TU Delft

Towards Evaluating the Strength of Cold Spray Repairs:

Can We Learn From Composites?

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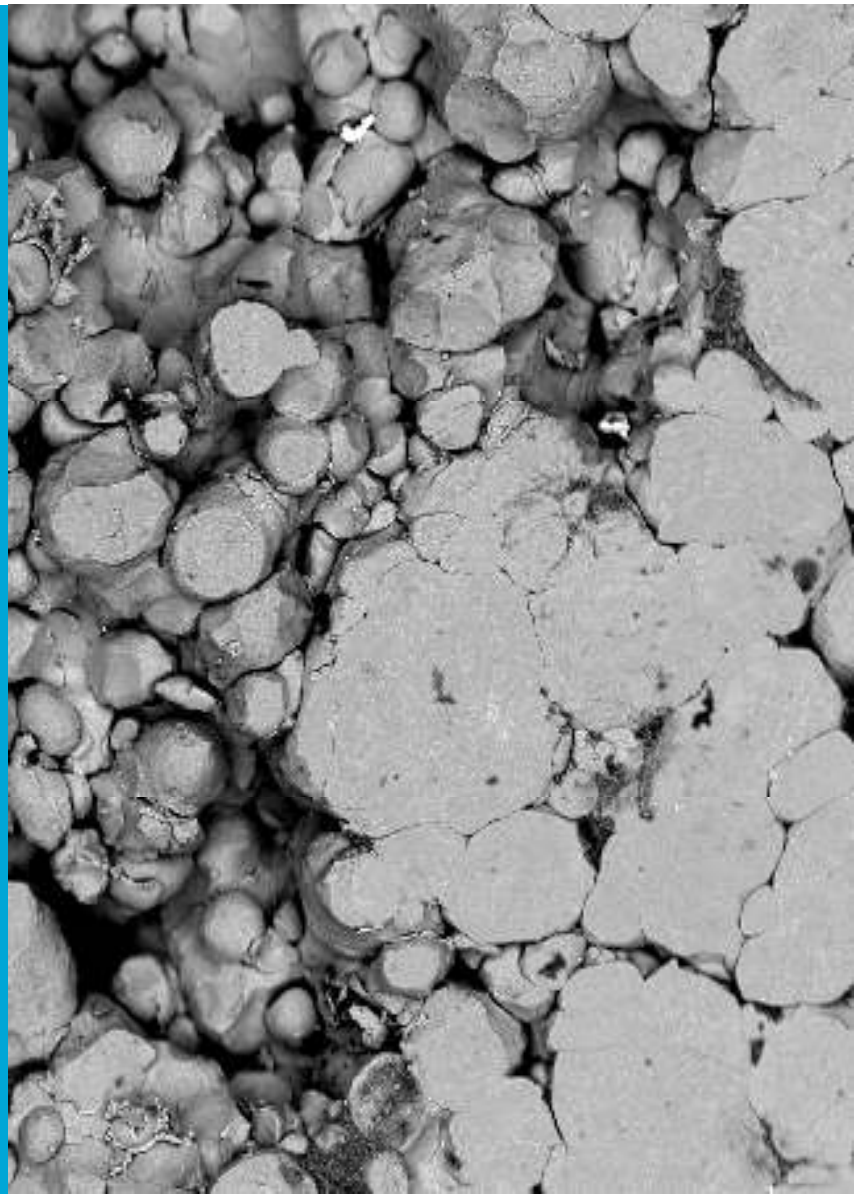
26-6-2025 – Cold Spray Club



Acknowledgements

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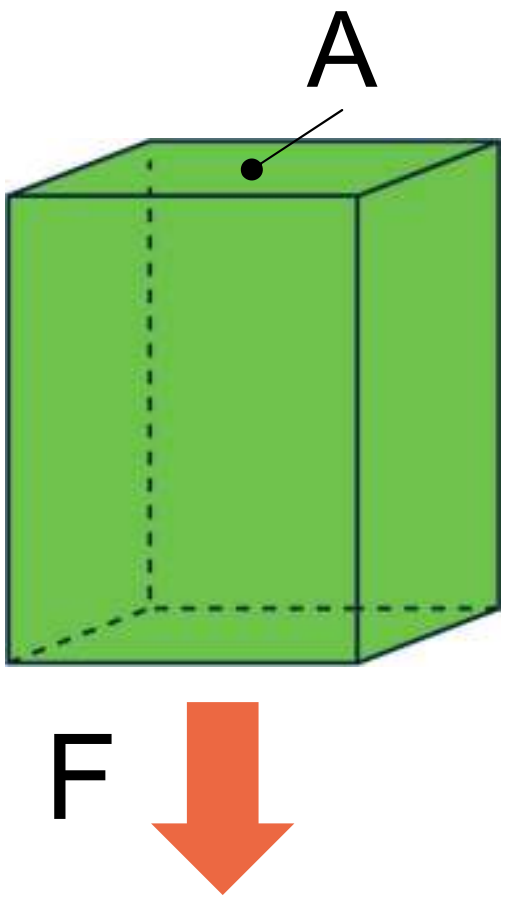
Image: USAF
Airman Ashley J. Thum / Public Domain

Tensile strength

Similitude & Failure Criteria



$$\sigma = \frac{F}{A}$$

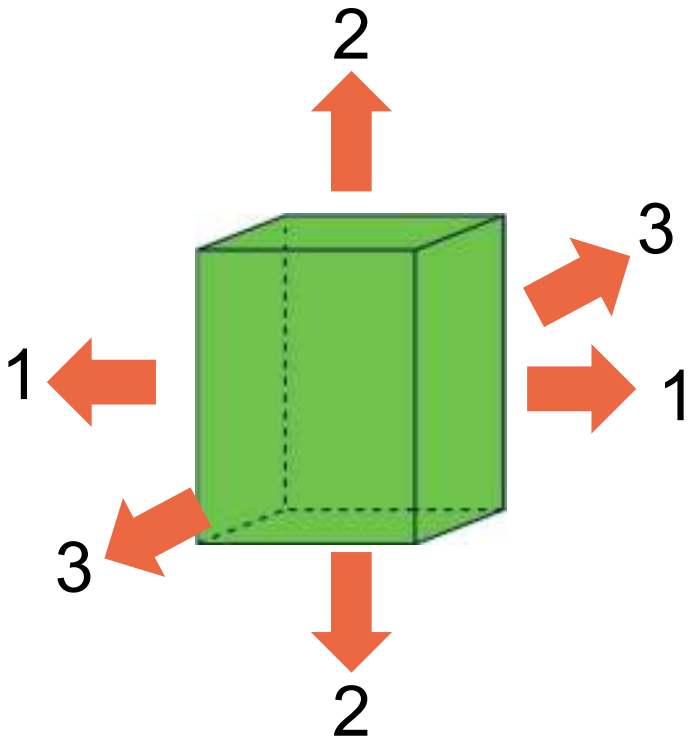
$$\sigma = \frac{F}{A} \geq \sigma_y$$

Force, Geometry

$$\frac{\sigma}{\sigma_y} \geq 1$$

Material

Multi-axial Loading



Von Mises:

