Advances in packaging interconnects

IMAPS-UK Research Showcase

11th & 12th of January, 2021

Dr Pearl Agyakwa & Prof Mark Johnson

Email: pearl.agyakwa@nottingham.ac.uk

Twitter: @DrMaterialsMum

Acknowledgements, colleagues & contributors

Dr Jingru Dai, Dr Bassem Mouawad, Dr Chris Parmenter, Dr Martin Corfield, Dr Li Yang, Dr Paul Evans, Dr Elaheh Arjmand, Dr Jianfeng Li, Dr Fang Xu, Prof Mark Johnson, Dr Imran Yacqub, Dr Yun Wang, Dr Rob Skuriat (University of Nottingham)

Dr Stuart Robertson, Dr Zhaoxia Zhou (Loughborough University LMCC)

Dr Lisa H. Chan, Dr Hrishikesh Bale, Dr Jun Sun (Carl Zeiss Microscopy & XNovo Tech)

Prof Chris Bailey, Prof Hua Lu (University of Greenwich)

Sincere thanks to Oscar Khaselev and Mike Marczi of Cookson Electronics for providing Ag nanoparticle paste, and to Dr Kim Evans & Dr Mumby-Croft, Dynex Semiconductor Ltd. for the provision of Al and Cu wire bond samples

The work was supported by Mentor Graphics, the UK Engineering and Physical Sciences Research Council projects EP/K035304/1 & EP/R004366/1 through the Centre for Power Electronics, the Innovative Electronics Manufacturing Research Centre (IeMRC) EP/H03014X/1, the Engineering and Physical Sciences Partnered Access Fund (2017) and the EU Commission's 7th Framework Programme Cleansky2 JU EMINEO

Overview of session

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

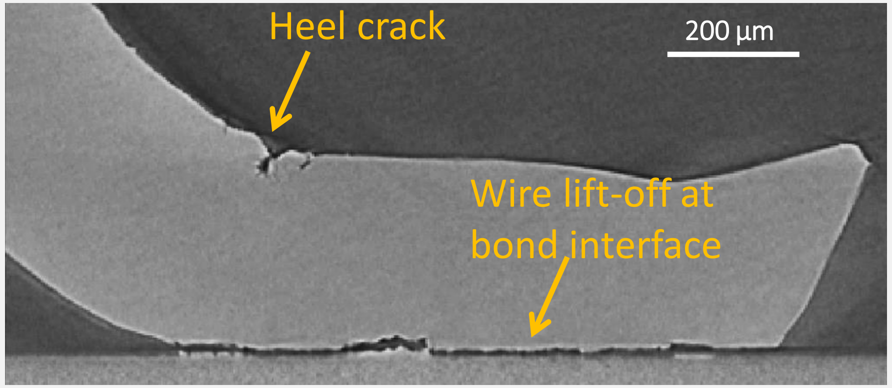
- Typical interconnect failures
- Overview of candidate interconnection technologies for higher operational temperatures
- Ultrasonic wire bond interconnects
  - Al, Cu, others…
- Die attach options
  - Pb-free solders, sintered nanoAg attach

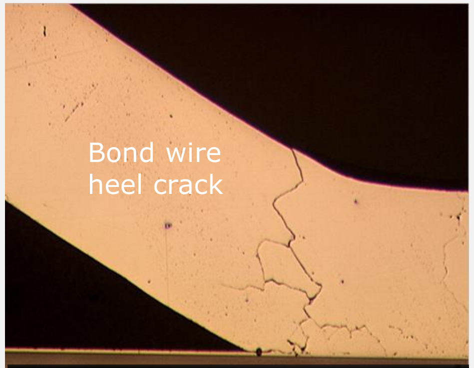
Interconnect failure mechanisms

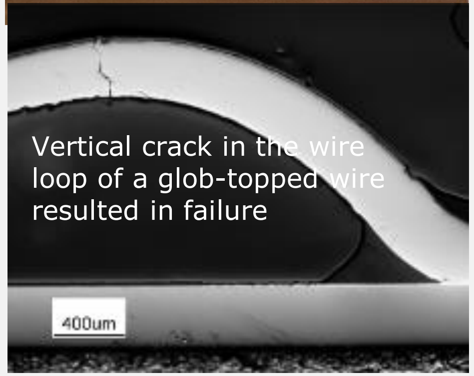
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

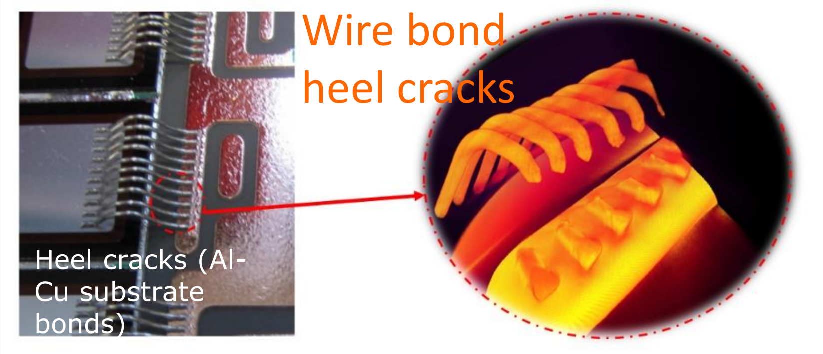
Interconnections dominate failure processes & ultimately determine package reliability

Wire bond cracking under temperature cycling



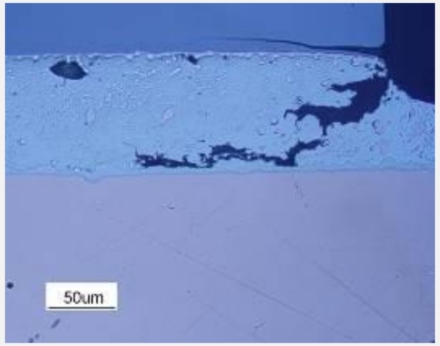


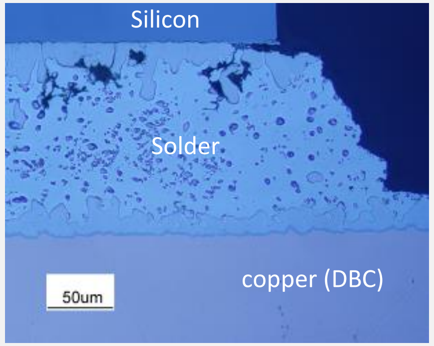


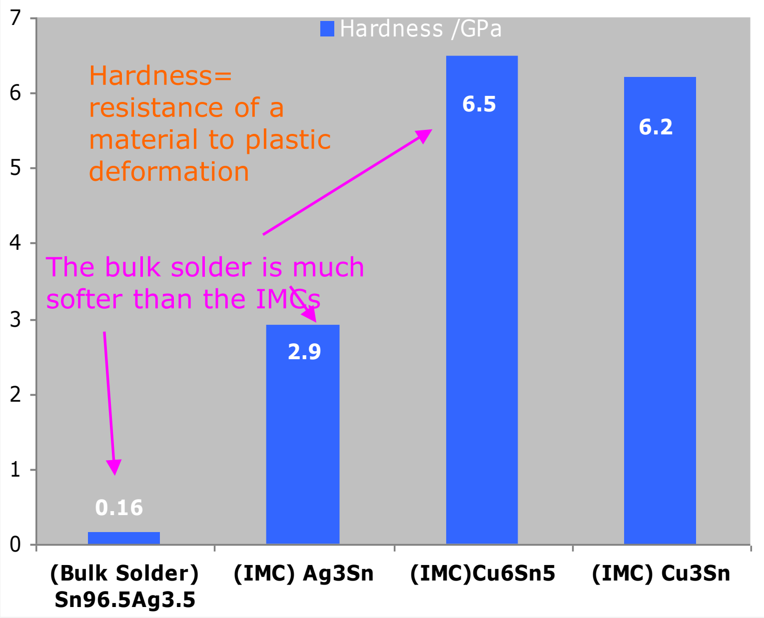


High-cycle fatigue resistance is sensitive to the nucleation of micro-cracks at microstructural inhomogeneities

Microstructural changes within solder affect its bulk properties over time







Sources: McNulty, 2008; Lau & Pao, 1997; Chomrik *et al.*, 2005; Chomrik *et al.*, 2003; Harris & Rubel, 2008.

Candidate interconnect technologies for WBG

Benefits, Challenges and Constraints

- High switching frequency, higher power densities, improved energy conversion efficiency
- Can exploit higher levels of package integration
- Higher power densities- higher packaging temperatures

Interconnections dominate failure process and ultimately determine package reliability

New attachment methods need to offer

- High temperature stability
- High performance in terms of thermal and electrical conductivity
- Manufacturing flexibility and compatibility with highly integrated designs and topologies
- High reliability and robustness (longevity under harsh/extreme operating environments)
- Sustainability (holistic appraisal & minimisation of environment, health, geopolitical impacts)

Candidate interconnect technologies

Ultrasonically bonded wires

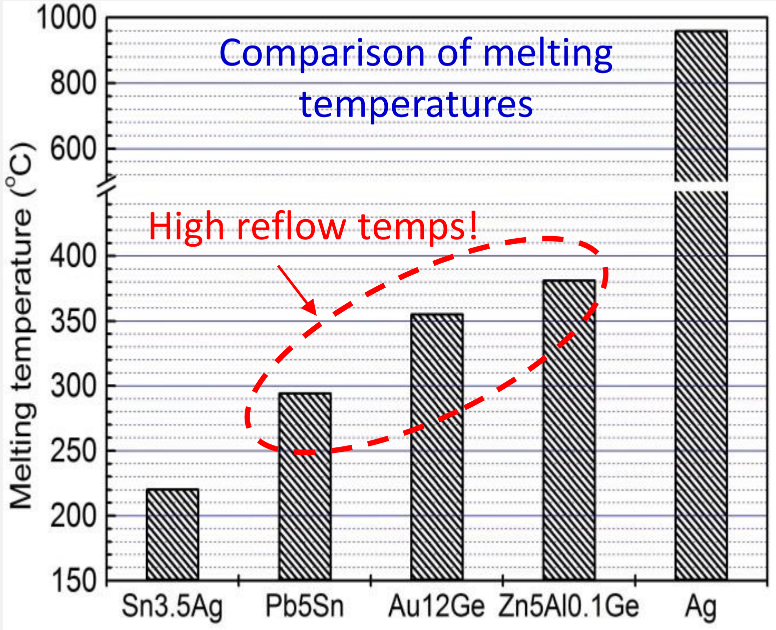
- Copper
- Aluminium
- Al clad Cu?
- Other metals – Au?

