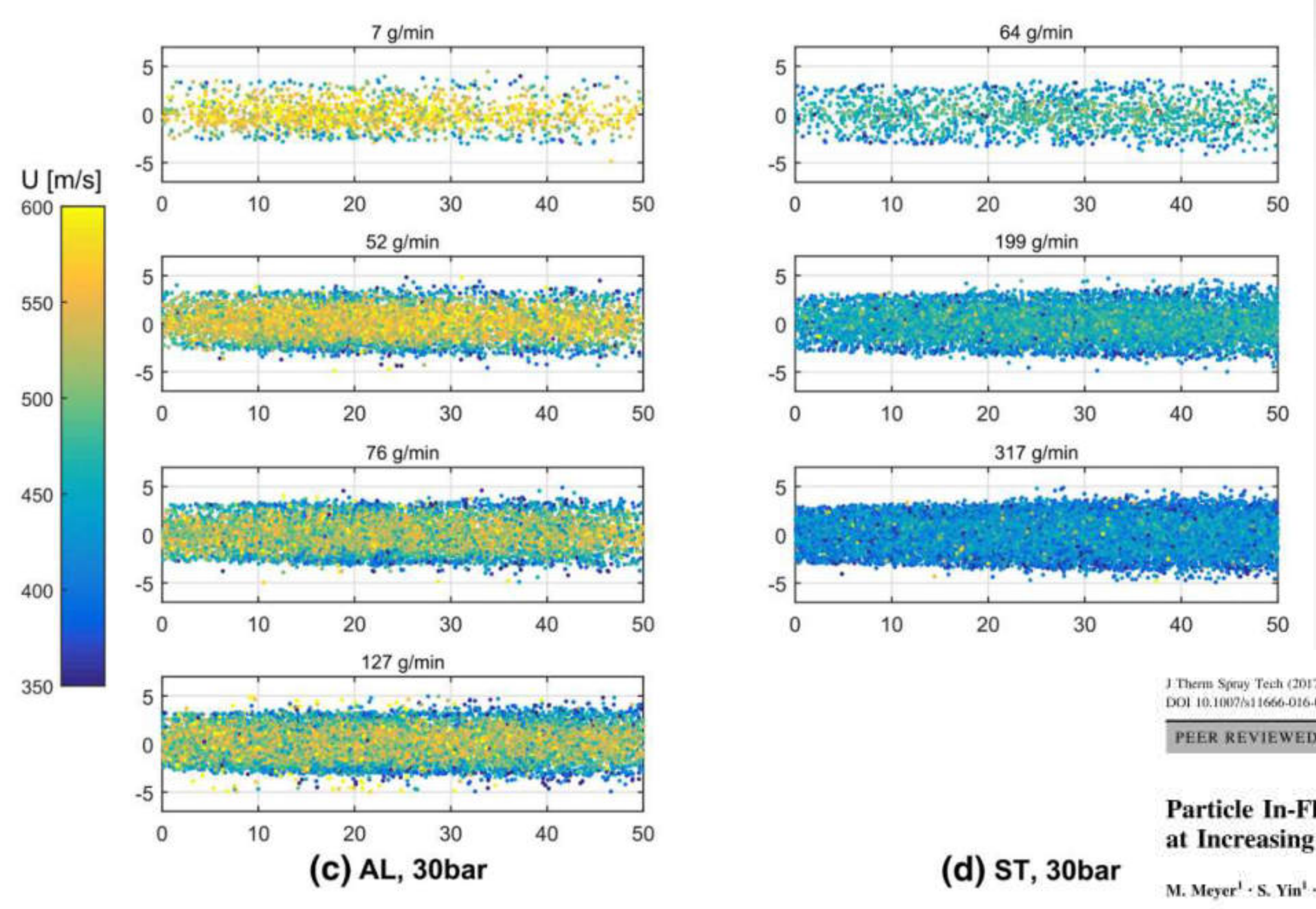
Factors influencing particle velocity: Internal boundary layer



B. Samareh, O. Stier, V. Lüthen, A. Dolatabadi. Assessment of CFD Modeling via Flow Visualization in Cold Spray Process. JTST, 18:934-943. 2009

Resulting particle velocity profiles

Particle acceleration



Mass loading factor

w = powder flow / gas flow

J Therm Spray Tech (2017) 26:60–70
DOI 10.1007/s11666-016-0496-3

CrossMark

PEER REVIEWED

Particle In-Flight Velocity and Dispersion Measurements at Increasing Particle Feed Rates in Cold Spray

M. Meyer[1] · S. Yin[1] · R. Lupoi[1]

Factors influencing particle velocity

Particle acceleration

$$m_p \frac{dV_p}{dt} = c_D \rho_g (V_g - V_p)(|V_g - V_p|) \frac{A_p}{2}$$

P, T are controlled by the CS system

M results from the nozzle contour

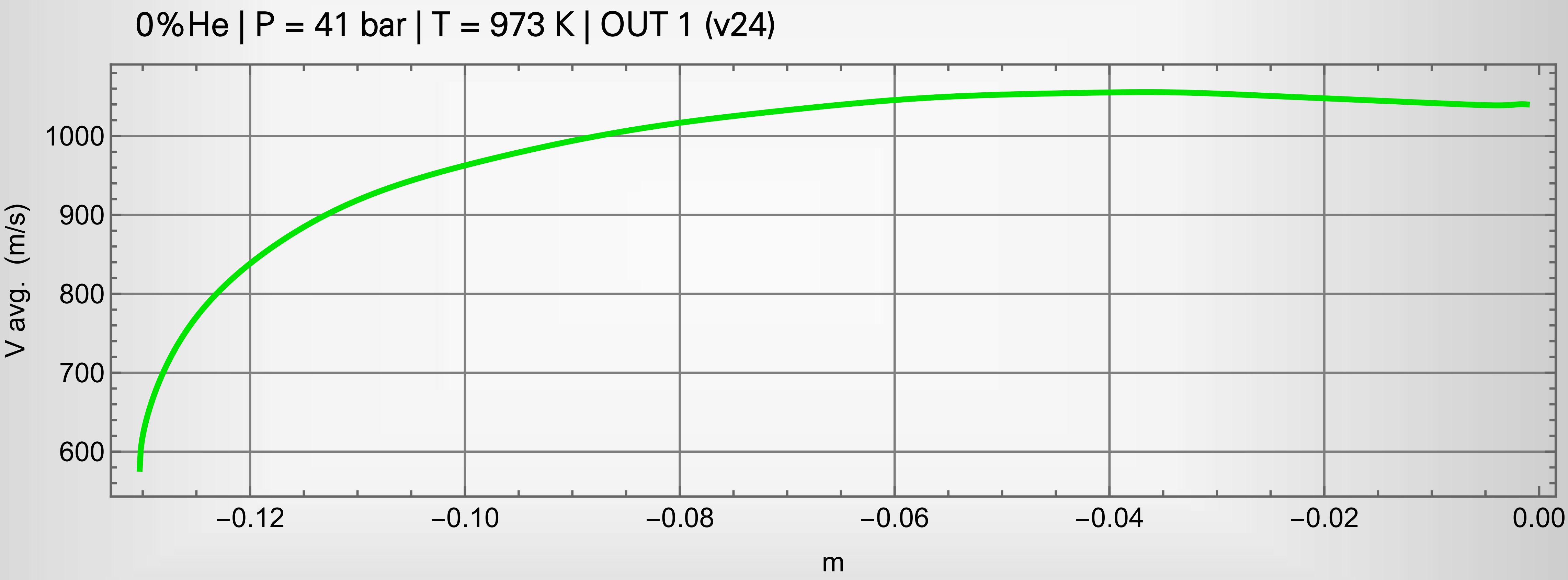
A_p, m_p, c_D are powder properties

$$V_g = M \sqrt{\gamma R T \Big/ \left(1 + \frac{\gamma - 1}{2} M^2\right)}$$

$$\rho_g = \frac{P}{RT} \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/(1-\gamma)}$$