Force, Geometry

Material

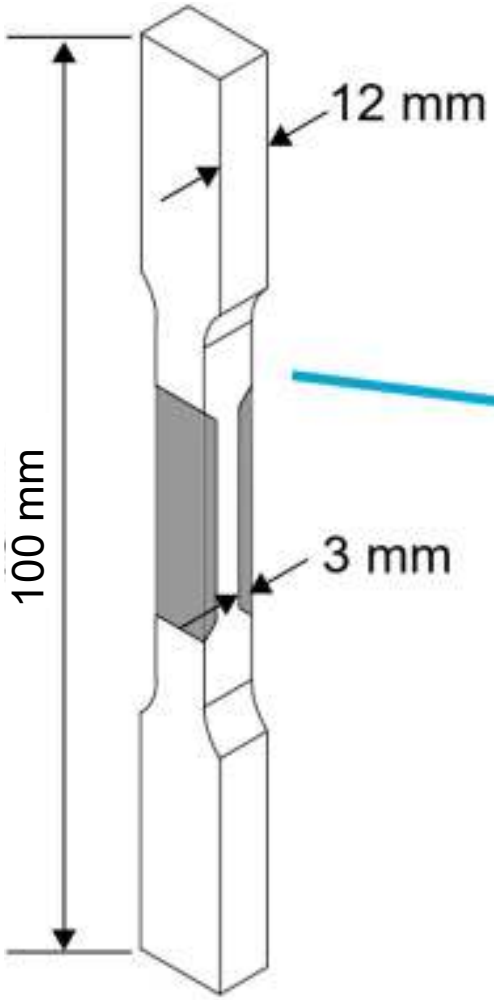
$$\sqrt{\frac{(\sigma_1-\sigma_2)^2}{2}+\frac{(\sigma_2-\sigma_3)^2}{2}+\frac{(\sigma_3-\sigma_1)^2}{2}} \geq \sigma_y$$

Tresca:

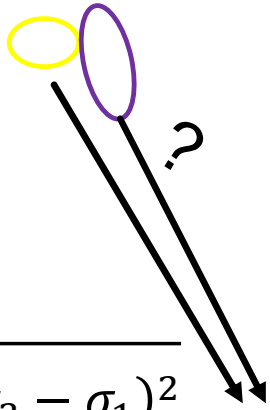
Force, Geometry

Material

$$\max\{|\sigma_1-\sigma_2|,|\sigma_2-\sigma_3|,|\sigma_3-\sigma_1|\} = \sigma_y$$



MSc thesis M. Beukelman (unpublished)

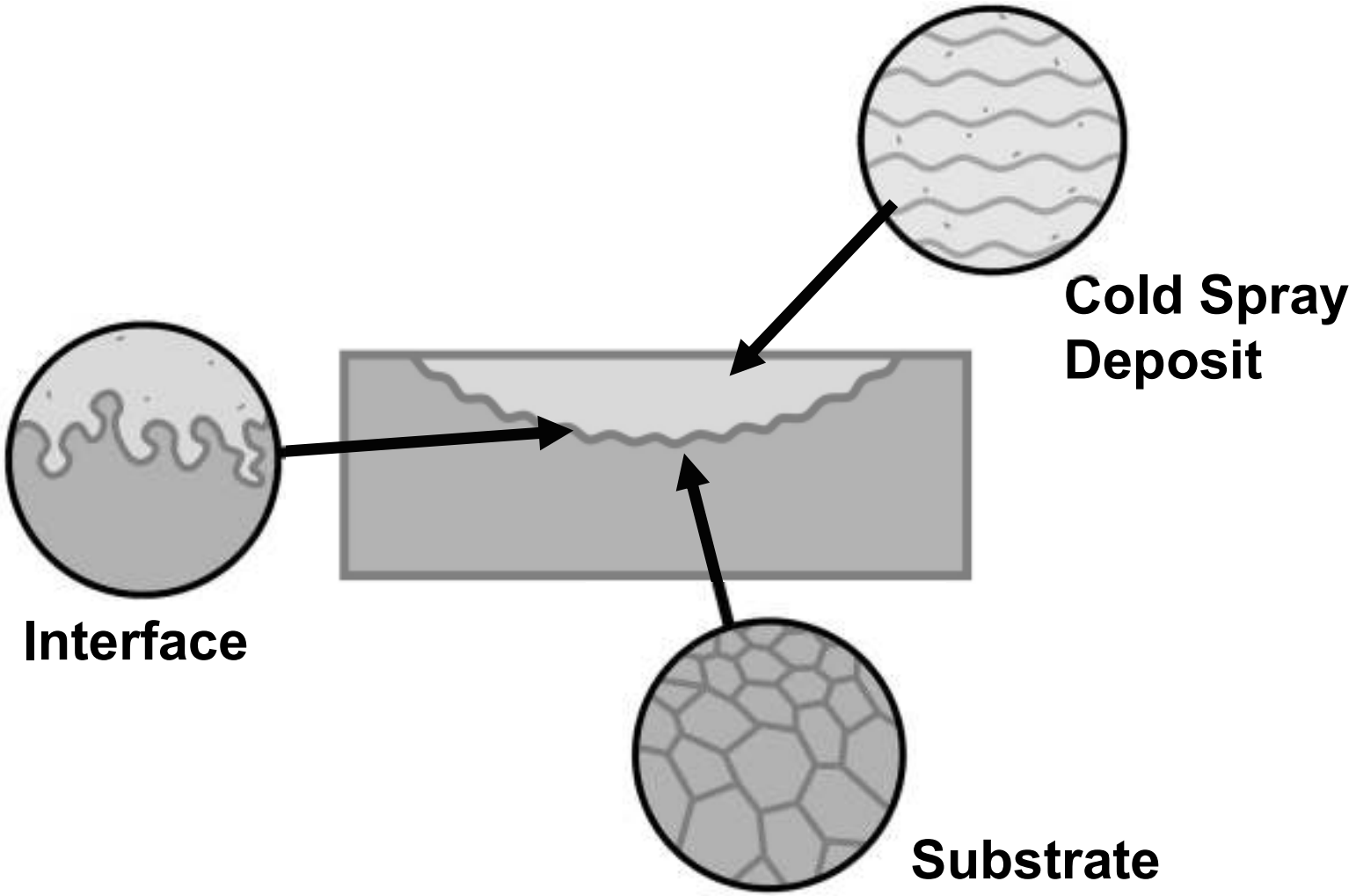


$$\sqrt{\frac{(\sigma_1-\sigma_2)^2}{2}+\frac{(\sigma_2-\sigma_3)^2}{2}+\frac{(\sigma_3-\sigma_1)^2}{2}} \geq \sigma_y \quad ? \; ? \; ?$$

