ADHESION OF COLD SPRAY COATINGS: EFFECT OF SUBSTRATE ROUGHNESS AND HARDNESS

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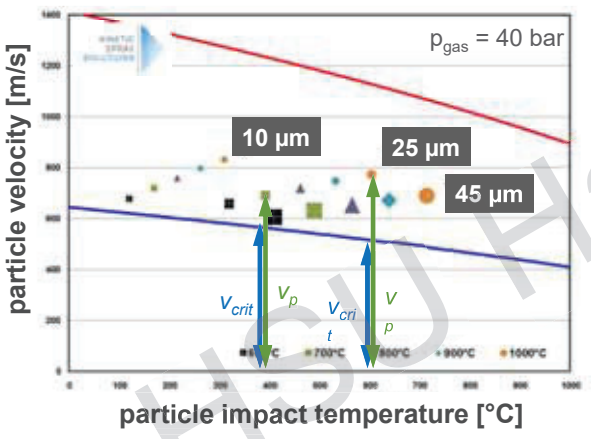
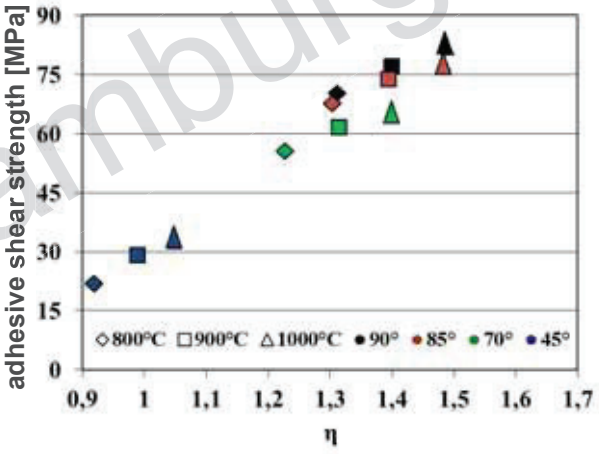
Cold Spray Club, Hamburg, October 20th 2023

CS: Influences on adhesion

- amount of adiabatic shear instabilities (ASI): ratio $\eta = v_p / v_{crit}$





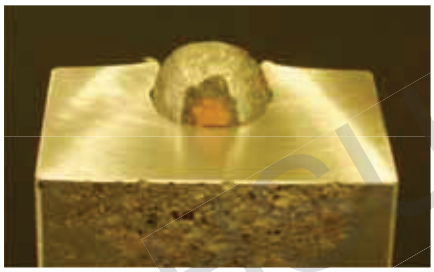
Ref.: K. Binder, „Kaltgasspritzen von ermüdungsfesten Titanschichten, PhD.-Thesis, Hamburg 2013

CS: Influences on adhesion

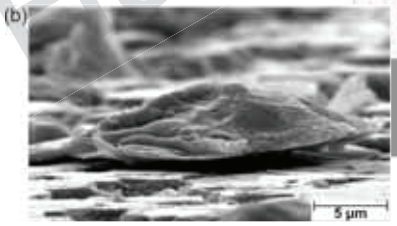
- **location of adiabatic shear instabilities (ASI):**
  - ➢ relative hardness, ASI on particle or substrate sites

hard on soft, ASI on substrate sides

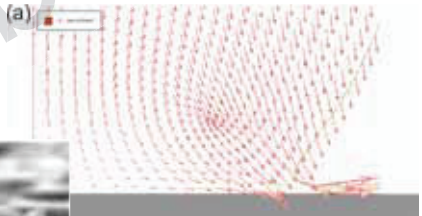
20 mm Cu ball on Al substrate, v = 800m/s



Cu-particle on S-HVOF sprayed Al_2O_3 layer.



soft on hard, ASI on substrate sides



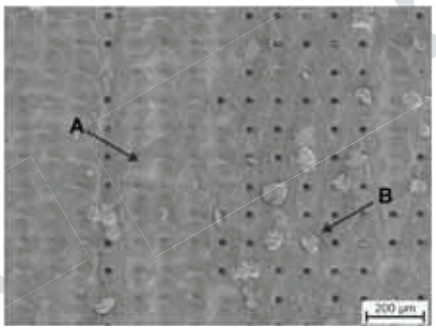
2-d simulation: Cu on rigid substrate, v = of 500 m/s

