Particle Impact Conditions and Corresponding Coating Properties in Cold Spraying

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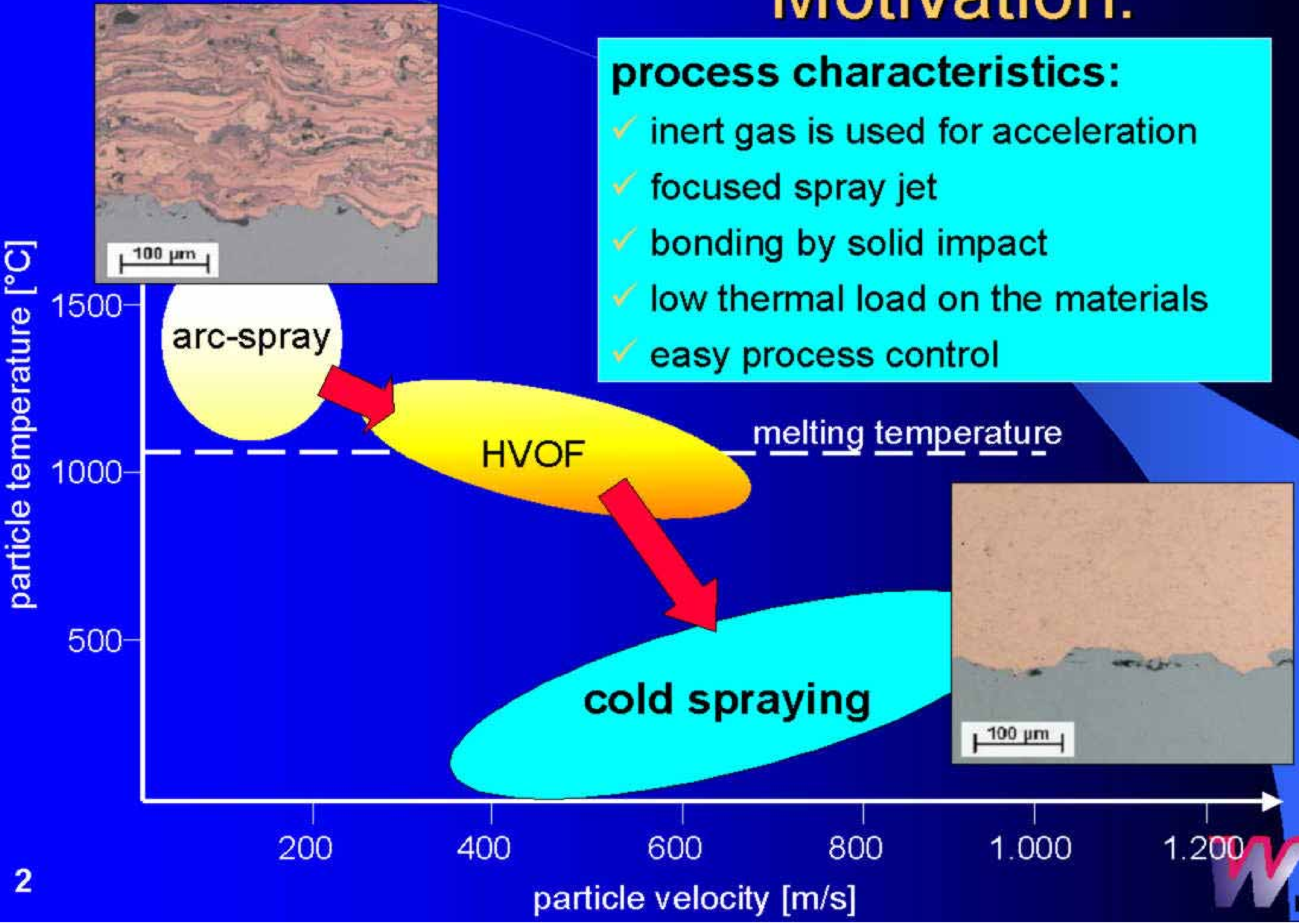
Motivation:

process characteristics:

- inert gas is used for acceleration
- focused spray jet
- bonding by solid impact
- low thermal load on the materials
- easy process control



Outline

- particle bonding in cold spraying
- impact simulations showing the
  - effect of particle size on critical velocity
- optimisation strategy:
  - using an optimised size distribution
  - generating a distinct exceeding of v_{crit} by v_P
- realization of these conditions (new equipment)
- correlation of coating properties with impact conditions using the **"window of deposition"**

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Particle Bonding in Cold Spray [2, 3]

- ✓ caused by a high strain rate deformation
- ✓ related to adiabatic shear instabilities
- ✓ requires sufficient high particle velocity $v_p > v_{crit}$

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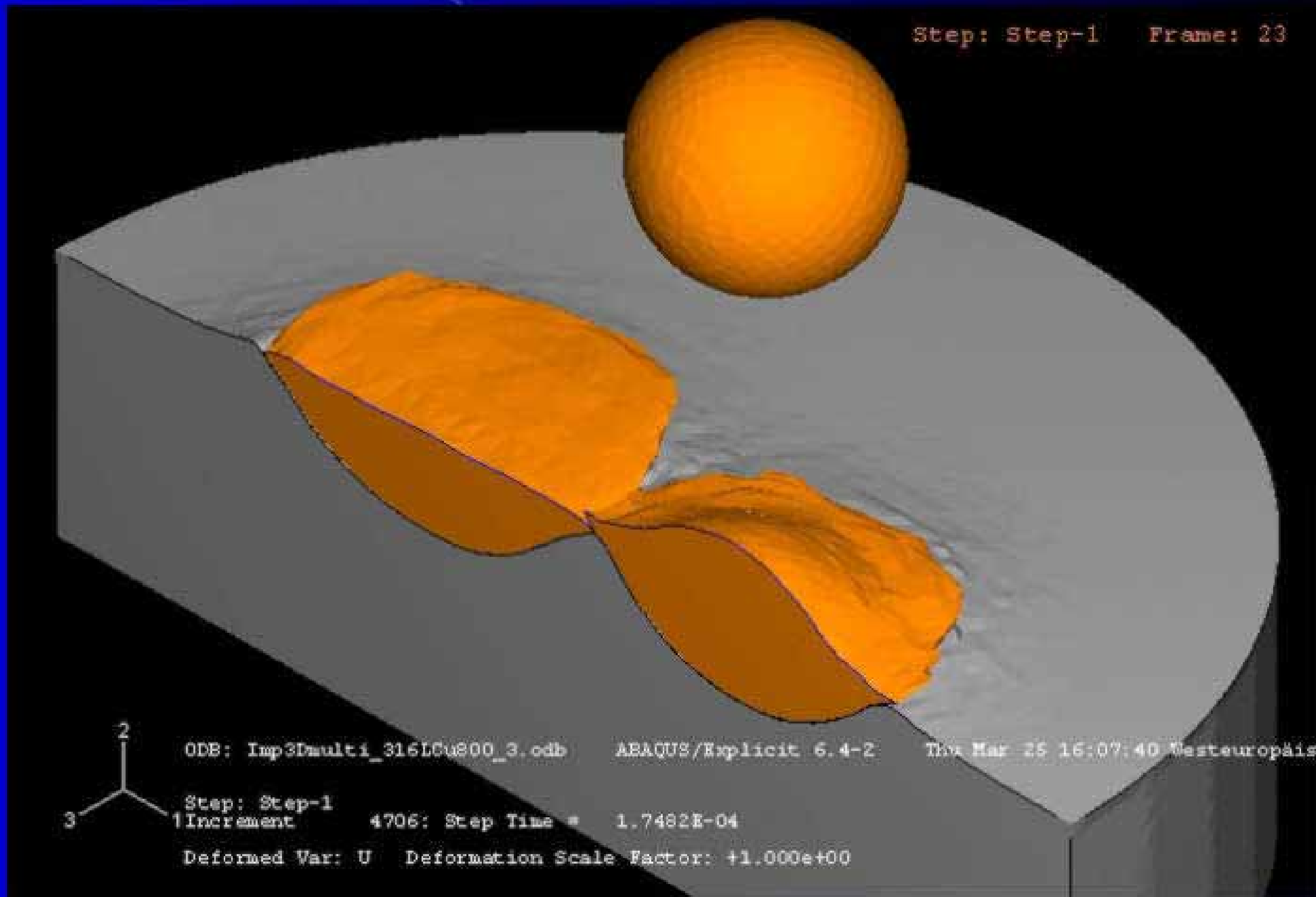
Particle Impact - FEM Modelling

software
- ABAQUS/Explicit



input
- material properties
- particle temperature
- particle velocity

output
- deformed shape
- field variables

<u>special</u>
- thermally coupled analyse
- propagation of heat, generated by straining, is considered

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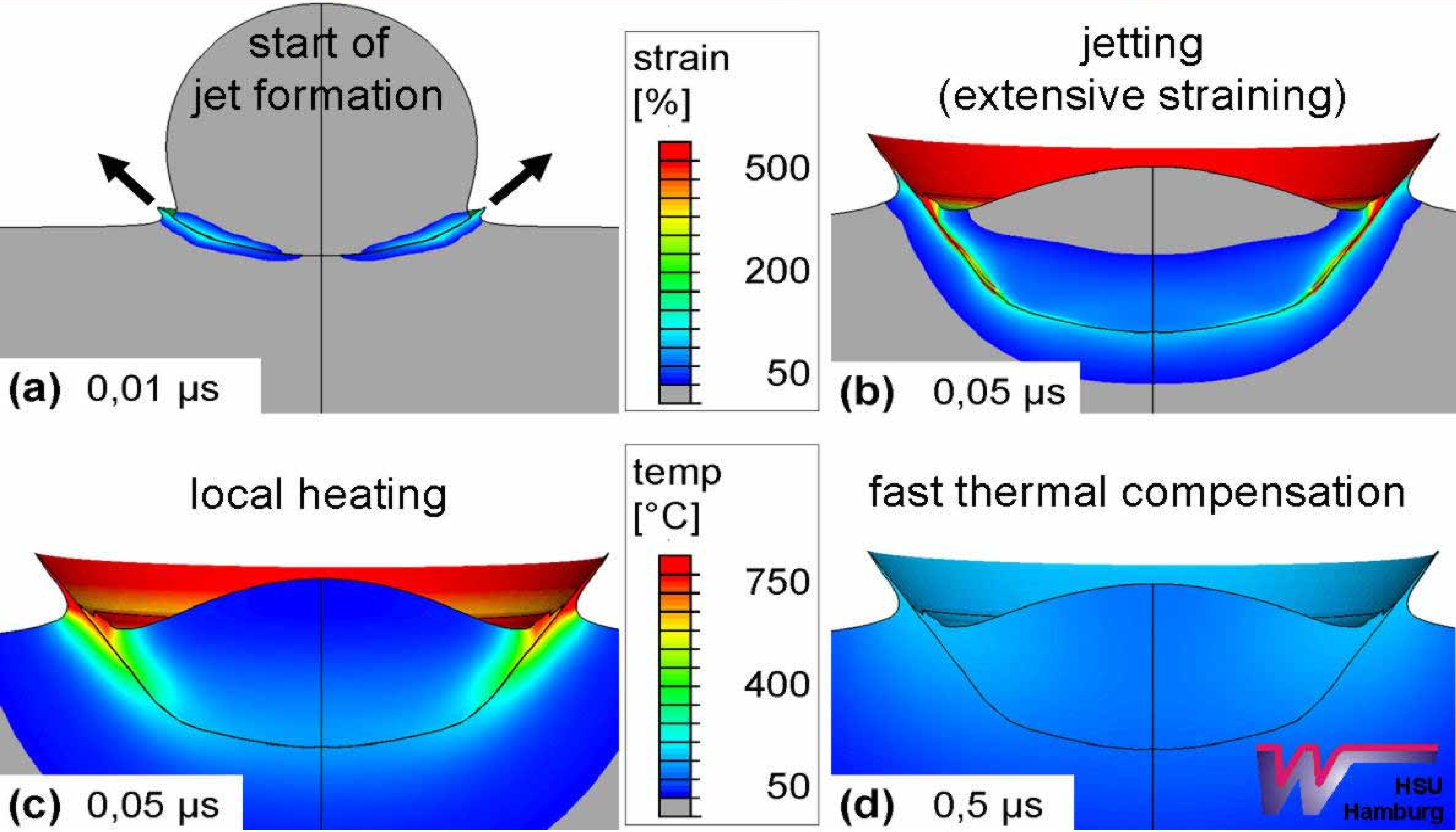
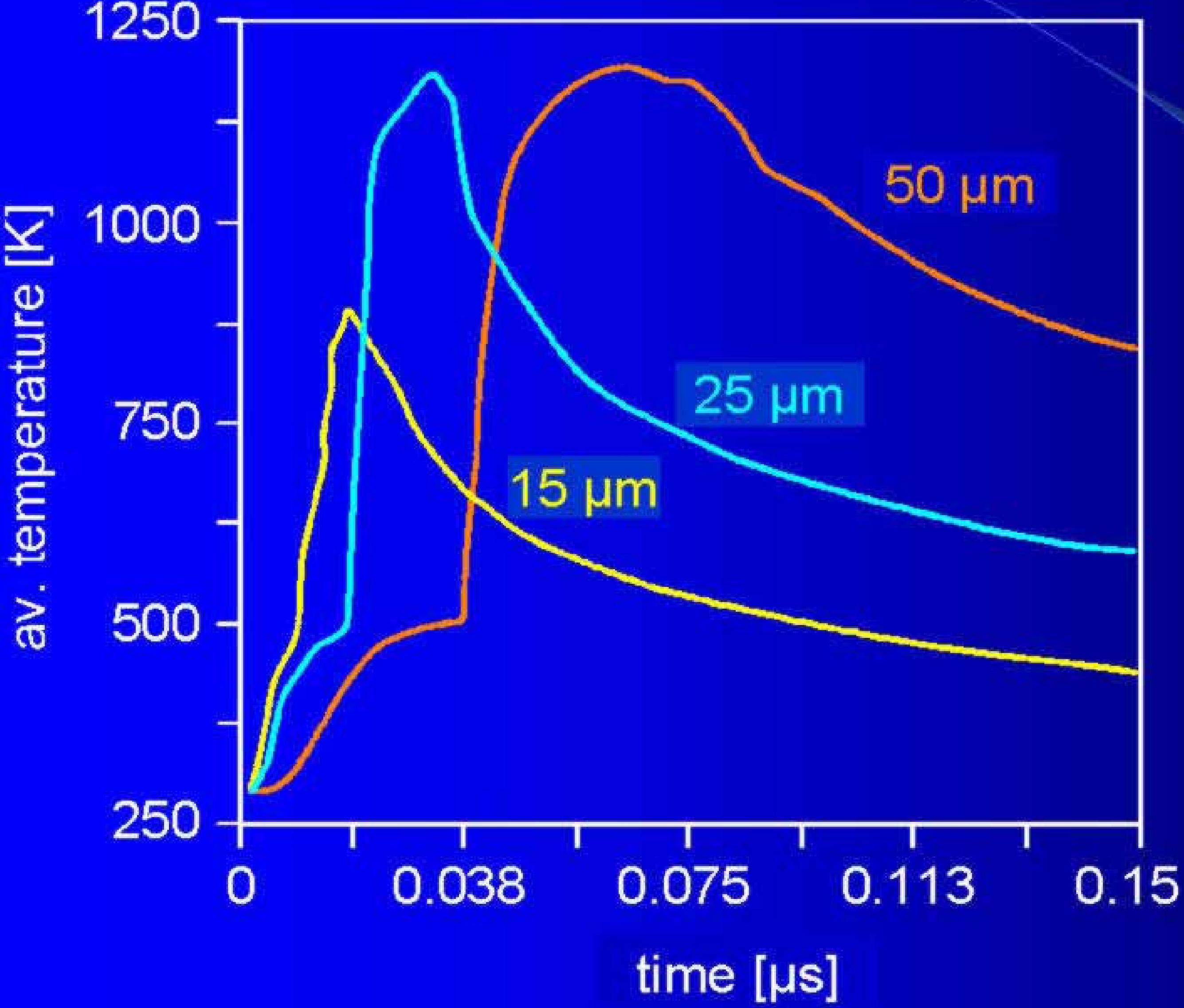
Particle Impact, Cu-Cu, 500 m/s, 20°C [3, 5]

cross-section particle - substrate, strain and temperature field



Effect of Particle Size

interface temperature Cu – Cu, 600 m/s, 20°C



temporal evolution of the interface temperature

for different particle size

at same conditions

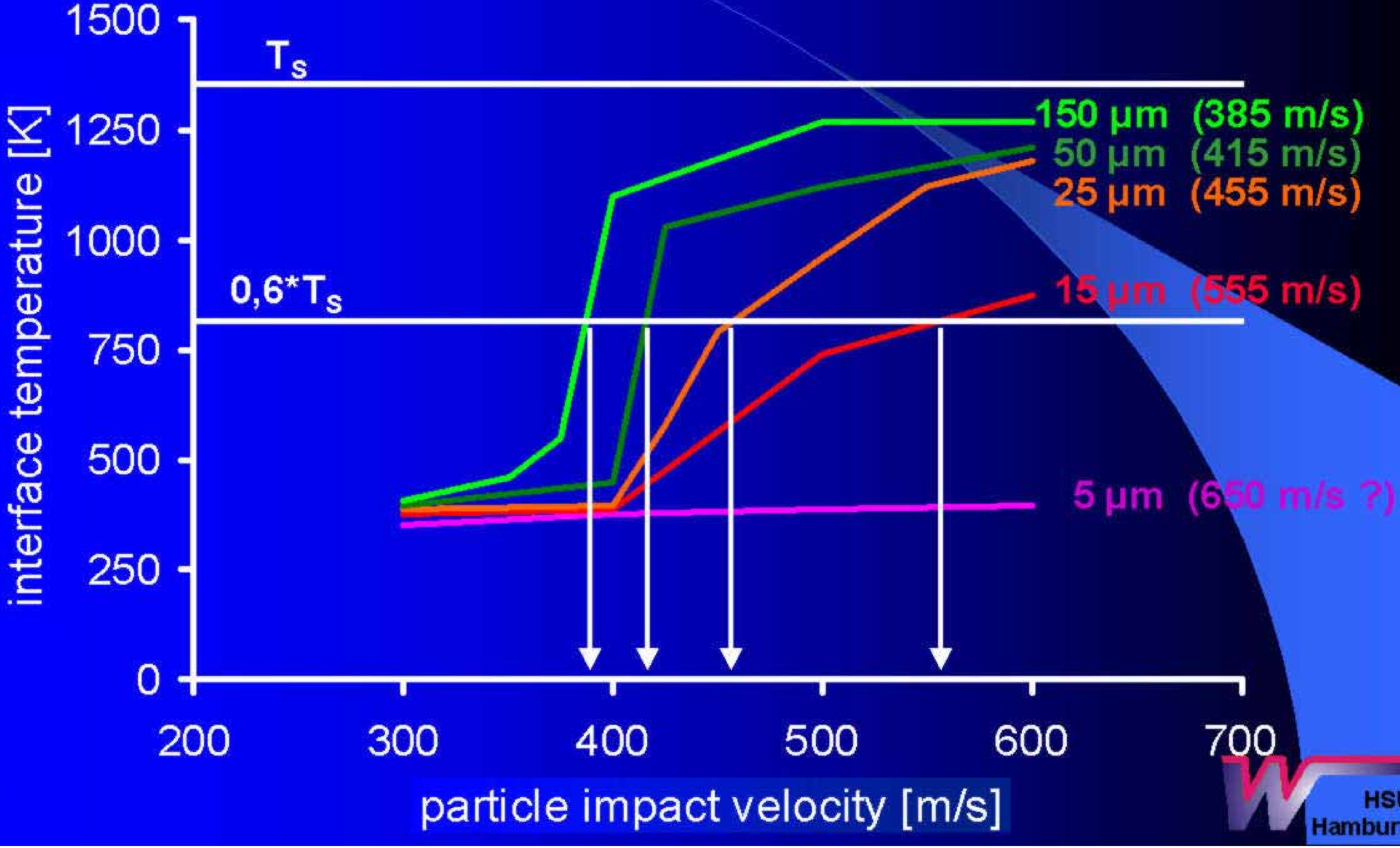
coarser particles:

- lower cooling rate
- interfacial heating is more effective

heating- and cooling-rates are in the range of 10^9 K/s !