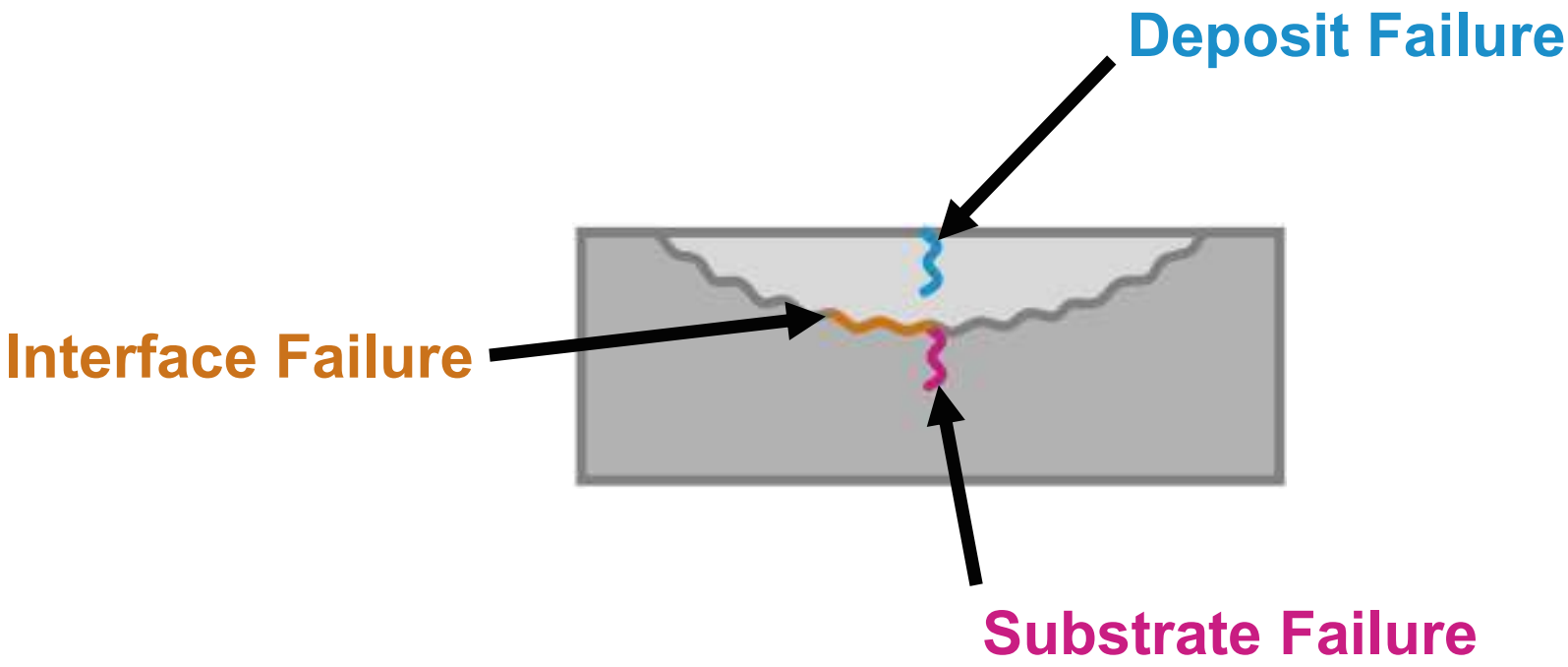
High pressure spray

Low pressure spray

Kundu & Stamoulis (2025), *Engineering Failure Analysis* **175,** 109581


Cold Spray
Deposit
Interface
Substrate

Each failure mode needs its own criterion!



What can we learn from composites?

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 + \left(\frac{\tau_{12}}{S_L}\right)^2 \geq 1$$ Fibre Tension (2D)

Force, Geometry

$$\left(\frac{\sigma_{11}}{X_c}\right)^2 \geq 1$$ Fibre Compression (2D)

Material

$$\left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_L}\right)^2 \geq 1$$ Matrix Tension (2D)

$$\left(\frac{\sigma_{22}}{2S_t}\right)^2 + \left[\left(\frac{Y_c}{2S_T}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_c} + \left(\frac{\tau_{12}}{S_L}\right)^2 \geq 1$$ Matrix Compression (2D)

Hashin Z. Failure criteria for unidirectional fiber composites. *J Appl Mech* 1980; 47: 329–334

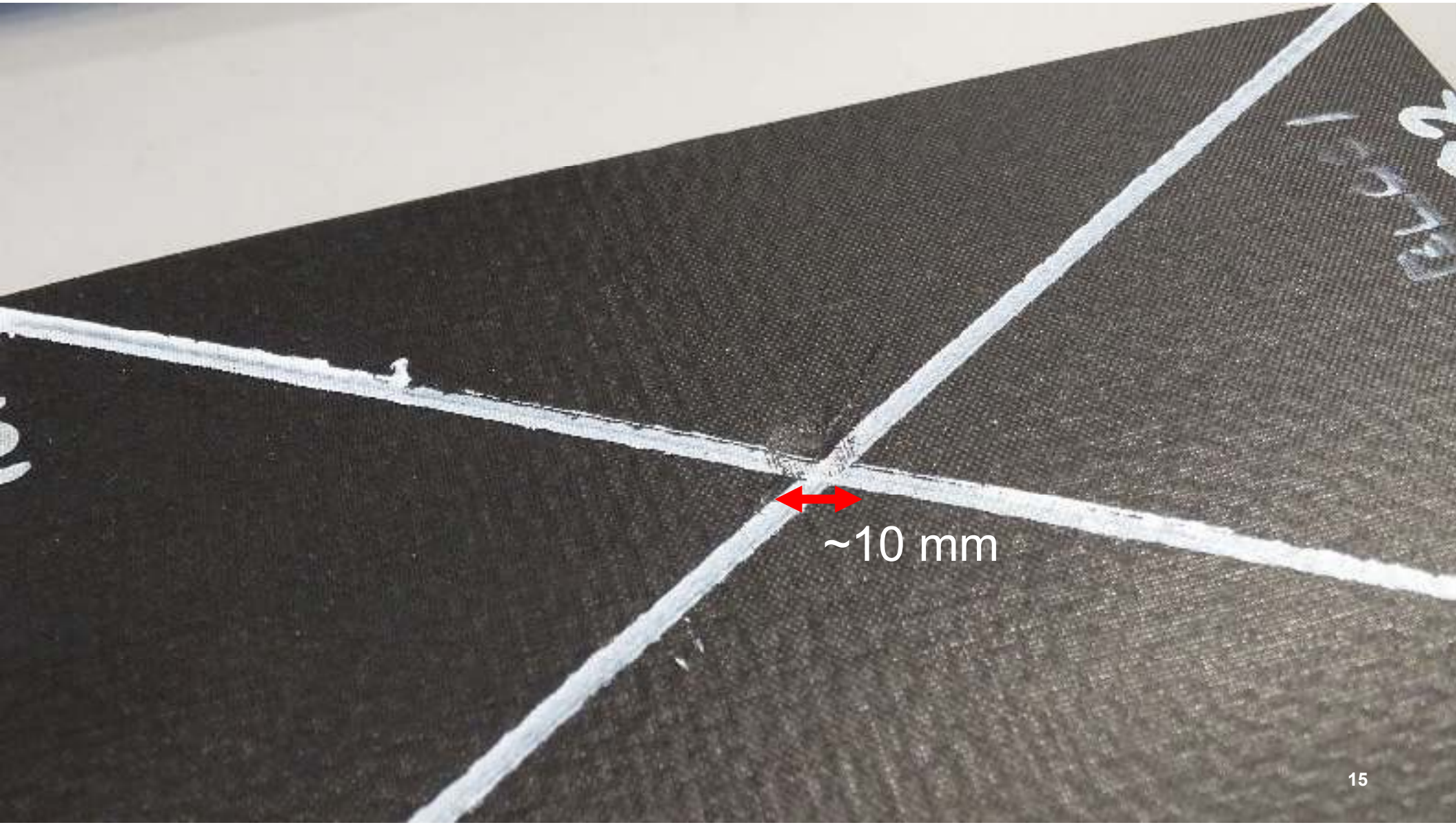
Don’t like Hashin?