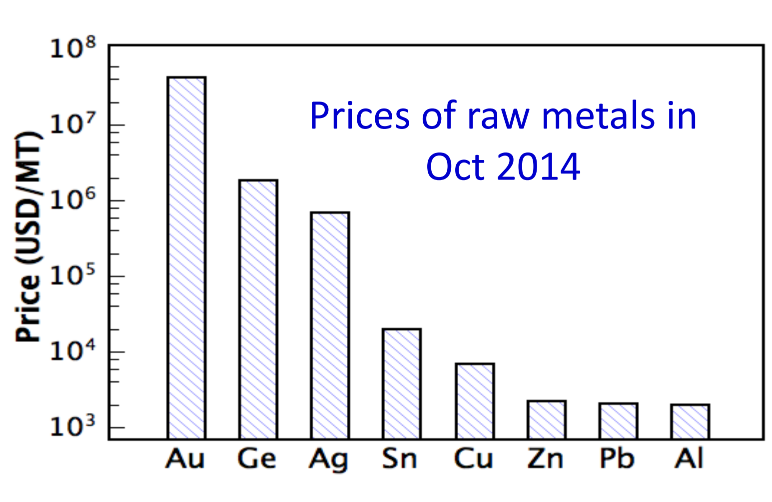
High temperature solders e.g. AuSn, AuGe, PbSn, ZnAl, …

- Au-based alloys are expensive, high reflow temps
- Pb: environmental concerns and legislation

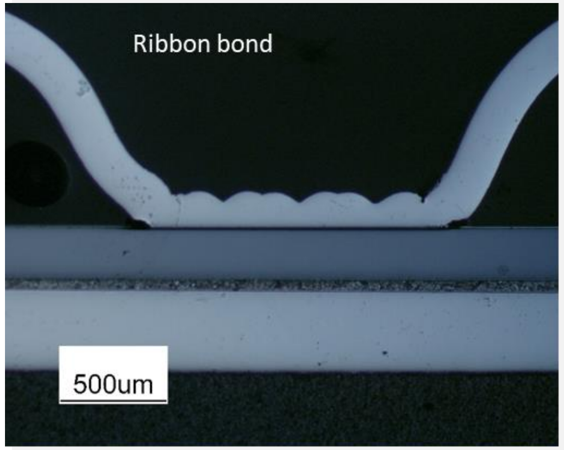
Alternatives to solder

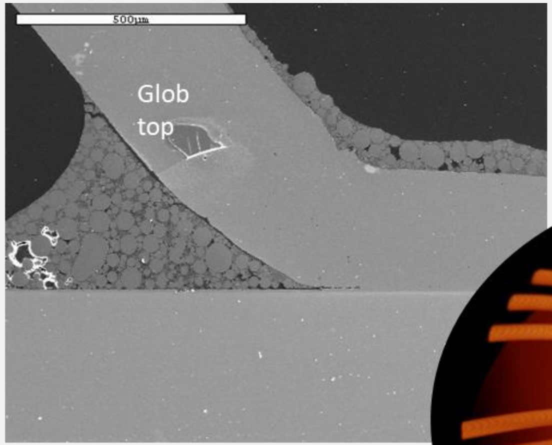
- Sintering of Ag particles or nanoparticles
- Emerging solder alloys
- Transient Liquid Phase soldering
- Liquid solder joints
- Local brazing
- Nanoparticle-enhanced solders
- Ultrasonic welding (e.g. for power terminals)

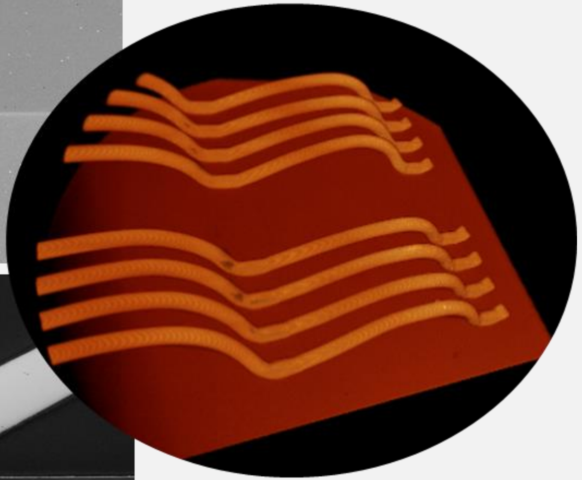


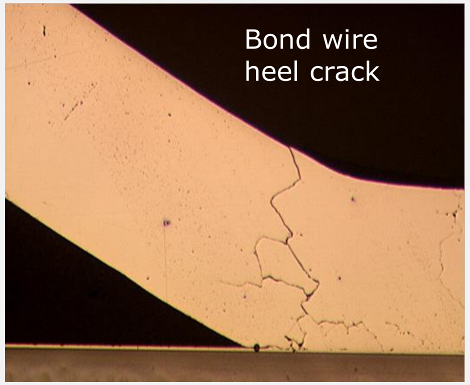


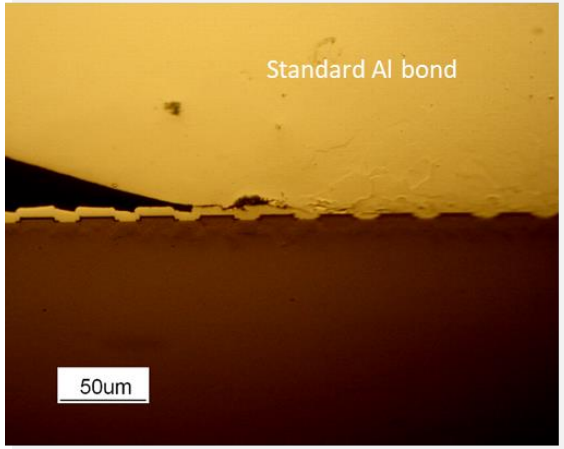
Are Al wire and ribbon bonds suitable for high temp?