Process Science of Cold Spray, T. Klassen, F. Gärtner, H. Assadi; chapter 2 in: High Pres-sure Cold Spray: Principles and Applications (Editors: C.M. Kay and J. Karthikeyan), ASM International, ISBN: 978-1-62708-096-5, p. 17-66

CS: Influences on adhesion

- **Surface topographies: trapping particle ASI**

soft Cu on hard Al_2O_3, ASI on particle sides,
➢ **adhesion only at locations of surface cavities (B), not smooth surface areas**



Ref.: K. Ernst, „Kaltgasspritzen für die Leistungselektronik – Werkstoffkombinationen und geometrische Randbedingungen, PhD.-Thesis, Hamburg 2021

CS Influences on adhesion,
➢ here: soft Cu on hard steel 304

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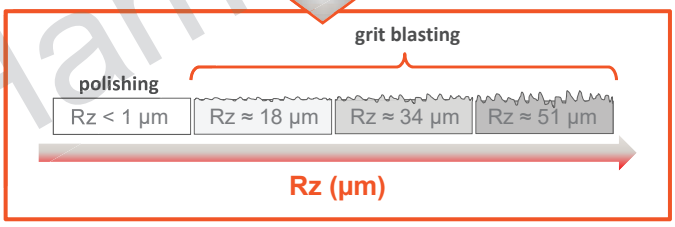
defined starting conditions

«as-received» AISI 304 steel plates → *1000 °C, vacuum, 30 min* → annealed AISI 304 steel plates ($HV_{0.3}$ = 181.5 ± 9.2) → *grit blasting* → **variation of surface roughness**

- **as grit blasted:**
  - ➢ **set of HARD SUBSTRATES**
- **additional vacuum annealing (30 min @ 1000°C):**
  - ➢ **set of SOFT SUBSTRATES**



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Surface roughness

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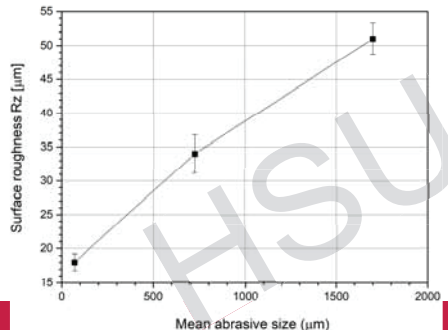
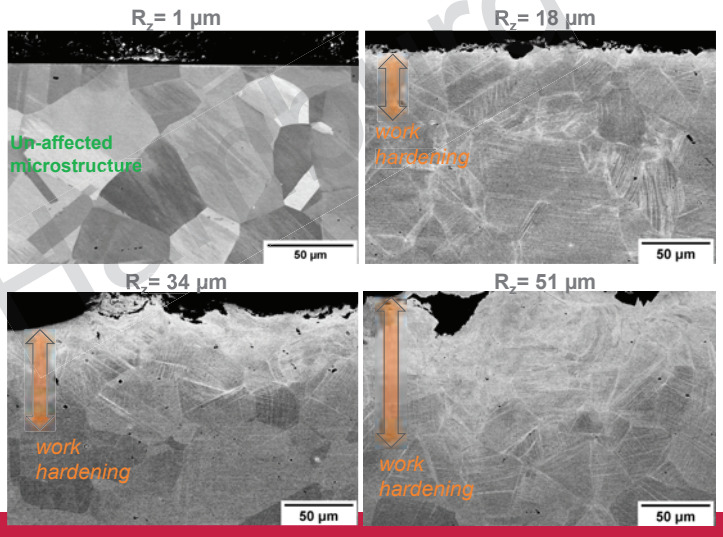
effect of grit size on substrate roughness

Grit	Size (µm)	P (MPa)	Rz (µm)
Corundum	46-90	0.8	18.1 ± 1.2
Corundum	600-850	0.8	34.0 ± 2.8
Corundum	1400-2000	0.8	51.2 ± 2.3



substrate microstructure and roughness (Set I)