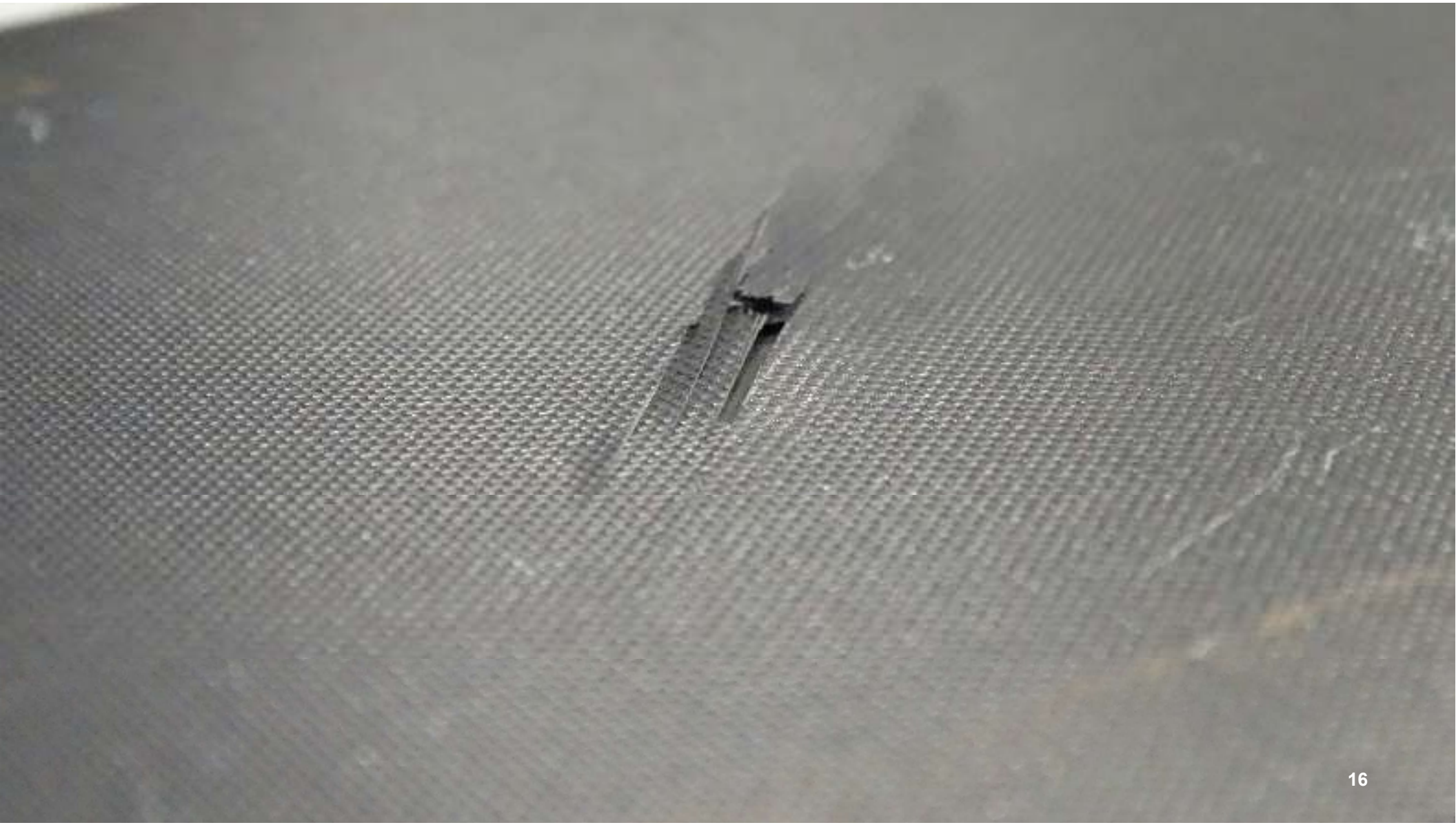
No problem!

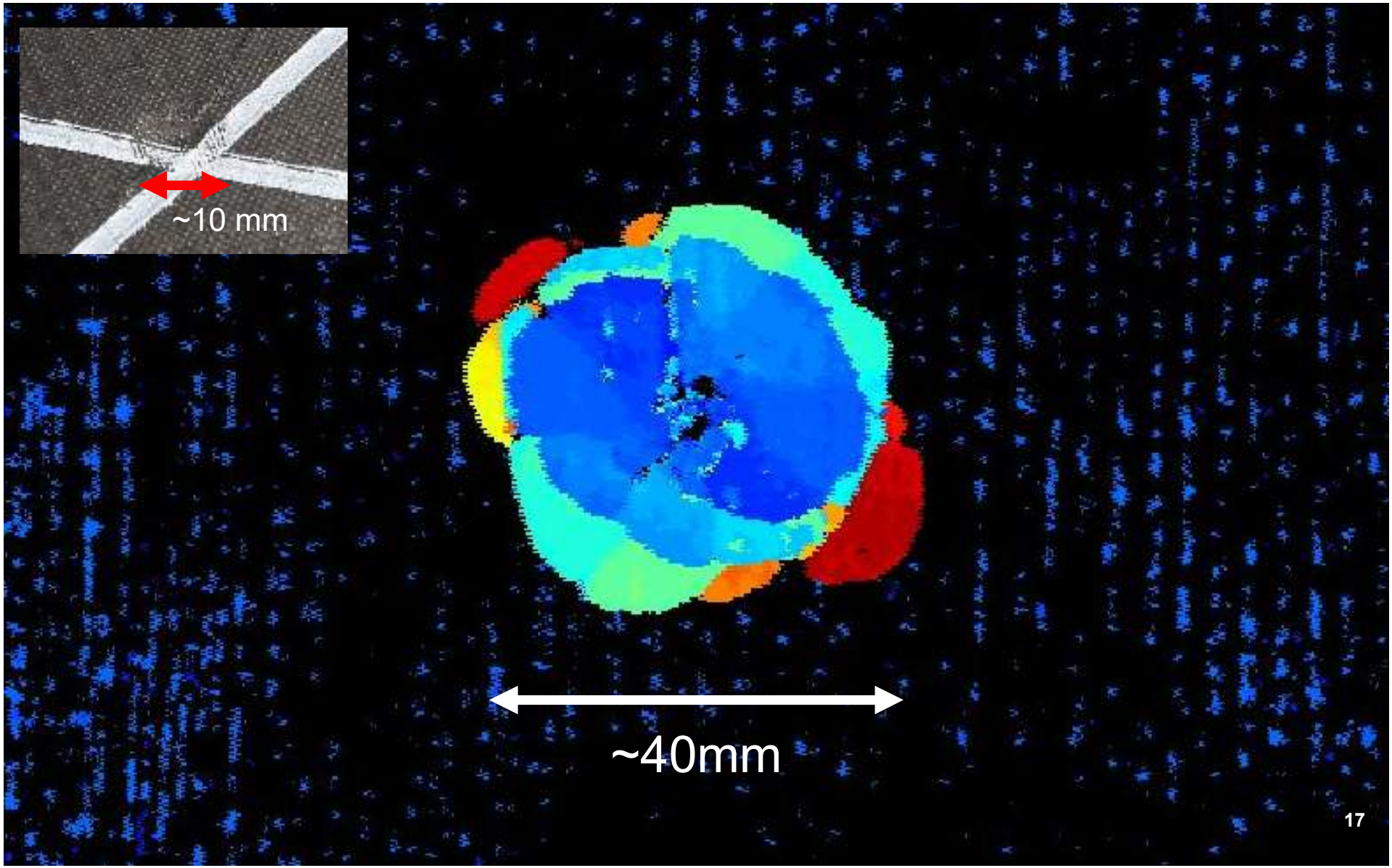
We also have:

- Tsai-Wu,
- Tsai-Hill,
- Puck,
- LaRC03,
- LaRC04,
- LaRC05
- Etc.