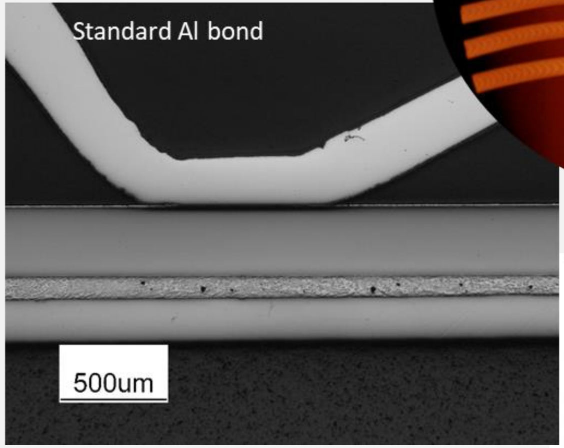


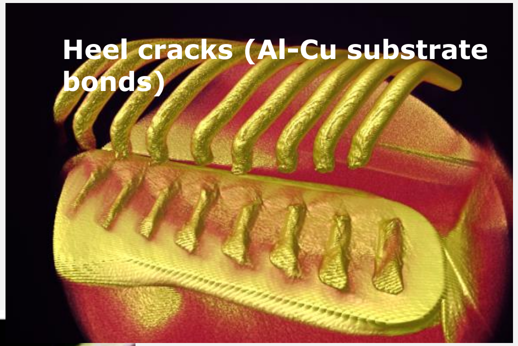


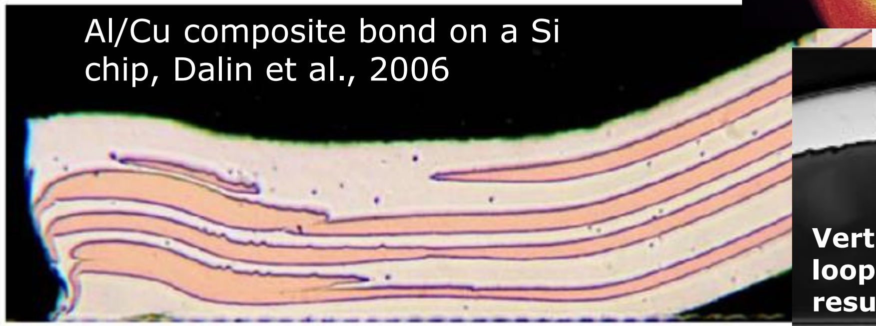


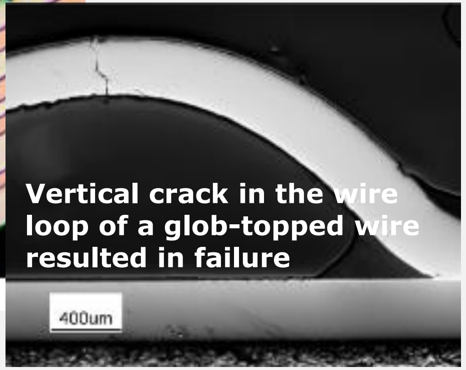




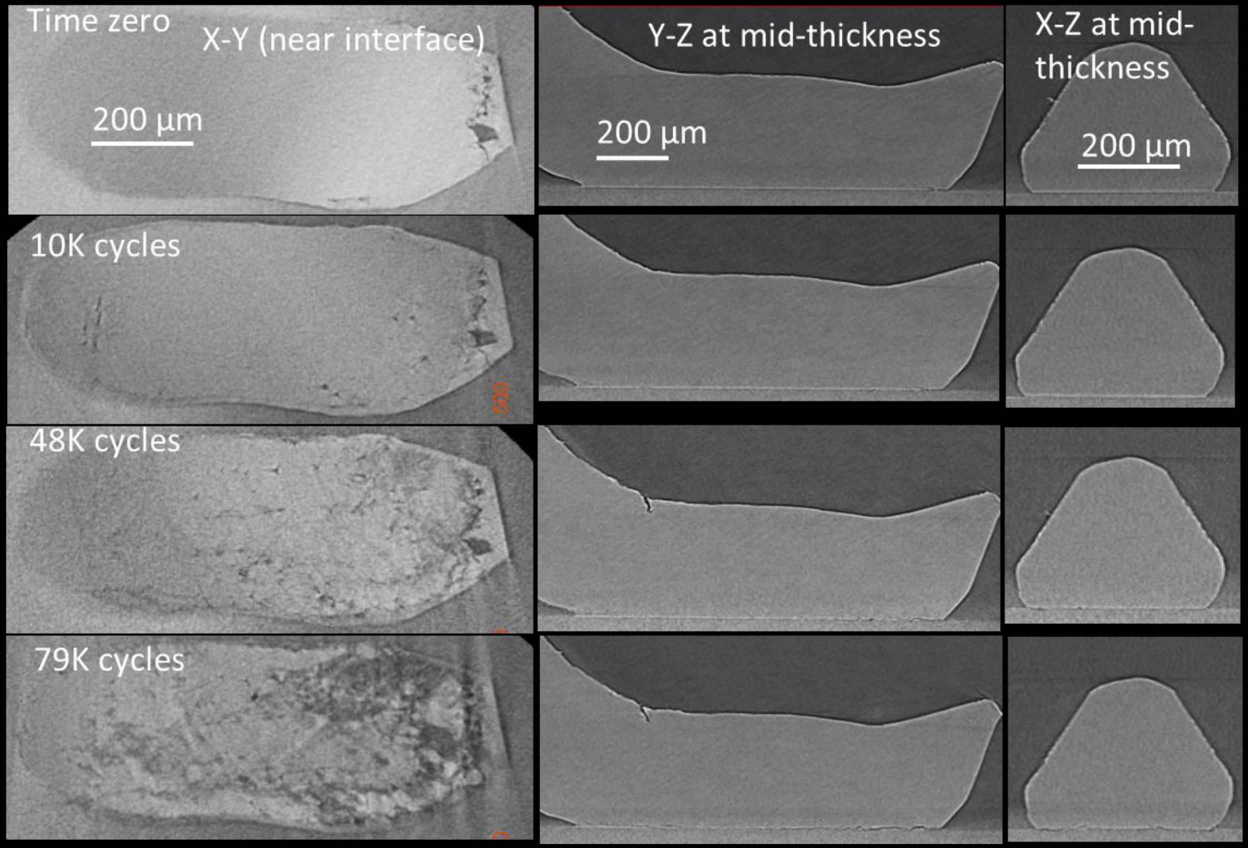






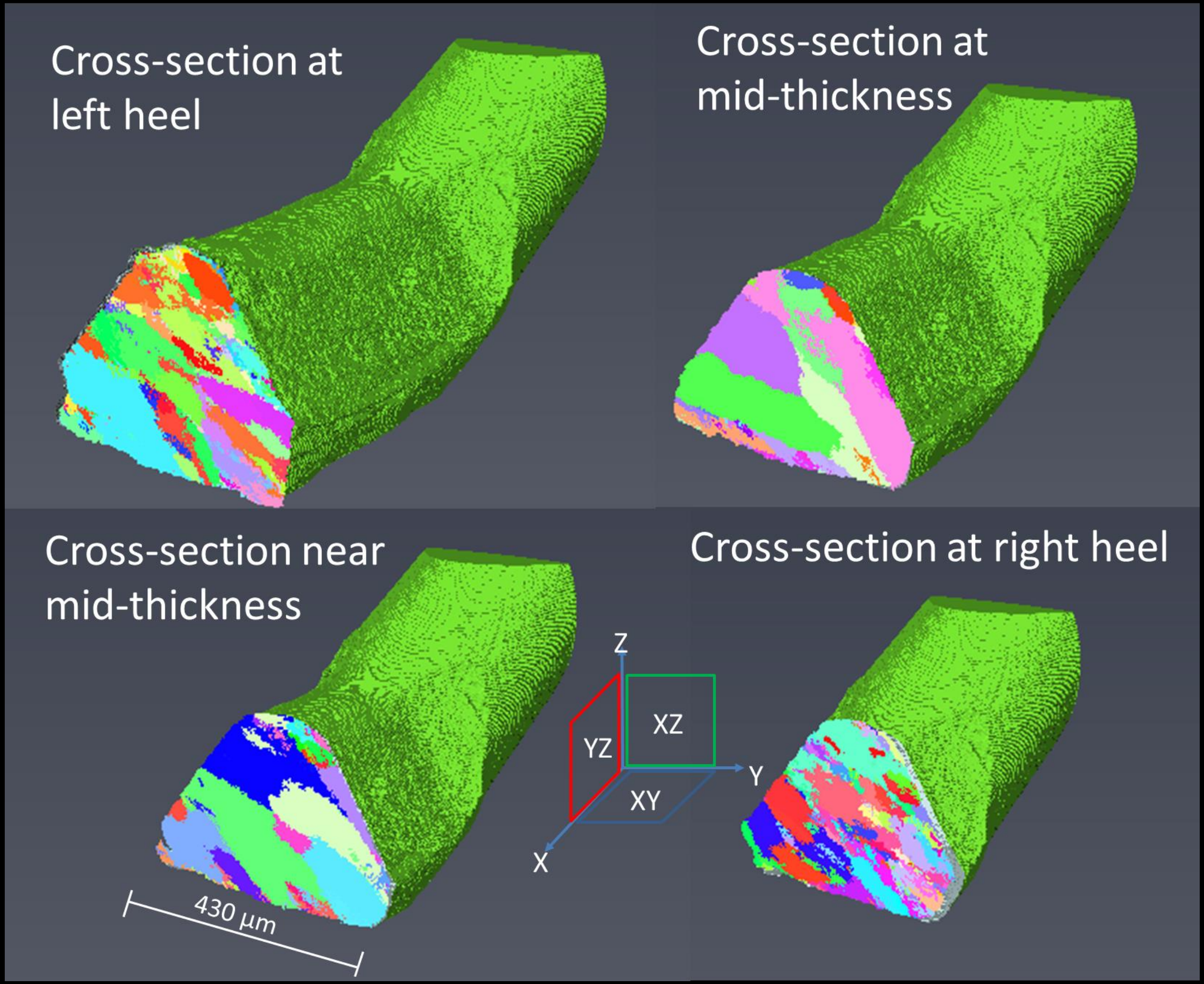


Power cycling reliability in Al bond wires (40 - 120°C)



Failure occurs from edges inwards by undulating cracks which have a high aspect ratio, are essentially planar and restricted to interface region

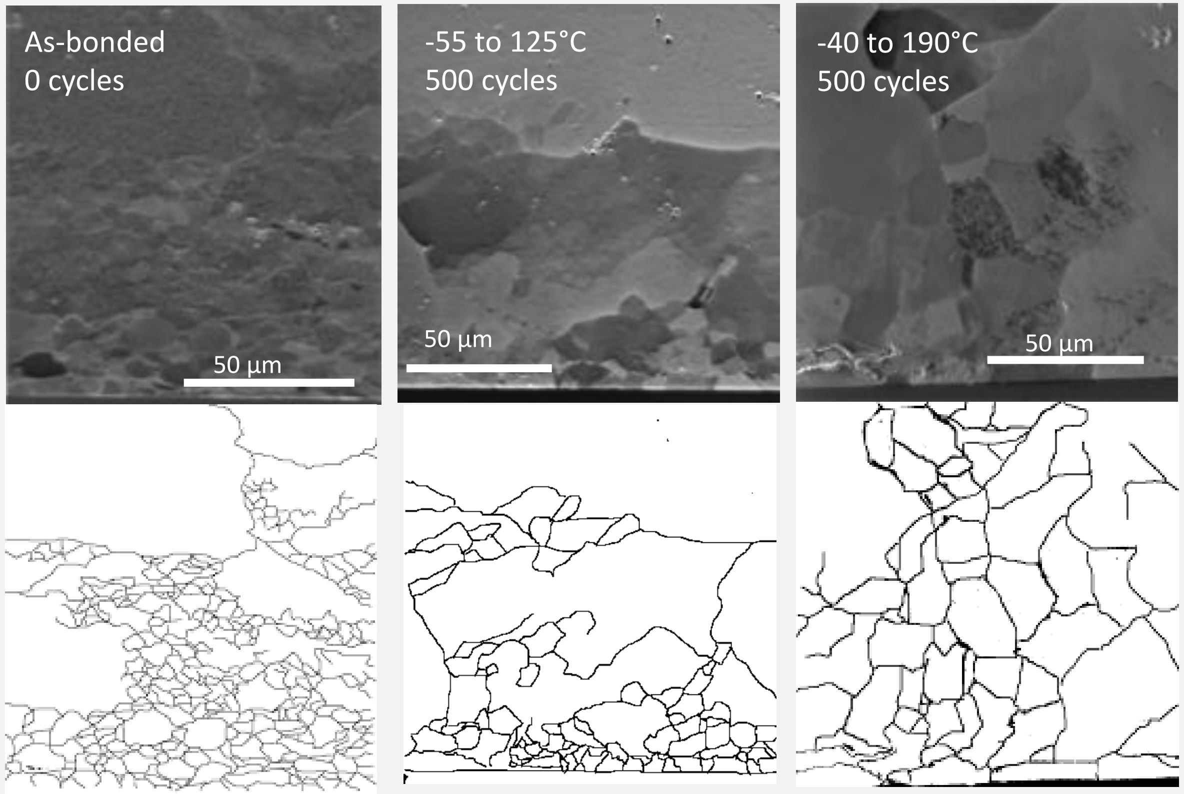
Correlative Diffraction & absorption contrast tomography

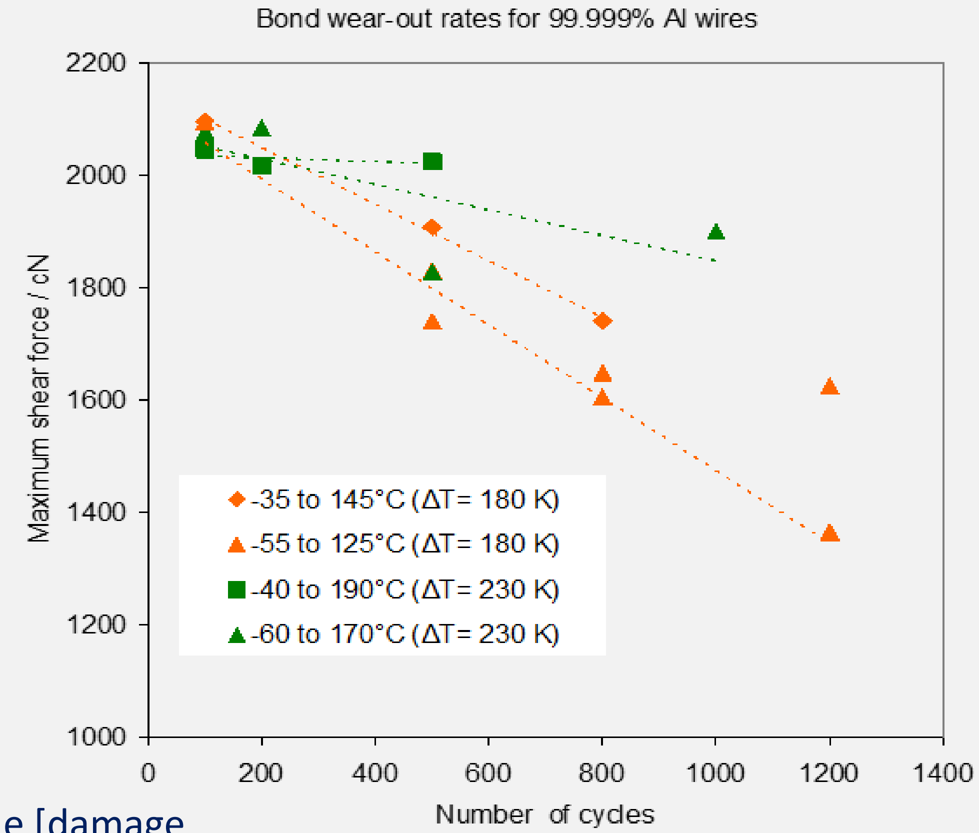


- Wire flexing during loop formation
- Flexing also occurs during power cycling (heel regions experience compressive and tensile forces)
- Electromagnetic forces tend to push the bonds off the die laterally

Deviation from Coffin-Manson behaviour due to time-at-temperature

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA



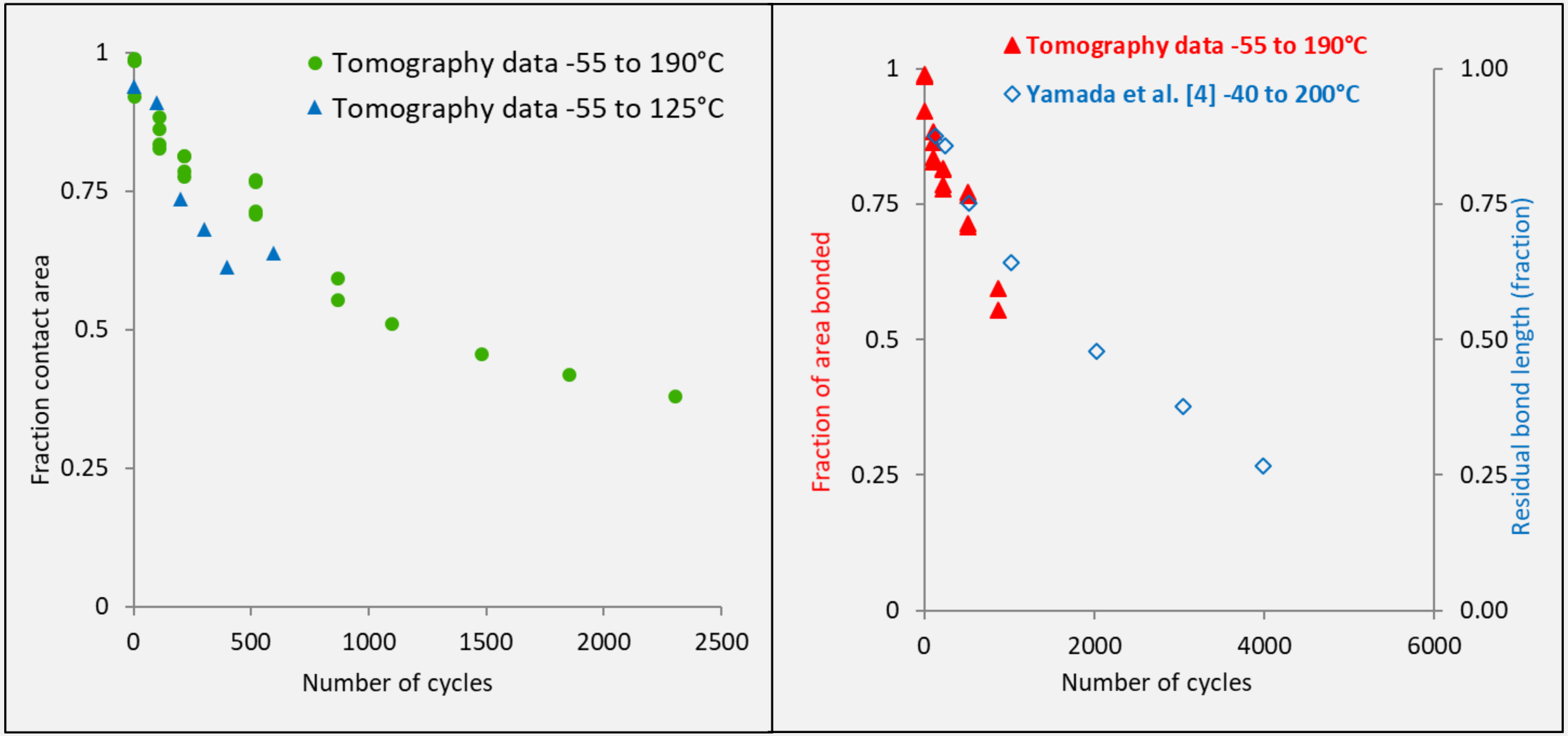


annealing during thermal cycling (dislocation removal) ⟷ Offsets thermomechanical fatigue [damage accumulation (dislocation generation)]

Al wire bonds show high performance under large ΔTs/high maximum junction temps

→ ~~$N_f = a(\Delta T)^{-c}$~~

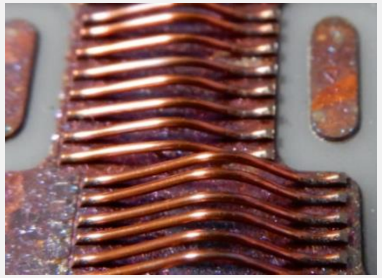
Are Al wire and ribbon bonds suitable for high temp?