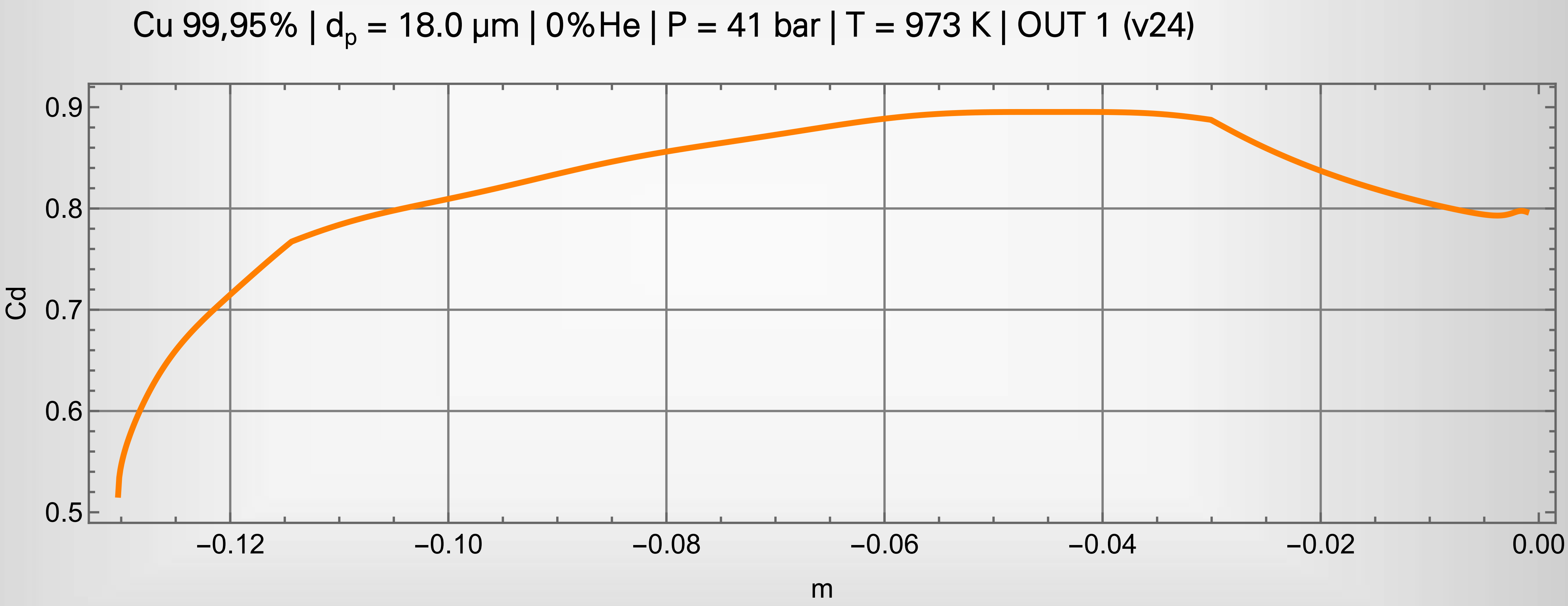
Particle acceleration

Factors influencing particle velocity: Gas speed is the driver



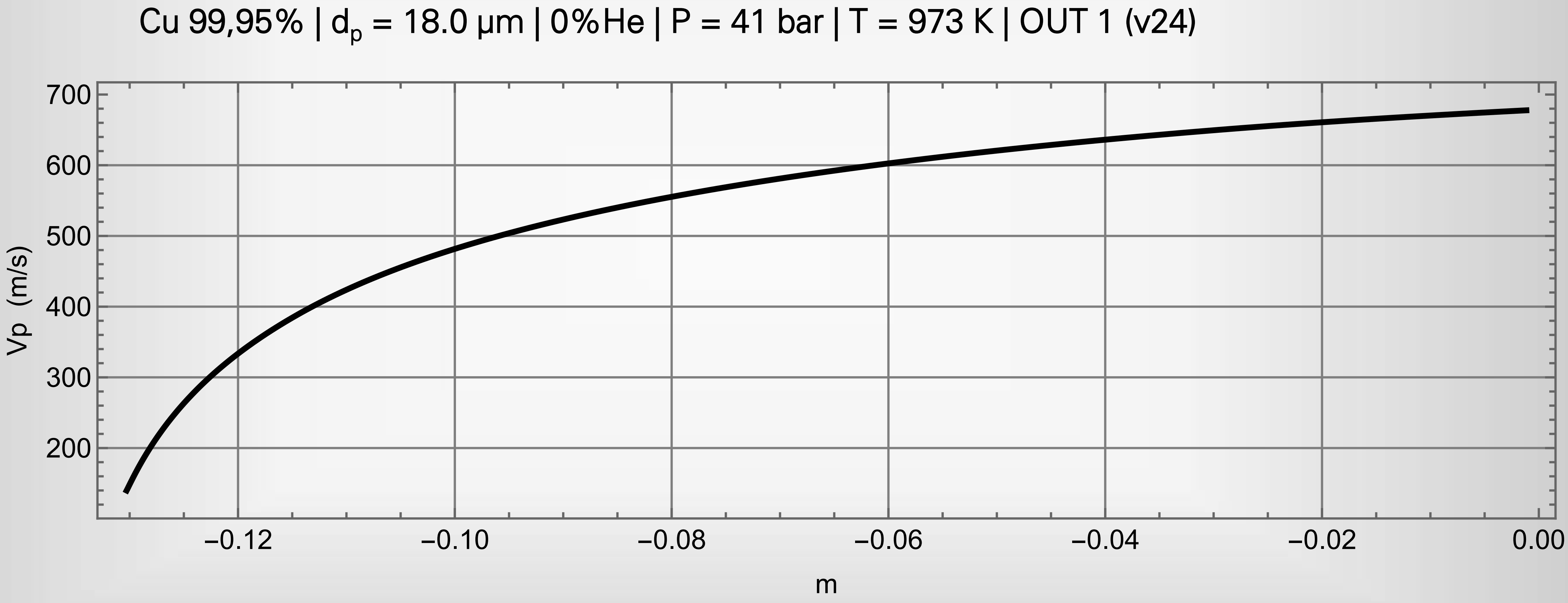
Factors influencing particle velocity: Drag

Particle acceleration

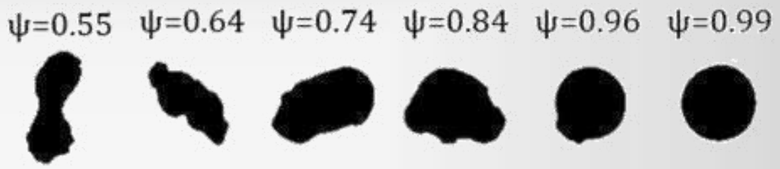


Factors influencing particle velocity: Result

Particle acceleration



Factors influencing particle velocity



(1) Powder meets specification (C_D, m_p , A_p)

AND

(2) Nozzle is intact (M)

AND

(3) Powder injection to propellant gas is continuous and meets specification (w)

AND

(4) Gas stagnation properties are in specification (T, P)

→ Particle acceleration is as required

Particle velocity is as required

Indirect monitoring of particle velocity

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(2) Nozzle performance monitoring