Interface Temperature –> Critical Velocity [3, 5]

interface temperature as a function of impact velocity



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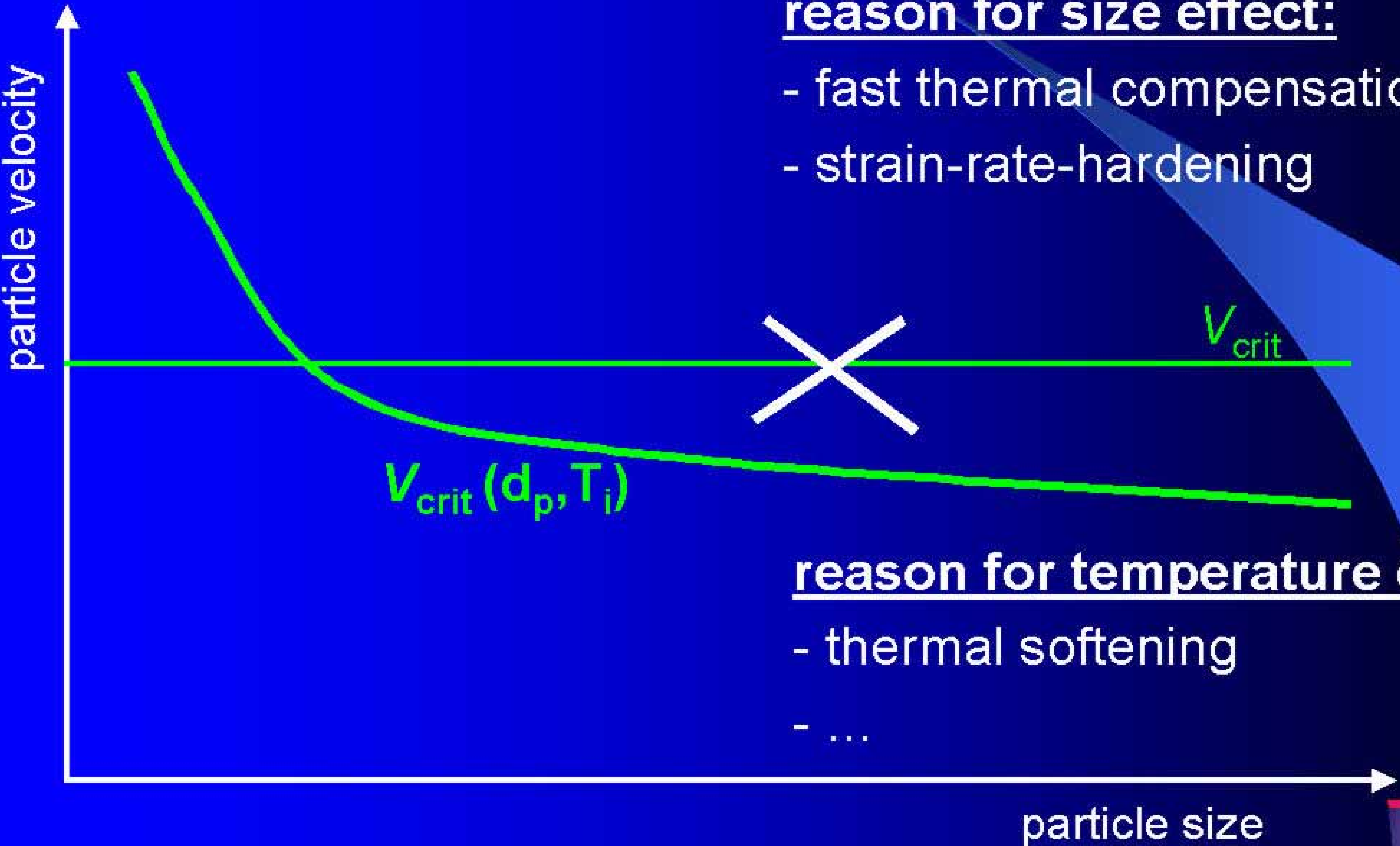
Critical Velocity is a Function of Particle Size and Particle Impact Temperature



reason for size effect:

- fast thermal compensation
- strain-rate-hardening

reason for temperature effect:

- thermal softening
- …

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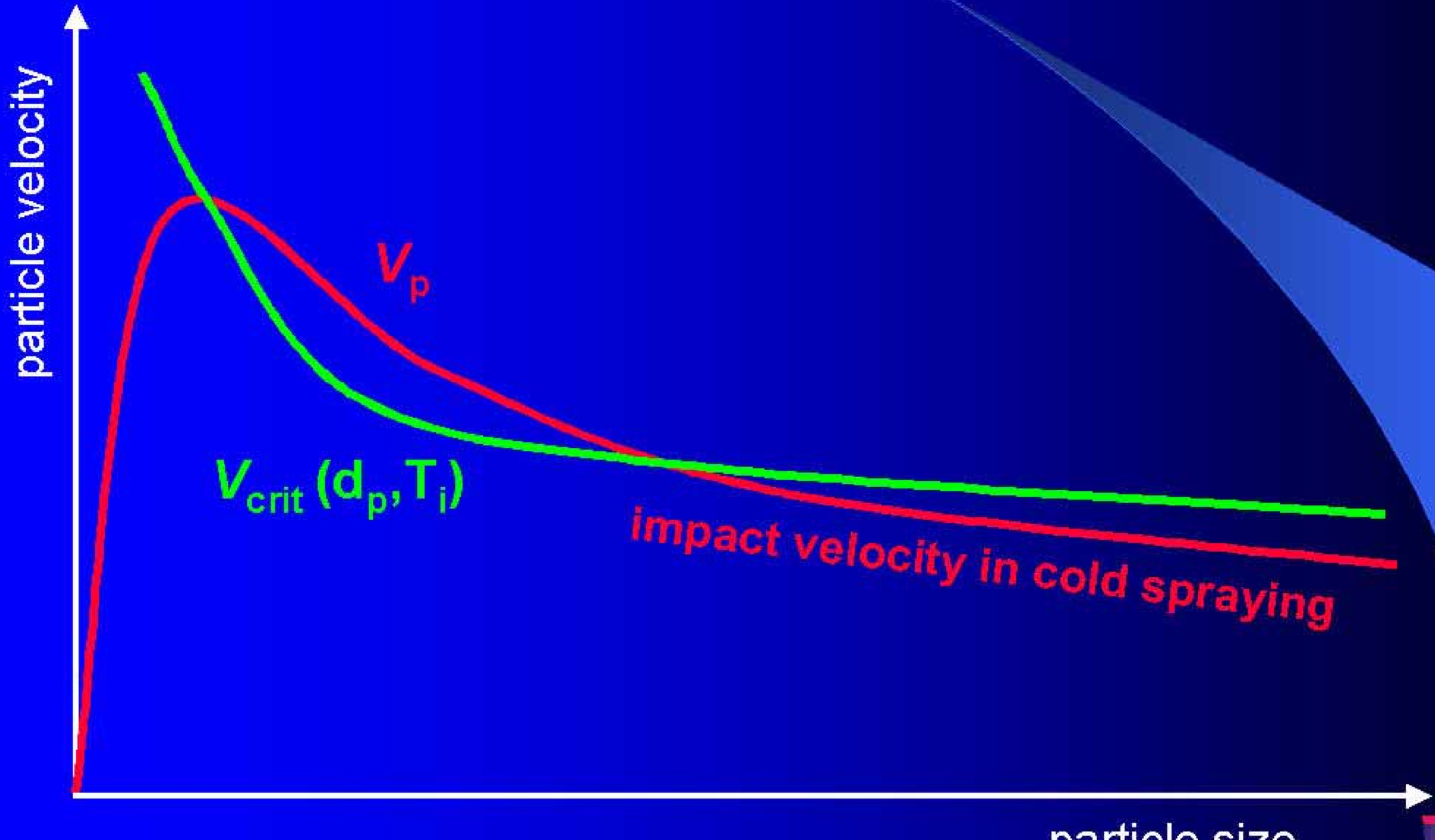
Critical Velocity and Impact Velocity
for a certain Spray Parameter



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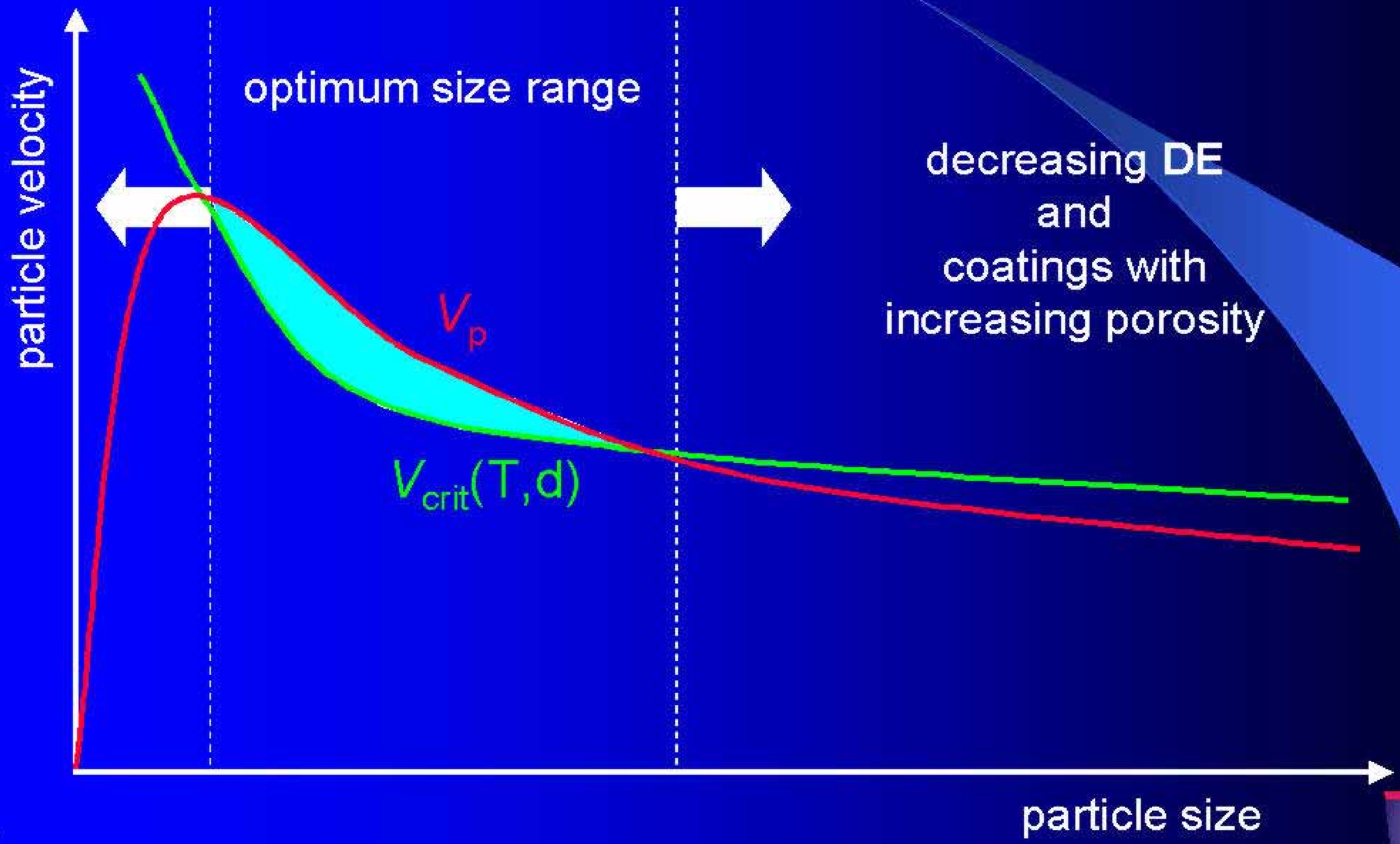
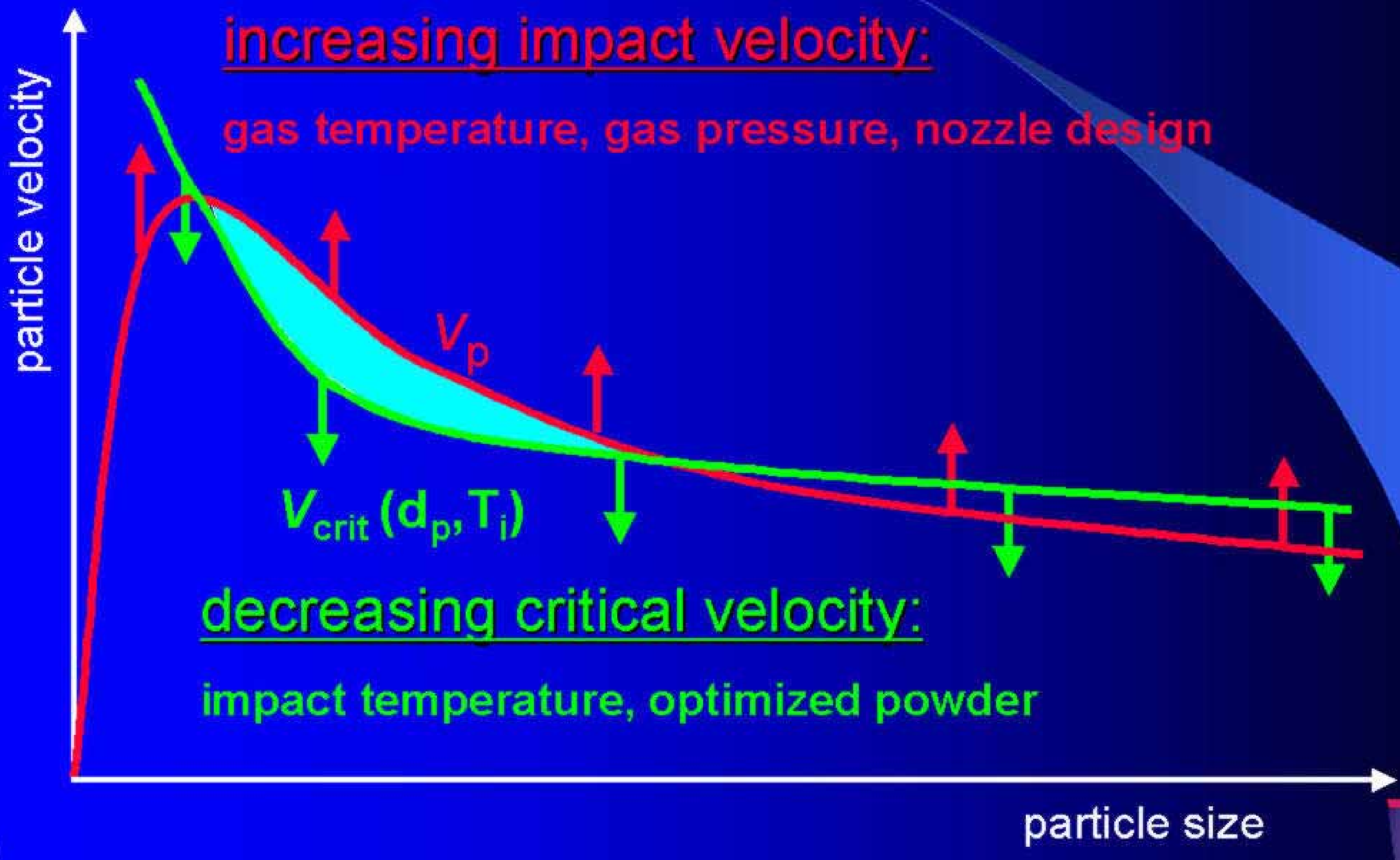
Critical Velocity and Impact Velocity [3]

for a certain Spray Parameter



Concept of Process Optimization:

distinct excess of impact velocity over critical velocity



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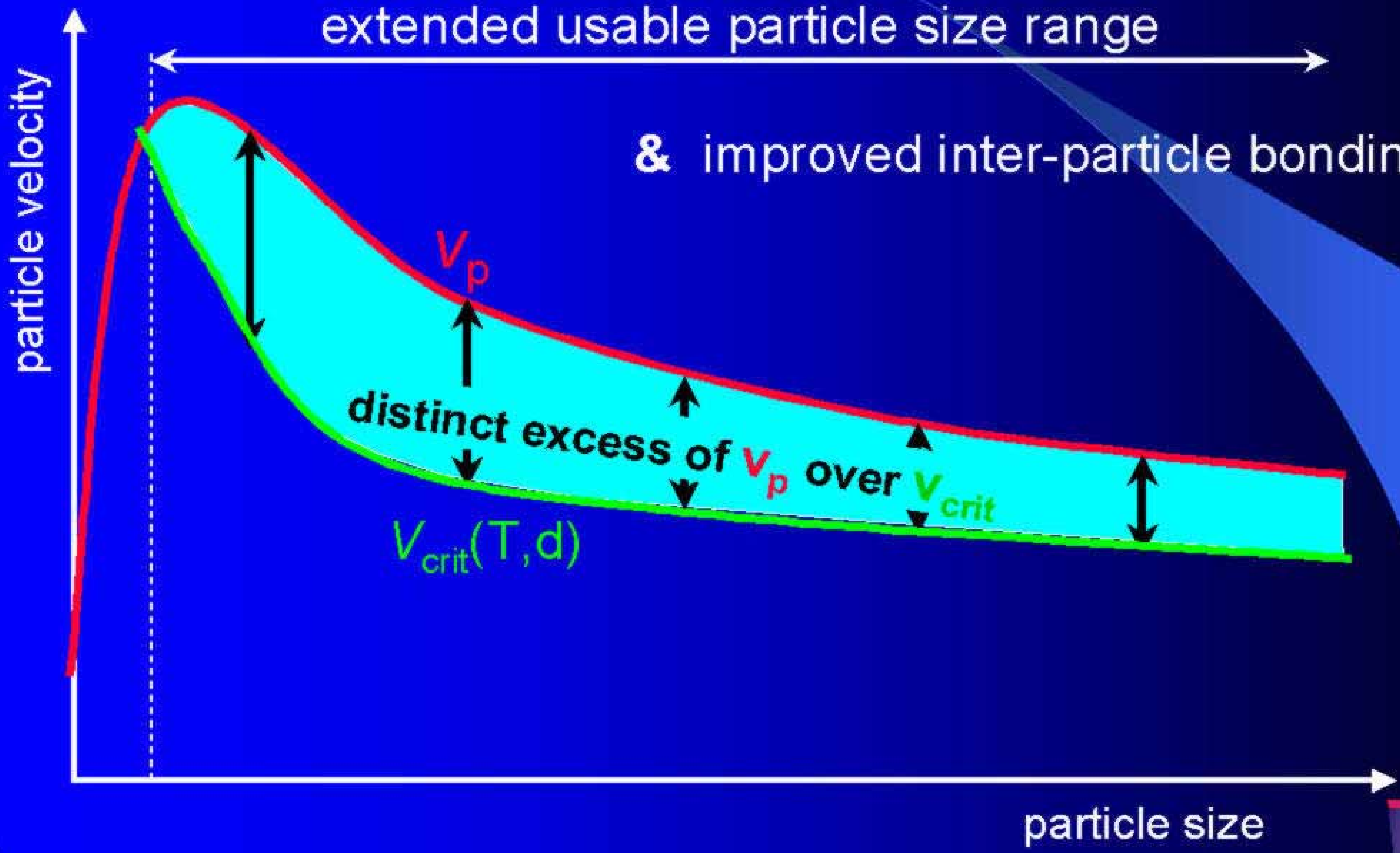
Aim of Process Optimization:

extended particle size range & improved particle bonding



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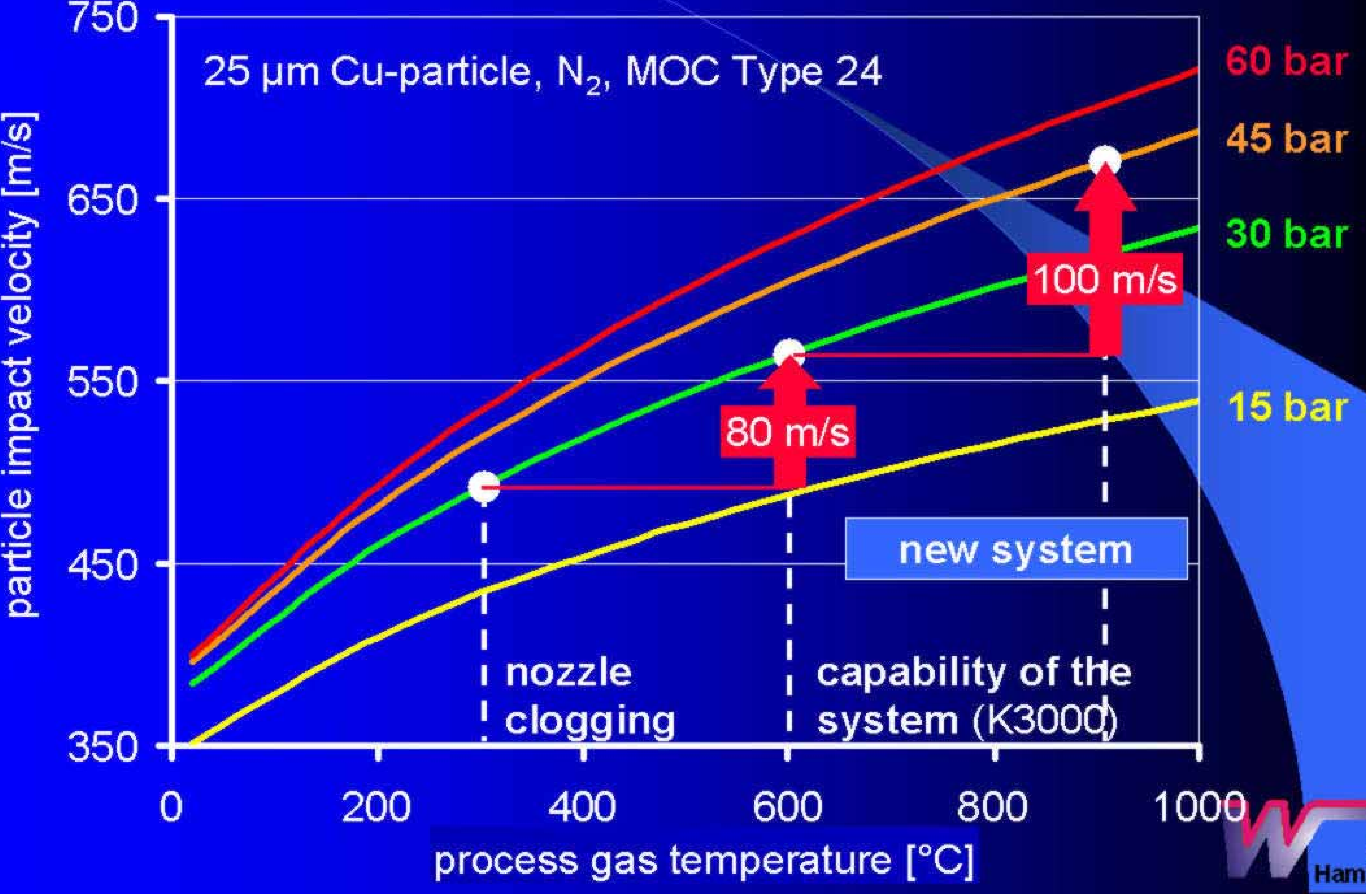
Higher Impact Velocity