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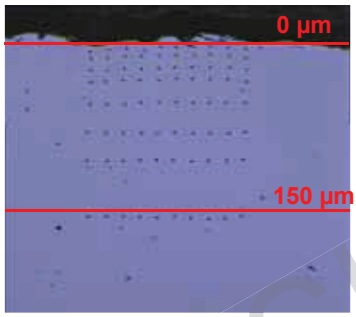
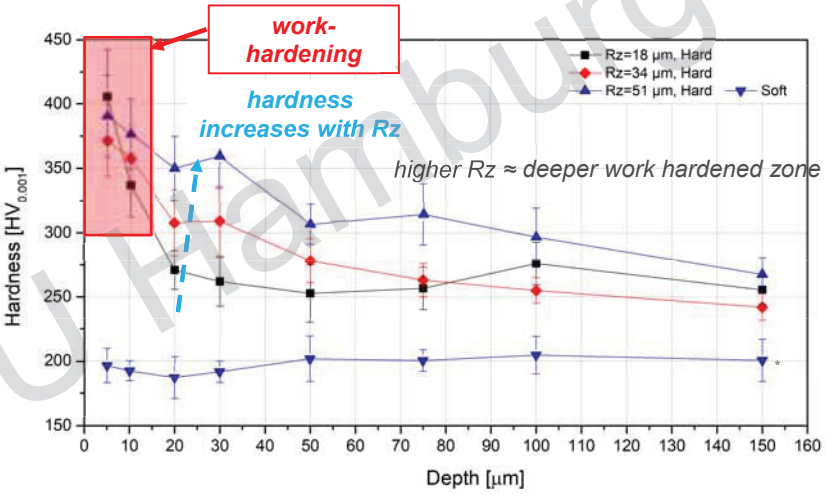
Surface hardness



10 indentations at different distance from the surface (depth)
Max load: 10 mN

substrate nano-hardness profiles



**Steel plates hardness before surface treatments: $HV_{0.3}$ = 181.5 ± 9.2*

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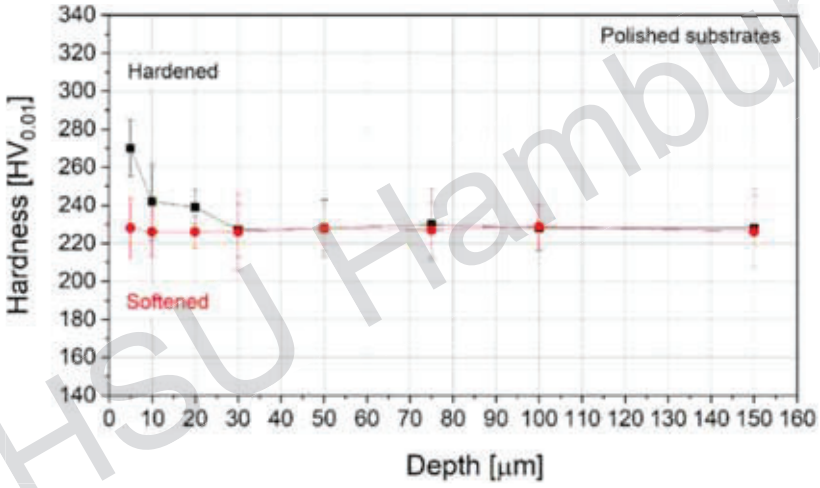
Surface hardness