AND

(3) Powder injection monitoring

AND

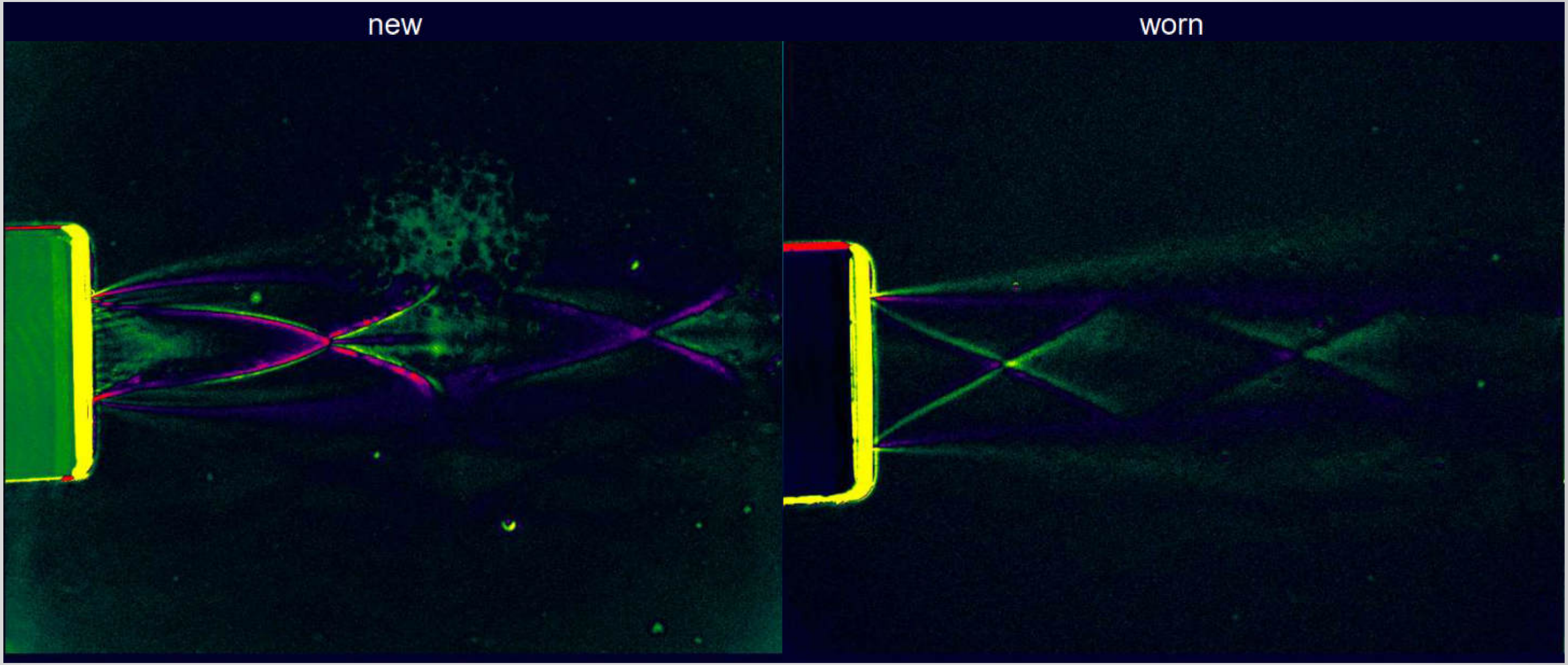
(4) CS system control

→ ensure that

particle velocity remains in spec

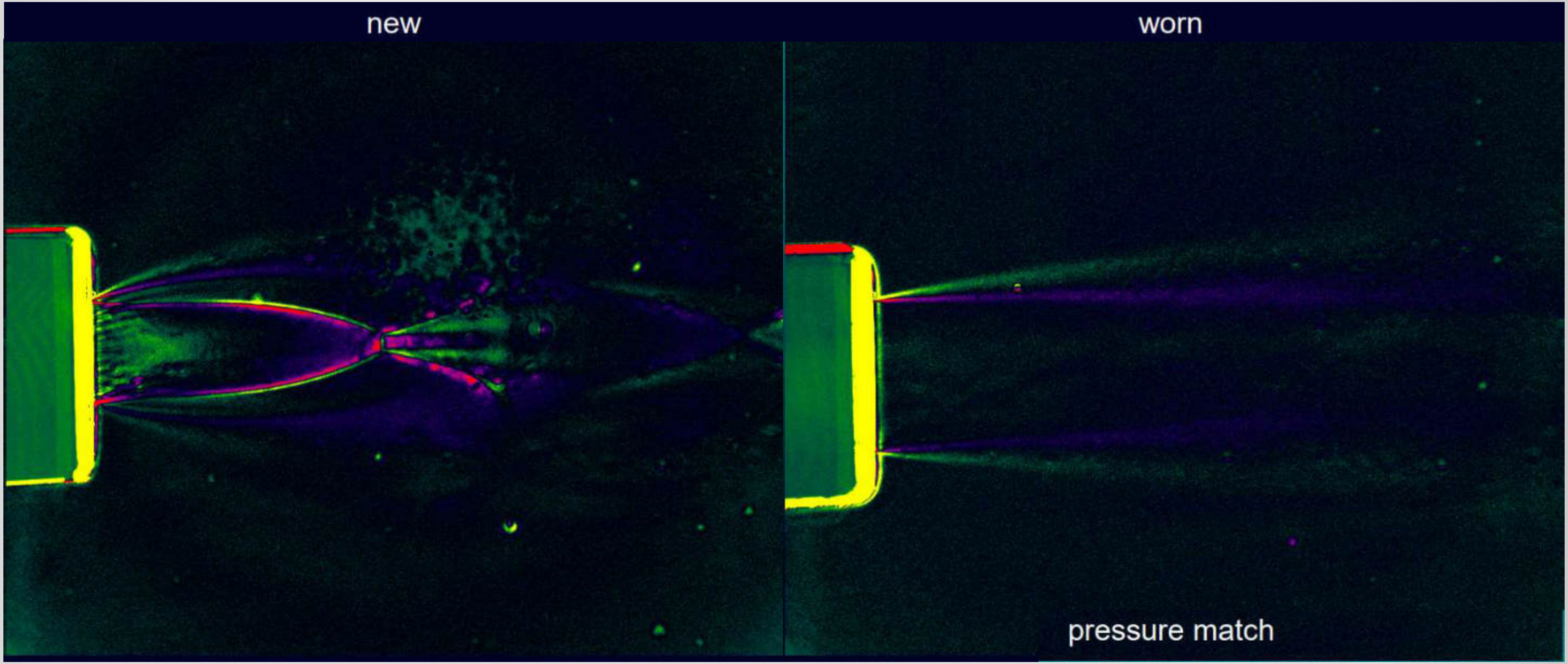
Nozzle performance monitoring: Wear

High pressure cold spray nozzle 50 bar, 500 °C



Nozzle performance monitoring: Wear

High pressure cold spray nozzle 66 bar, 600 / 700 °C

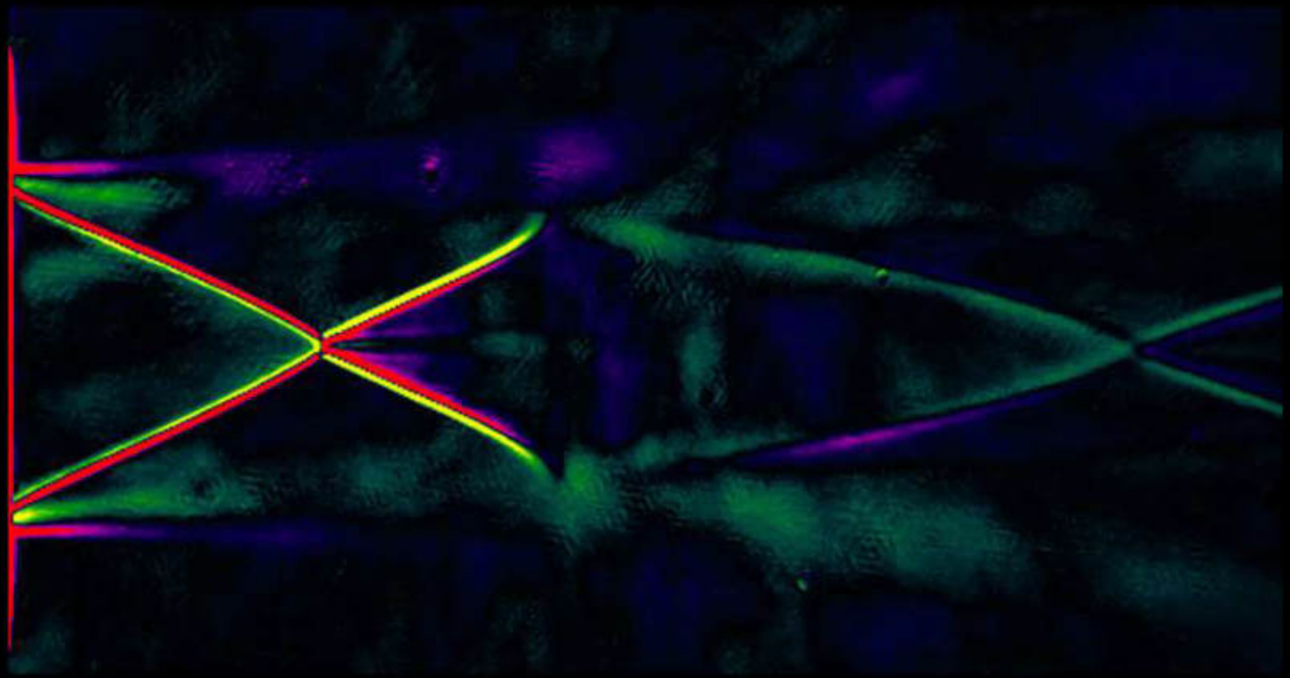


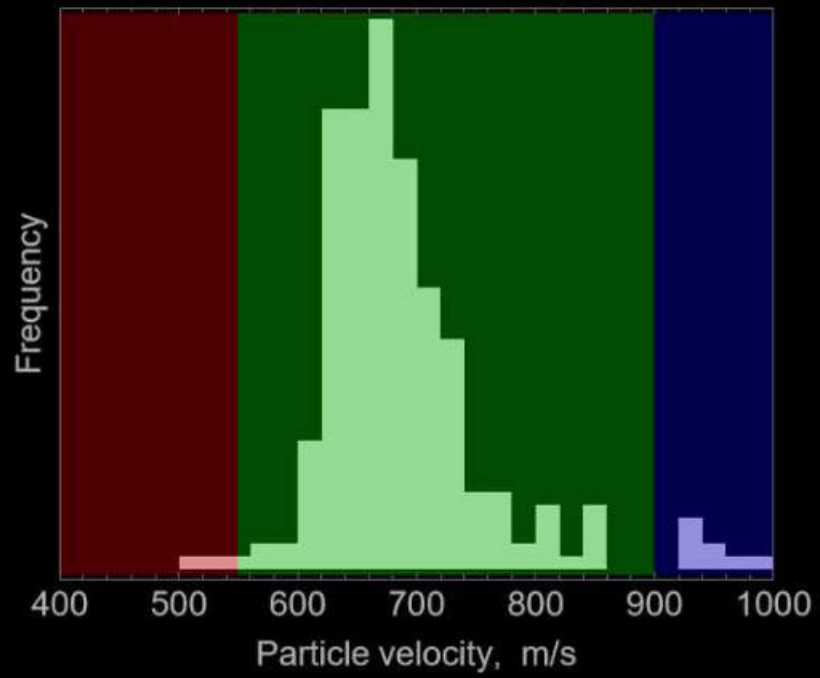
Nozzle performance monitoring: Clogging

Early warning for impending clogging