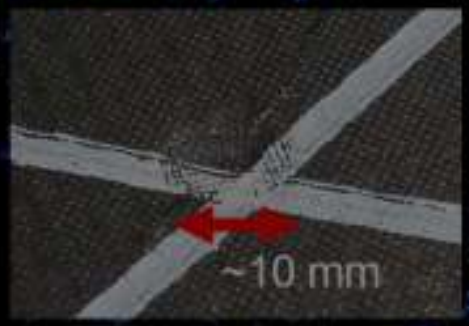
Impact

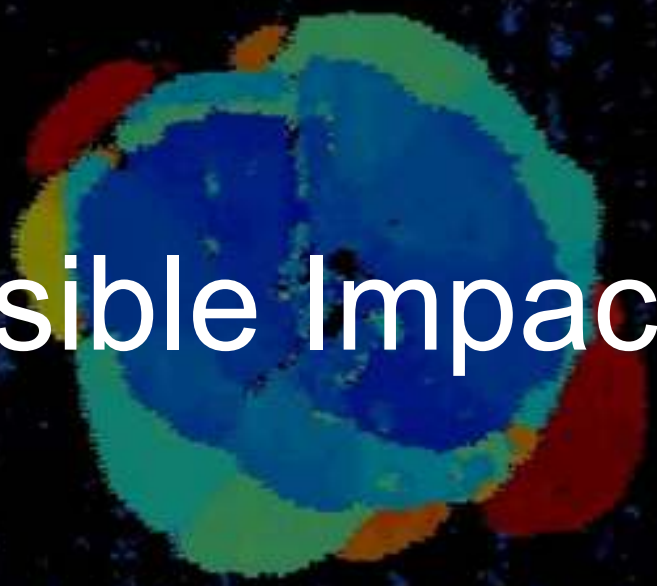

~10 mm




~10 mm
~40mm

Barely Visible Impact Damage

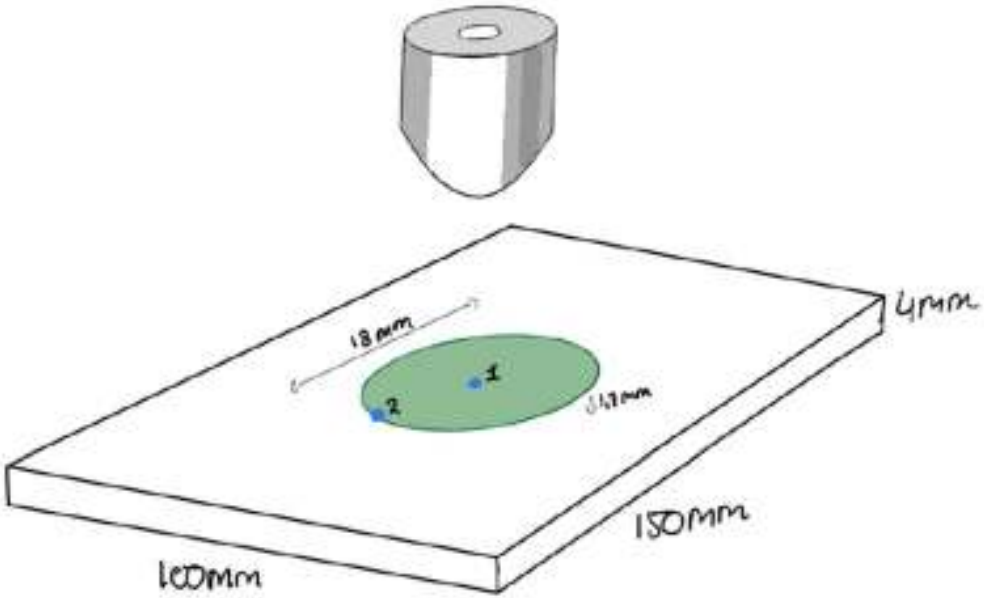


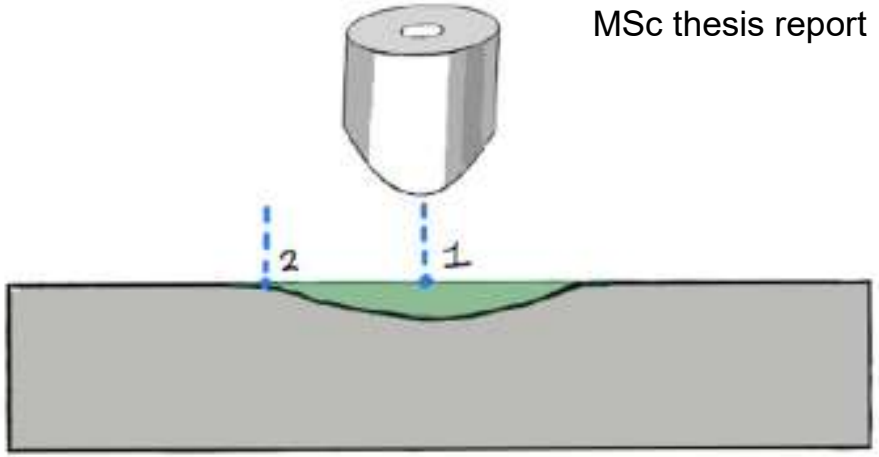


https://repository.tudelft.nl/record/uuid:218e2cc5-5ca9-40f0-a91c-81863deac71c

Impact on a cold spray repair

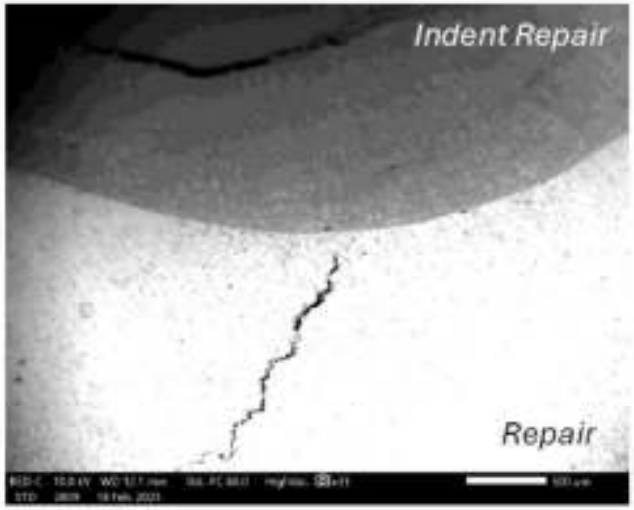
MSc thesis report



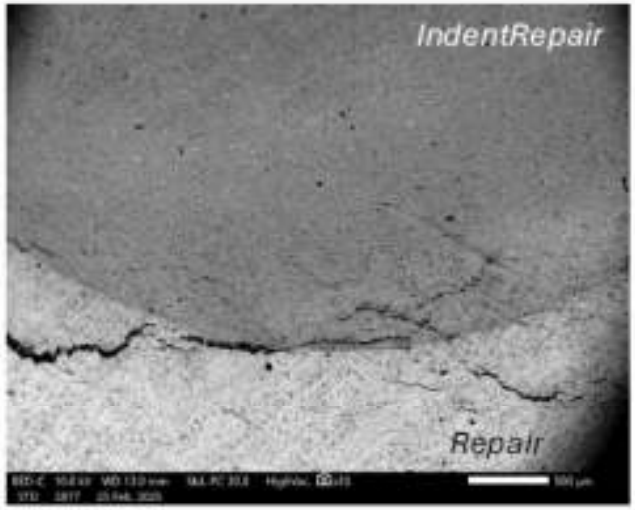


1 Center of Repair
2 Side of Repair

Dents & Cracks



Radial crack

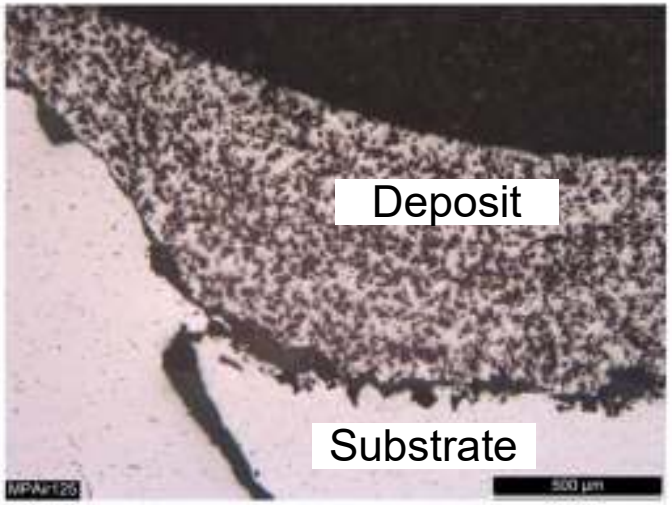


Tangential crack (straight)

Tangential crack (ring-like)