by higher gas pressure and temperature



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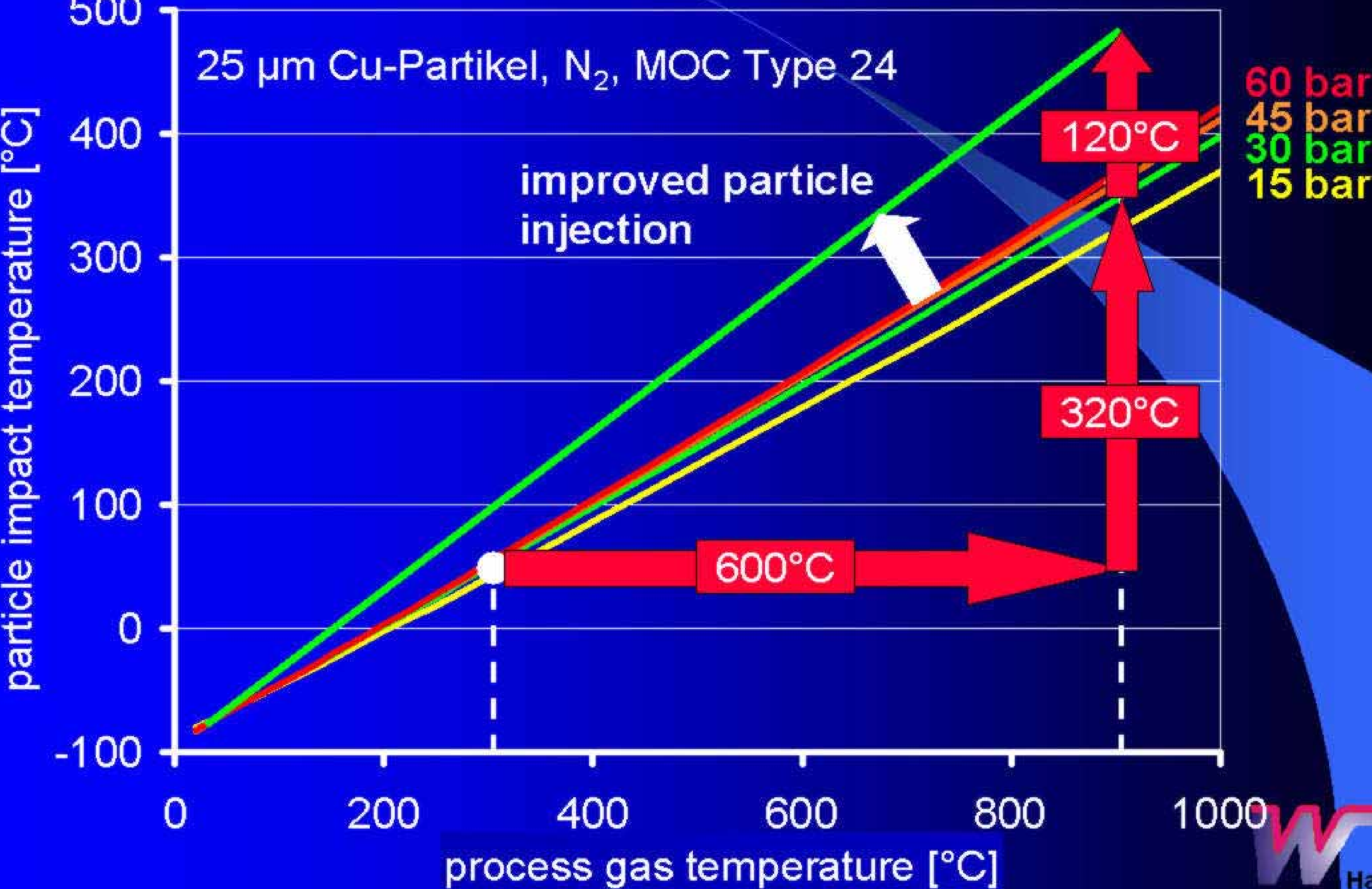
Higher Impact Temperature

by higher gas temperature and preheating



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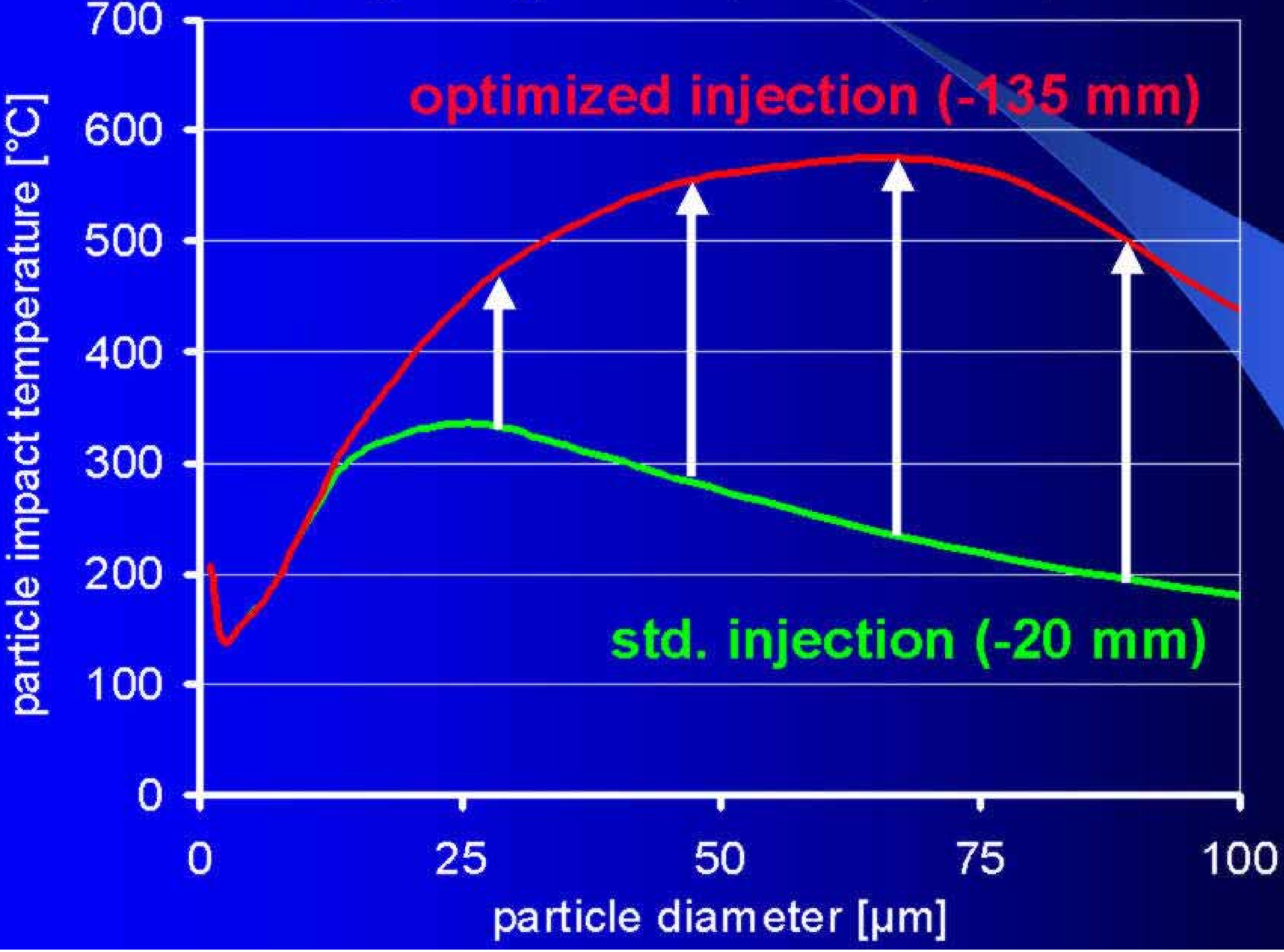
Optimized Particle Injection (Preheating) [4, 5]
>> higher impact temperatures

process gas N_2, 40 bar, 900°C, Cu-particles



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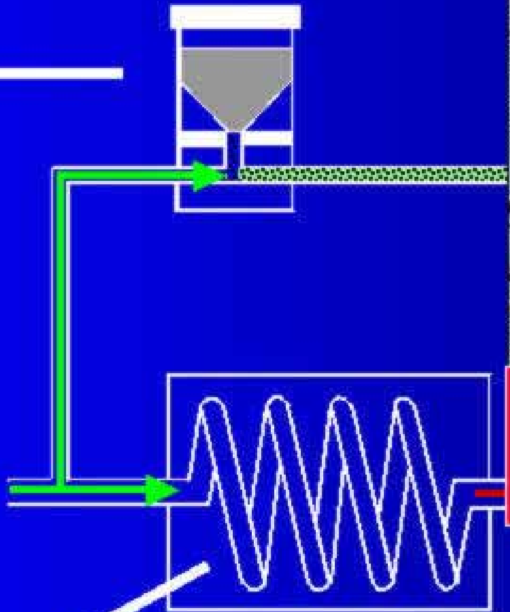
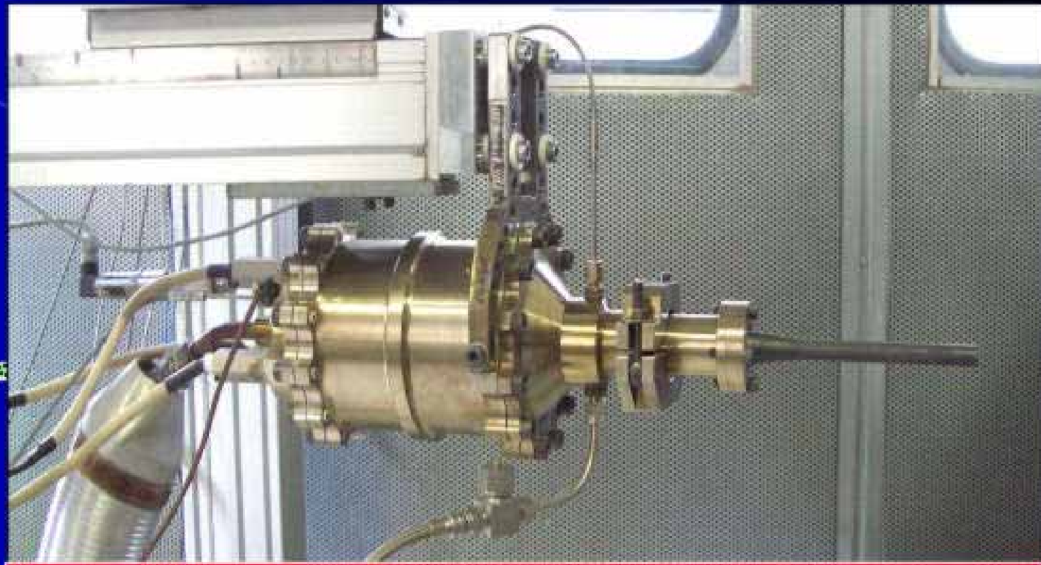
System for Extended Conditions [4, 5]:

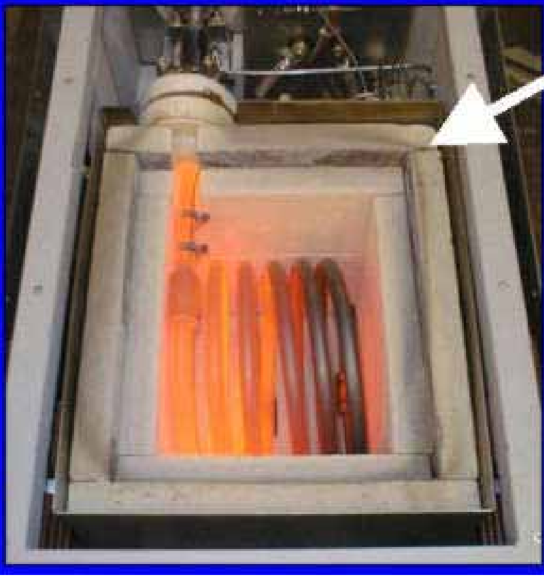
powder feeder
45 bar





New spray gun with 17 kW heater
40 bar, 900 °C

gas supply
45 bar



heater:
~ 25 kW, 650 °C

wide range of process conditions:

✓ flexible range of impact conditions

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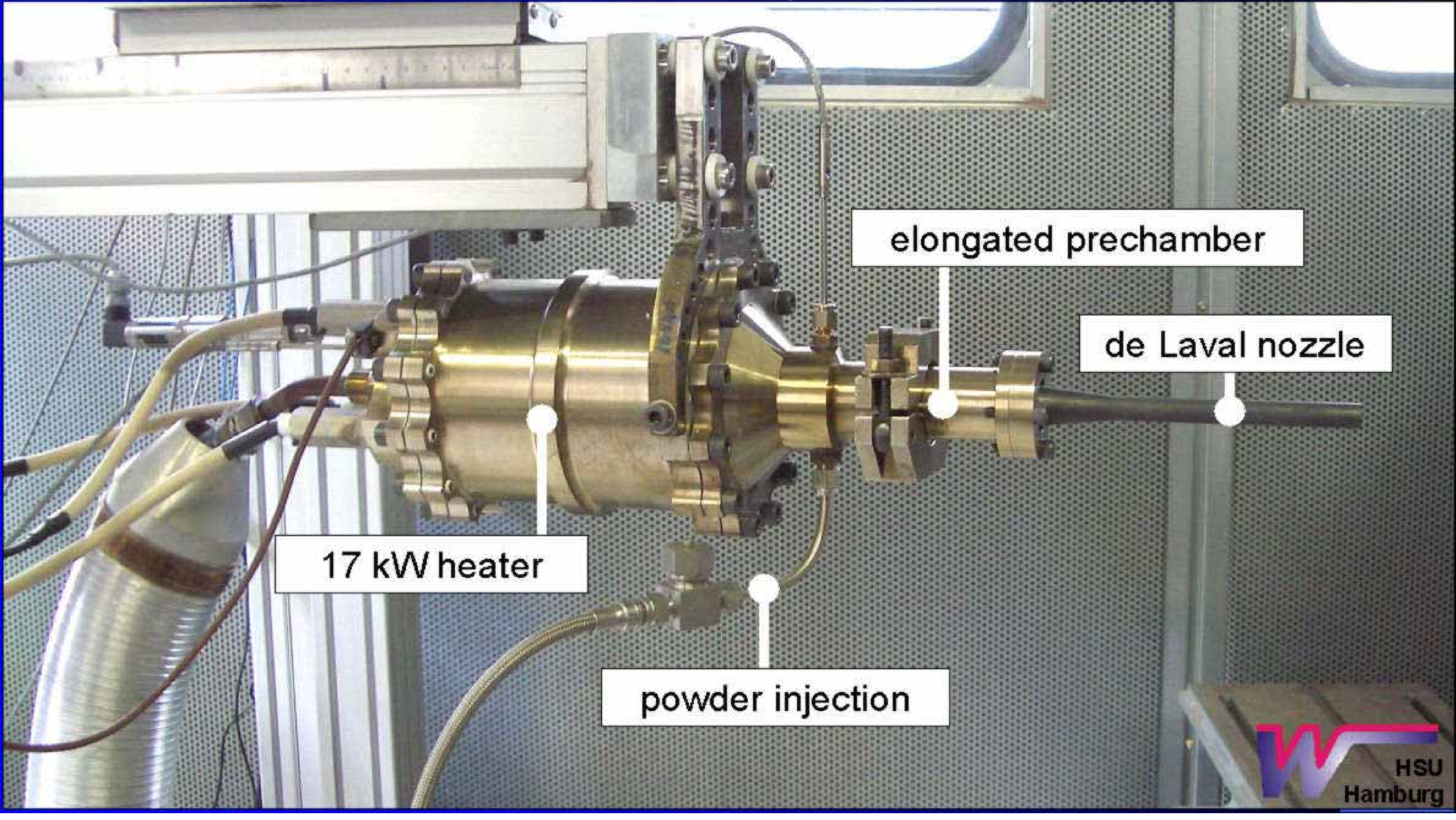
New Spray Gun Developed at HSU Hamburg

prototype of the “Active Jet of K4000”



Investigation of Inter-Particle Bonding

Micro-**F**lat-**T**ensile-Test (MFT-test), strength and ductility of coatings

Micro Tensile Sample:

sample preparation:	spark erosion
initial coating thickness:	2 - 3 mm
sample size:	28 mm x 5 mm x 1 mm
gauge length:	9 mm
strain measurement:	laser extensometer

Micro Flat Tensile test

(MFT-test)

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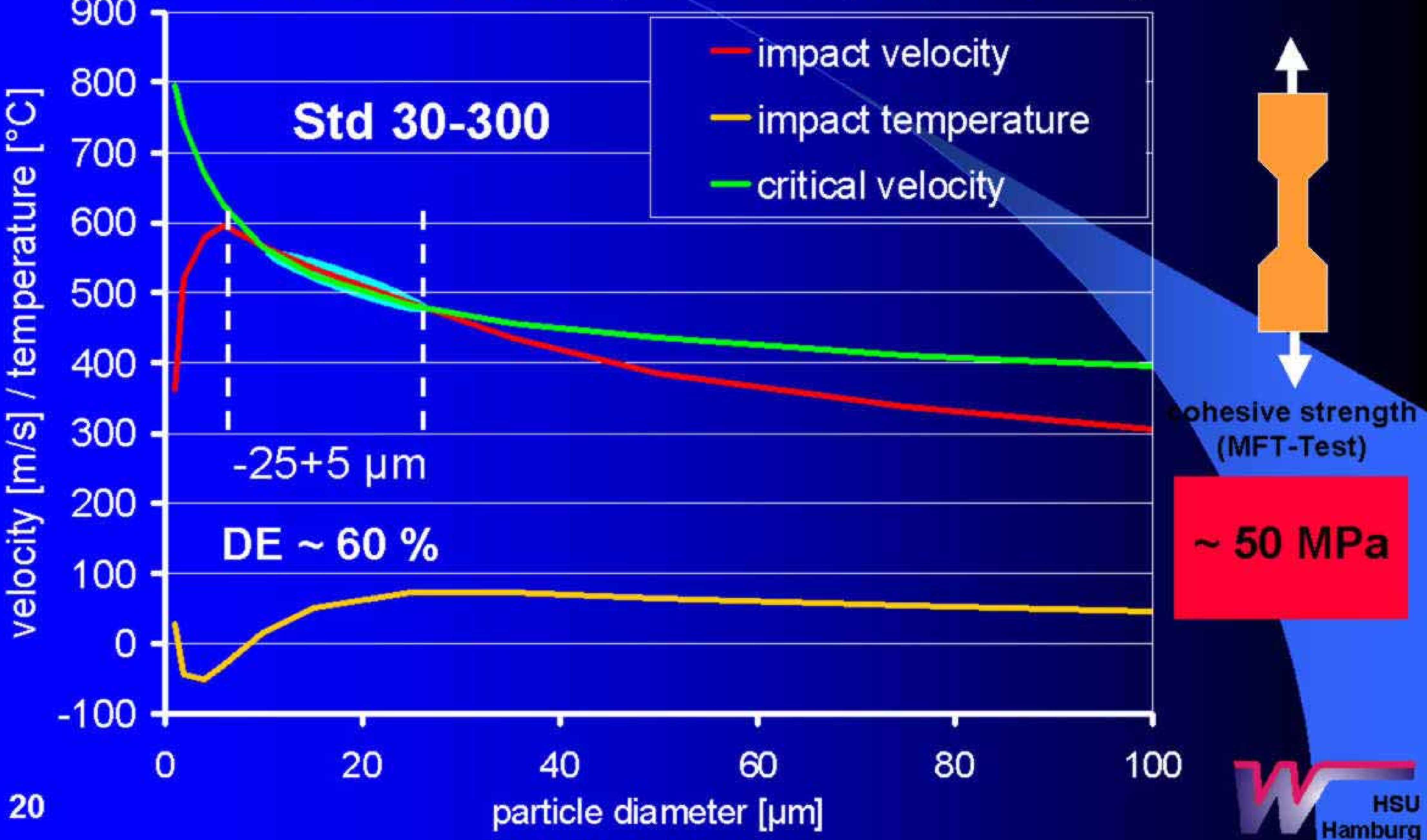
Cold Spraying of Copper, State 2001 [4, 5]

critical velocity and impact velocity



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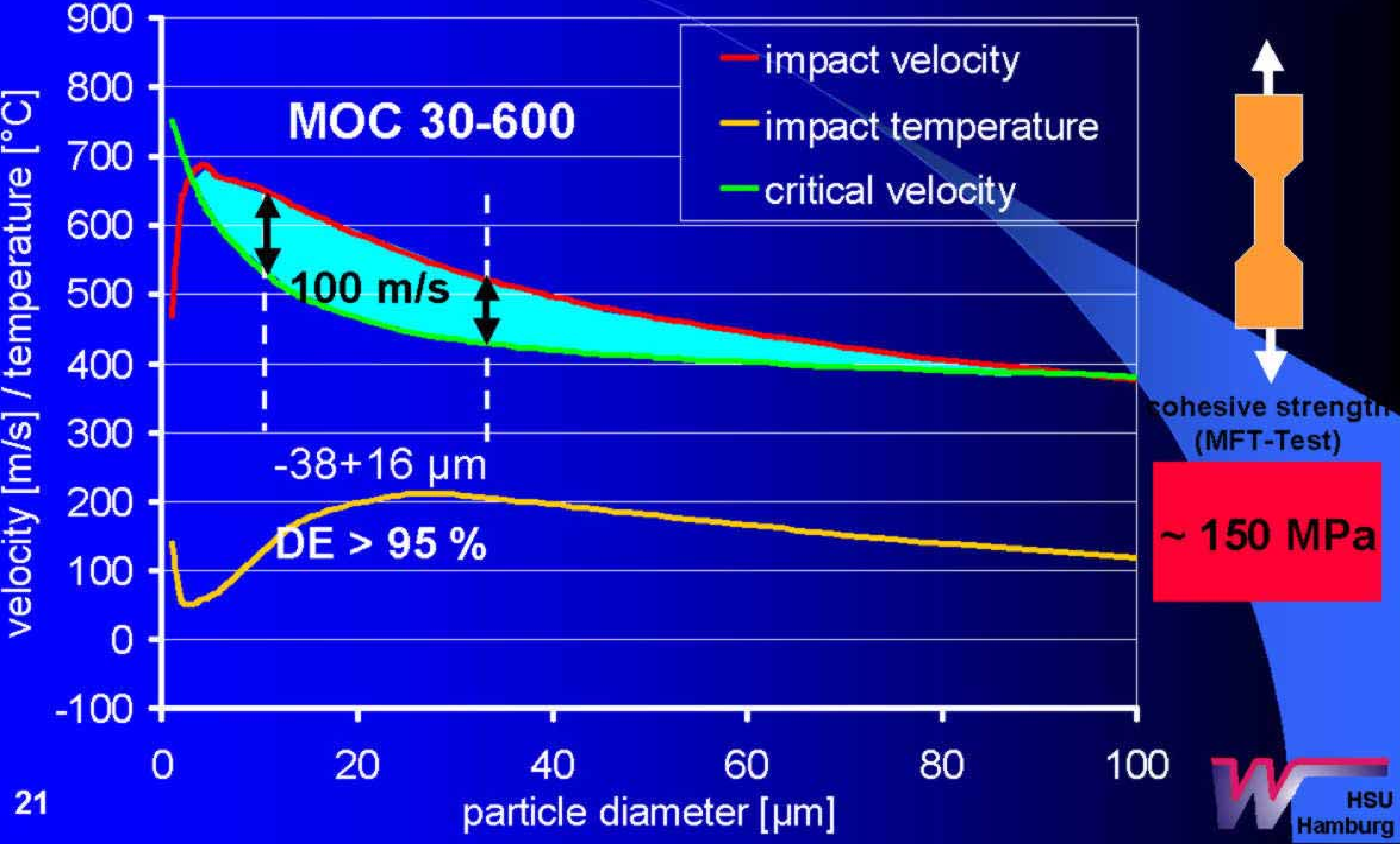
Cold Spraying of Copper, **State 2004** [4, 5]