Process monitoring

Schlieren monitoring



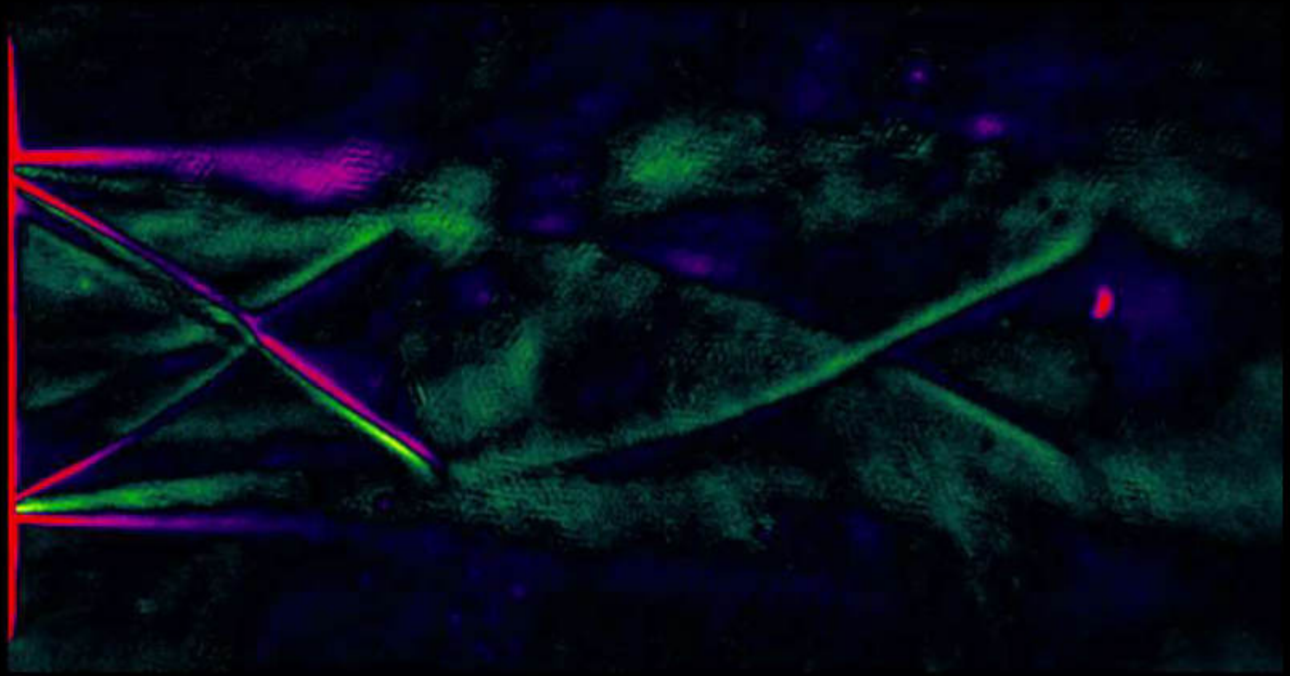


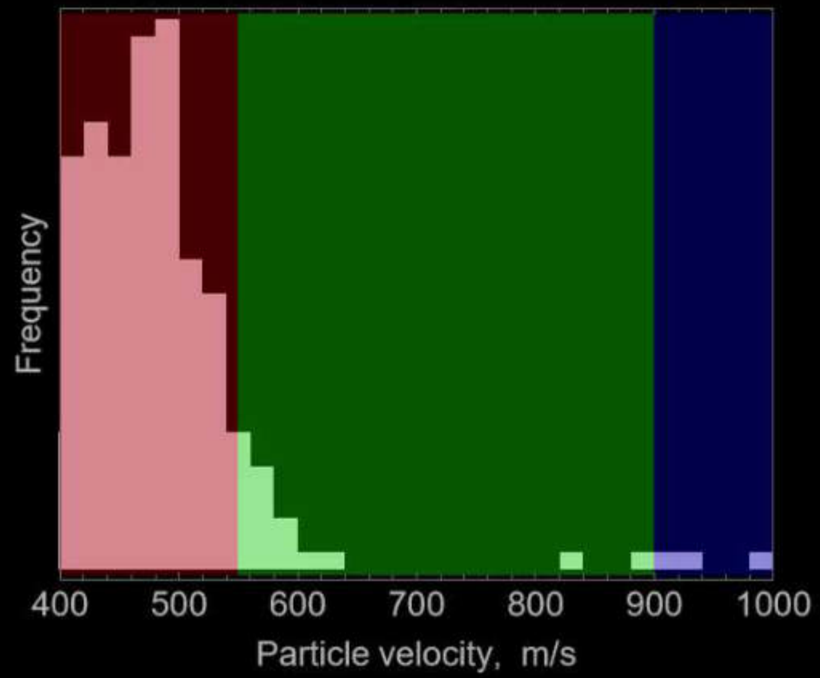
Powder feeding time: 41 s

Nozzle performance monitoring: Clogging

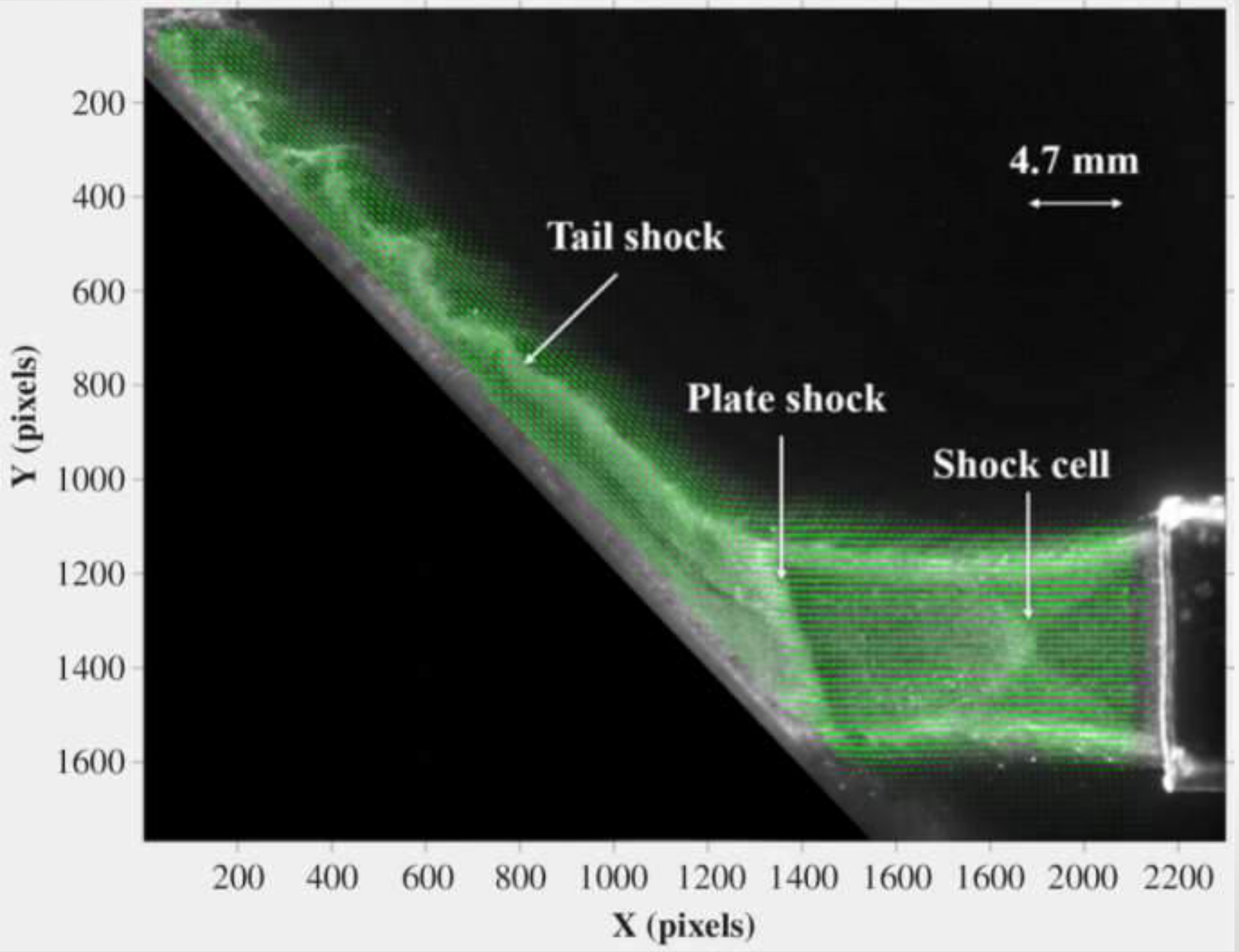
Early warning for impending clogging

Process monitoring



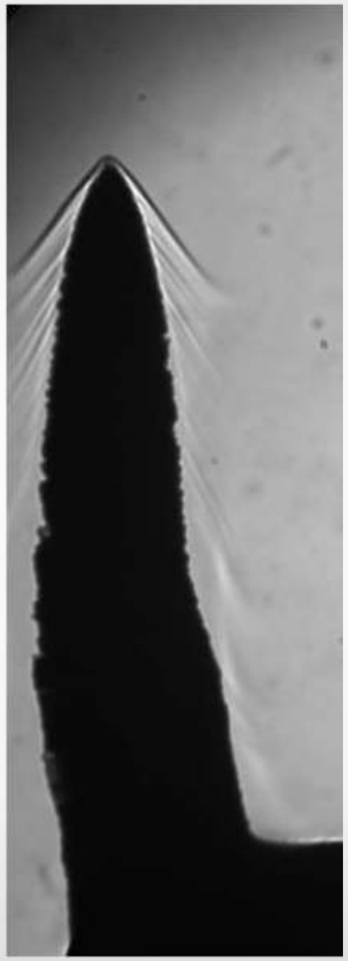


Effect of impact angle



T. Nguyen, B. Maher, Y. Hassan,
Flowfield Characteristics of a Supersonic Jet Impinging on an Inclined Surface,
AIAA JOURNAL, Vol. 58, No. 3, March 2020