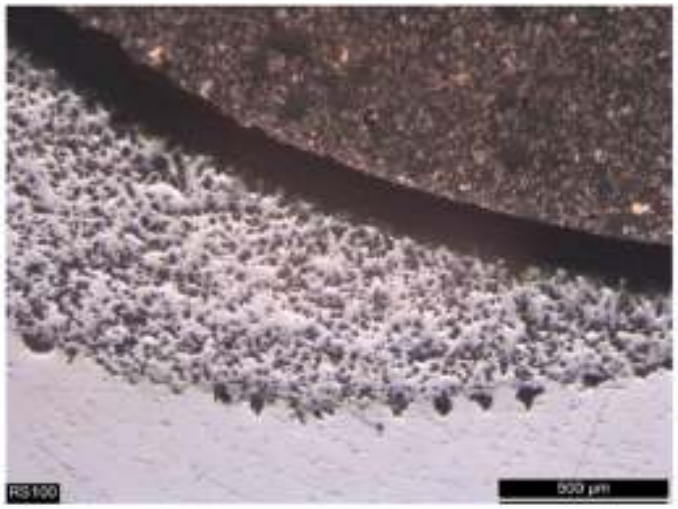
Delamination

MPAir 125

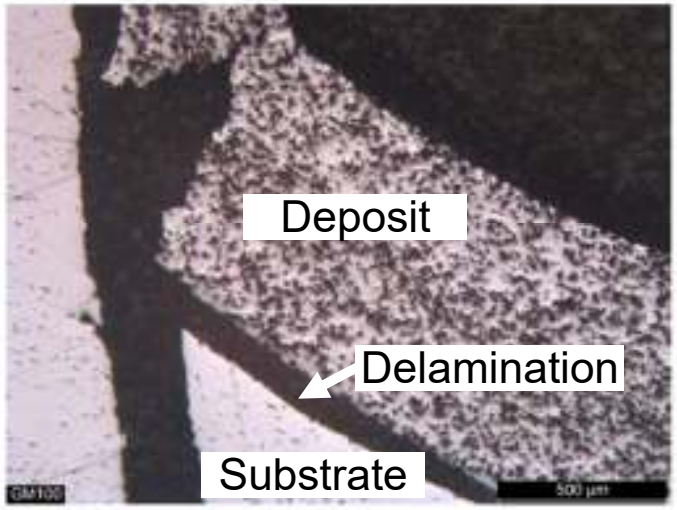


RepAirMid 100

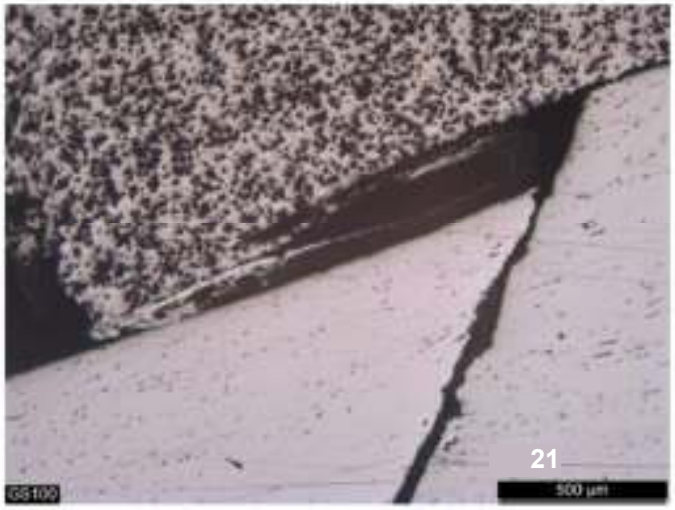
RepAirSid 100



GunMid 100

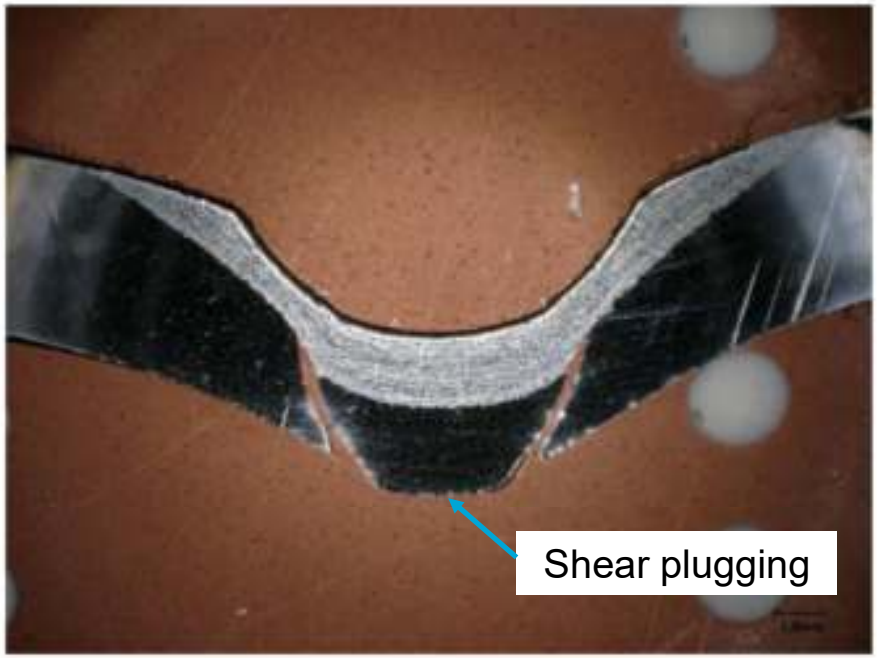


GunSid 100

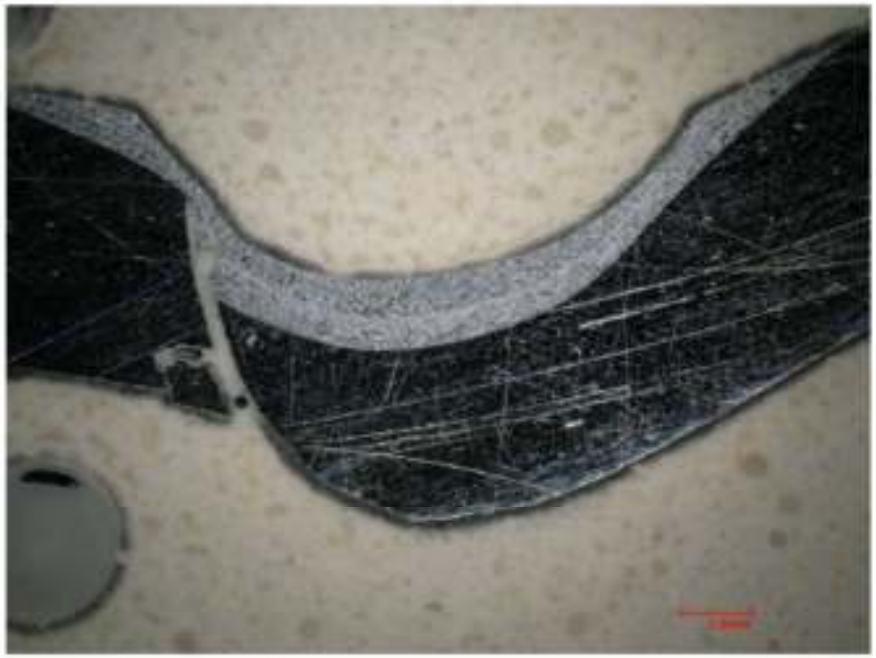


NB: Material appears intact from impact side (= outside!)