distinct exceeding of **critical velocity** by **impact velocity**



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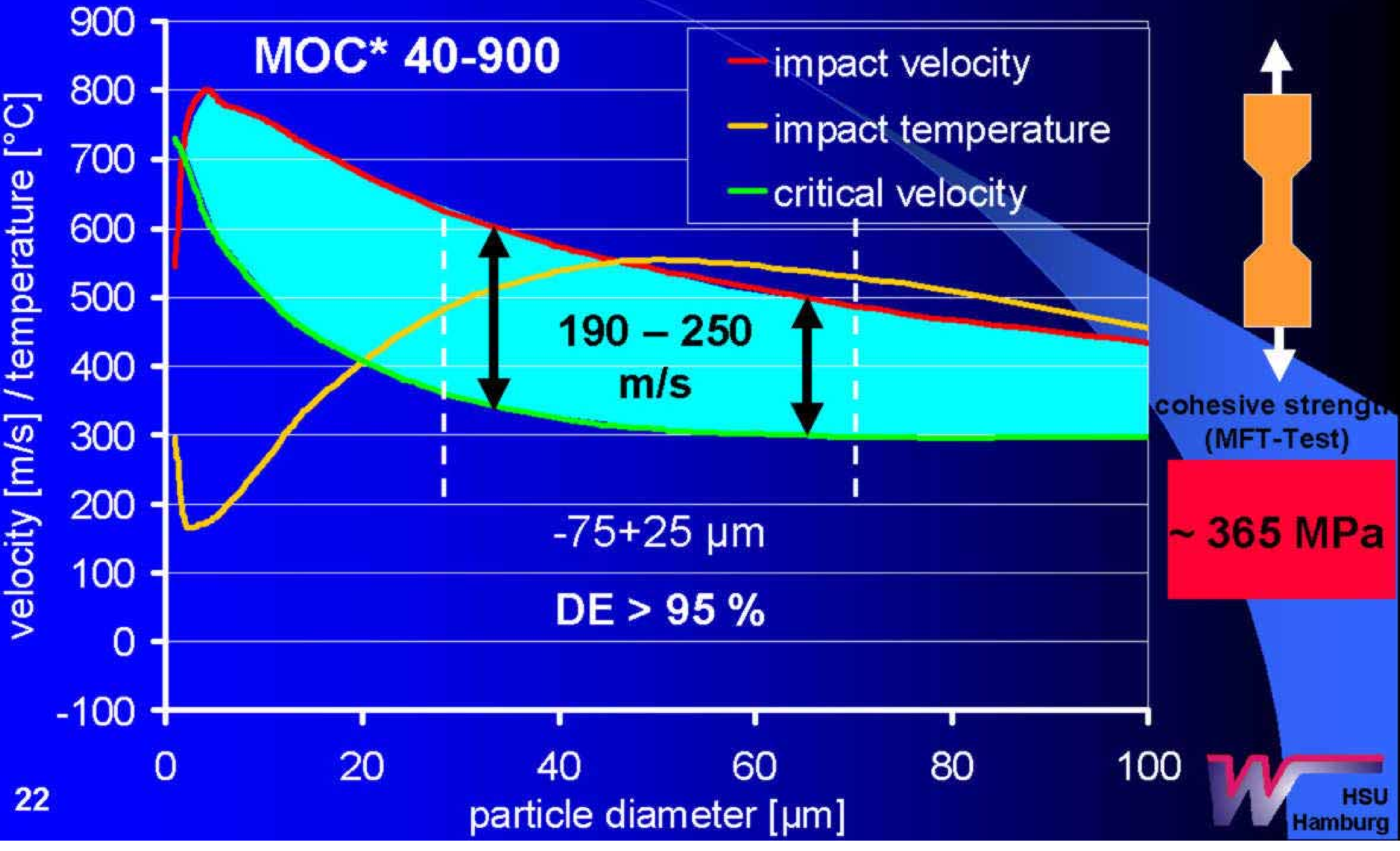
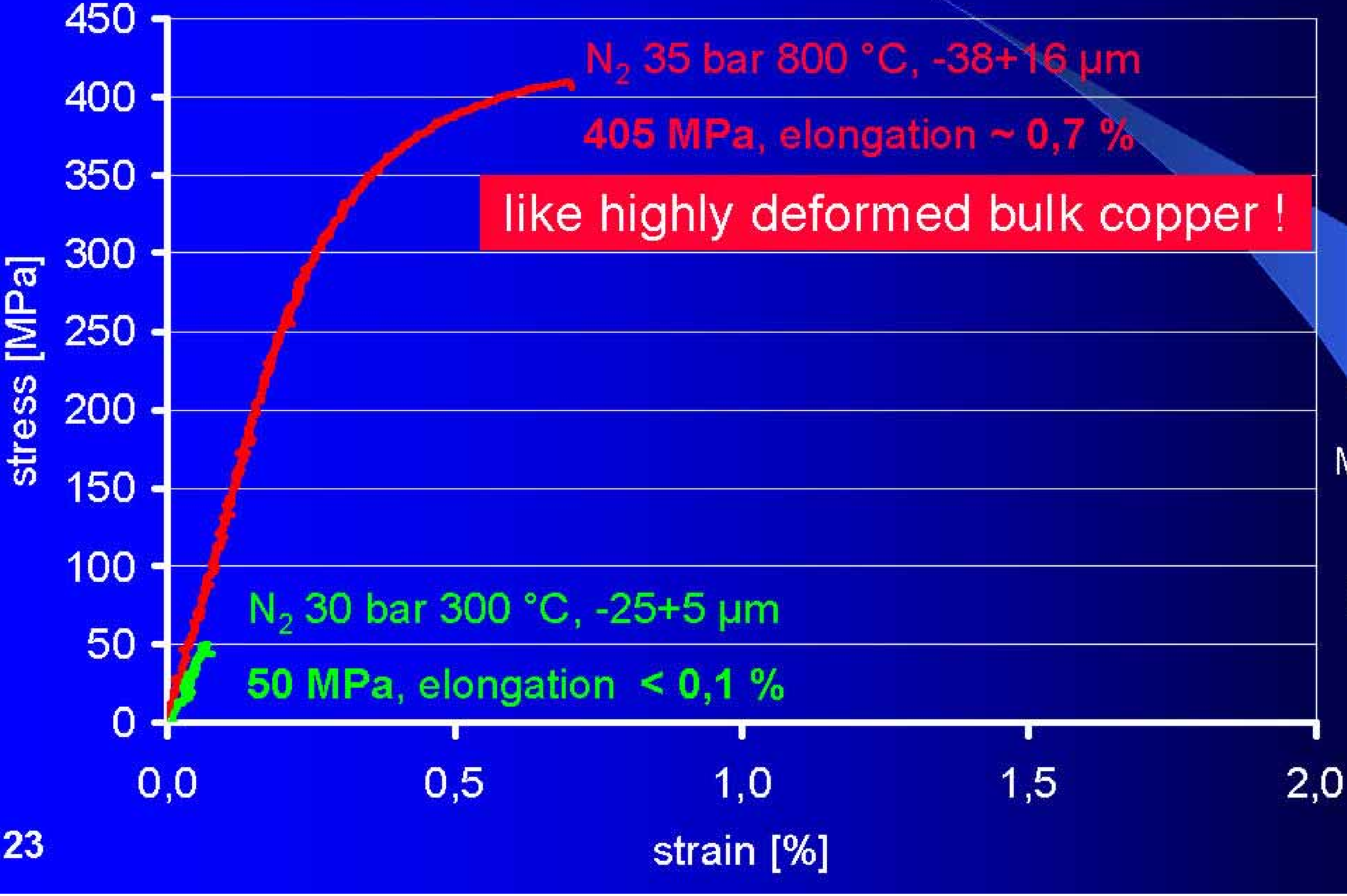
Cold Spraying of Copper, **State 2007** [4, 5]

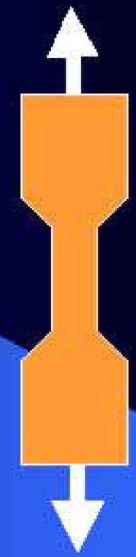
distinct exceeding of **critical velocity** by **impact velocity**



Strength and Ductility, MFT-Test [4, 5]

old and **new** parameter setting for Cu





Micro Flat Tensile test

(MFT-test)

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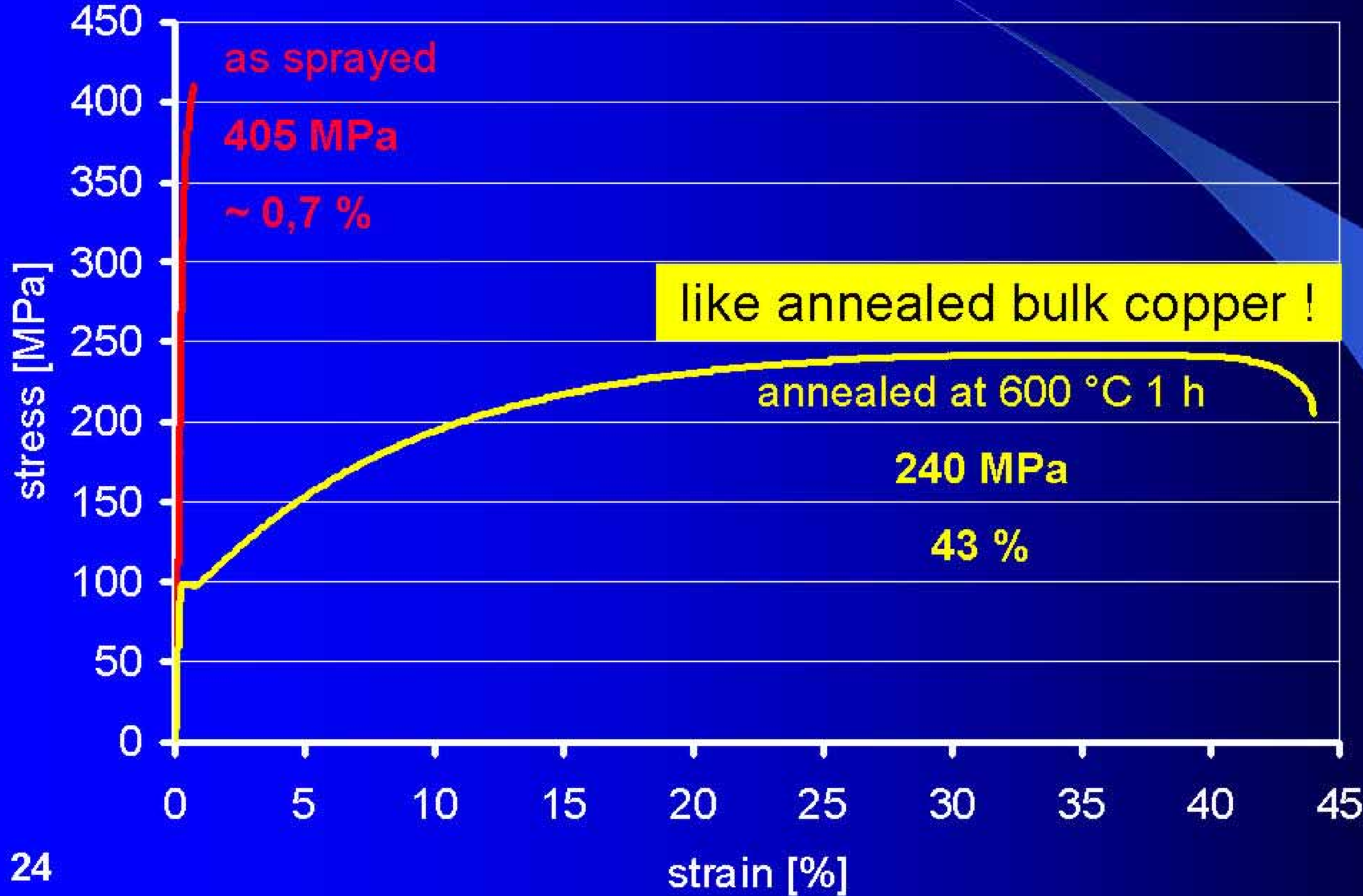
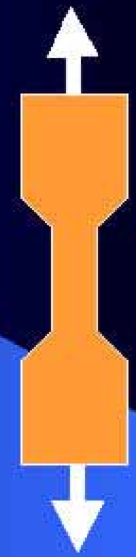
Strength and Ductility, MFT-Test [4, 5]

new parameter setting for Cu, coating annealed





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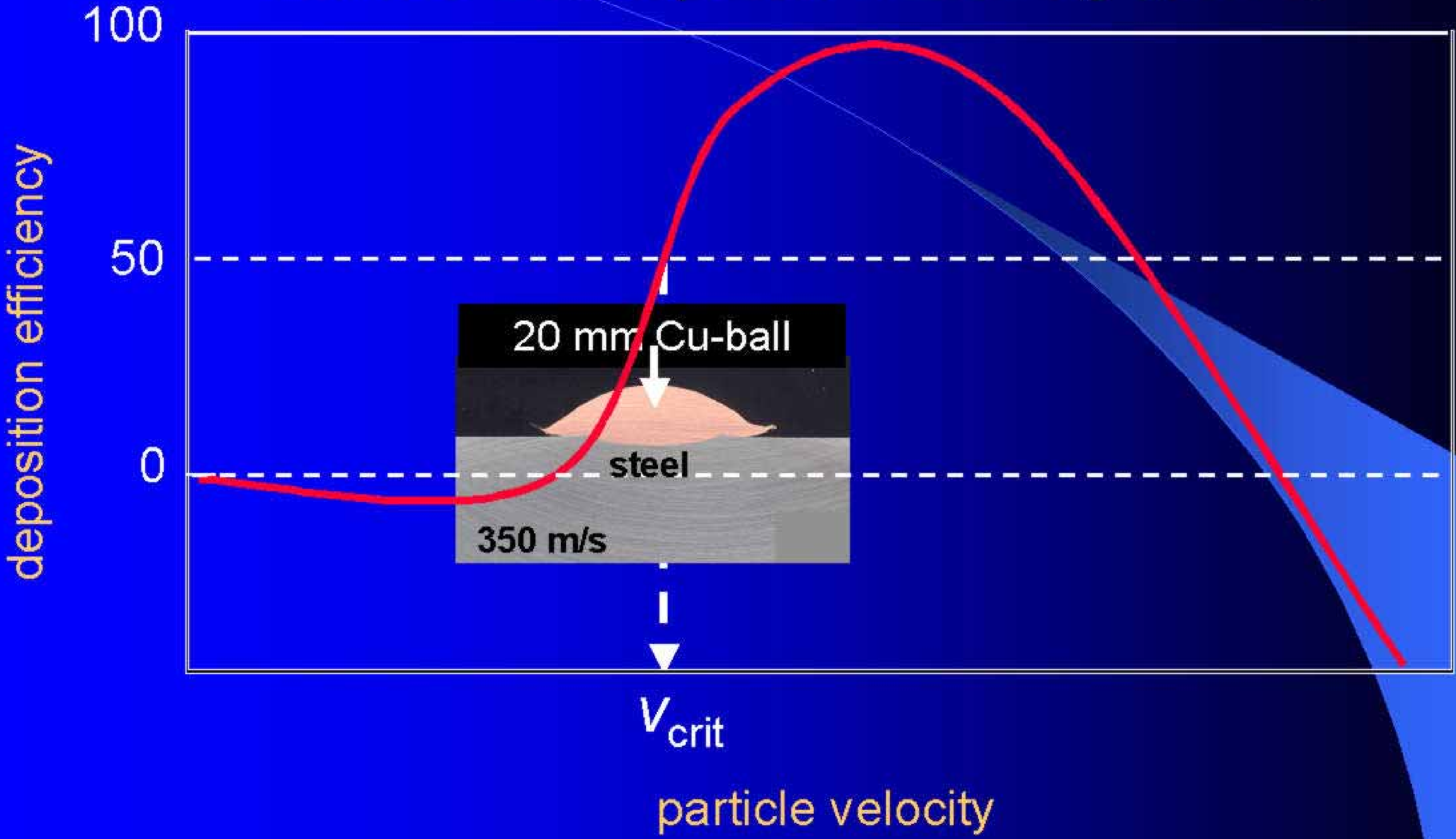
Effect of Impact Velocity [3, 4, 5]



- at a certain velocity particles start to stick
- ✓ at a <u>DE of 50 %</u> the <u>critical velocity</u> is defined

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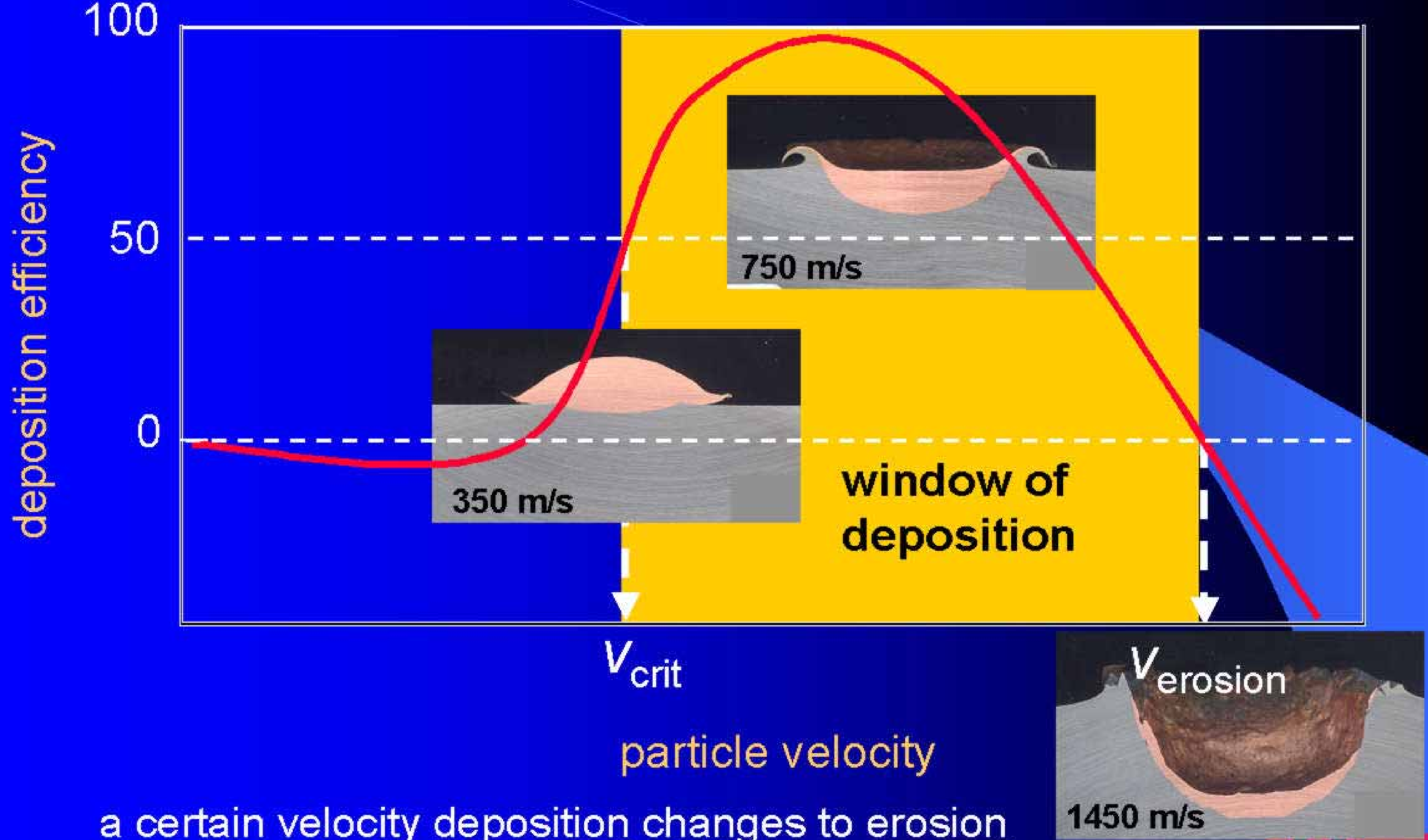
Parameter Window for Deposition [3, 4, 5]