Control of impact angle ?



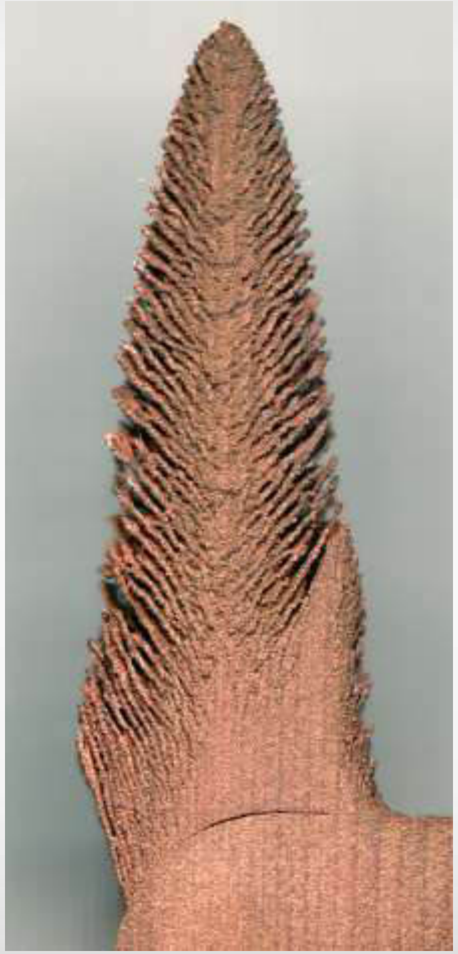
Effect of impact angle: Shadowing

(1) The particle velocities were constantly in spec during the spraying of this object.

(2) Nevertheless, material quality deteriorates over time.

(3) Impact angle is an independent process key characteristic.

(4) Particle velocity alone is insufficient for quality assurance.



Effect of impact angle: Vertical delamination

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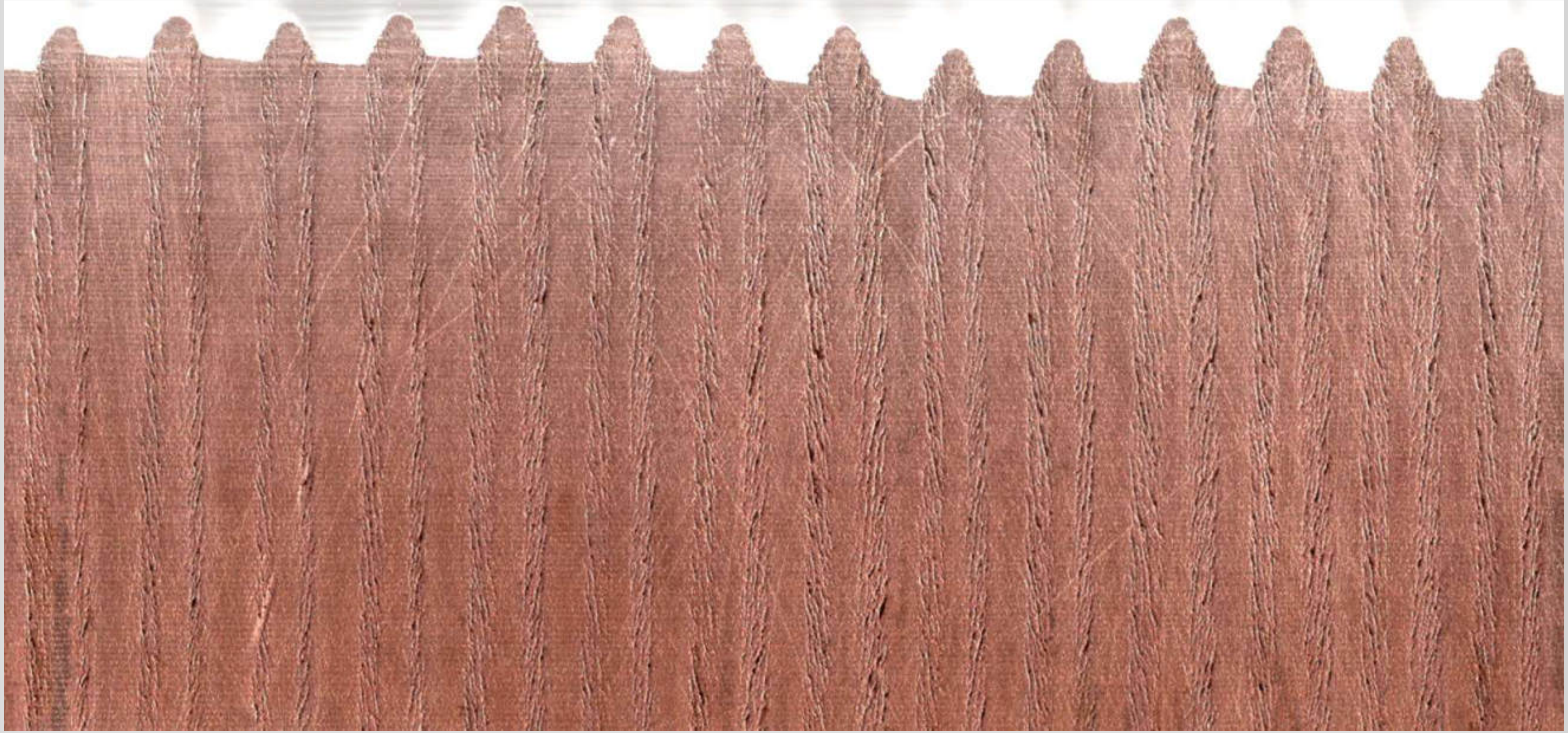