substrate hardness profiles: polished surfaces



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Cu powder feedstock

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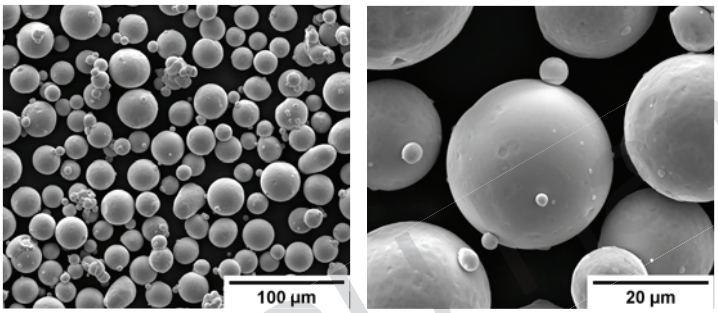
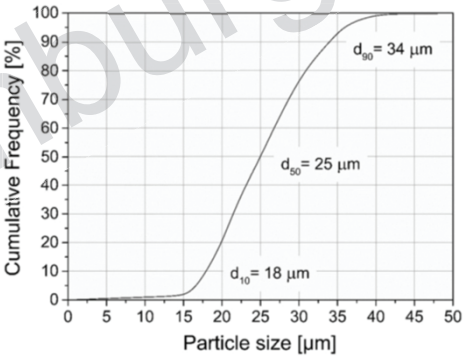
particle morphologies



particle size distribution



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CS process parameters

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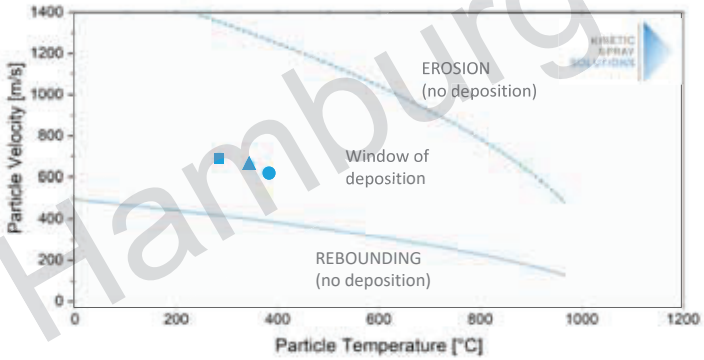
Parameters	Values
Equipment Powder feeder	K8000 X PF 4000
Gas	N_2
Gas temperature	600 °C
Gas pressure	40 bar
Stand-off distance	60 mm
Pre-chamber	60 mm
Nozzle	D24WC



- **Ø 18µm** – 619m/s, 272°C, **η(=v/v$_{crit}$): 1.48**
- **Ø 25µm** – 592m/s, 333°C, **η: 1.56**
- **Ø 34µm** – 592m/s, 367°C, **η: 1.60**

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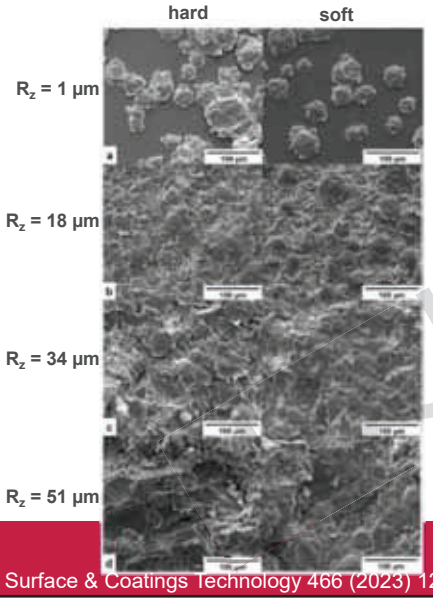
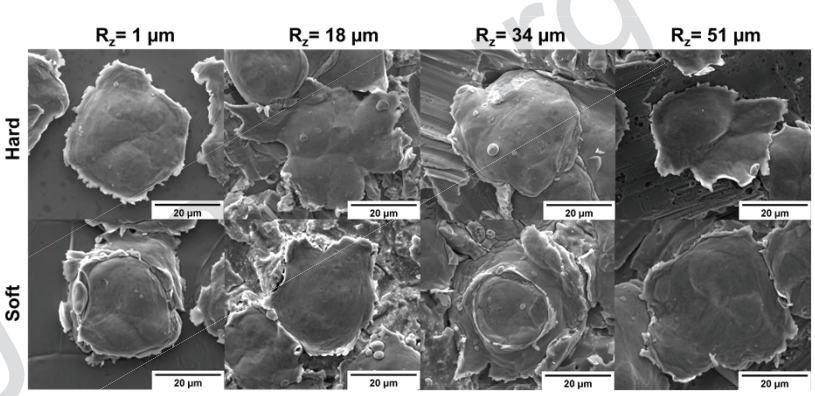
Single particle impact morphologies