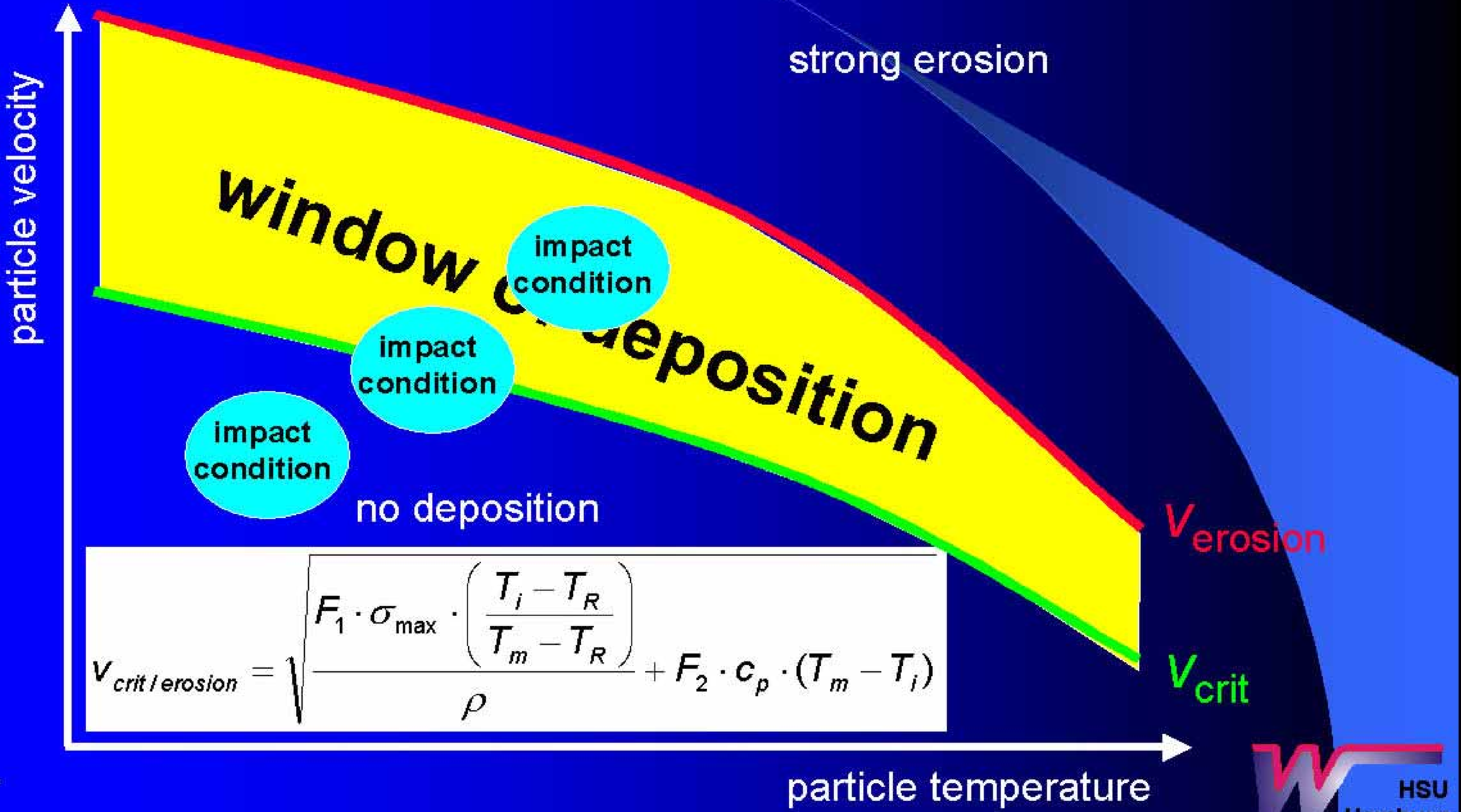


a certain velocity <u>deposition</u> changes to <u>erosion</u>

✓ at this point (DE 0 %) the erosion velocity is defined

Parameter Window for Deposition [3]

prediction of optimal impact conditions



$$v_{crit/erosion} = \sqrt{\frac{F_1 \cdot \sigma_{max} \cdot \left(\frac{T_i - T_R}{T_m - T_R}\right)}{\rho} + F_2 \cdot c_p \cdot (T_m - T_i)}$$

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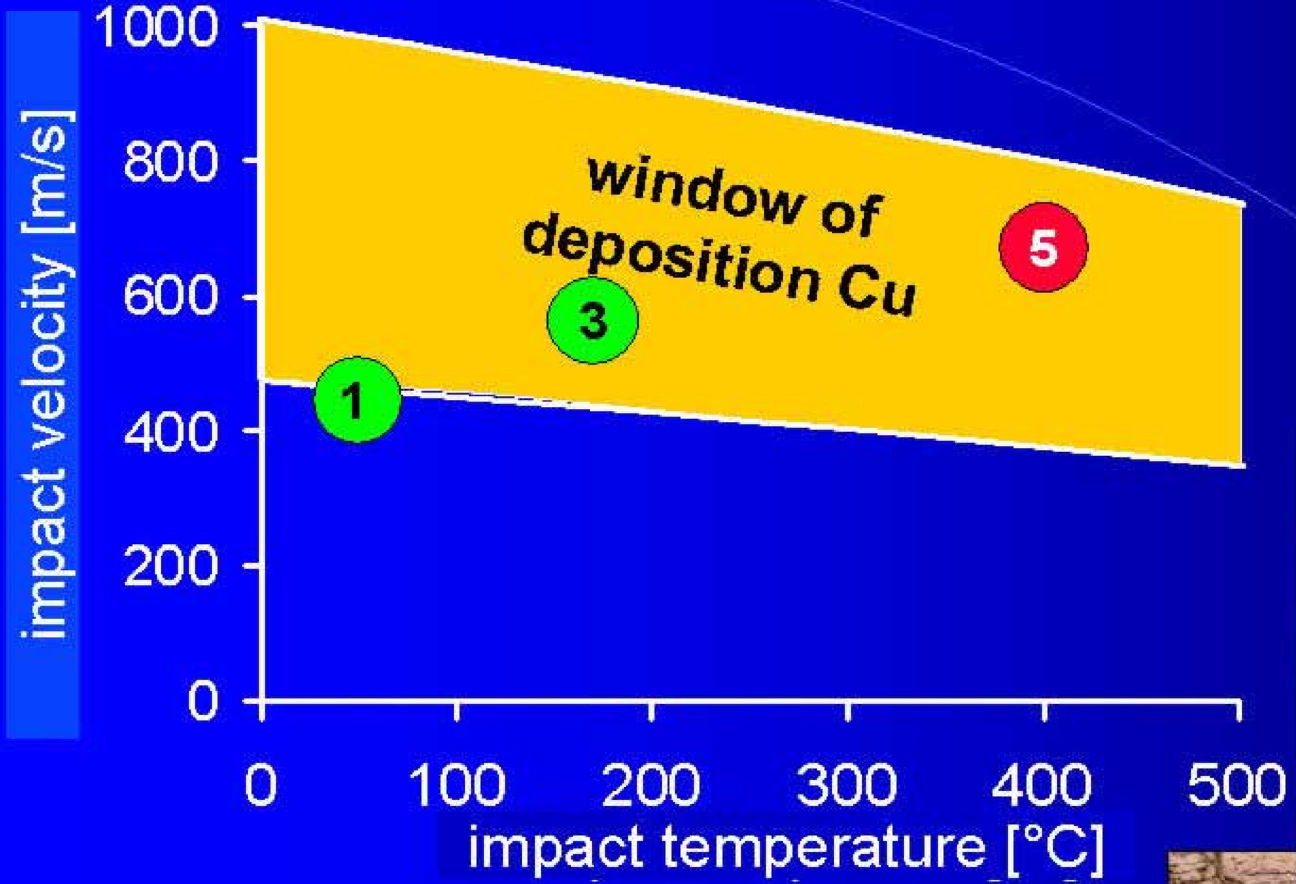
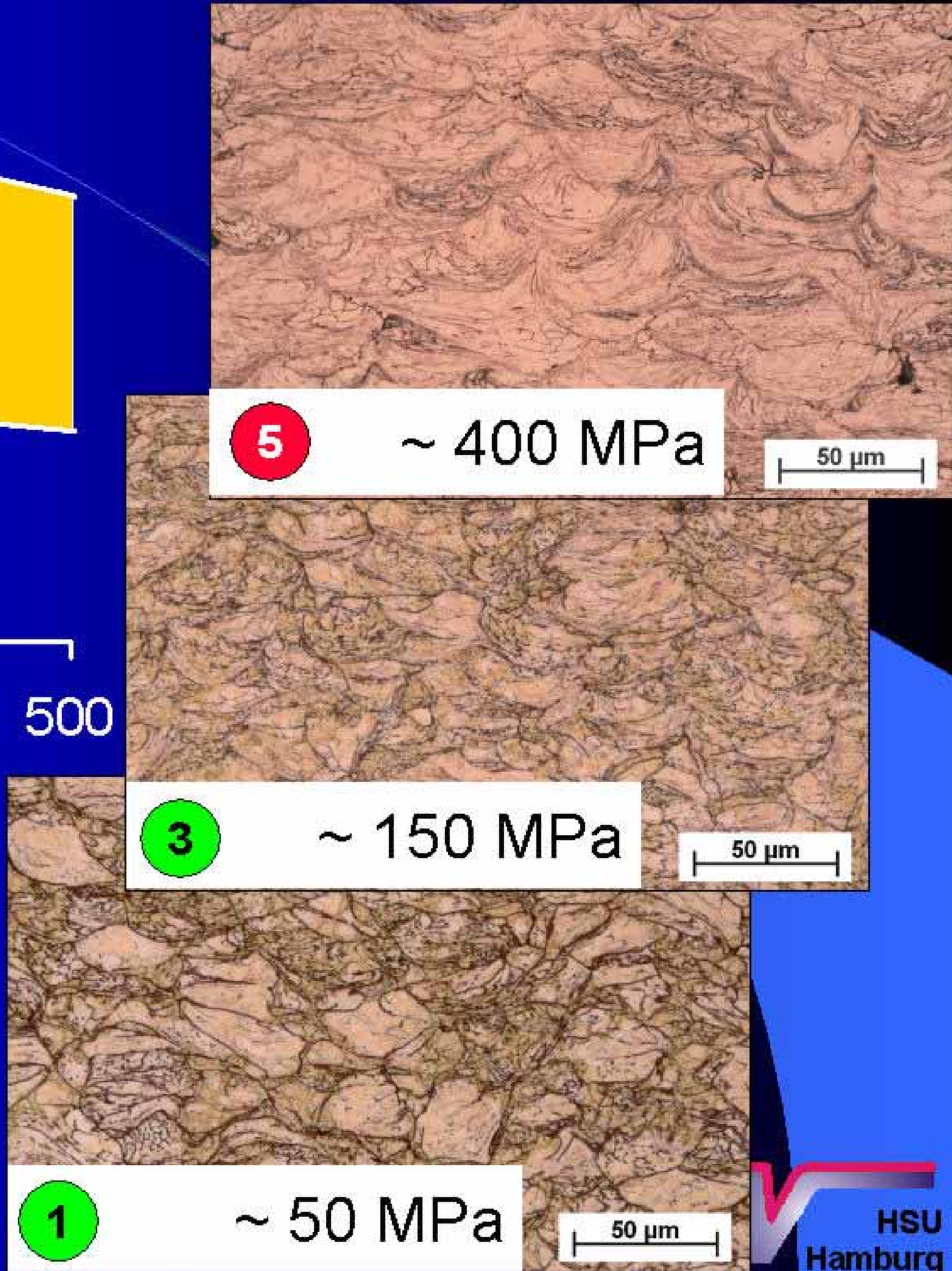
Impact Conditions, Microstructure, Properties [4, 5]





Kinetiks 3000:

1: steel nozzle Type 2 (2001)

3: WCCo nozzle Type 24 (2004)

New Equipment (Kinetiks 4000):

5: new spray gun (2006)

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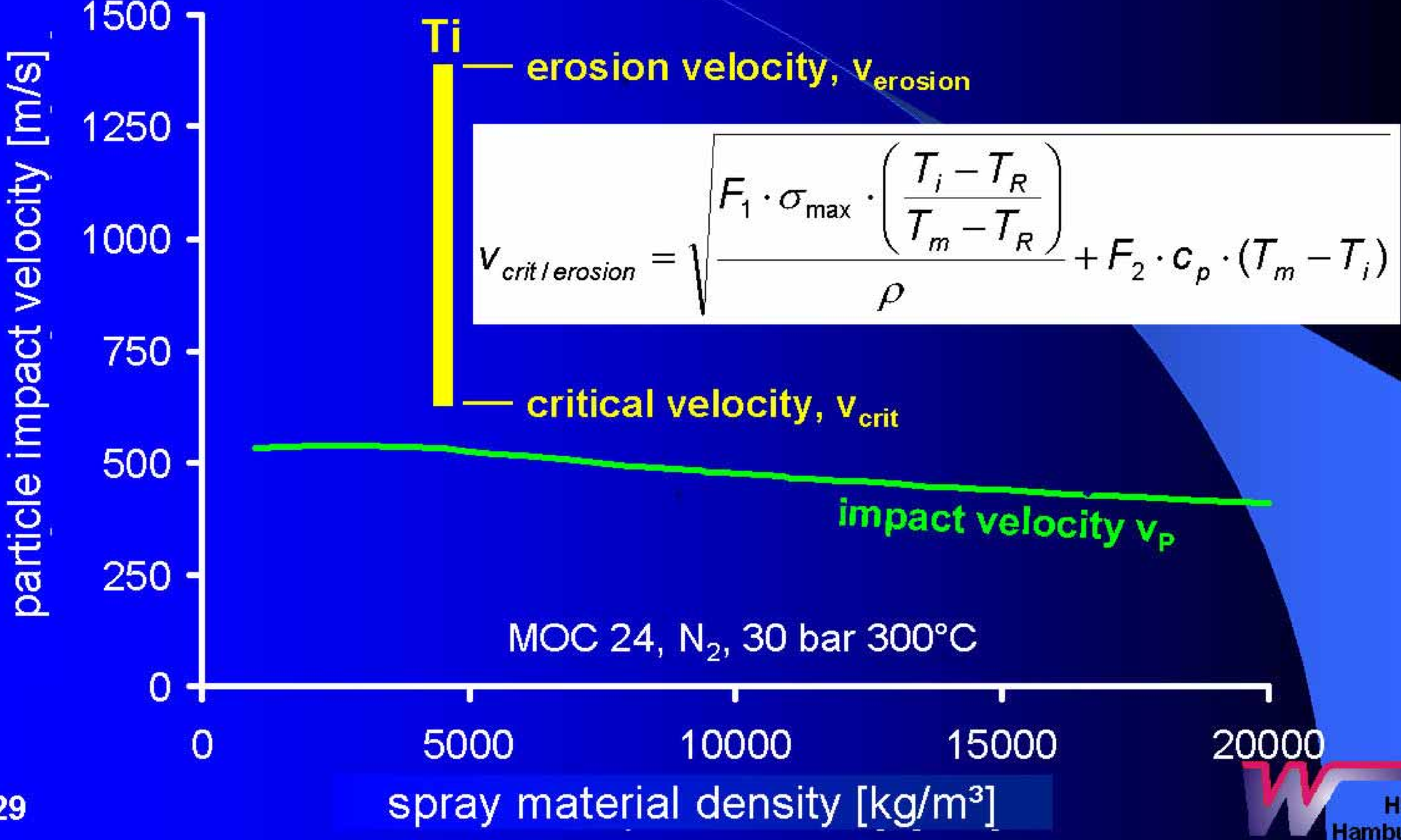
Window for Deposition [3, 5]

transfer of results to other materials, calculated for 25 µm particles



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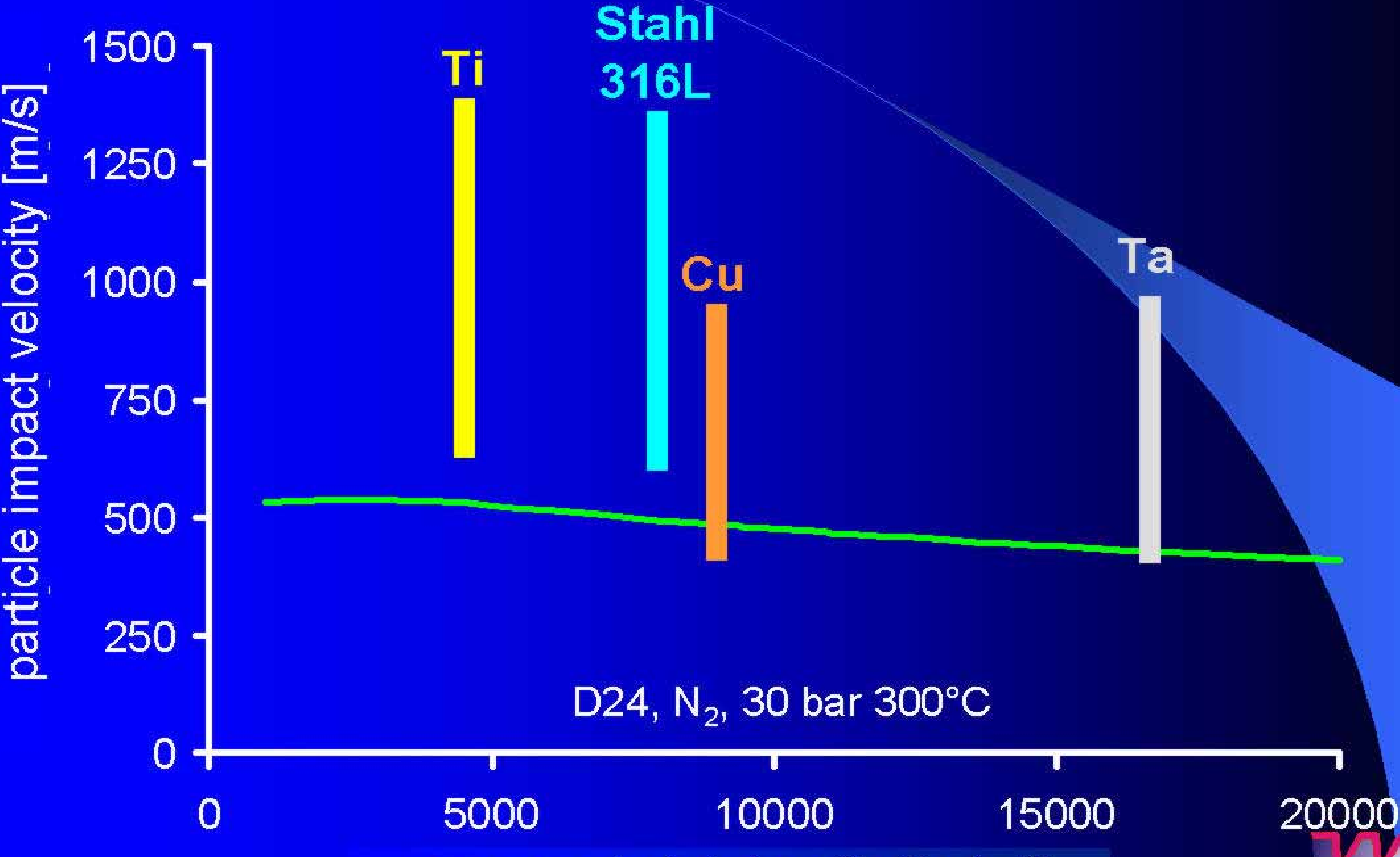
Window for Deposition, State 2001 [5]

transfer of results to other materials, calculated for 25 µm particles



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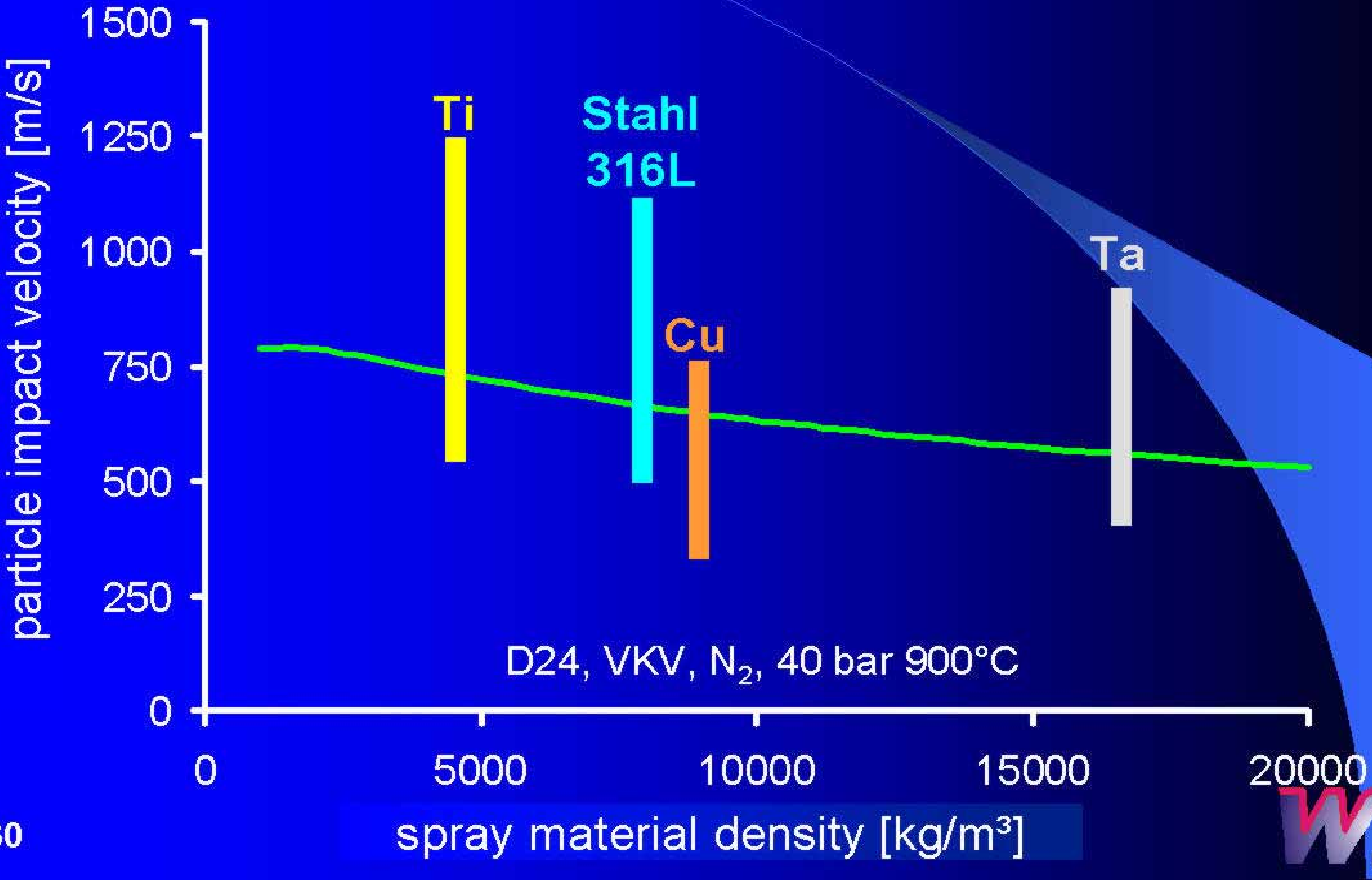
Window for Deposition, State 2007 [5]