Particle impact

Effect of impact angle: Porosity

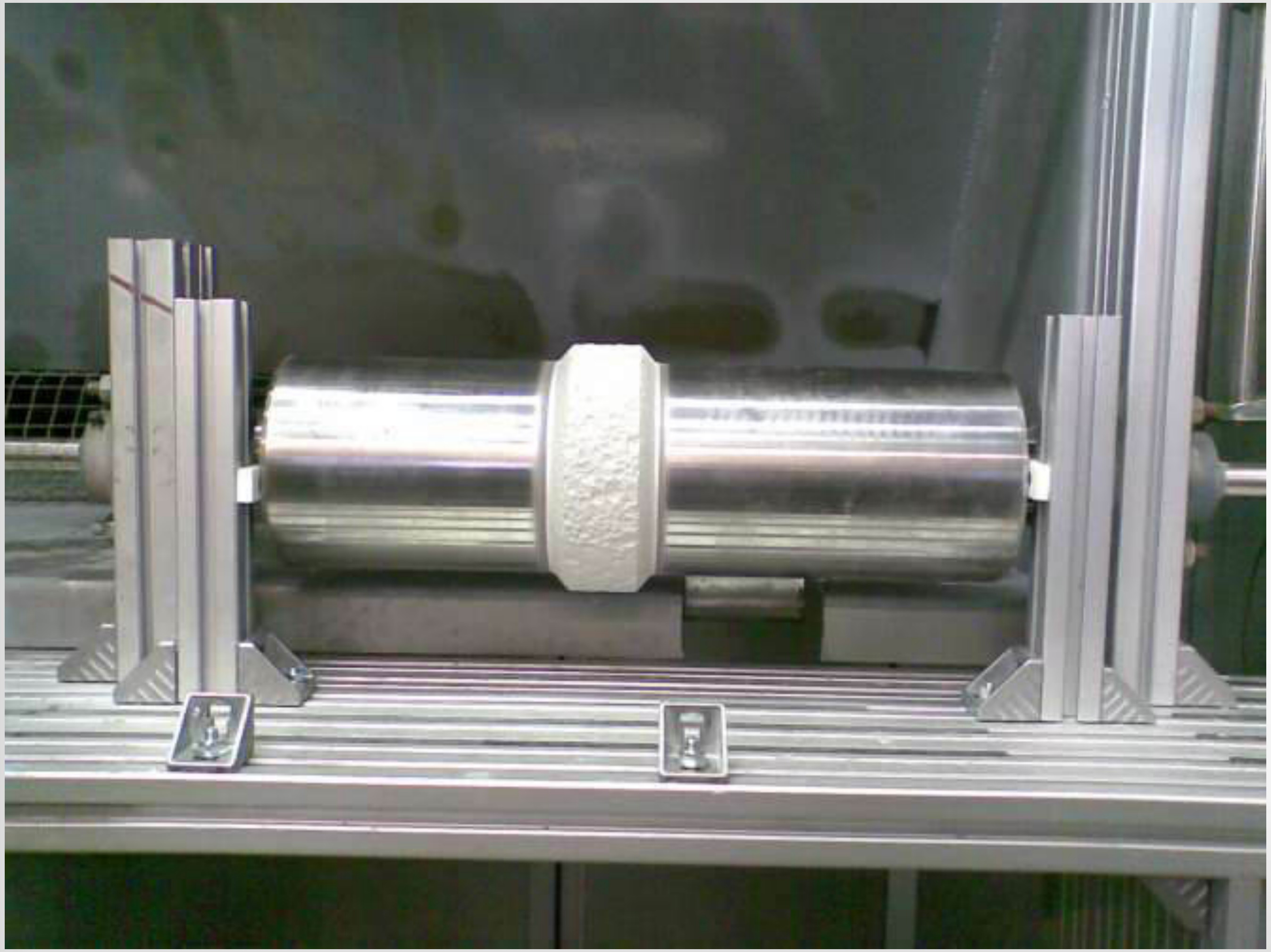
J Therm Spray Tech
https://doi.org/10.1007/s11666-024-01730-6

ORIGINAL RESEARCH ARTICLE

Prediction of Geometry-Induced Porosity in Cold Spray Additive Manufacturing of Leading Edges

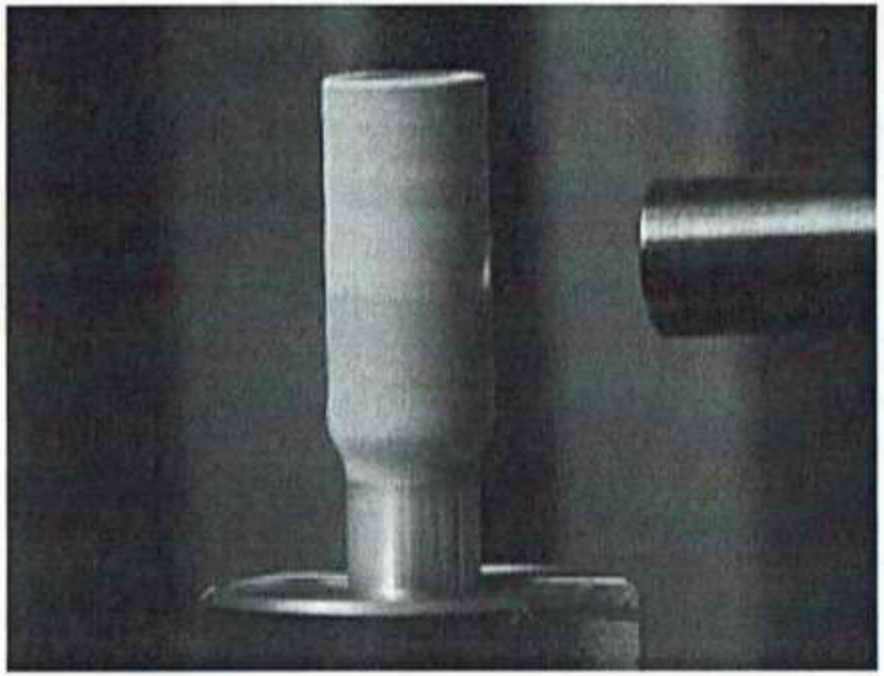
Isaac M. Nault[1] · Marius Ellingsen[2] · Aaron Nardi[2]

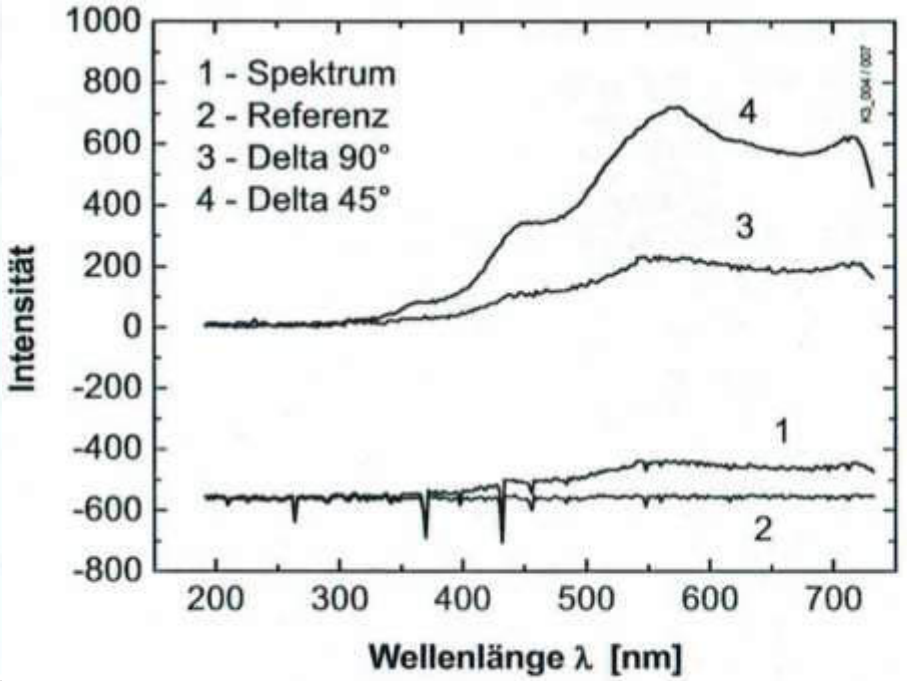
Effect of impact angle: Surface corrugation