- Degradation rate quantified simply by measuring fraction of area bonded from X-ray CT ‘same-sample’ data
- Comparison with metallurgical cross-section data from Yamada *et al*. (2007) shows reasonable agreement

Copper Wire Bonding

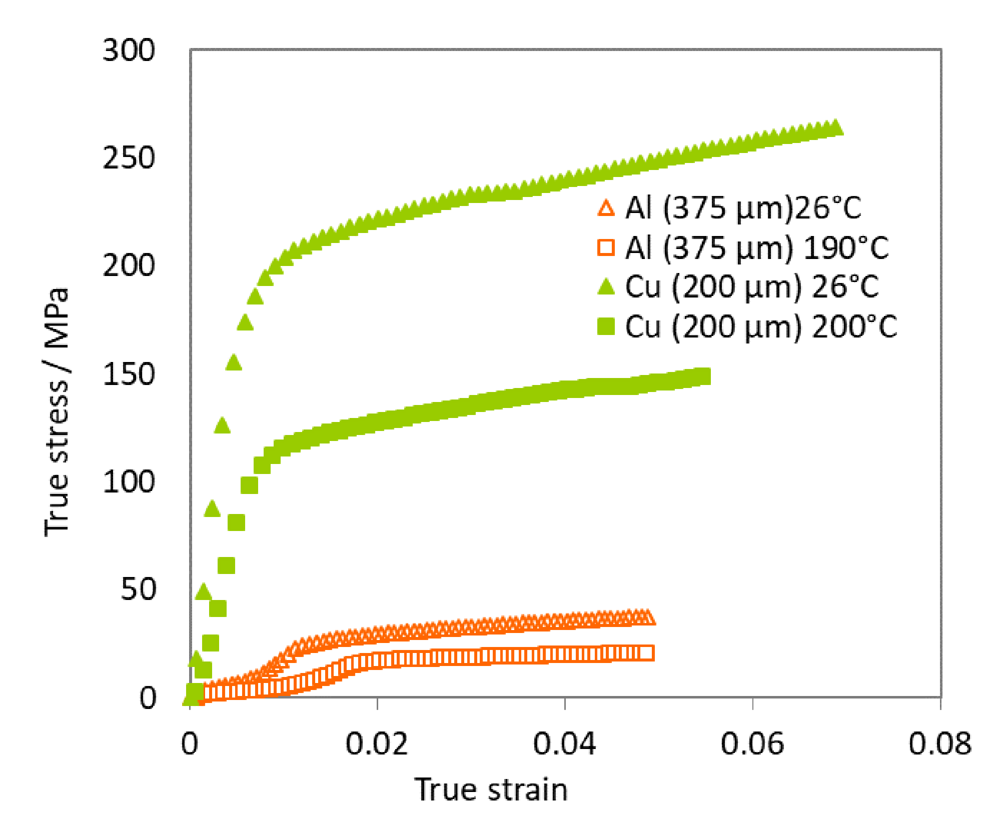
Copper is of increasing of interest as an alternative material to Al because



- Higher electrical and thermal conductivity that provide higher current densities
- Higher yield strength and mechanical stability which are expected to result in improved reliability

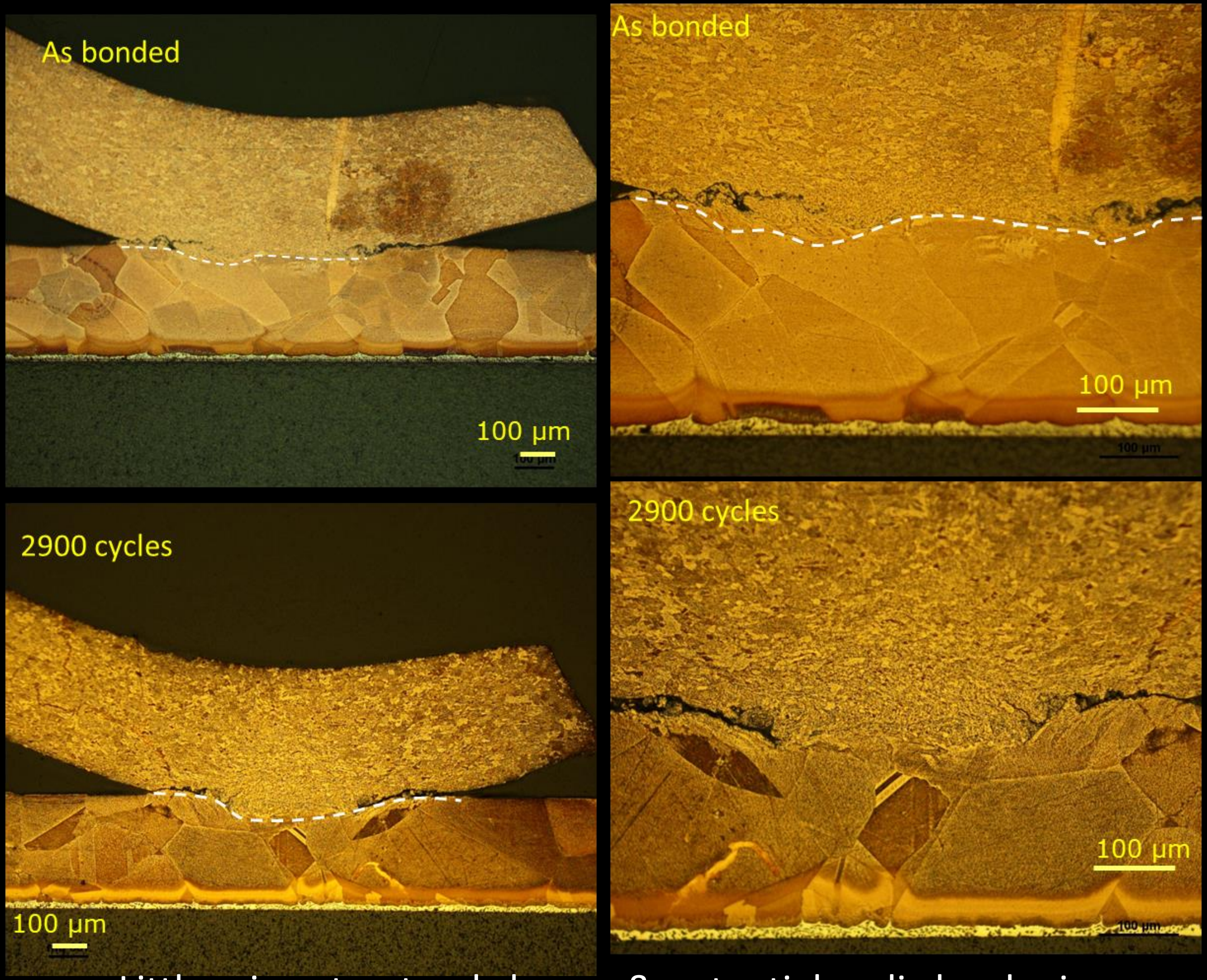
Problem:
Copper wire is much harder compared to aluminium and so requires higher bonding force and power which can potentially damage the bond pad area, this applies to both copper metalized die or DBC substrates

Material Properties	Aluminium	Copper
Thermal conductivity	220 W/m.K	400 W/m.K
CTE	25 ppm	16.5 ppm
Yield Strength	29 MPa	140 MPa
Melting point	660 0C	660 0C
Elastic modulus	50 GPa	110-140 GPa
Electrical resistivity	2.7 µOhm.cm	1.7 µOhm.cm



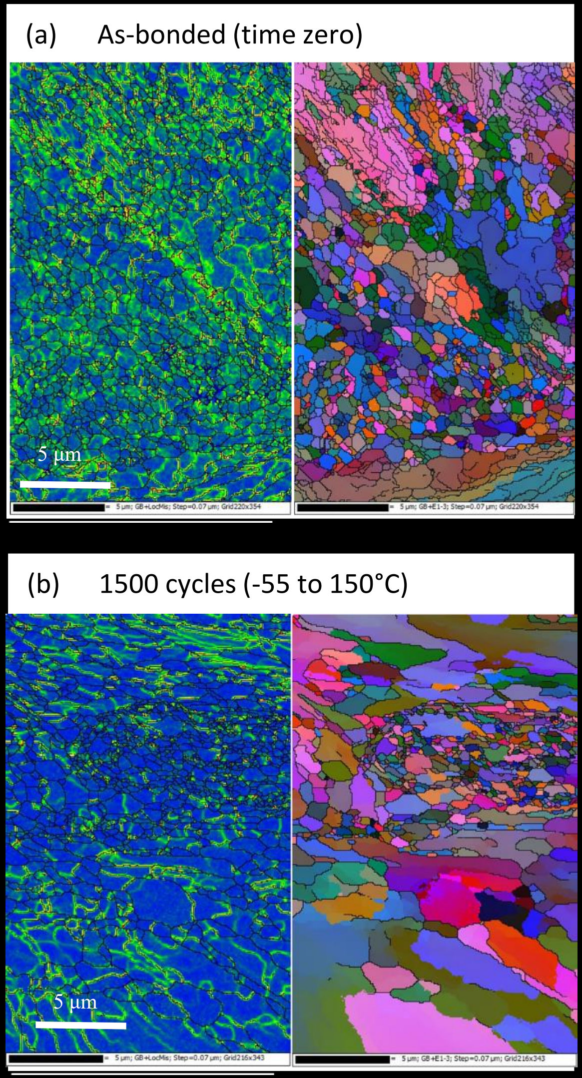
Cu-Cu bond interface

Microstructure of Cu-Cu (substrate) bond interface under passive cycling, -55 to 125°C