- *particle deformation*
- *jetting*

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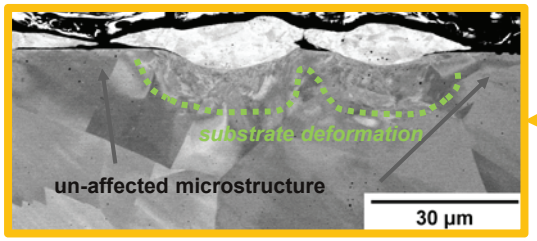
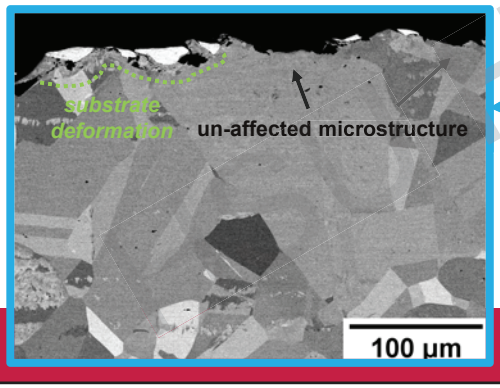
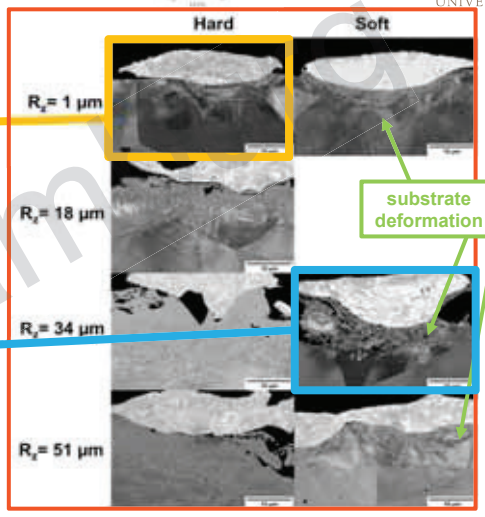
Single particle cross sections

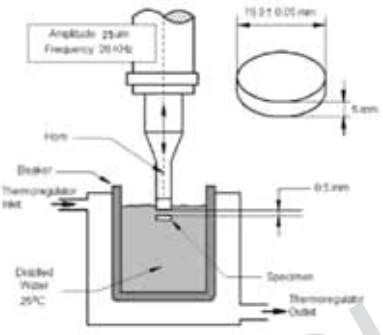


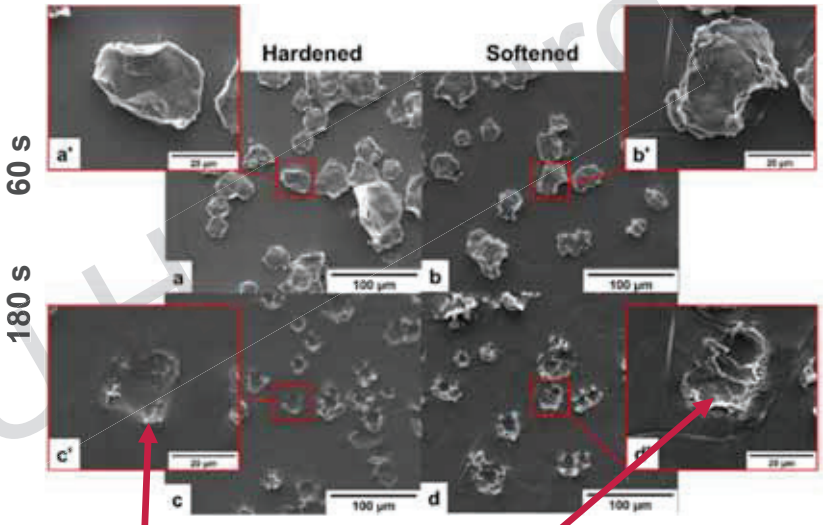




- *minor ASI on substrate sides (more on soft)*
- *ASI on particle sides NOT necessarily in contact*
- *work hardening under impact*