Spray spot observation

Particle impact





Spray spot observation

Particle impact

JOURNAL OF APPLIED PHYSICS **100**, 013529 (2006)

Luminescence induced by high-velocity impacts of metallic particles on metal surfaces

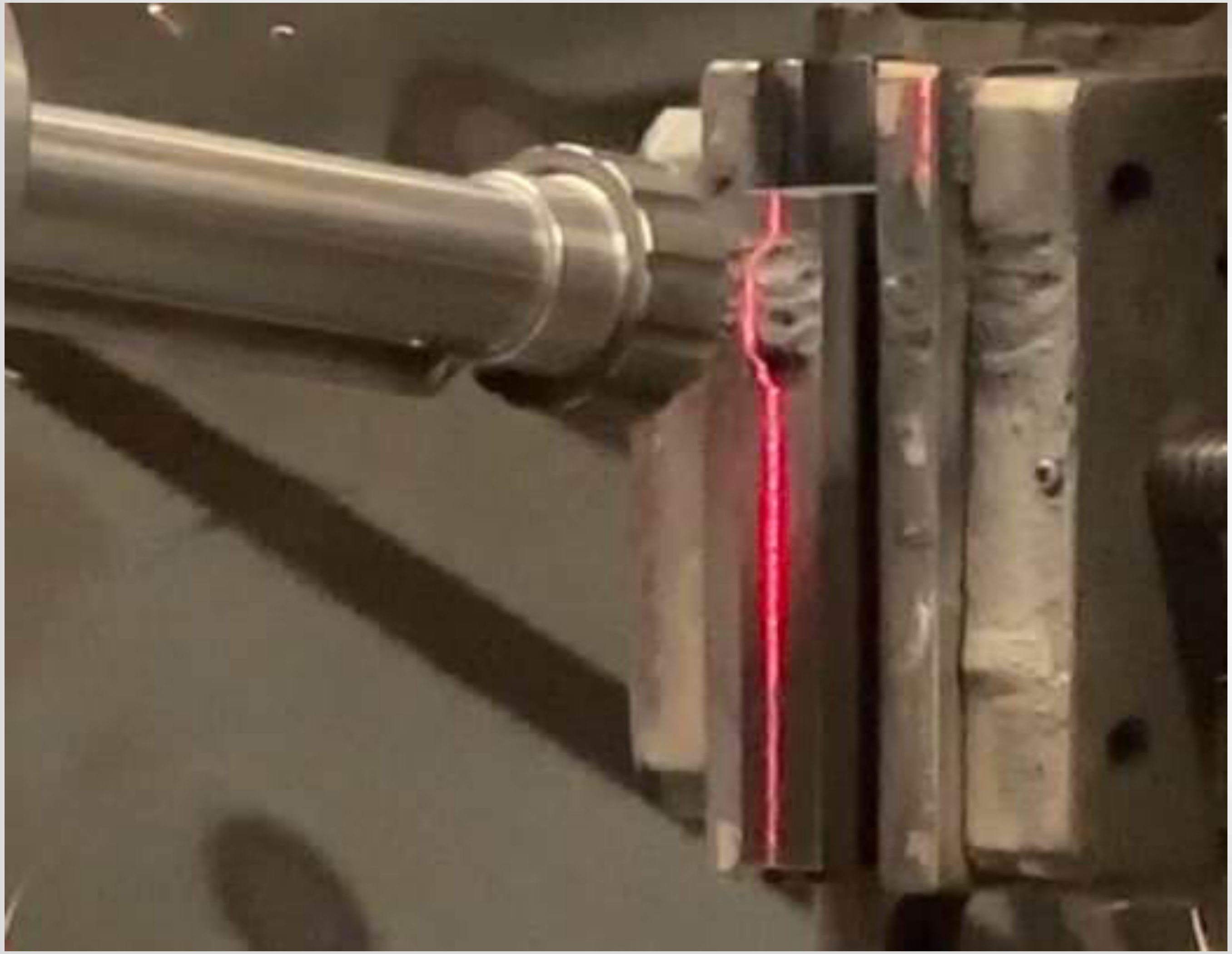
Konstantin V. Klinkov[a] and Martin Rein[b]
Institute of Aerodynamics and Flow Technology, DLR, Bunsenstrasse 10, 37073 Göttingen, Germany

(Received 2 December 2005; accepted 21 April 2006; published online 14 July 2006)

On impact of metallic particles on a metal surface light can be emitted from the region of impact. This phenomenon is studied experimentally for impact conditions that are typical of the cold spray

- Impact-induced luminescence can be due to various mechanisms
  - thermal radiation
  - ignition of metals involved in the process
  - gas discharge
  - mechanoluminescence

Spray spot observation



Spray spot observation

Particle impact

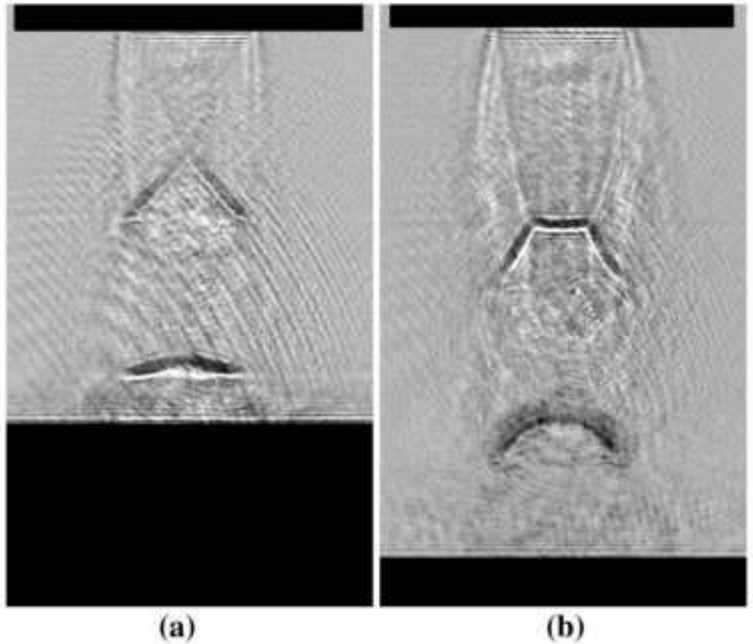
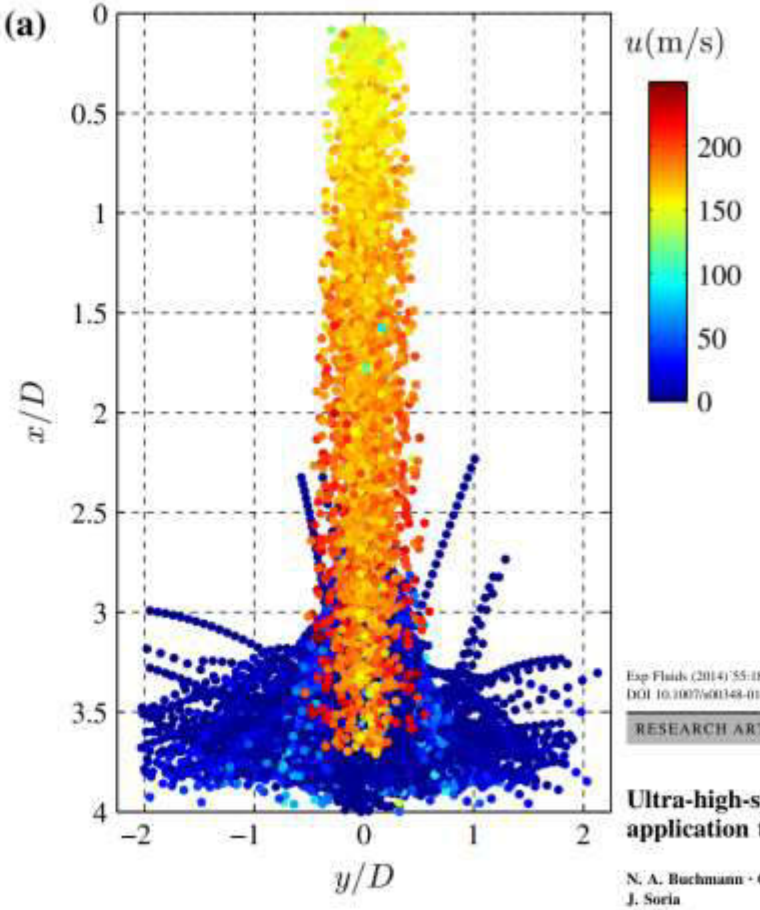
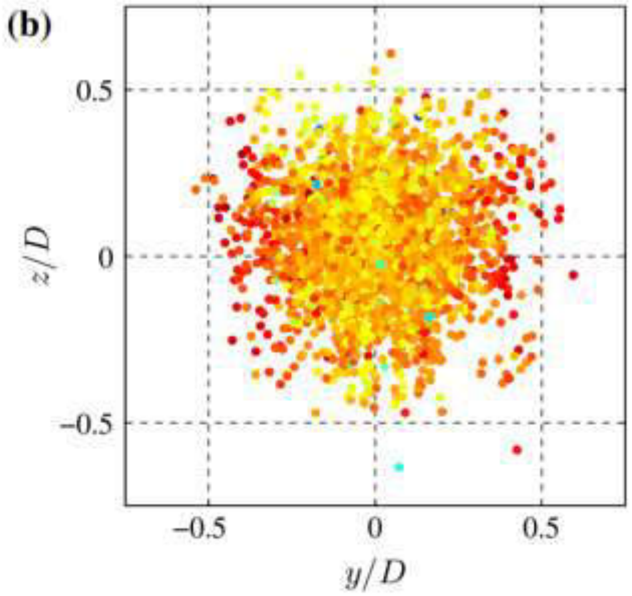