Little microstructural change & potential cyclic hardening

Pre-annealed 380µm wires bonded on Orthodyne system (Dynex) -55 to 150°C

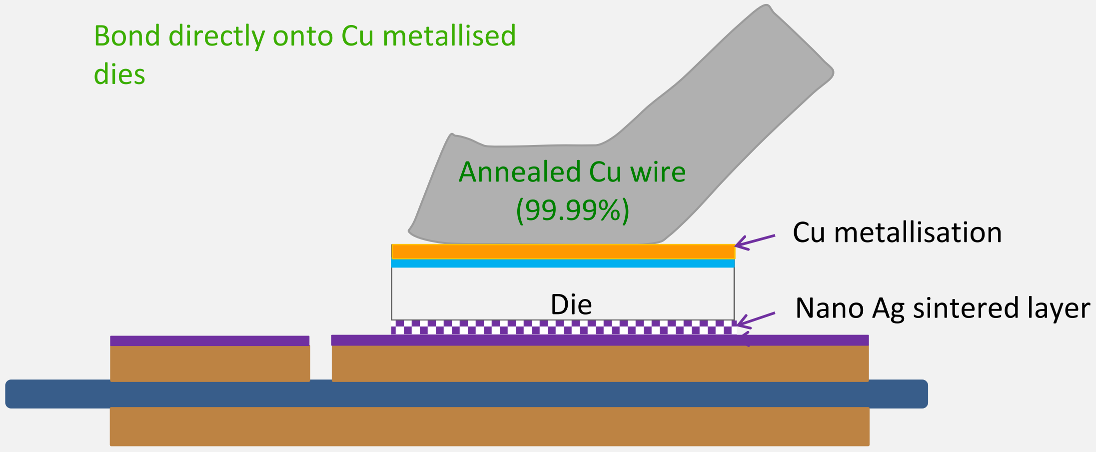


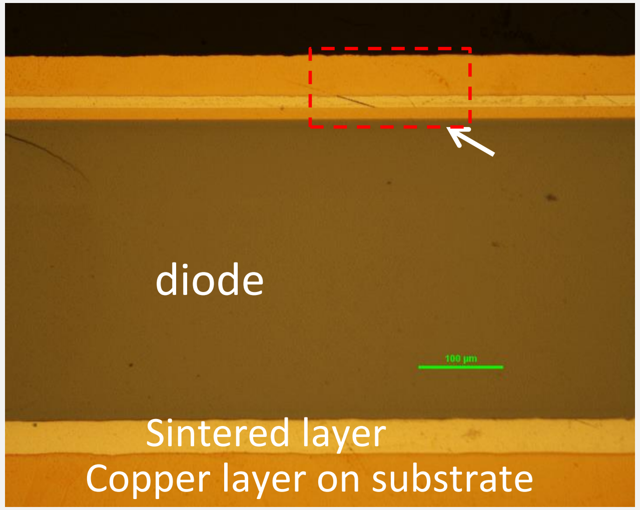
Continued recrystallisation under cycling & modest softening

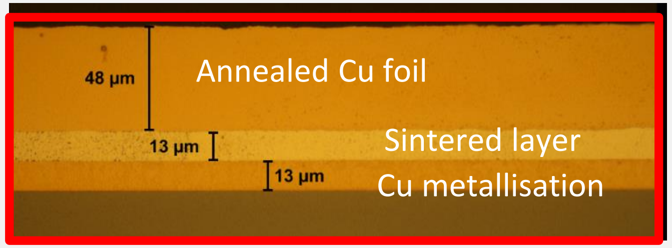
Ongoing research: bonding onto devices

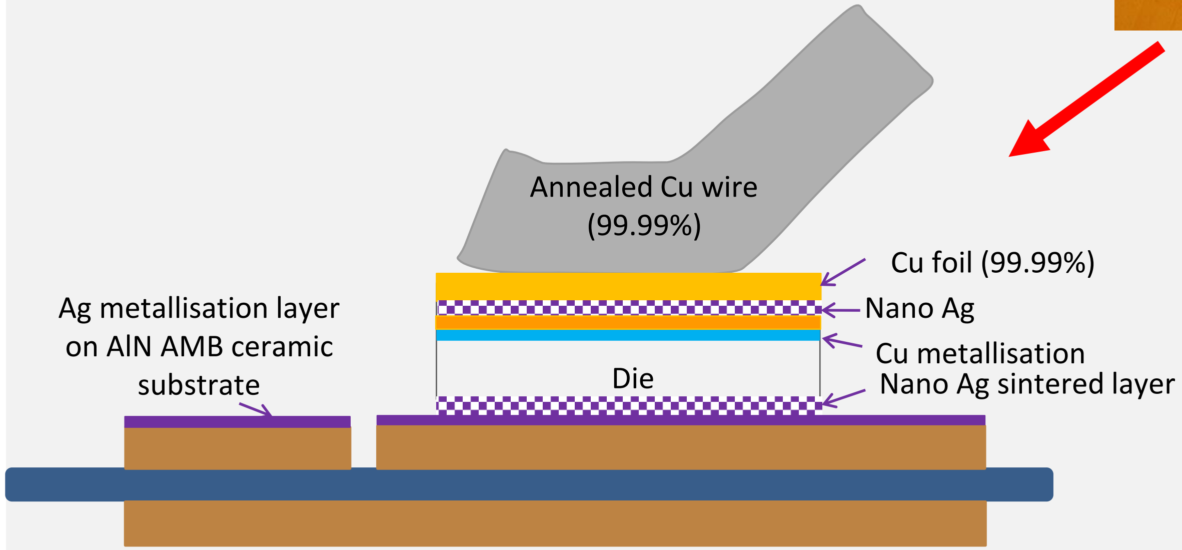
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

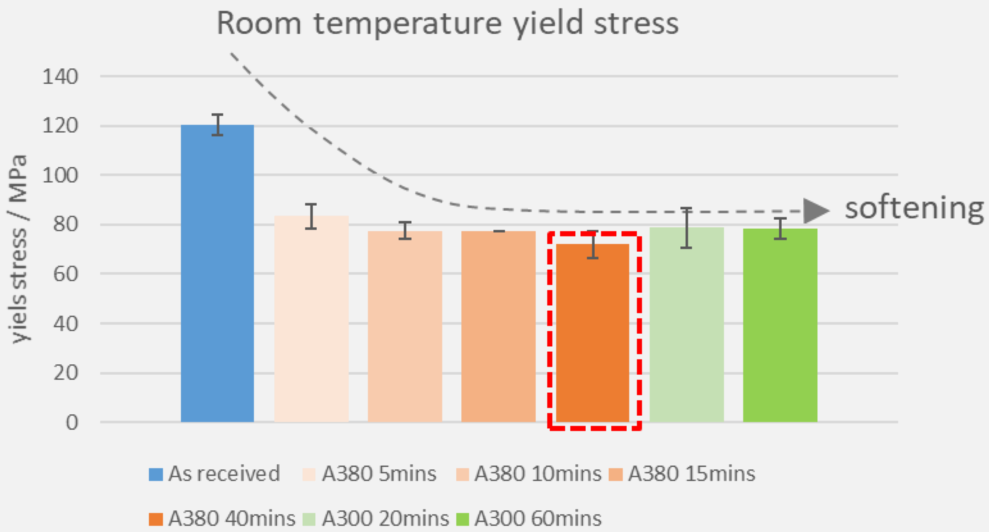
Bond directly onto Cu metallised dies





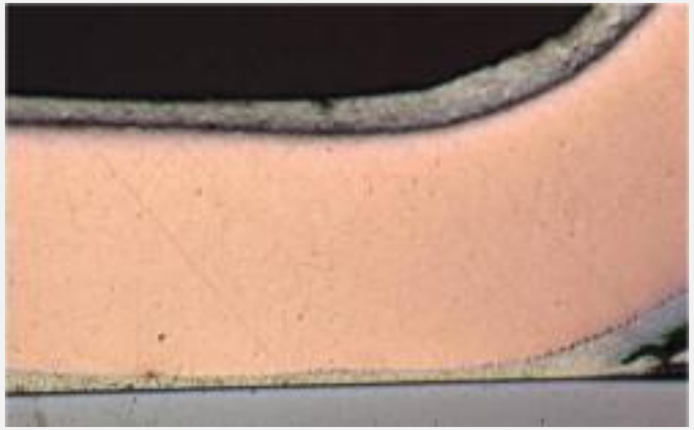




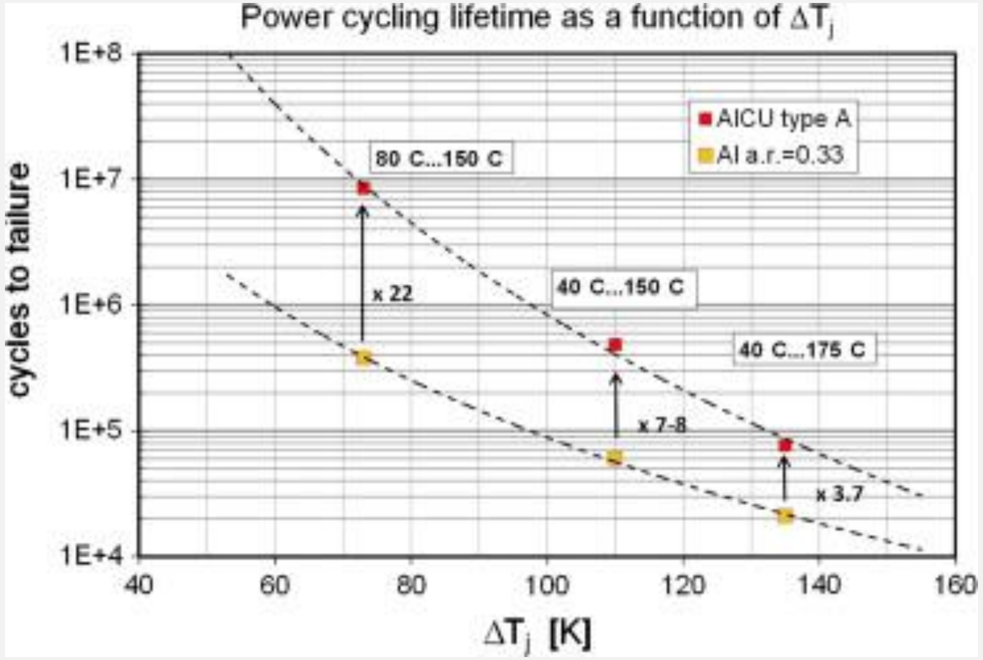


Pre-annealing of wire moderately reduces yield strength & facilitates bonding

Al-clad Cu wires?



Degradation mechanism? CTE issues?



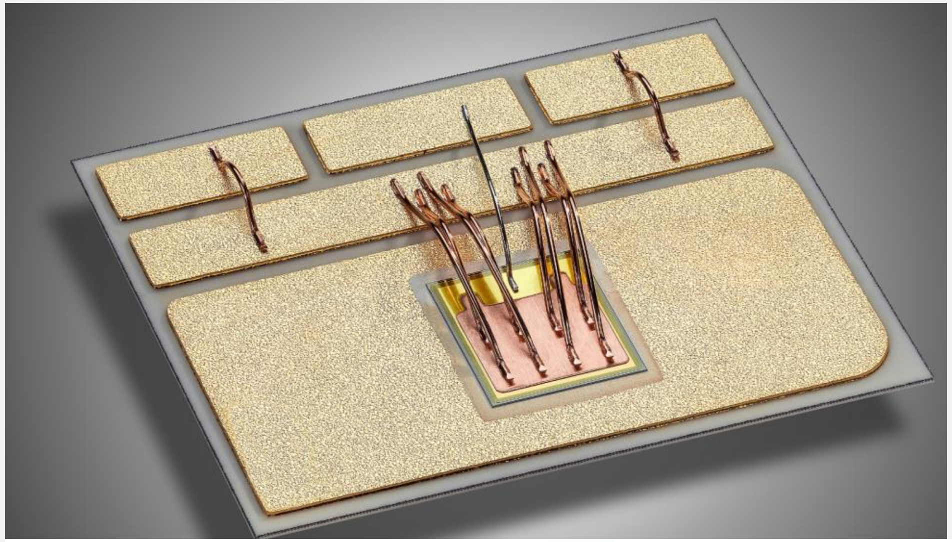
Schmidt et al.,
Microelectronics Reliability
Volume 52, Issues 9–10, Pages 2283-2288