transfer of results to other materials, calculated for 25 µm particles



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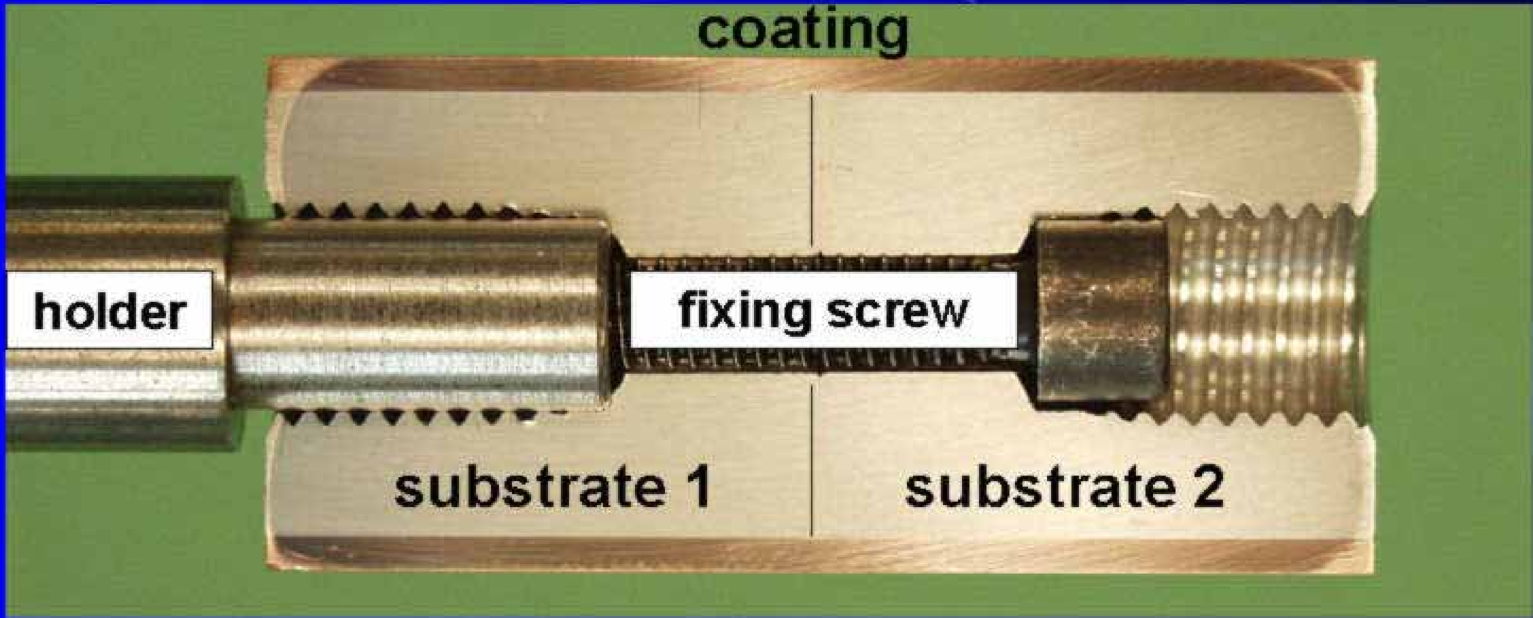
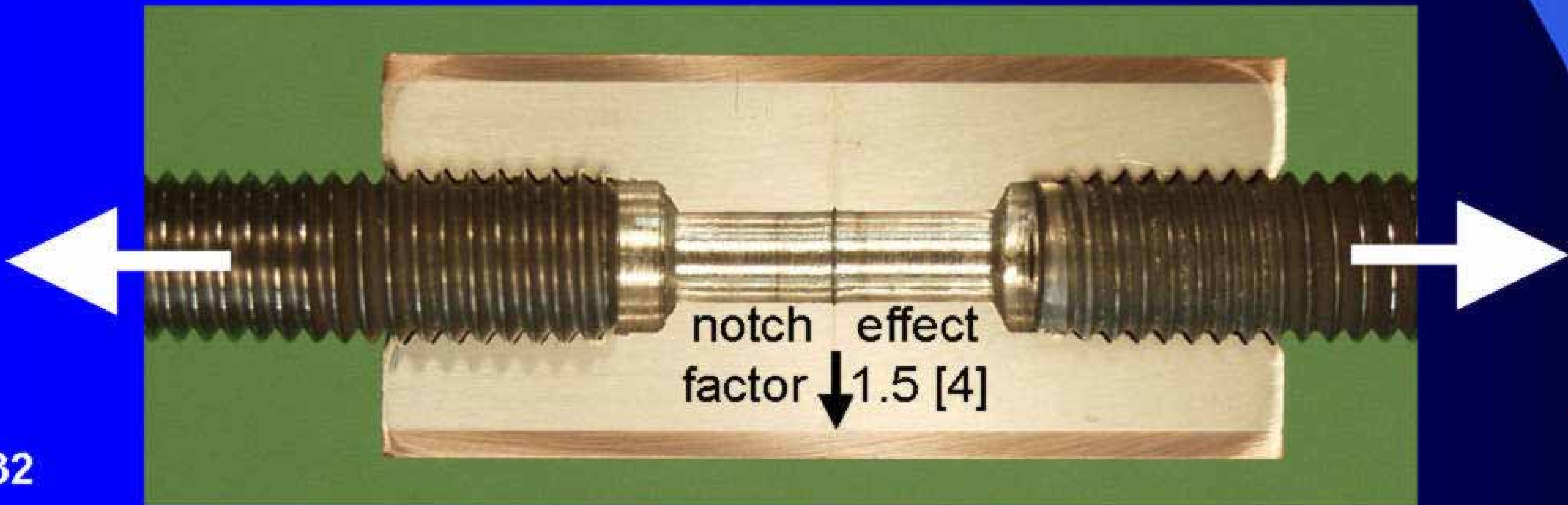
Cohesive Strength of Coatings [3, 4, 5]

Tubular-Coating-Tensile-Test (TCT-Test)





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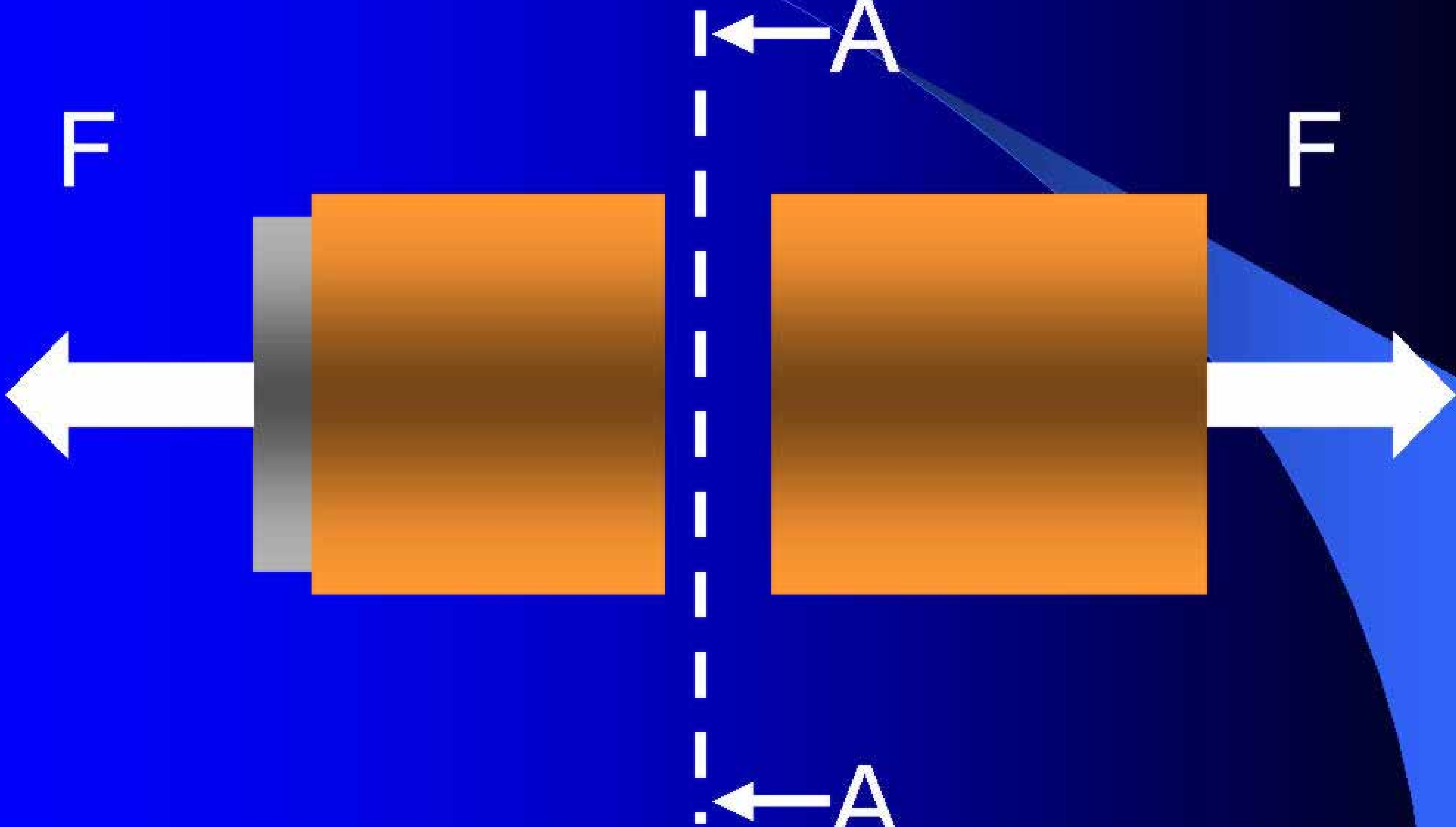
Cohesive Strength of Coatings

Tubular-Coating-Tensile-Test (TCT-Test)



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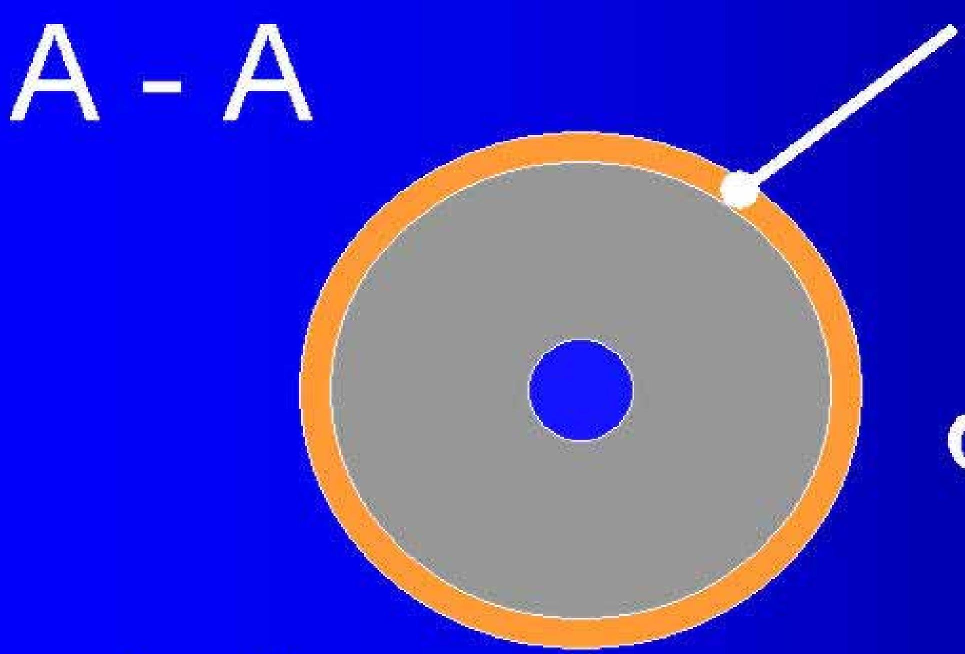
Cohesive Strength of Coatings

Tubular-Coating-Tensile-Test (TCT-Test)



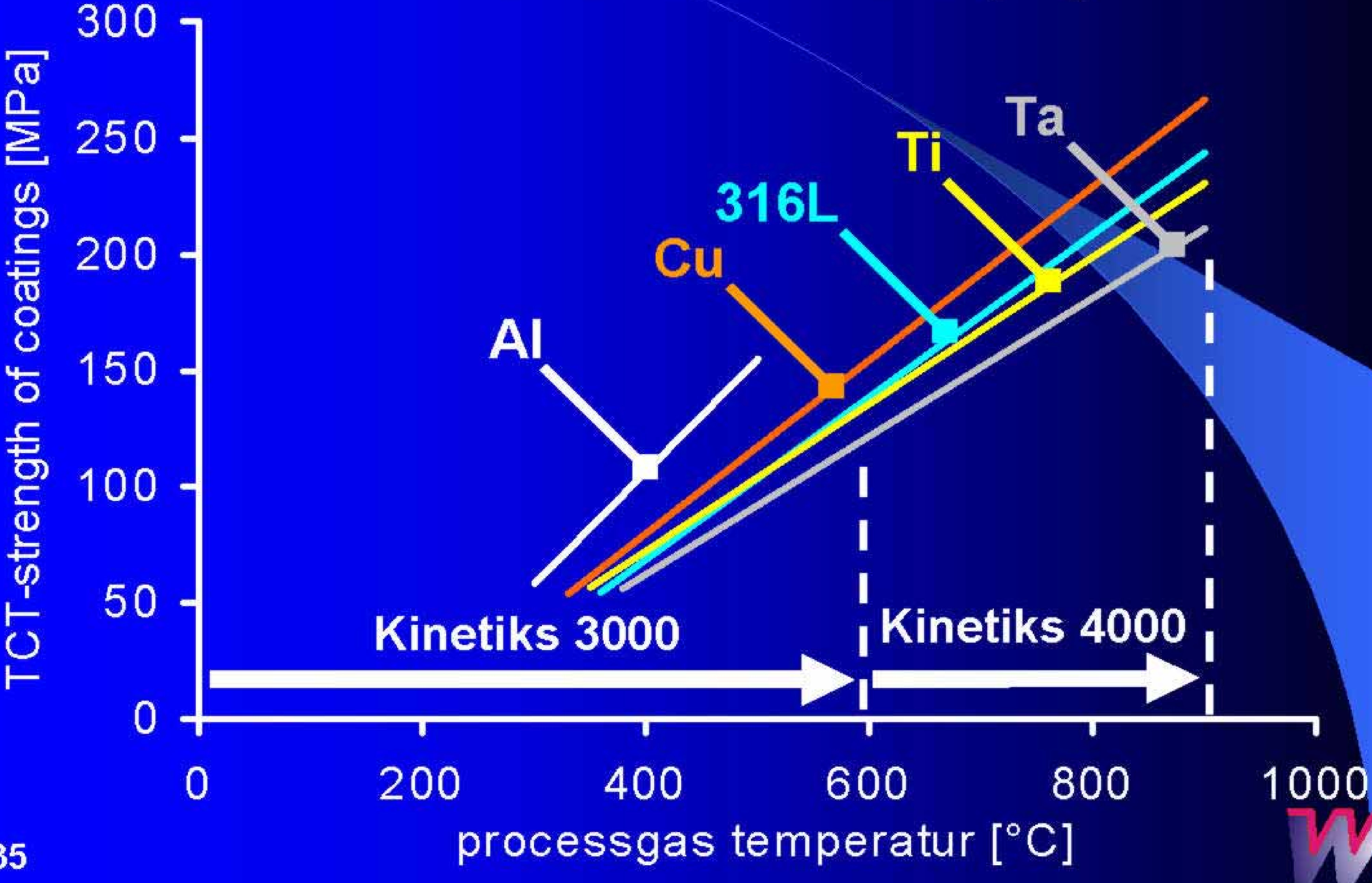
$$\sigma_{TCT} = F/A$$

<u>advantages:</u>

- ✓ easy to perform
- ✓ quick evaluation
- ✓ same equipment than for the bond strength
- ✓ ideal for process control and process optimization

Cohesive Strength of Coatings (TCT-Test)

measured trend lines for different spray materials



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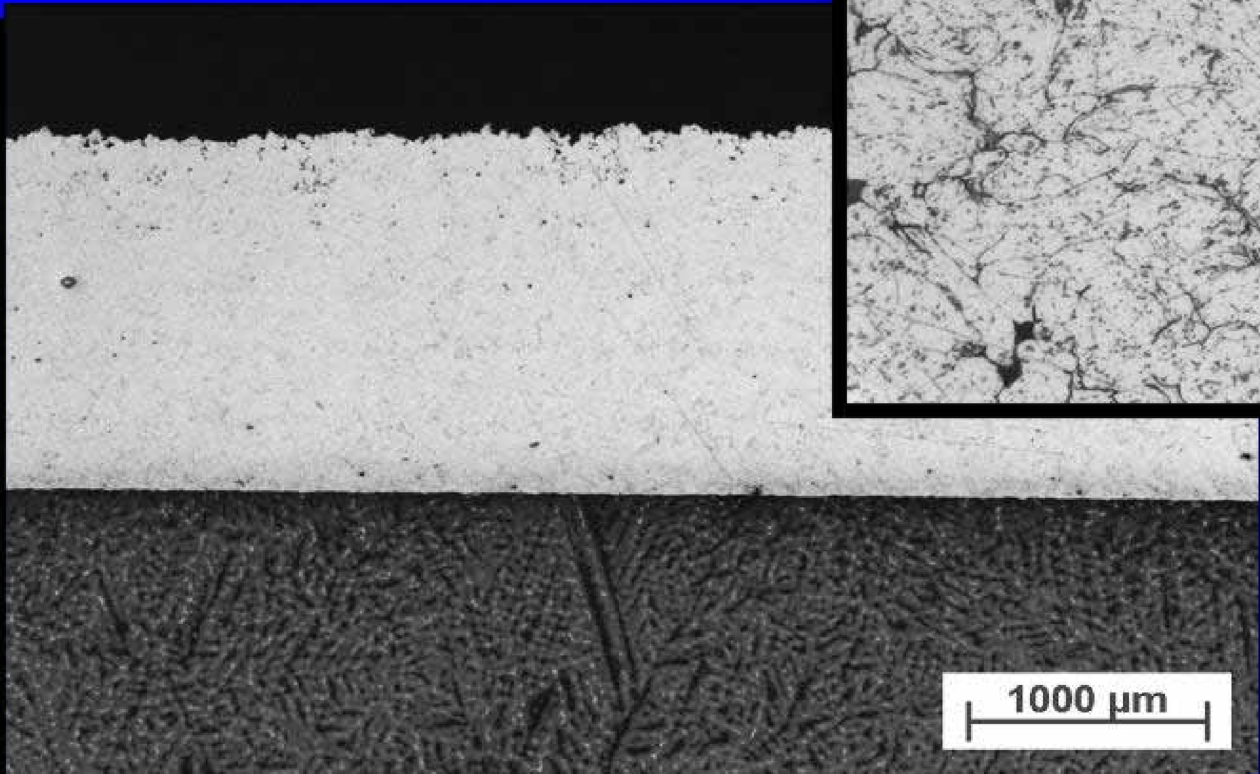
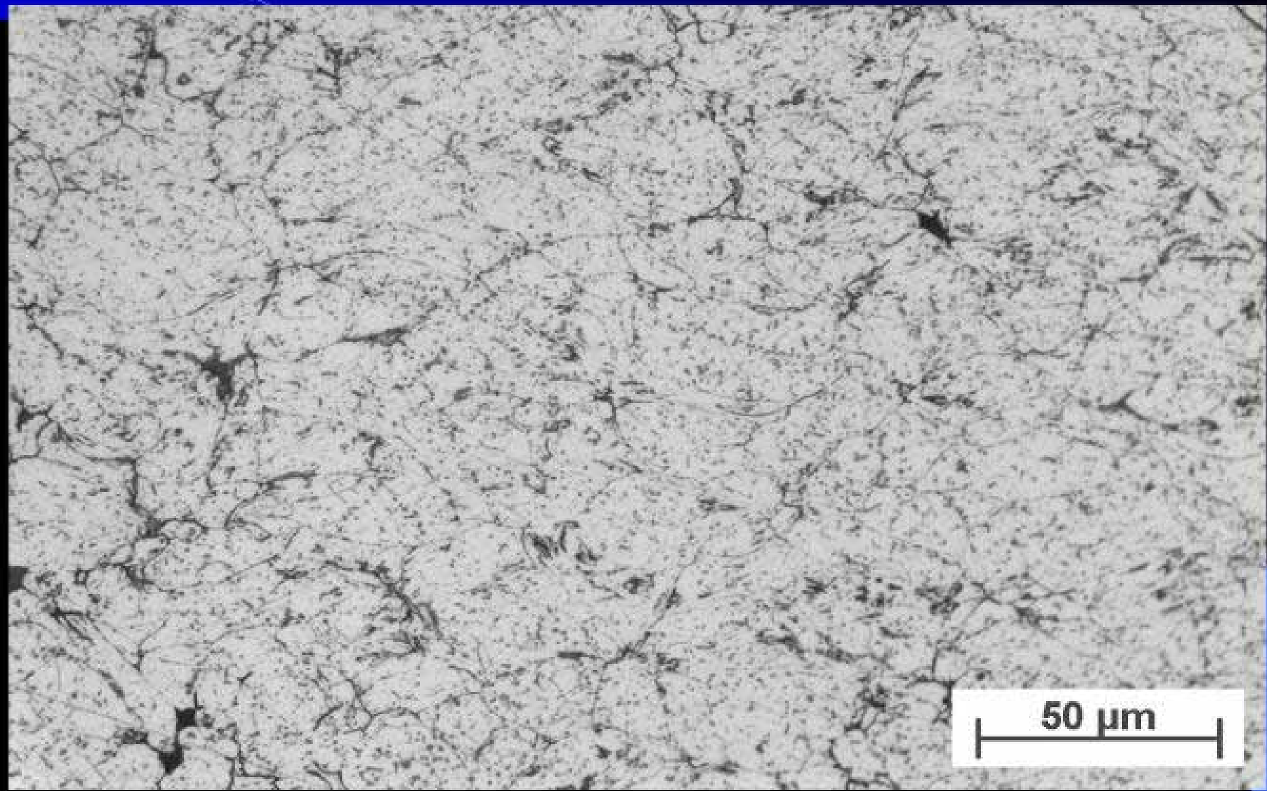
Al Coating (N_2)