Single particle removal by cavitation





➢ *traces of ASI after particle removal*

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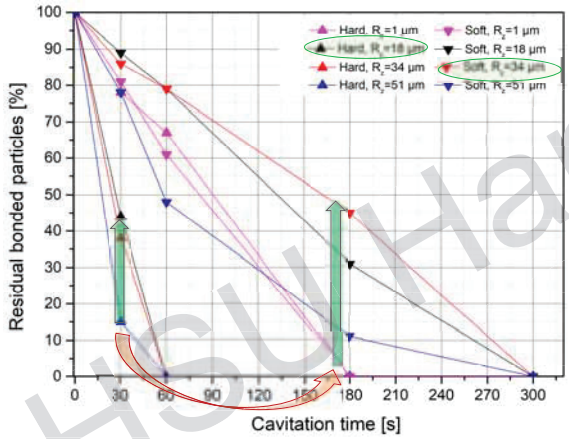
Single particle removal by cavitation

resistance against removal
➢ **measure for single particle adhesion**



➢ *influences by surface topographies*

➢ *influences by surface hardness*

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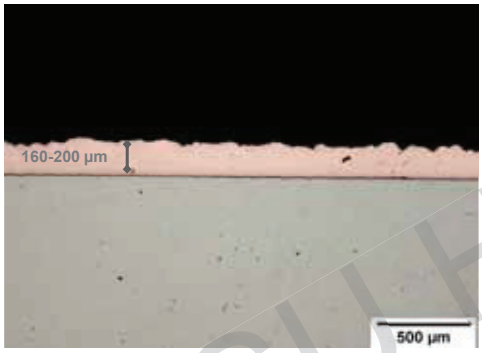
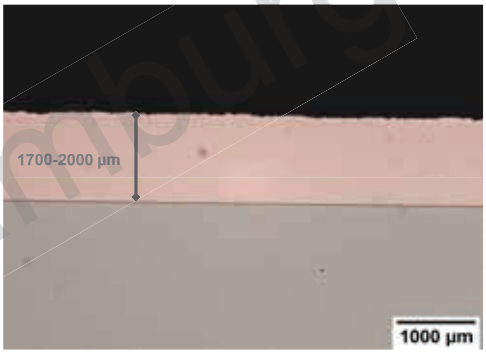
Full coatings: microstructures

1 layer



10 layers



- ***deposition efficiency > 90%***
- ***porosity < 0.5%***
- ***$HV_{0.3}$ = 135-145***

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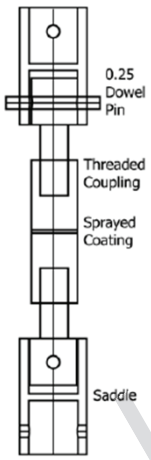
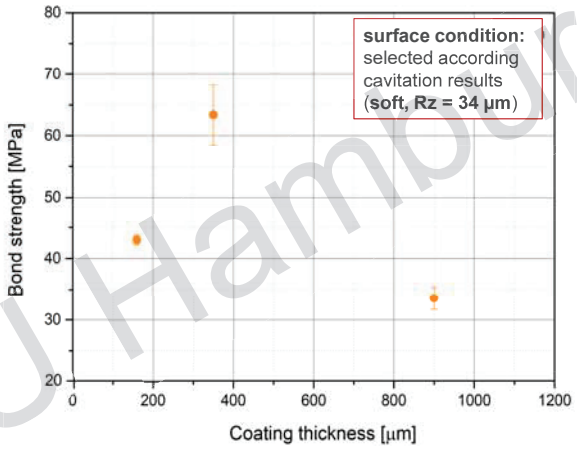
Full coating adhesion: f(thickness)

bond strength:
according to DIN EN 10002





- ***thicker coatings: influences by internal stresses***
- ***optimum thickness ~ 350 µm***