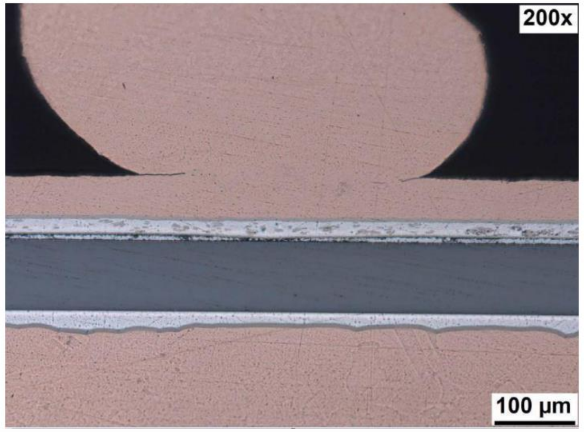
Heraeus Die Top System

https://www.heraeus.com/media/media/het/doc_het/products_and_solutions_het_documents/material_systems_1/die_top_system_docs/Flyer_Die_Top_System-05-2018.pdf

The University of Nottingham

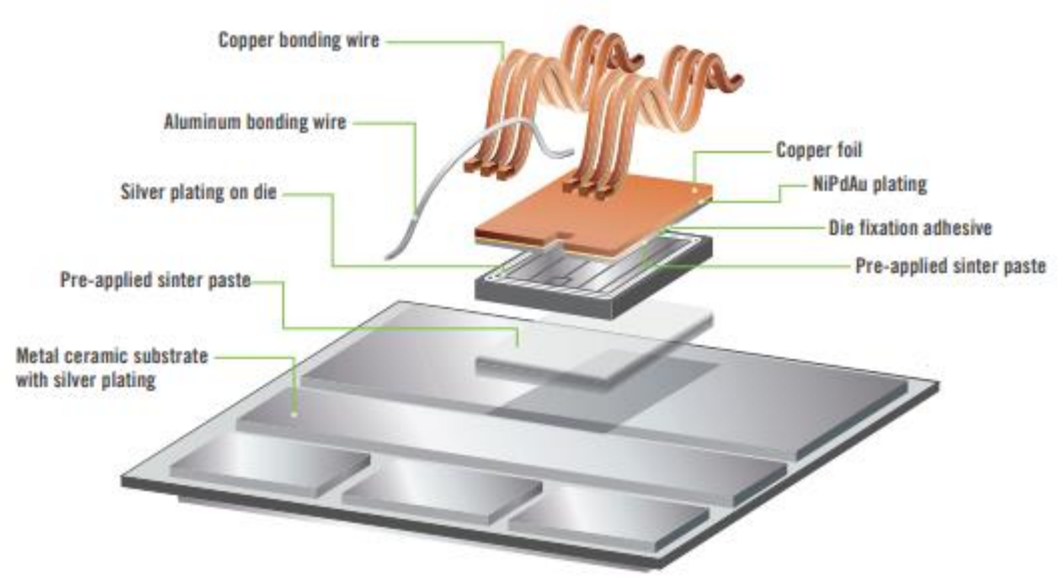
UNITED KINGDOM · CHINA · MALAYSIA

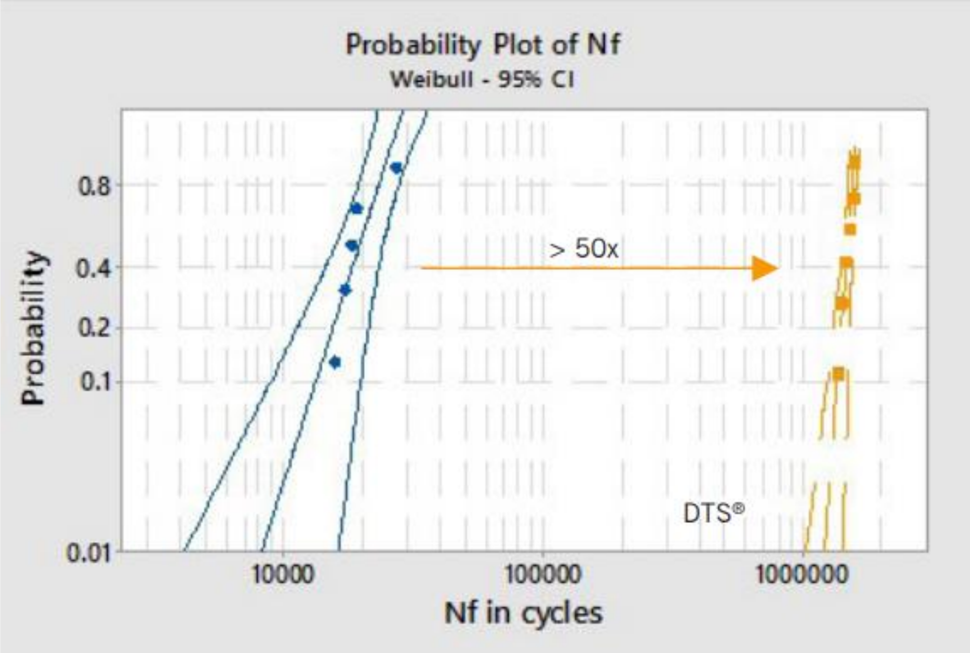




Die Top System®

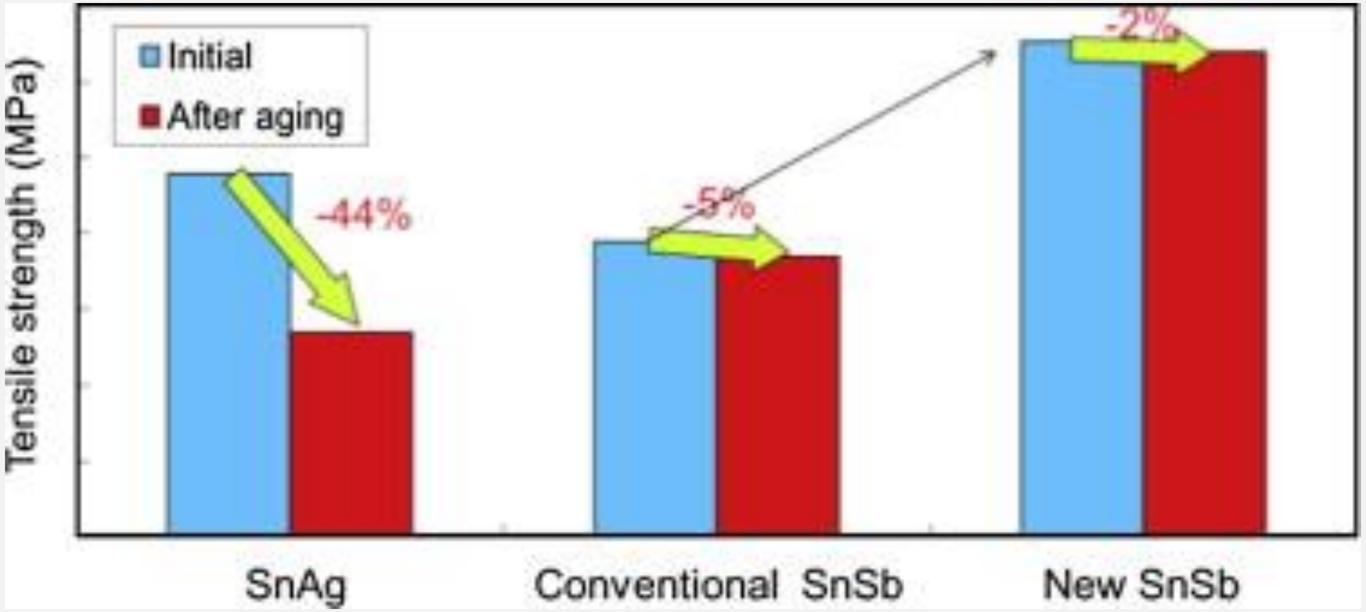
- Silver-sintering Copper foil on top of each die
- Die protection against high bond forces during thick Copper wire bonding
- Spreads current flow
- Heat spreader → lowers hot spot
- Significant increase of lifetime





Solder alternatives & other interconnect

Solid-solution strengthened solders have been proposed



Tin-Antimony

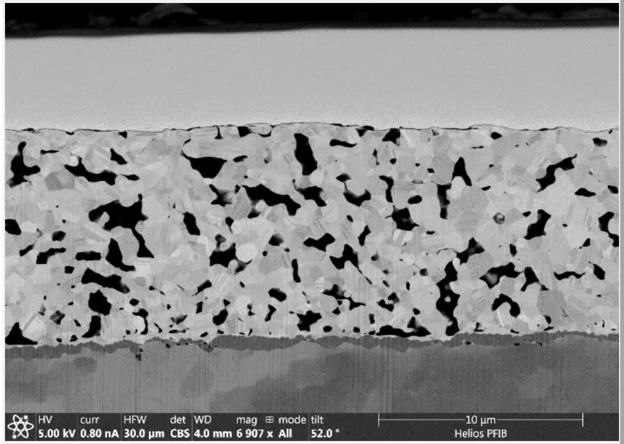
No secondary precipitates, restricted deformation by solid-solution atoms, complex solidification thermodynamics- tight reflow temperature window

Dietrich, Microelectronics Reliability 54 (2014) 1901–1905

Sintered nano-silver attachments

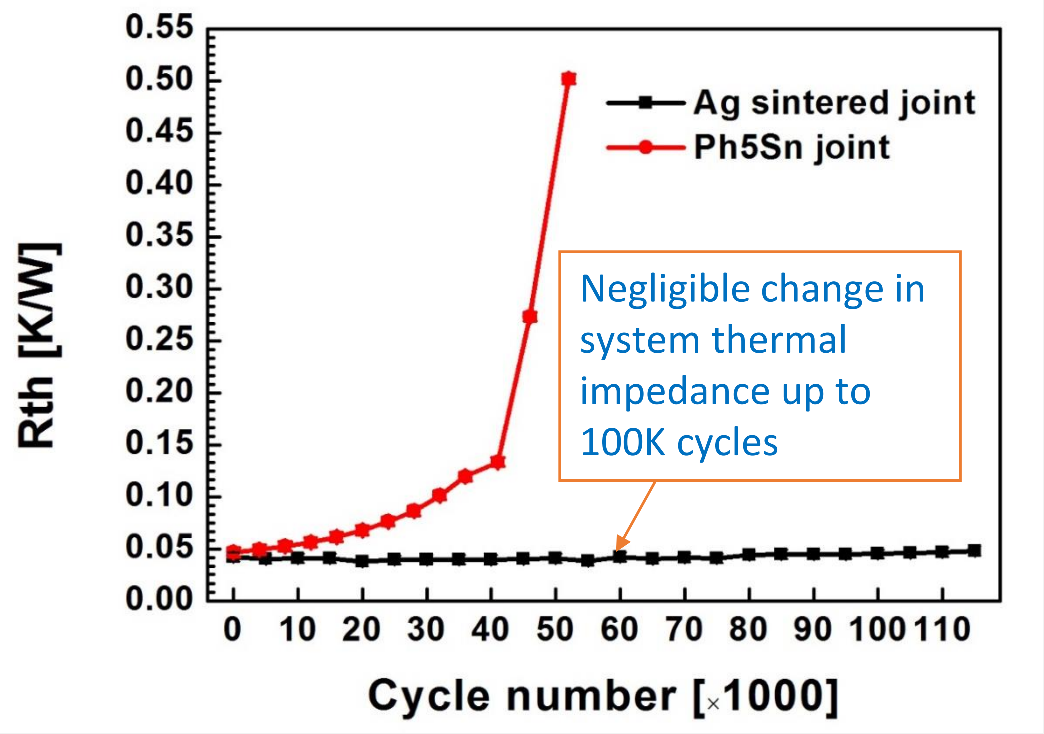
- Higher thermal & electrical conductivity
- Single-phase material (no intermetallic compounds)
- Higher meting point, superior reliability
- Lower cost, less toxicity
- Modest sintering temperatures
- Processing challenges associated with ZnAl alloys and transient liquid phase soldering

	SnAg (3.5)	Ag sintered
T_m / °C	221	962
Thermal conductivity / W/M/K	70	240*
Electrical conductivity / MS/m	8	41
CTE / ppm/K	28	19
Tensile strength / MPa	30	55



* Schueurmann *et al*.