TCT-test: 130 MPa





etched

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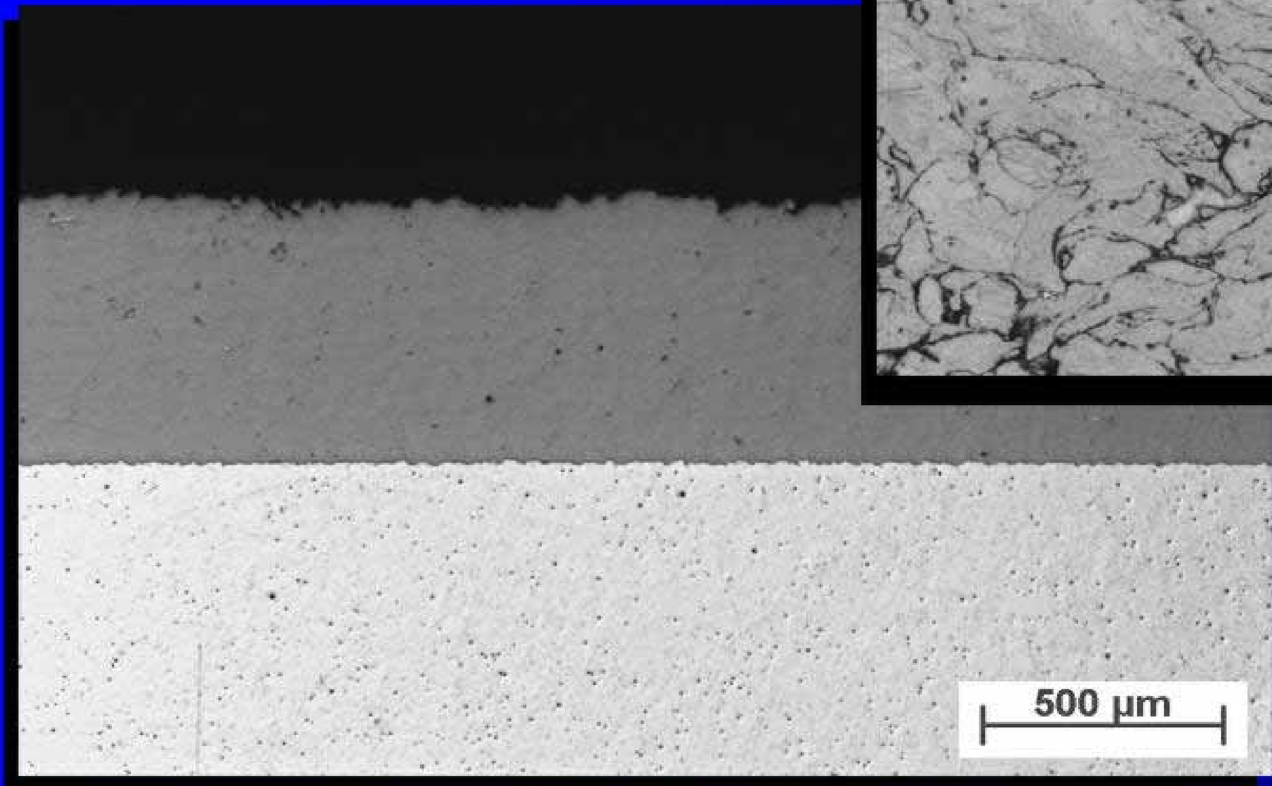
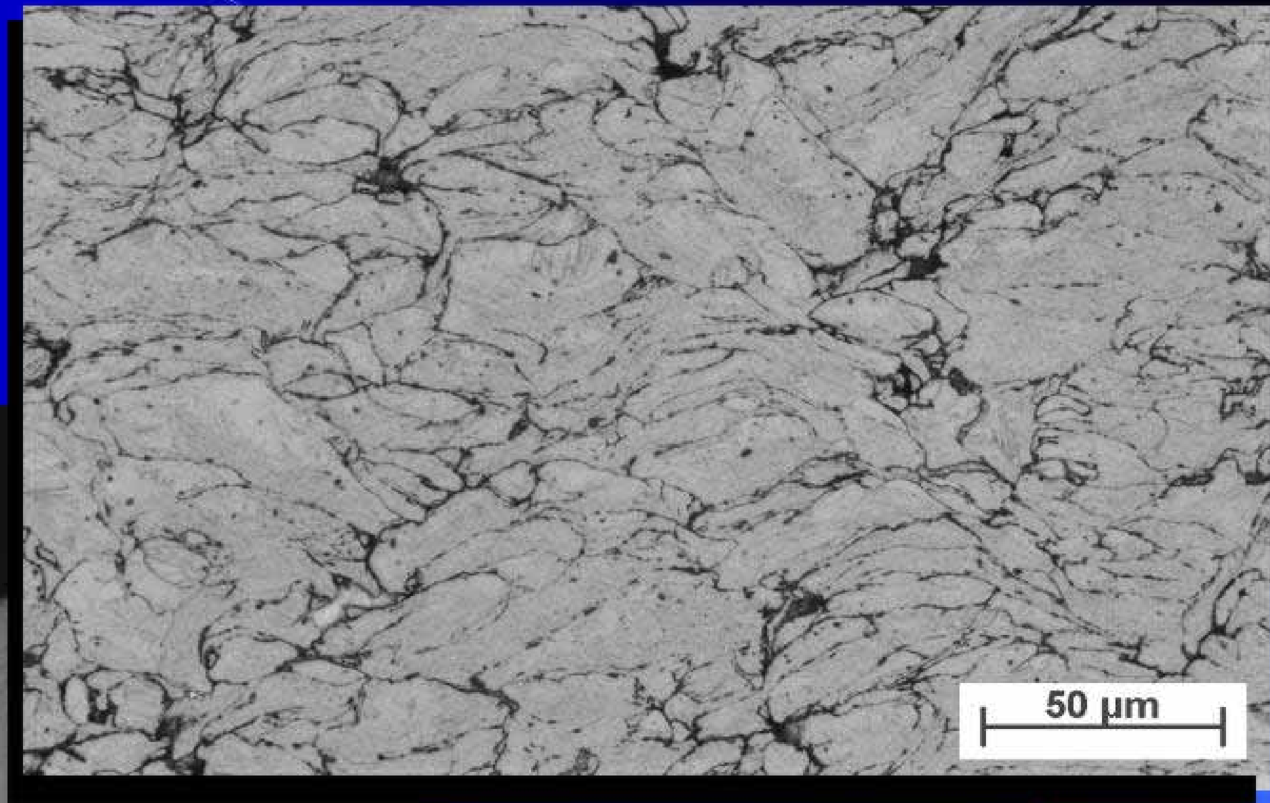
Ti Coating (N_2)

TCT-test: 225 MPa





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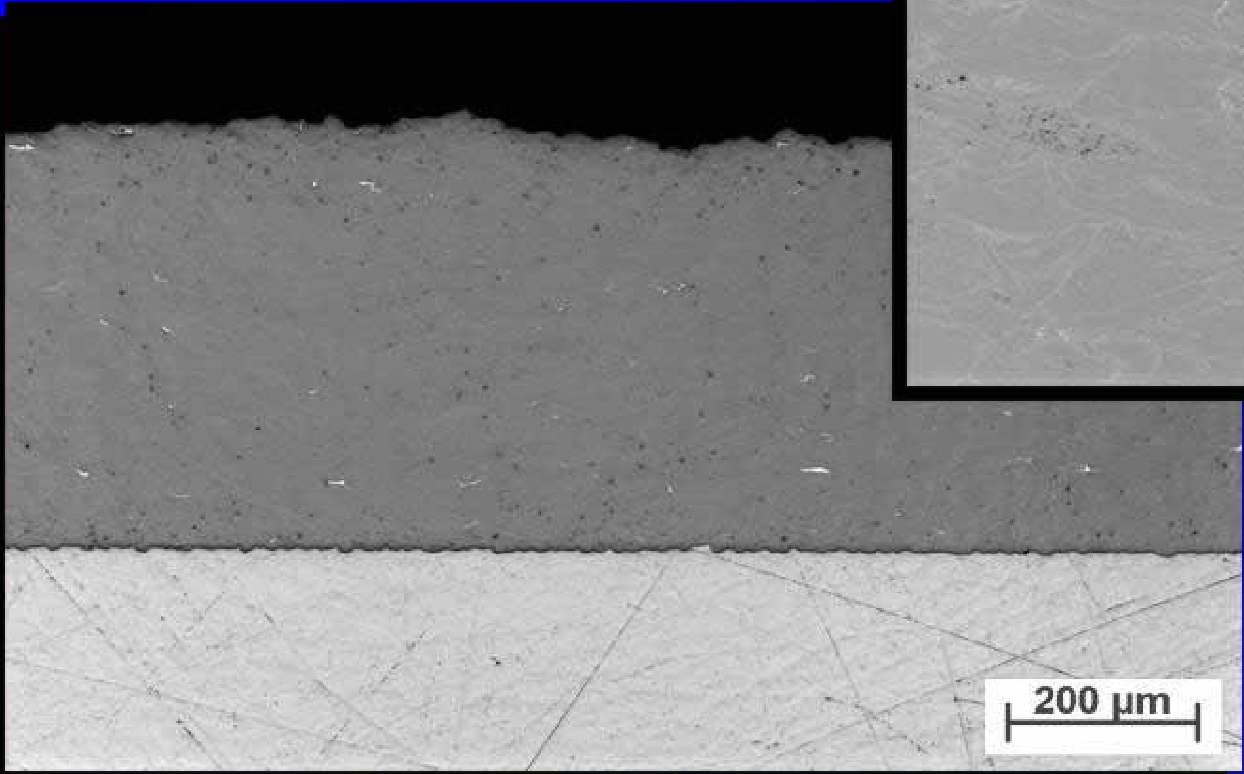
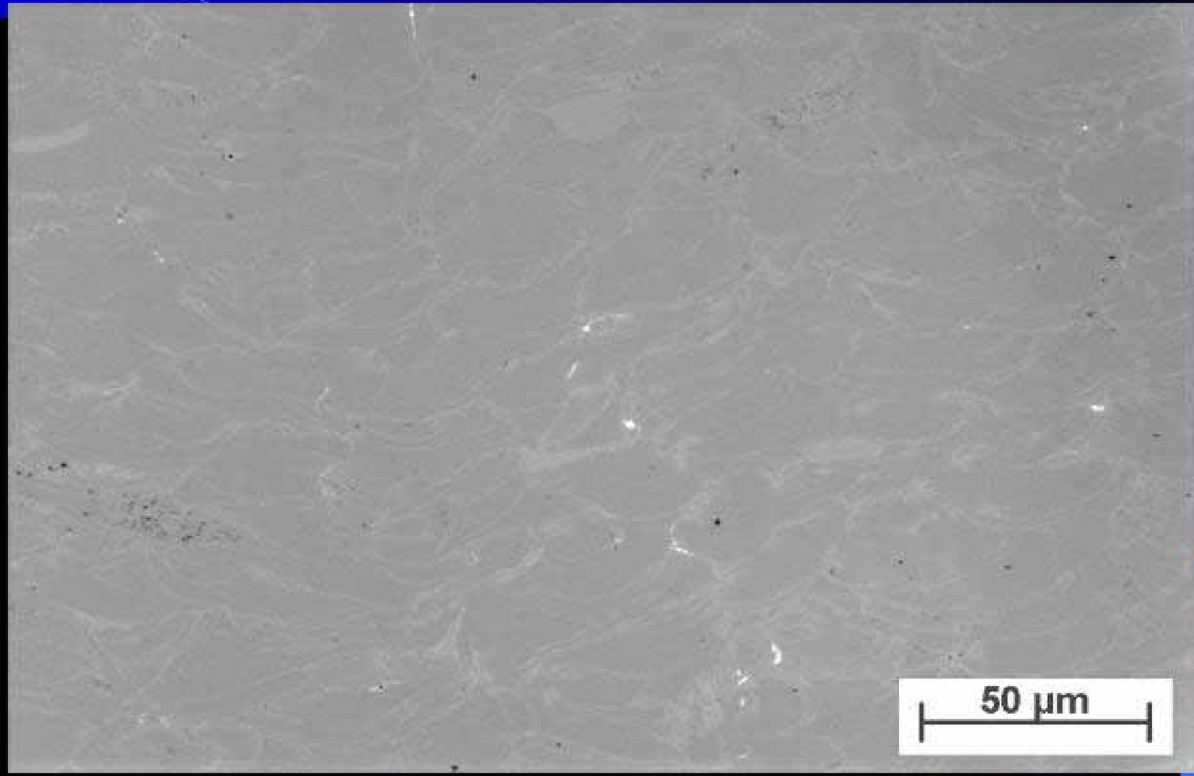
Ta Coating (N_2)

TCT-test: 210 MPa





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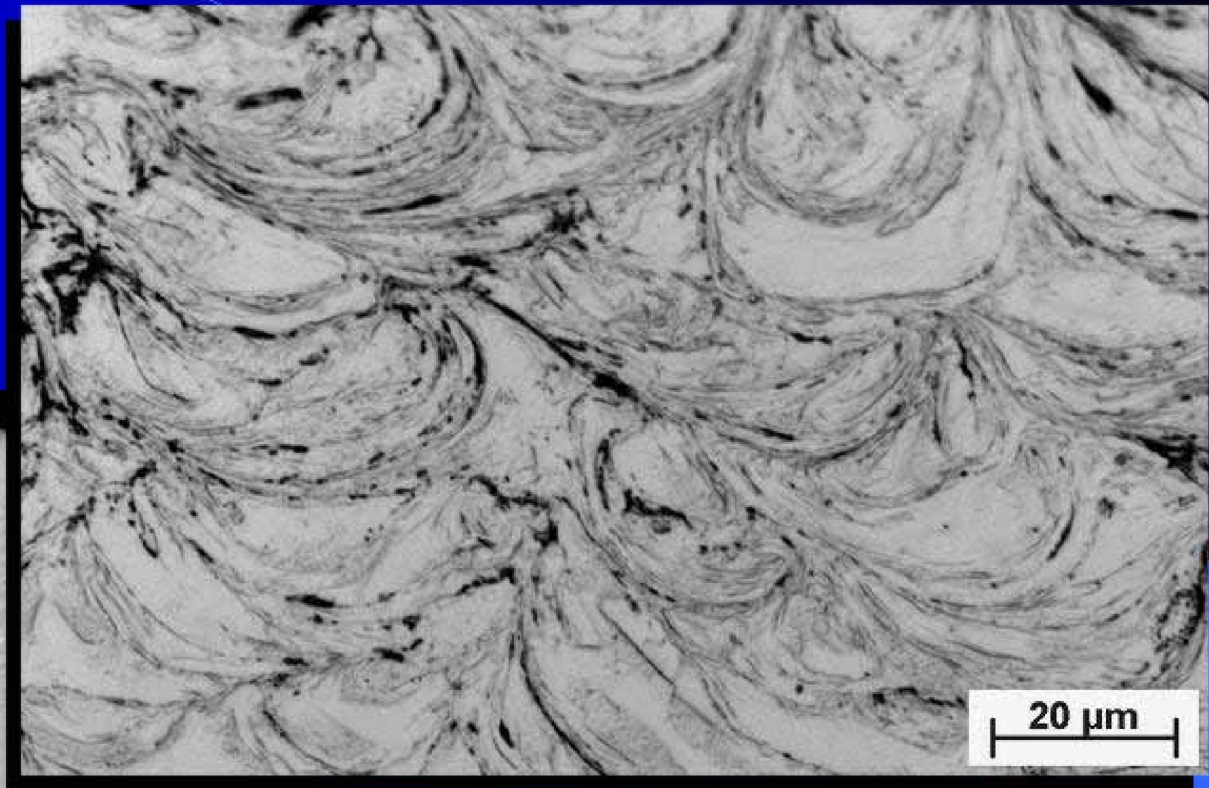
Ta Coating (He)

TCT-test: 290 MPa



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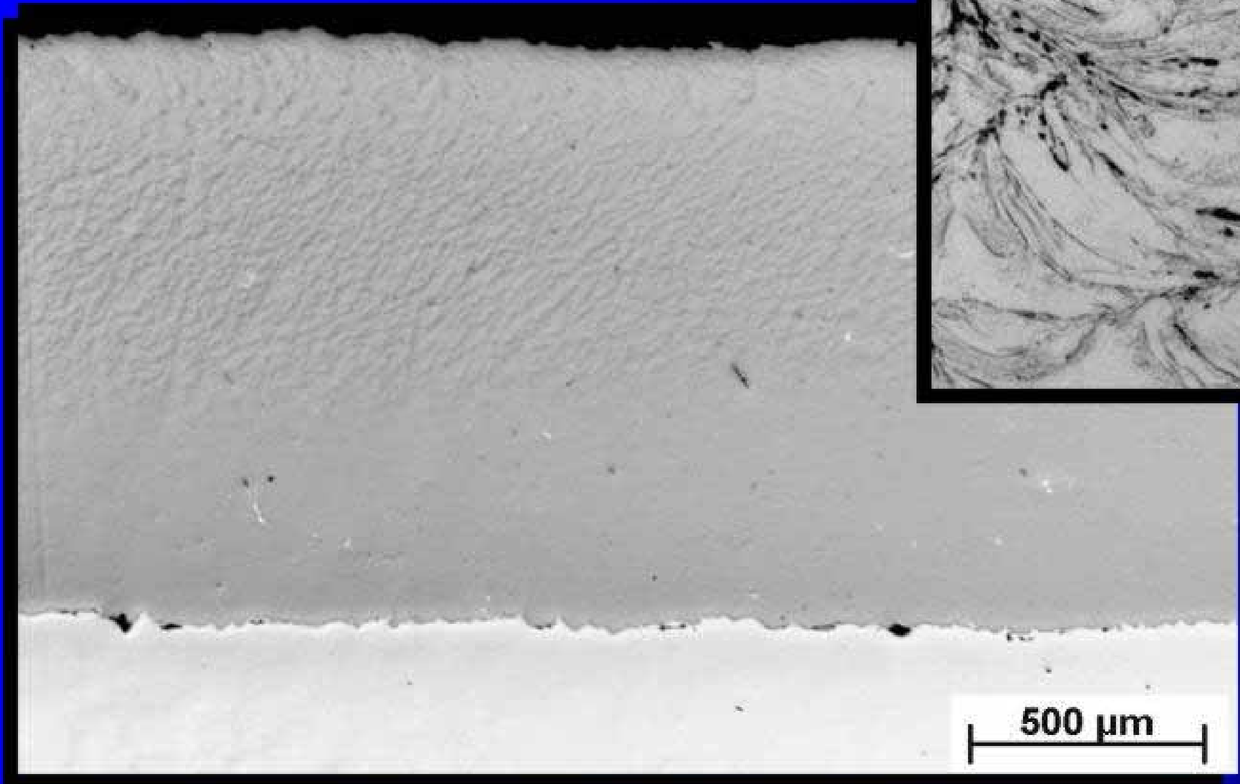