Shear plugging & stretching



RepAir Mid 100J – 20M



Gun Mid 100J – 30M

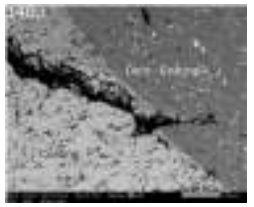
Thresholds

0 – 10 J Dent

10 – 20 J Cracking

50 -100 J Delamination

50 -100 J Back-face cracking

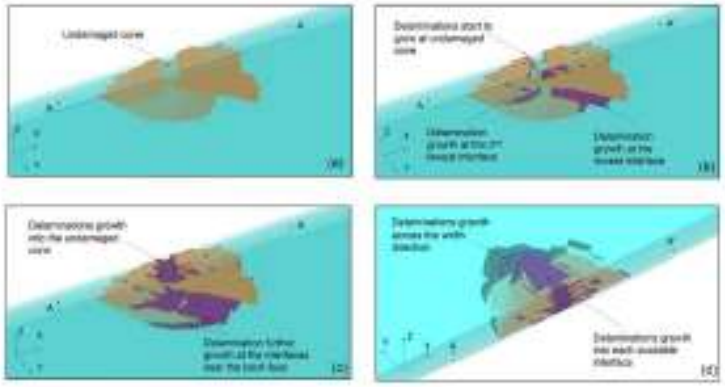


Impact Energy

What can we learn from composites ?

- No BIVD… but!
  - Hidden cracking

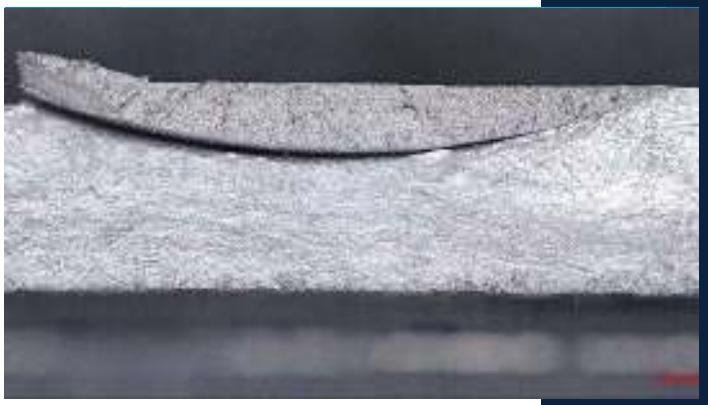
- Multiple interacting failure modes



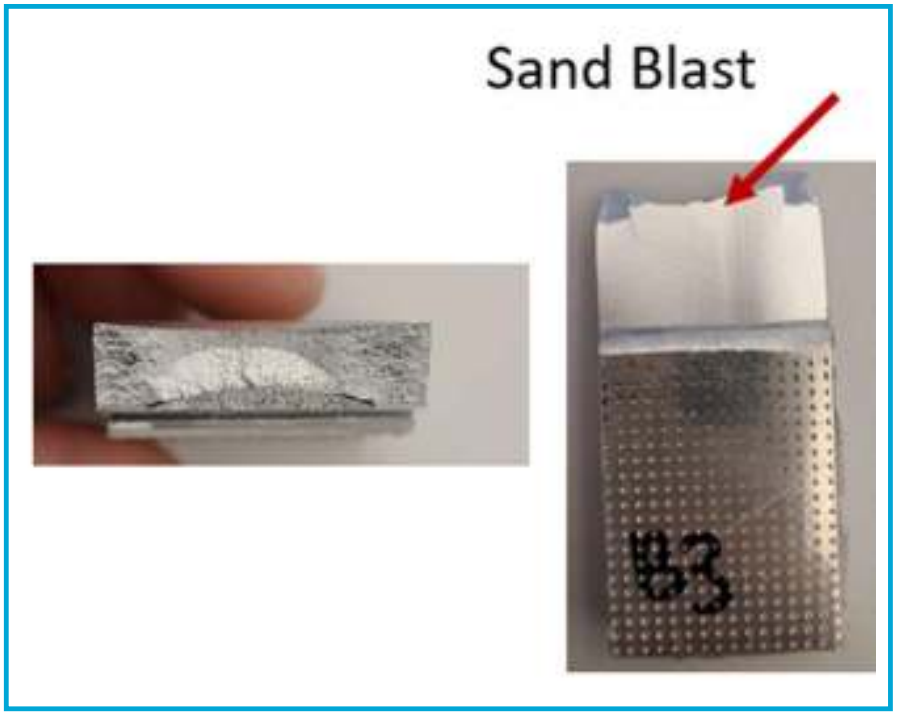
Failure mechanisms and damage evolution of laminated composites under compression after impact (CAI): Experimental and numerical study

X.C. Sun *, S.R. Hallett

Composites: Part A 104 (2018) 41–59



Fatigue



Single crack

Limited delamination

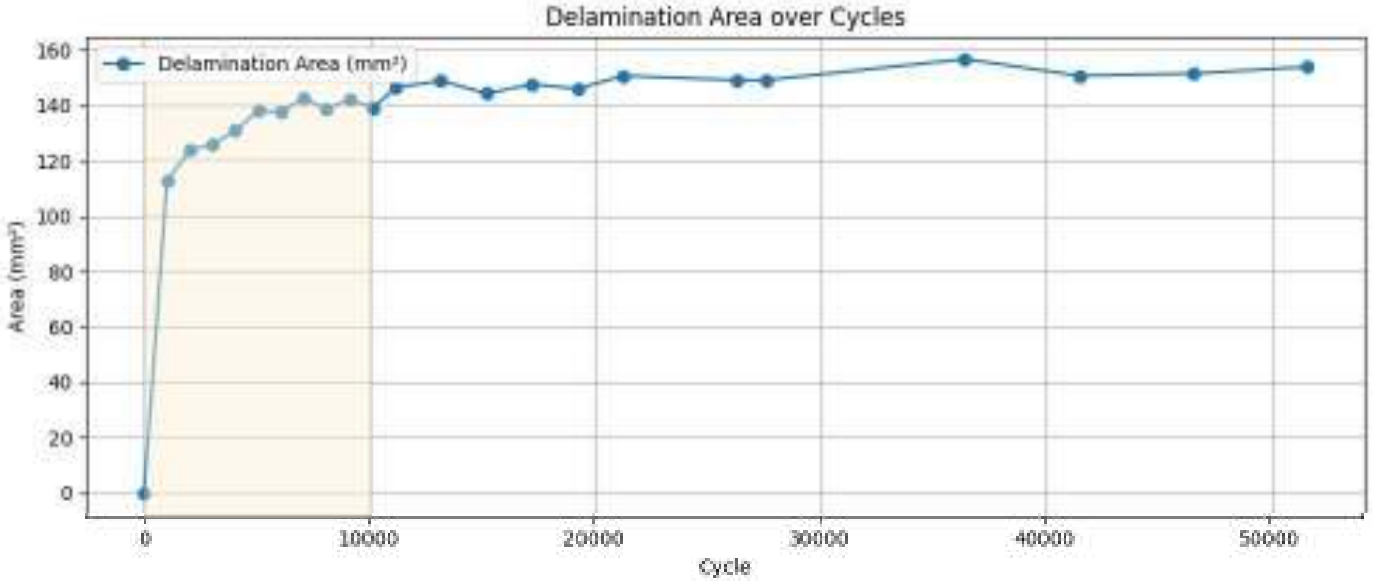
$N_{f,avg} = \sim 51{,}000$

Multiple cracks

Extensive Delamination

$N_{f,avg} = \sim 94{,}000$

Delamination Measurement with C-scan



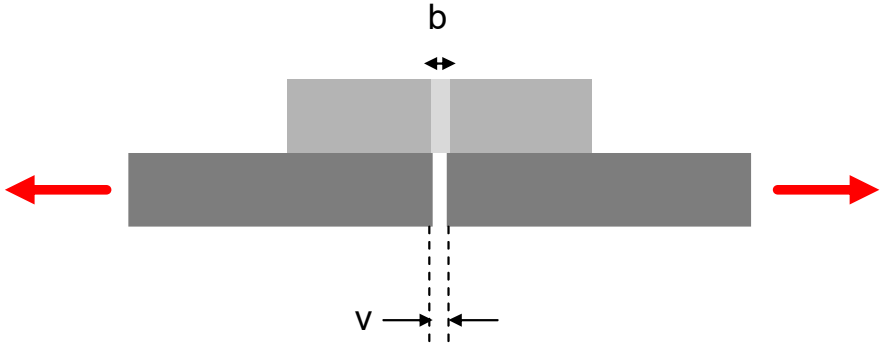
Graph courtesy Pascal Dinglinger

What can we learn from composites / FMLs?