Previous work show sintered attachments are significantly more reliable

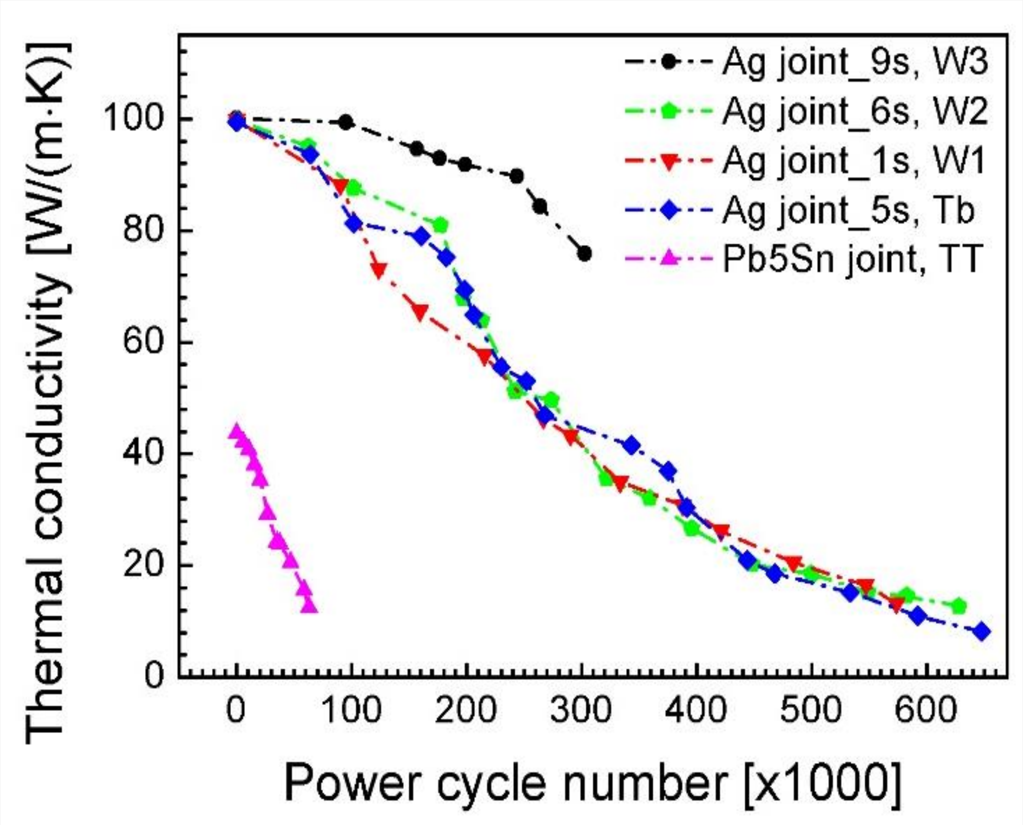


However, degradation processes require characterisation & modelling

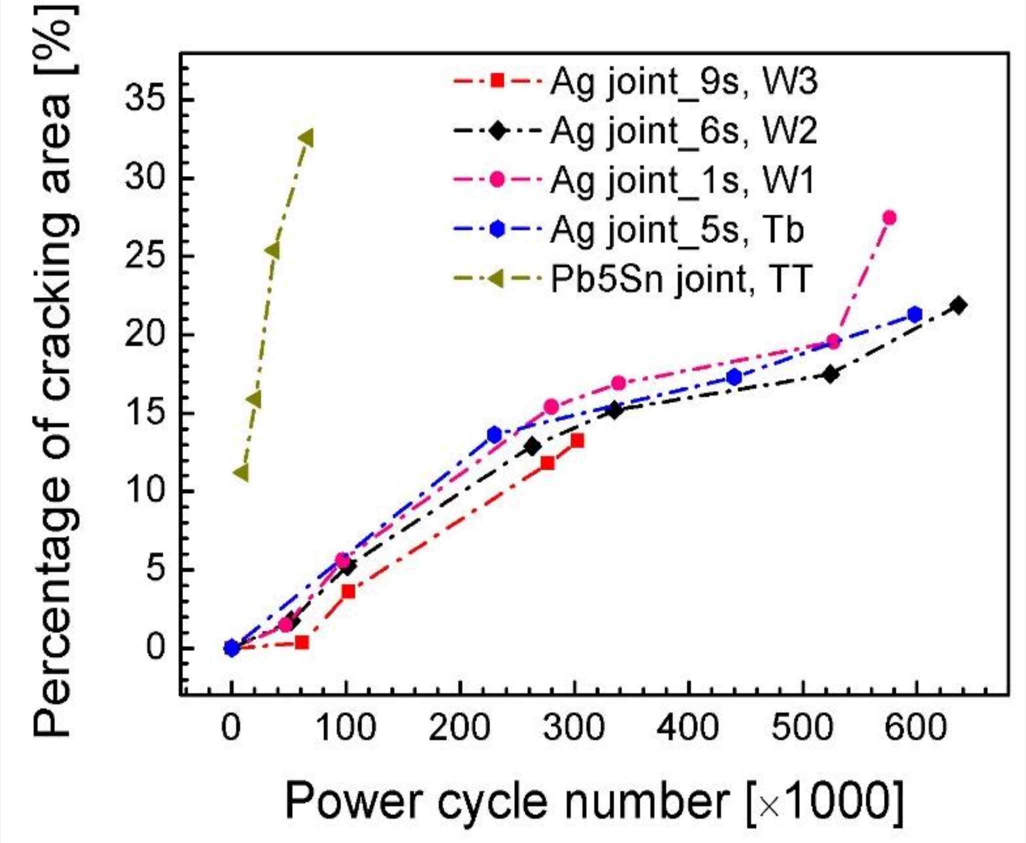
Dai, J *et al.*, 2018.

Power cycling behaviour of sintered nanoAg attachments

Non-destructive assessment of the **same specimen** using different techniques shows excellent correlation between thermal conductivity decrease & crack growth



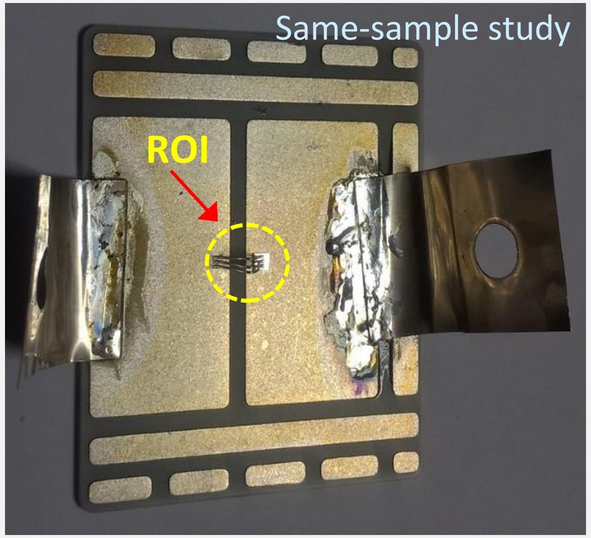
Power testing (Mentor graphics) data

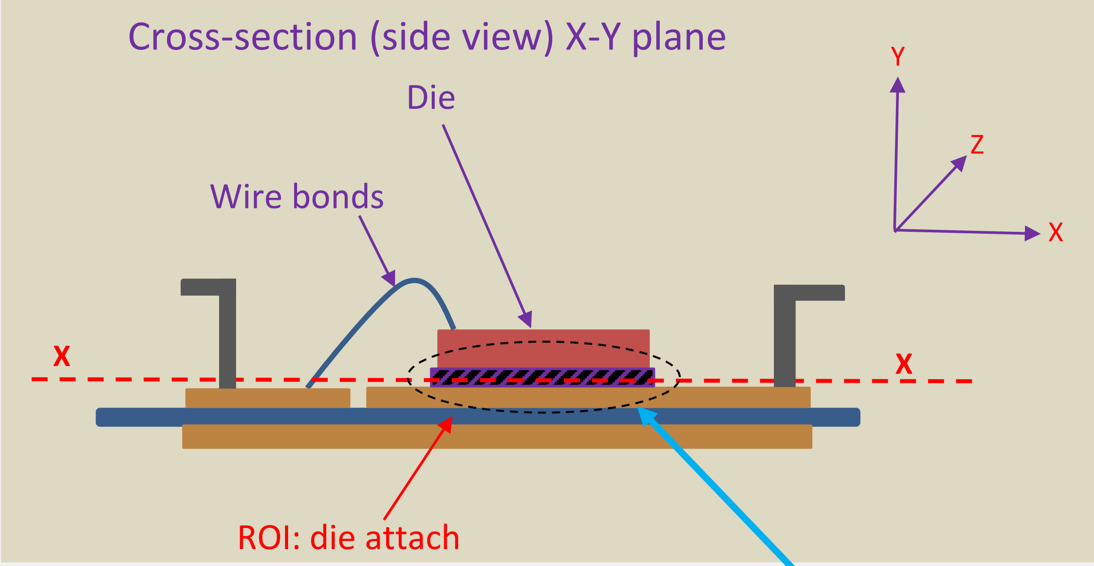


X-ray CT data

J. Dai, PhD Thesis 2018

Reliability characterisation of sintered nanoAg die attach

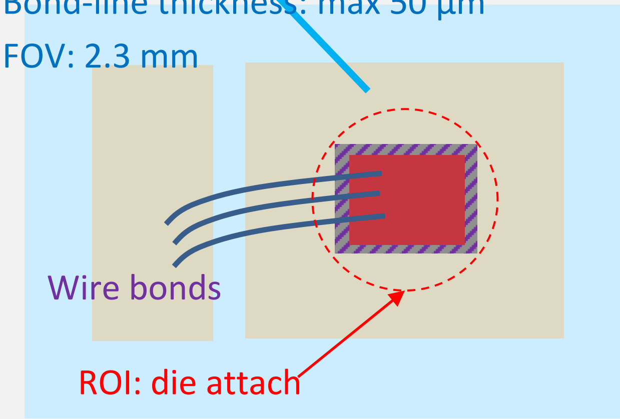




Dr Jingru Dai, 2018

- Materials:
  - CREE CPW4-1200-S010B SiC power diodes with 1.4 mm thick Ni/Ag metallization on the cathode and ~4 mm thick Al metallization on the anode
  - AlN- substrates (1 mm thick AlN ceramic tile sandwiched between 0.3 mm Cu tracks actively brazed on both sides, with 0.2 µm thick Ag finish)
  - Nano Ag film (Argomax 2020): 62.3 µm thick, average particle size of ~20 nm
- Power cycling and thermal impedance characterisation on Mentor Graphics platform, ΔT= approx. 50 to 200 °C (150K)
- Correlation with non-destructive imaging using Zeiss Xradia Versa XRM500 3D X-ray microscope
- Image visualisation and analysis using Xradia 3D Viewer, Avizo Fire 9.01 & Dragonfly

Die size: 2.26mm x2.26mm
Bond-line thickness: max 50 µm
FOV: 2.3 mm



Plan view through X-X (XZ plane)