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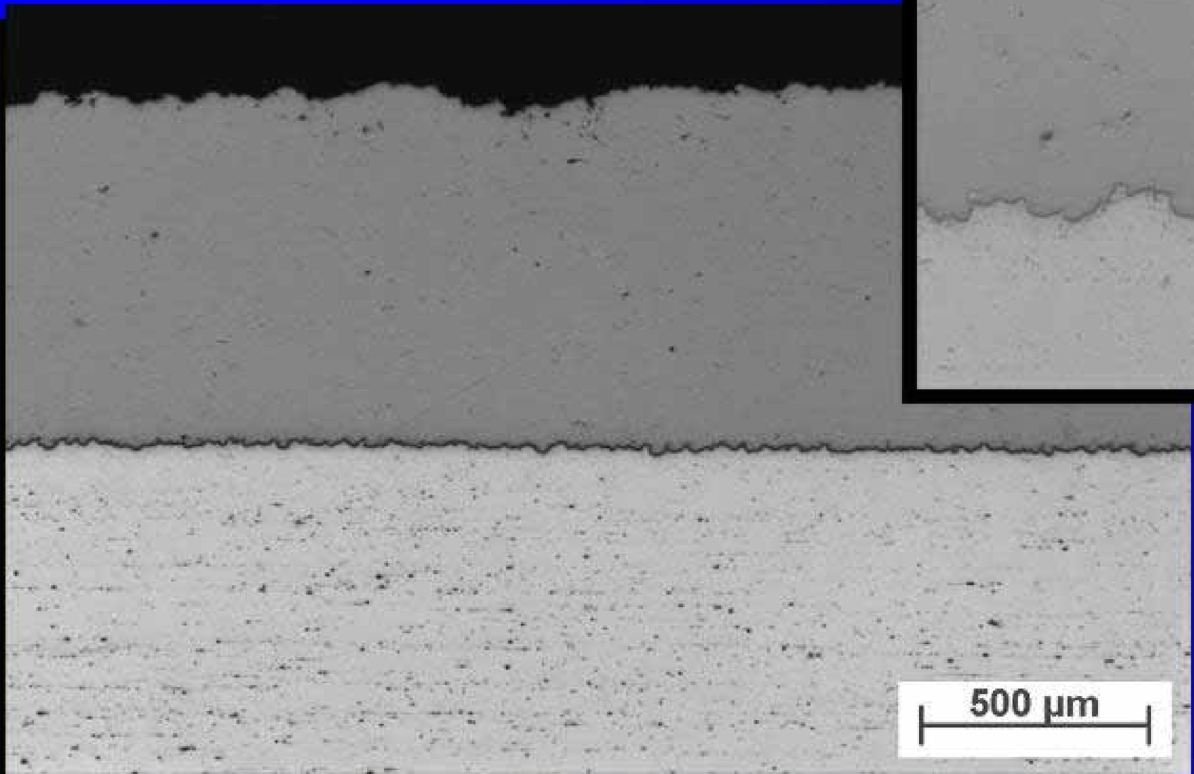
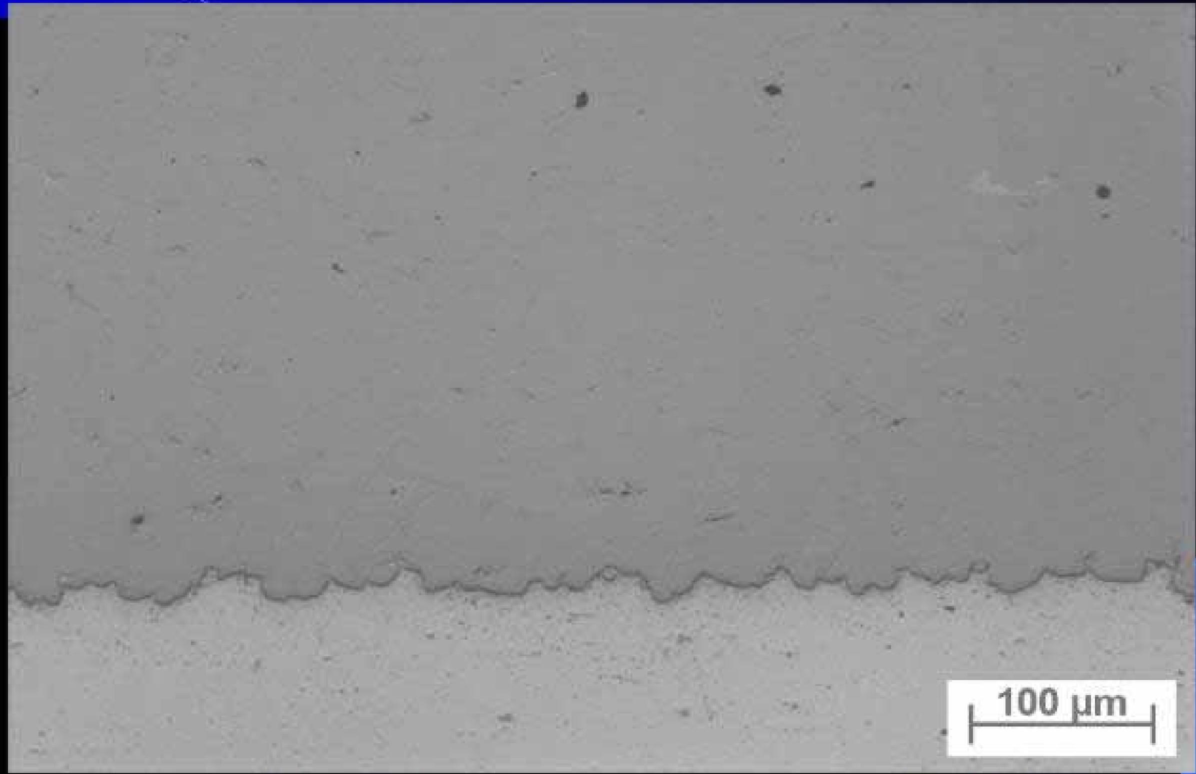
Steel 316L Coating (N_2)

TCT-test: 230 MPa





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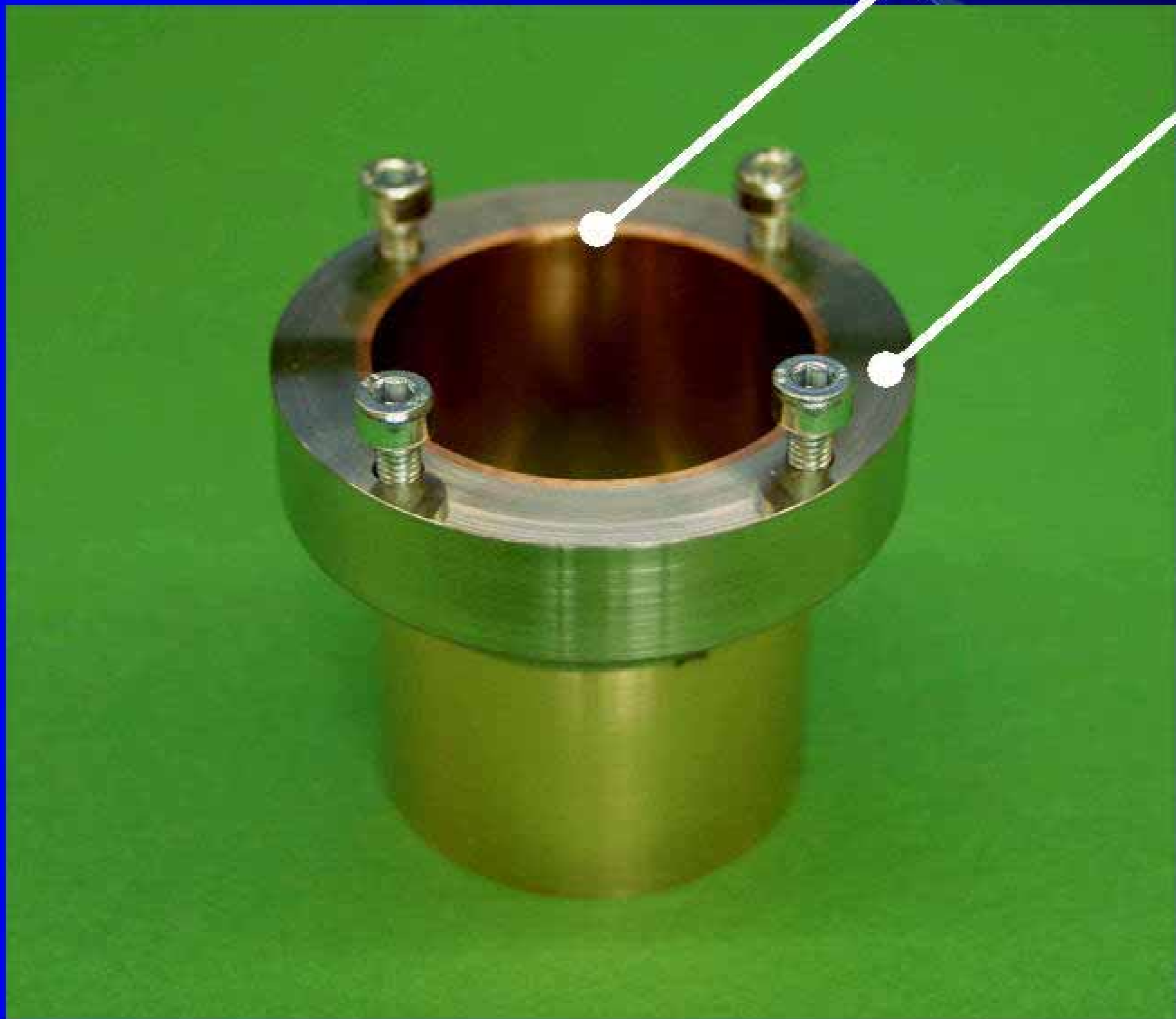
Spraying of Thick Coatings

repair applications, spray forming, rapid prototyping



Conclusions I

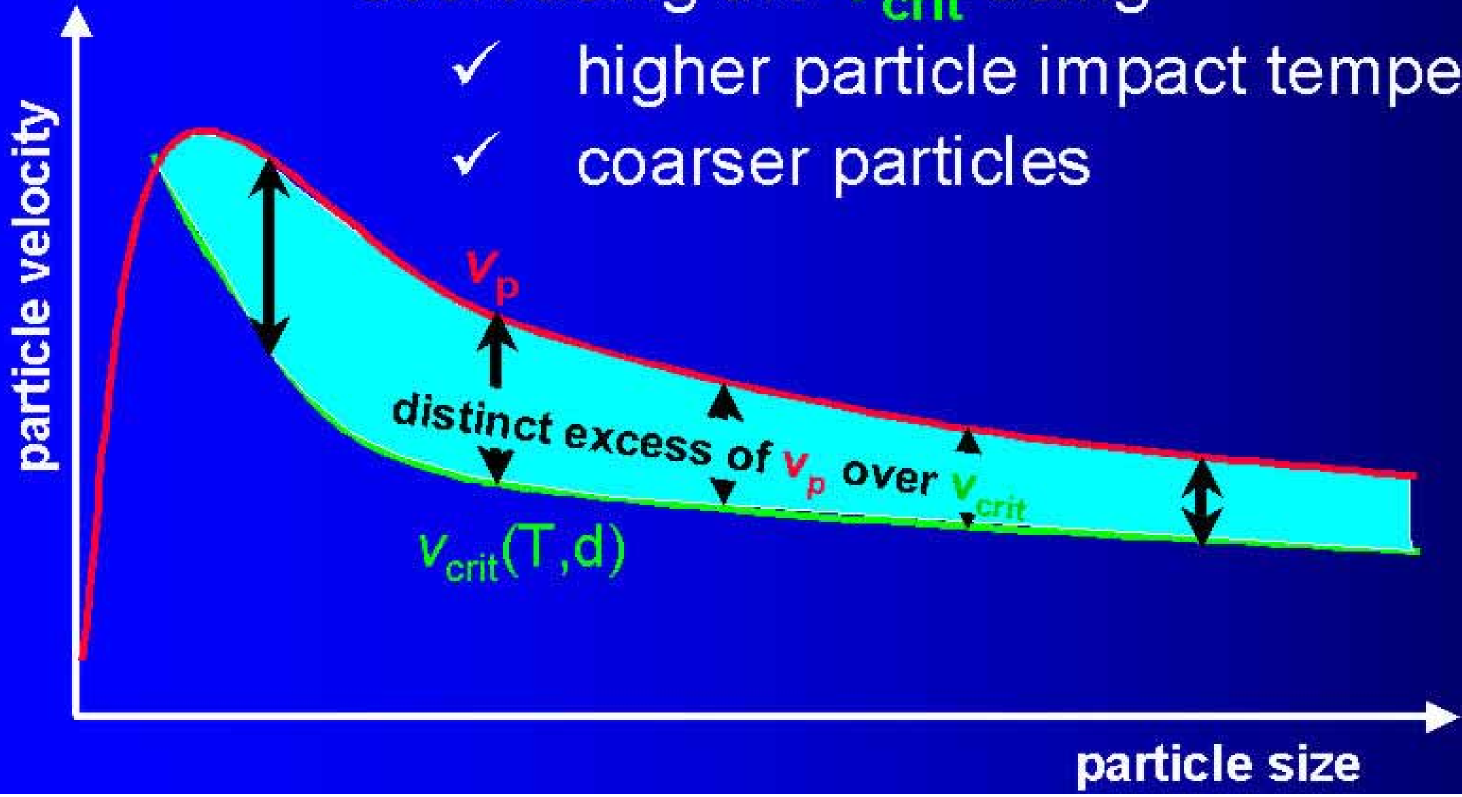
distinct excess of impact velocity over critical velocity was achieved by:

higher impact velocities using

- ✓ higher gas temperatures and gas pressures
- ✓ optimized nozzle shape and length

decreasing the v_{crit} using

- ✓ higher particle impact temperatures and
- ✓ coarser particles



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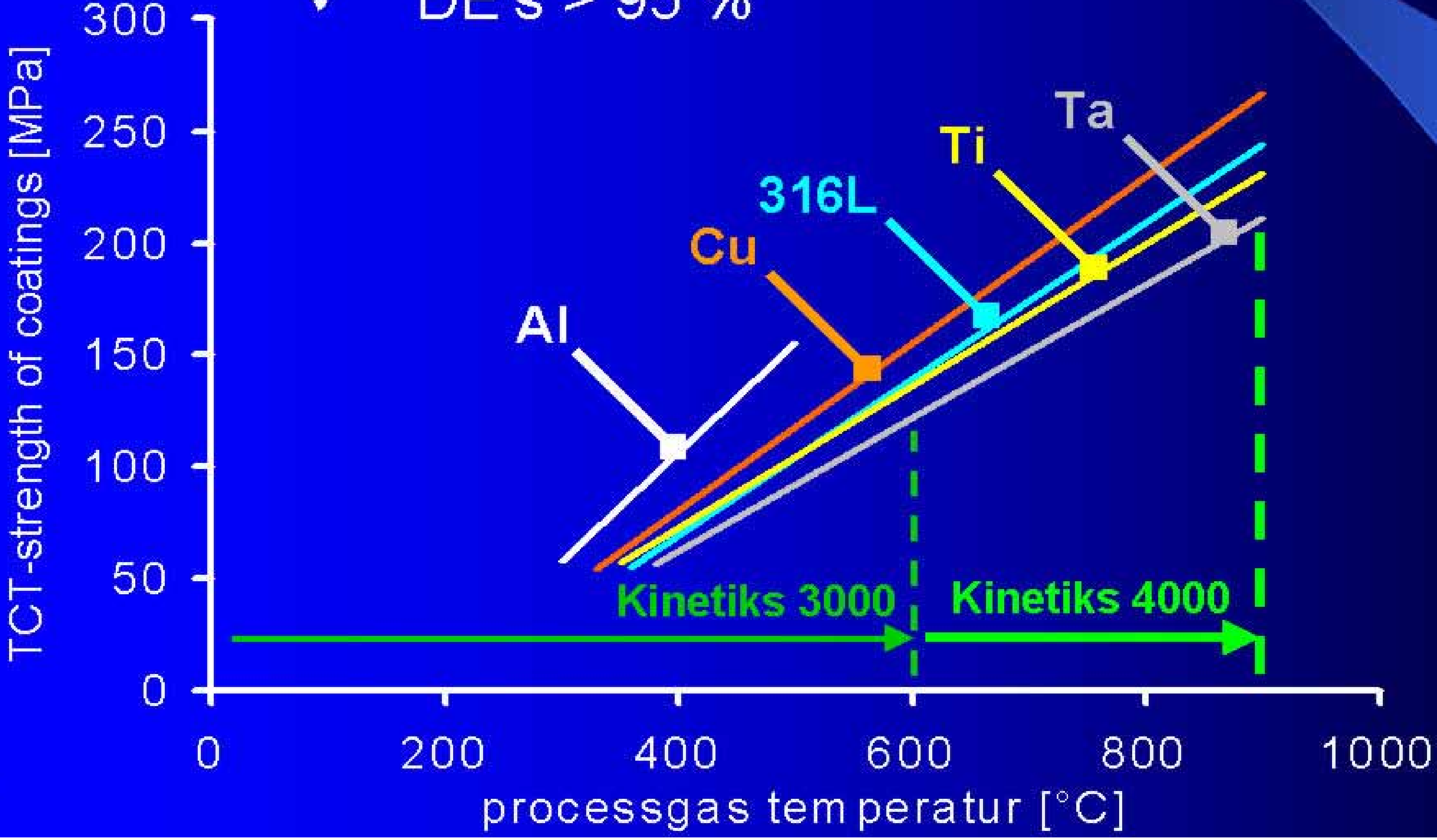
Conclusions II

The results of these optimization steps are

- ✓ extended range of usable spray materials
- ✓ high coating strength
- ✓ dense coatings
- ✓ DE's > 95 %



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Literature

[1] **An Analysis of the Cold Spray Process and its Coatings**: T. Stoltenhoff, H. Kreye, and H.J. Richter, *J. Thermal Spray Technol*., 11, 2002, p 542-550.

[2] **Bonding Mechanism in Cold Gas Spraying**: H. Assadi, F. Gärtner, T. Stoltenhoff, and H. Kreye, *Acta Mater. 51*, 2003, p 4379-4394.

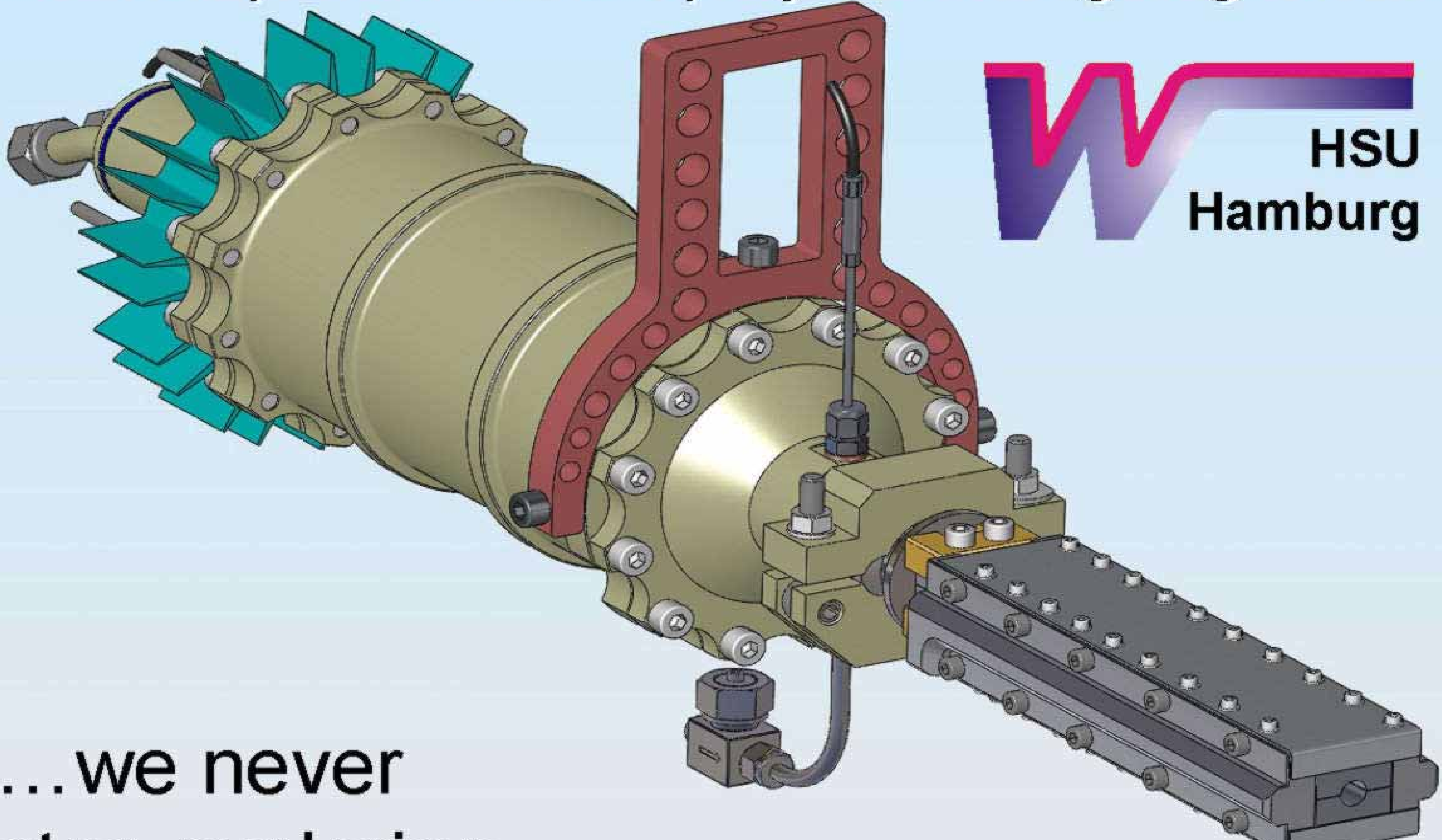
[3] **Development of a Generalized Parameter Window for Cold Spray Deposition**: T. Schmidt, F. Gärtner, H. Assadi, and H. Kreye, *Acta Mater. 54*, 2006, p 729-742.

[4] **New Developments in Cold Spray Based on Higher Gas- and Particle Temperatures**: T. Schmidt, F. Gärtner, and H. Kreye, Journal of Thermal Spray Technology, 15(4), 2006, S. 488-494.

[5] **Kaltgasspritzen – Eine Analyse des Materialverhaltens beim Partikelaufprall und die daraus abgeleitete Prozessoptimierung**: T. Schmidt, Shaker Verlag, Mai 2007, ISBN 978-3-8322-6399-7.

[6] **Mechanical Properties of Cold Sprayed and Thermally Sprayed Copper Coatings**: F. Gärtner, T. Stoltenhoff, J. Voyer, and H. Kreye, Surf. Coat. Techno. 200, 2006, p 6770-6782.

Development of CS Spray Guns is going on at



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...we never
stop exploring.

Collaboration

Cold Spray Competence Group

Thayer School of Engineering at Dartmouth College — H.J. Richter — fluid dynamics

HSU Hamburg — T. Klassen, H. Kreye — materials science

Linde Gas, Linde — P. Heinrich — gas technology

CGT COLD GAS TECHNOLOGY GmbH — P. Richter — spray systems

H.C.Starck, Empowering High Tech Materials — A. Eiling — spray materials

mechanisms, materials, equipment (Thayer School of Engineering, HSU Hamburg)

gas supply (Linde)

equipment, license (CGT)

spray powder (H.C.Starck)

evaluation of applications

support to industry