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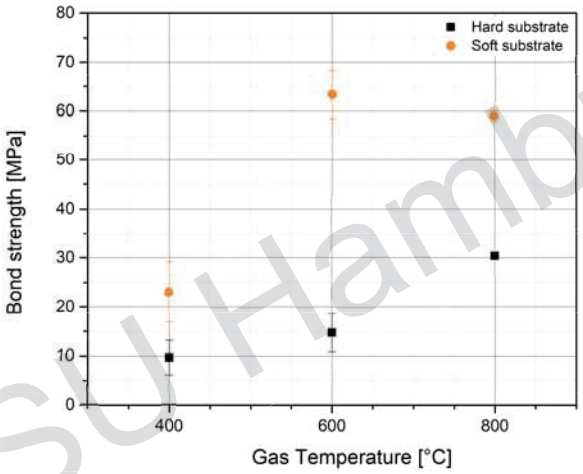
Full coating adhesion: f(η)



➢ ***bond strength ~ process conditions***

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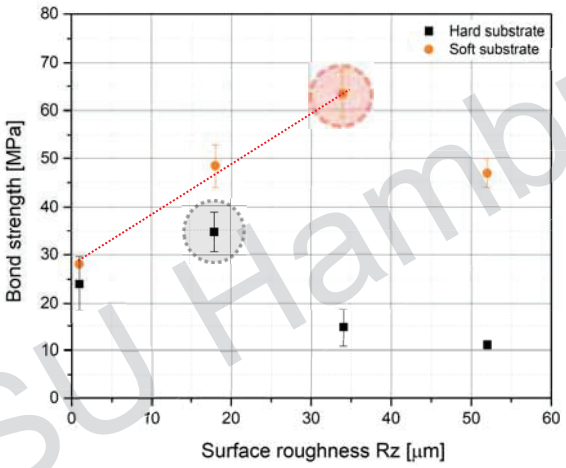
Full coating adhesion: f(roughness)



➢ ***optimum roughness ~ f(surface hardness)***
➢ ***optimum roughness (coating) ~ single particle adhesion***

Locations of failure after BS-test

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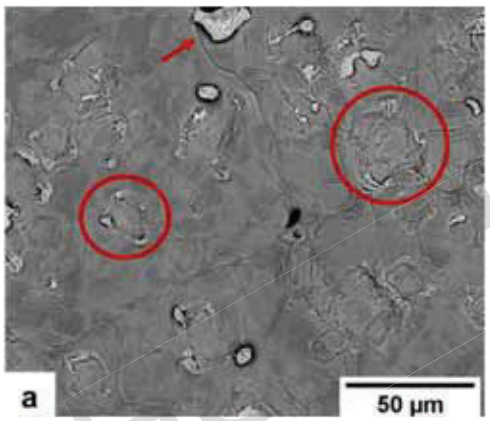
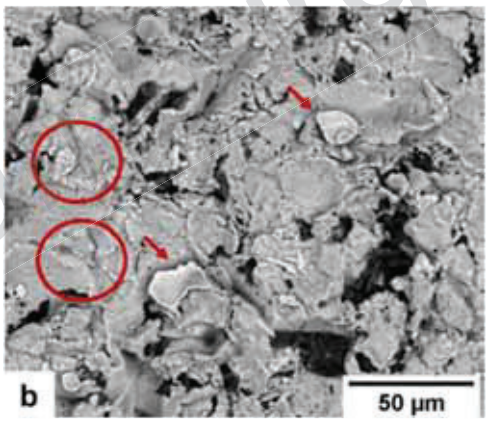
Cu-residues

smooth surface (hard)



rough surface (hard)