Delamination / crack interaction

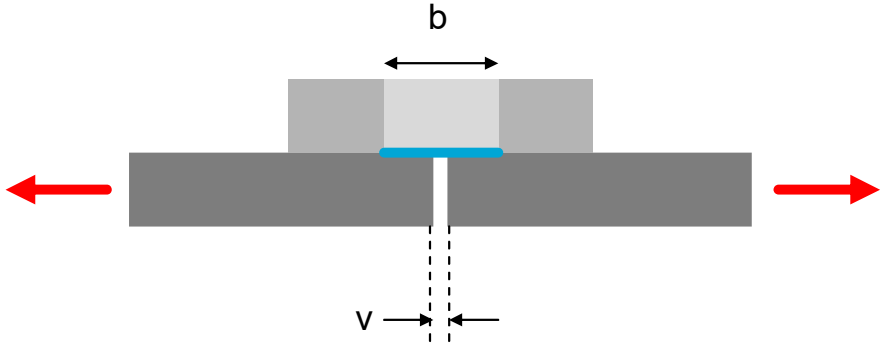
No delamination

$$\epsilon = \frac{v}{b}$$



With delamination

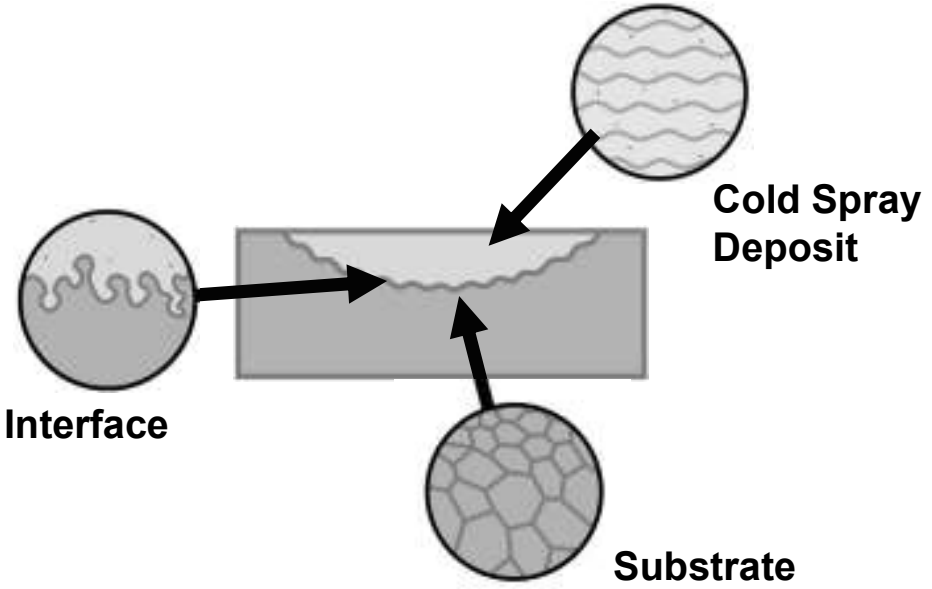
$$\epsilon = \frac{v}{b}$$



Conclusions

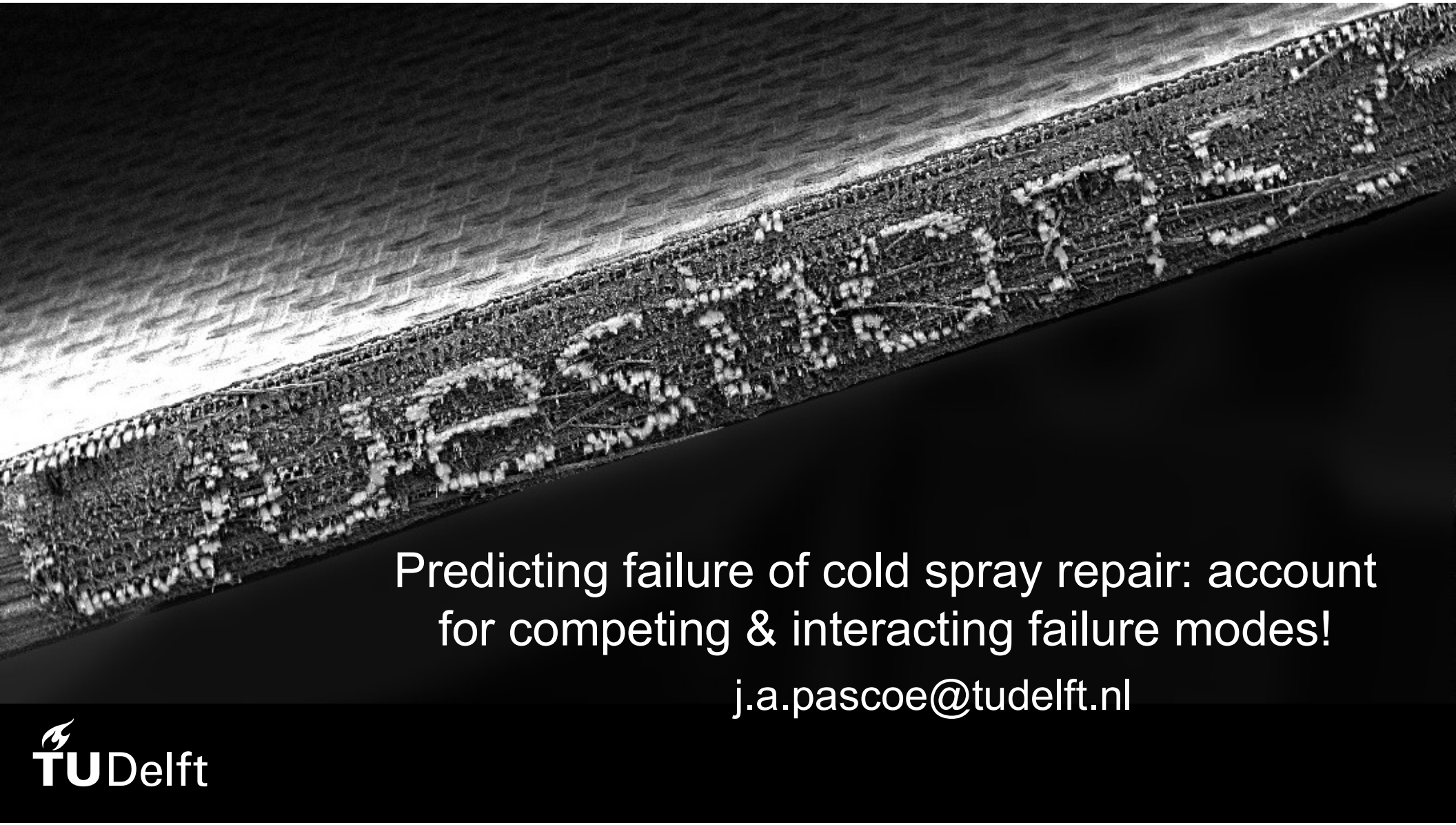
Conclusions

- Multiple failure modes
  - Competition
  - Interaction



- Need for individual characterisation

- We can draw inspiration from the composites community!



Predicting failure of cold spray repair: account for competing & interacting failure modes!

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