Fig. 6 Coherent image visualisation of the gas phase of the underexpanded jet; **a** NPR = 3.75, $Z/D = 3$; **b** NPR = 6, $Z/D = 4$. Flow is from *top* to *bottom*

a thin plane within the jet and standard 2D tracking methods would result in a depth-averaged particle velocity





Exp Fluids (2014) 55:1842
DOI 10.1007/s00348-014-1842-1

RESEARCH ARTICLE

Ultra-high-speed 3D astigmatic particle tracking velocimetry: application to particle-laden supersonic impinging jets

N. A. Buchmann · C. Cierpka · C. J. Kähler · J. Soria

Spray spot observation – Intensity

$$I = \frac{P}{A} = \frac{\Delta E}{\Delta t \cdot A}$$

Photons

$\Delta E_{ph} = n \cdot h \cdot f_{ph}$

h = Plancks quantum

$P_L = \frac{\Delta E_{ph}}{\Delta t} = \frac{n}{\Delta t} \cdot h \cdot f_{ph}$

- P_L: Light power
- $\frac{n}{\Delta t}$: Count rate
- $h \cdot f_{ph}$: avg. Photon energy

(Light) intensity: $I_L = \frac{P_L}{A}$ — A: Detector area

CS particles

$\Delta E_{part} = \frac{m_{part}}{2} \cdot v_{part}^2$

$P_{ETR} = \frac{\Delta E_{part}}{\Delta t} = \frac{n}{\Delta t} \cdot \frac{m_{part}}{2} \cdot v_{part}^2$

- P_{ETR}: Energy transfer rate
- $\frac{n}{\Delta t}$: Impingement rate
- $\frac{m_{part}}{2} \cdot v_{part}^2$: avg. Kinetic energy of particles

Deposition intensity: $I_D = \frac{P_{ETR}}{A}$ — A: Area of impingement zone

Process monitoring

Spray spot observation: Deposition Intensity

$$I_D = \frac{P_{ETR}}{A} = \frac{1}{A} \cdot \frac{\Delta E_{part}}{\Delta t} = \frac{1}{A} \cdot \underbrace{\frac{n}{\Delta t}}_{\text{Impingement rate}} \cdot \underbrace{\frac{m_{part}}{2} \cdot v_{part}{}^2}_{\text{avg. Kinetic energy of particles}}$$

Deposition intensity varies depending on

- Kinetic energy of particles (v_p)

AND / OR

- Particle impingement rate

I_D effected by →

- Slower / faster particles
- Particle count

Spray spot observation: Deposition Intensity

What else can be observed?

1. Internal delamination
2. Substrate / surface incliniation ➡ corrugation
3. Work piece boundaries
4. Non-uniform / non-constant powder feeding

Process monitoring

Process monitoring methods

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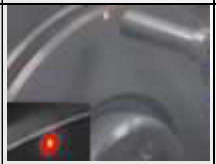
High pressure CS systems		Nozzle integrity			Gas flow field			Particle phase			Deposition intensity
		wear	clogging		total gas flow	conformance with reference	constancy	total mass flow (TMF)	TMF constancy	velocities	
			present	impending							
CS system control		in throat	eventually	✗	✓	✗	✗	✓	✗	✗	✗
Acoustic monitoring		?	possibly [1]	?	✗	✗	✗	✗	possibly [2]	possibly [2]	possibly [1]
Schlieren imaging [3]		✓	✓	✓	✗	✓	✓	✗	✗	✗	✗
PIV		unreliable	✓	unreliable	✗	✗	unreliable	✗	✓	✓	✗
Spot imaging [4]		✗	✓	unreliable	✗	✗	✗	✗	✓	unreliable	✓
Deposition profile dimensional scan		✗	✓	✗	✗	✗	✗	✗	✓	unreliable	unreliable

Process monitoring methods (References)

Process monitoring

1 D. Schimbäck, M. Steierl, M. Kettner, R. Sommerhuber, Online process monitoring for Cold Spray by using an acoustic measurement method
28th Cold Spray Club Meeting, Dublin, 28 April 2023

2 S. Koufis, N. Eskue, D. Zarouchas, J.A. Pascoe, Monitoring the Cold Spray Process: Real-time particle velocity monitoring through airborne acoustic emission analysis
30th Cold Spray Club Meeting, Barcelona, 26.04.2024

3 O. Stier, A. Creuz, J. Dahl Jensen, U. Krüger, Industrial Multi-Axis Cold Spray Manufacturing Using SIEMENS Software
CSAT Meeting, Leominster, MA, 23 June 2021

4 A. Creuz, O. Stier, Quick spray parameter assessment by in-situ measurement of material deposition
29th Cold Spray Club Meeting, Hamburg, 20 October 2023

Combination of monitoring methods

(1) CS system control + PIV + Schlieren imaging + Spot imaging

- all properties can be monitored

(2) CS system control + Schlieren imaging + Spot imaging

- no velocity measurements during spraying
- velocity measurement at the beginning of a new cycle is sufficient

(3) CS system control + PIV + Schlieren imaging + deposition profil dimensional scan

- Deposition intensity unreliable

(4) Accoustic monitoring looks promising today, but needs further advancement

Conclusions

1. $\eta = \frac{v_p}{v_{crit}}$ is a figure of merit for product quality (not merely v_p)
2. v_p and v_{crit} may change when powder type changes, PIV for process monitoring needs powder dependent calibration
3. PIV measurements should resolve particle sizes, otherwise acceptance criteria based on η cannot not be evaluated
4. Constancy of particle velocity can be assured indirectly by monitoring nozzle integrity (Schlieren imaging) and constancy of powder injection (spot imaging)
5. Initial PIV measurement is sufficient to ensure process constancy across powder (batch) changes
6. Schlieren imaging works independent of powder type, for different kinds of gas (N_2, He, H_2O) and yields early warning for impending nozzle clogging, suited for mounting on spray gun
7. A combination of (initial) PIV, Schlieren imaging, and spot imaging is presently necessary for comprehensive process monitoring in closed-loop manner for QA purposes

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To watch the videos originally shown in this presentation please visit www.volinesystems.com

Many Thanks!