➢ *more Cu-residues on rough surface*

Locations of failure after BS-test

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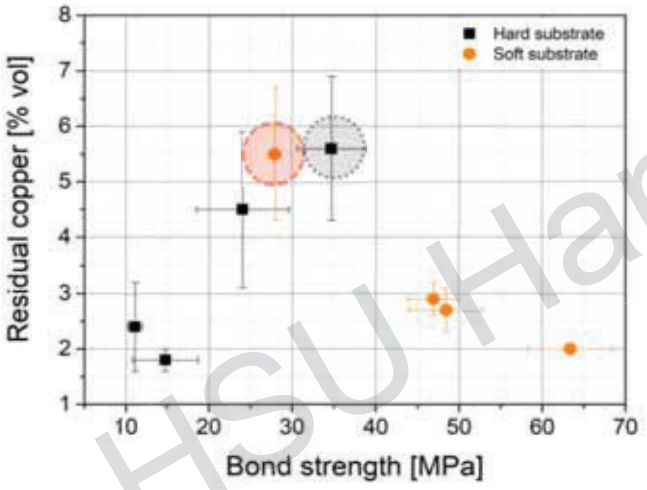
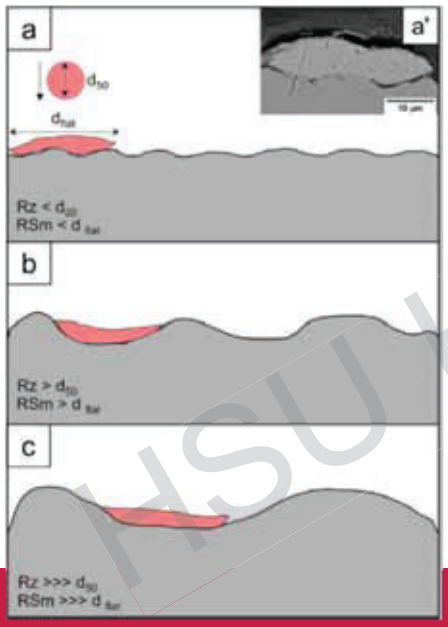
Cu-residues (by EDS)



- ***hard substrates:***
  - ➢ ***amount of Cu increases with BS***
  - ➢ ***ASI on Cu-sides***
- ***soft substrates:***
  - ➢ ***amount of Cu shows maximum***
  - ➢ ***ASI on Cu-sides + ASI on steel-sides***

Conditions for ASI in contact

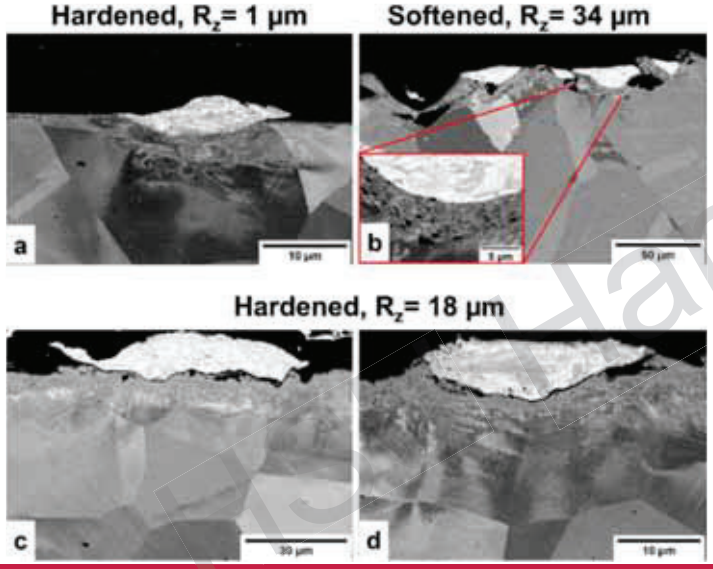


too fine surface topographies to trap ASI

ideal surface topographies to trap ASI

too coarse surface topographies to trap ASI (similar to flat surface)

Locations of ASI, single particle events



but

- *roughness*

➢ *ASI in contact*
➢ *ASI location*
➢ *on soft: common ASI on Cu and steel sites*

Take home messages: CS adhesion

- **ideal:**
  - **same particle and substrate deformation, common ASI**
- **hard on soft:**
  - **substrate deformation determines topography and ASI on substrate sites**
- **soft on hard:**
  - **ASI on particle sites must be trapped in suitable surface topographies**
  - **suitable surface topographies depend on particle deformation, flattening**
  - **substrate softening:**
    - **enabled surface deformation**
    - **common ASI:**
      - **better BS**
      - **wider spread for needed surface topographies**

Folie 23

many thanks for your kind attention!

thanks to the team:

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Levke Wiehler
Honjian Wu