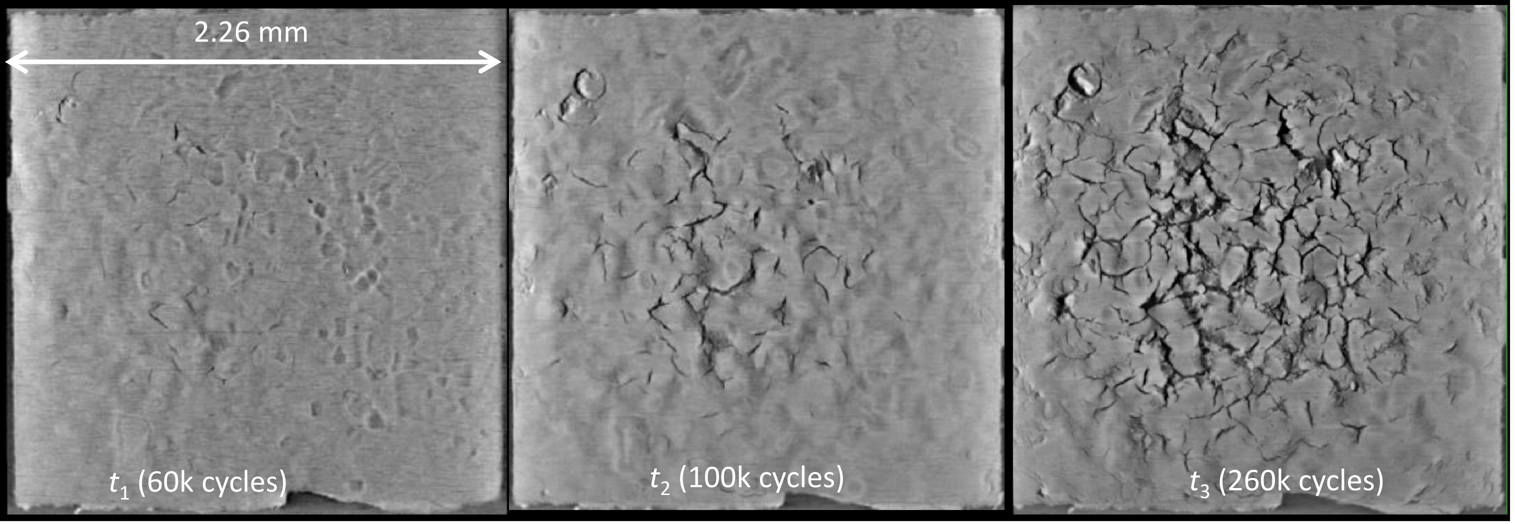
X-ray CT slices through same sample over time (lateral plane)

Sample A

300 °C, 19.5 MPa, 9 s

Shear str.=52.7 MPa
Porosity= 24.7%

-Pronounced imprint of roughness from Cu grain structure

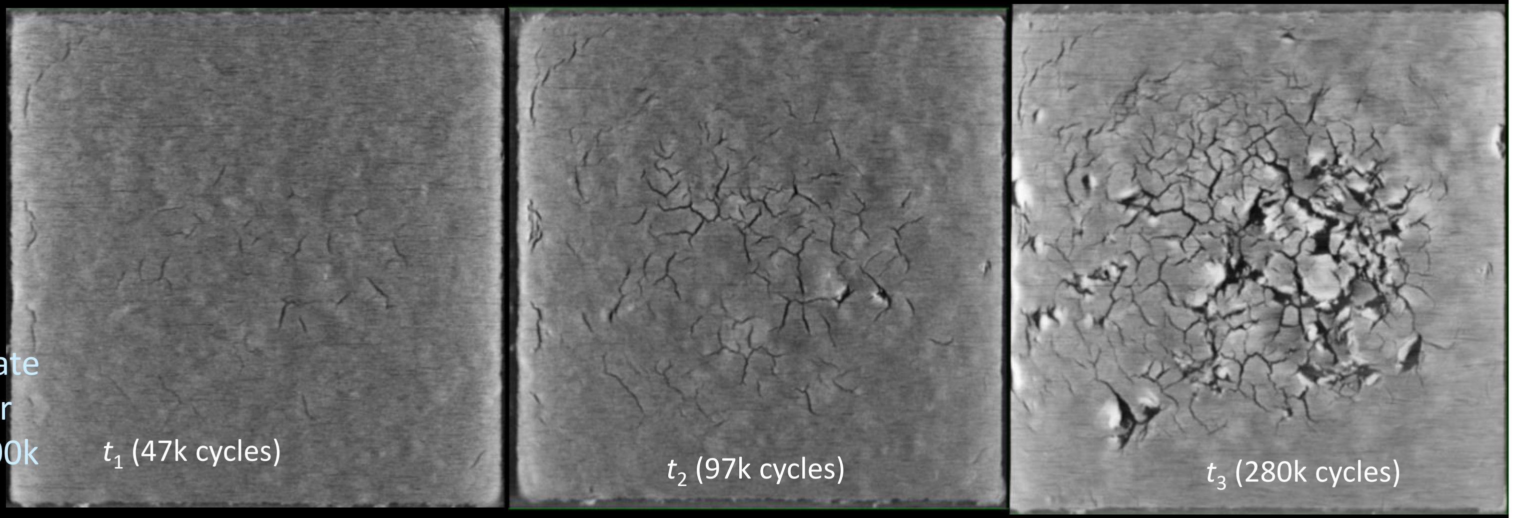


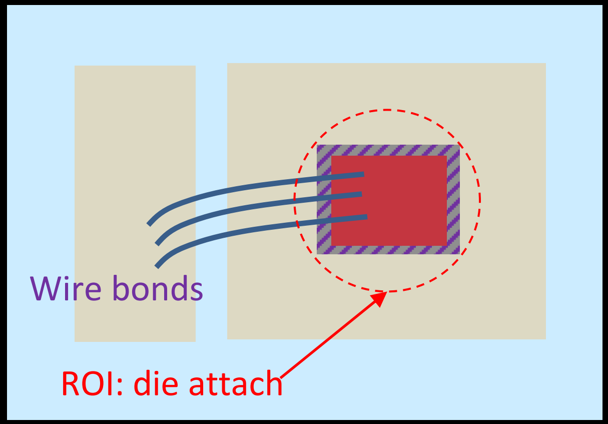
Sample B

220 °C, 6 MPa, 1 s

Shear str.=20.5 MPa
Porosity= 50.9%

-Less pronounced substrate roughness imprint. Larger crack apertures after >200k cycles



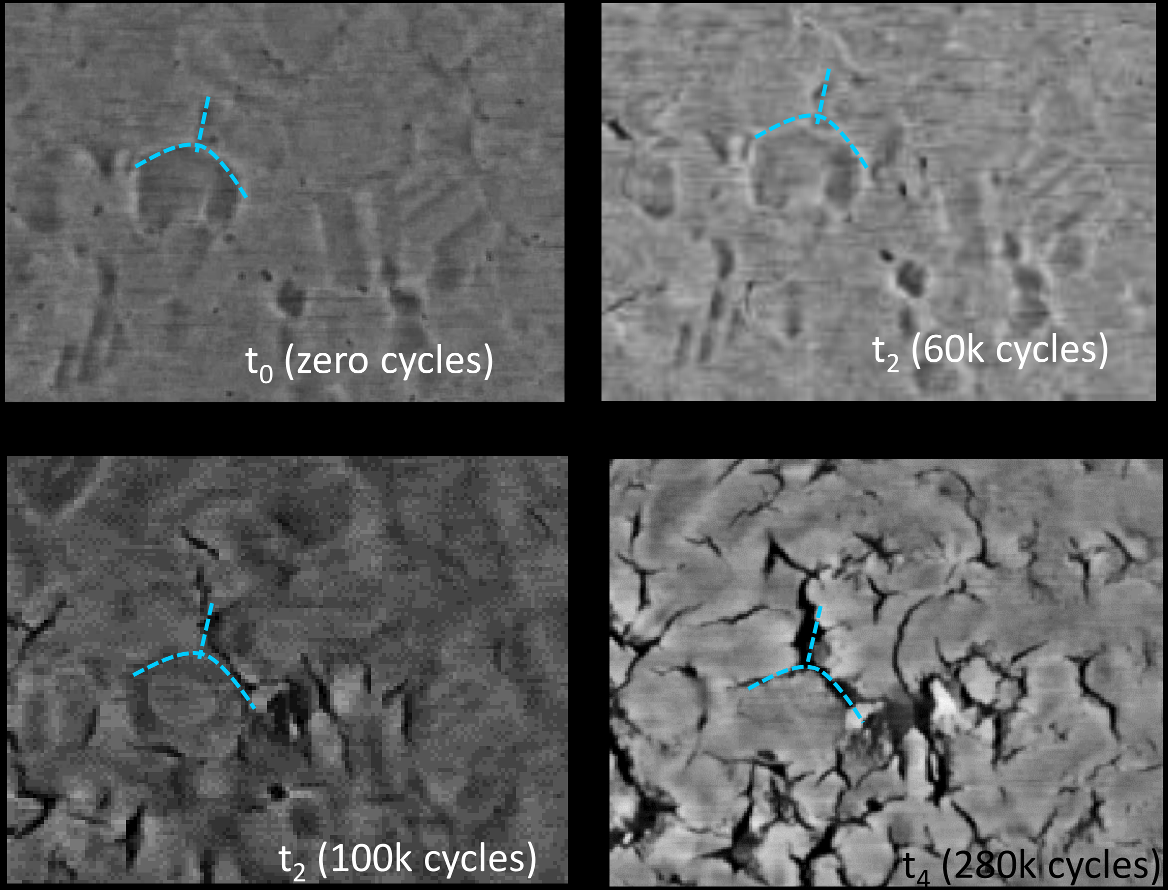


Plan view

Densification-driven shrinkage and crack formation

high shear force, low porosity sample

XZ plane

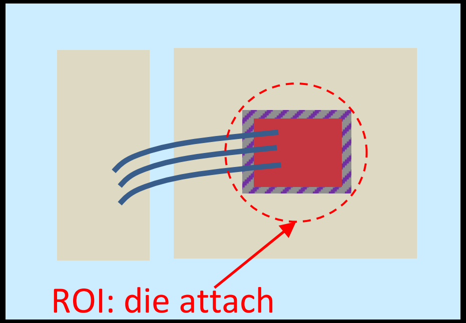


Note high pixel intensities adjacent to cracks

Texture of images (differing levels of x-ray absorption) is linked to non-uniform packing density due to depressions on the substrate

Cracks initiate in less dense areas, especially at points correlating to grain boundary triple points on substrate beneath

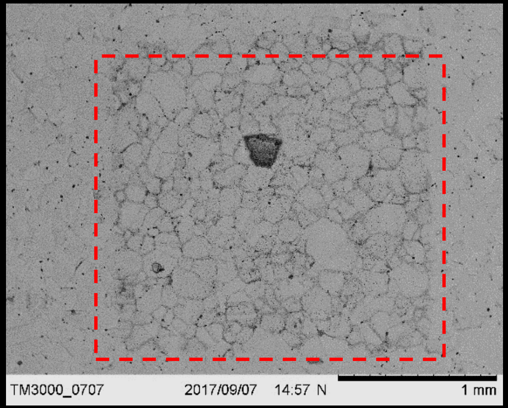
Propagation occurs along grain boundaries



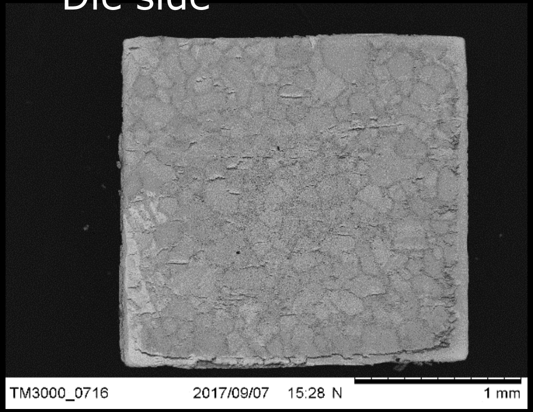
Plan view

Shear/fracture surfaces

Substrate side (Cu)

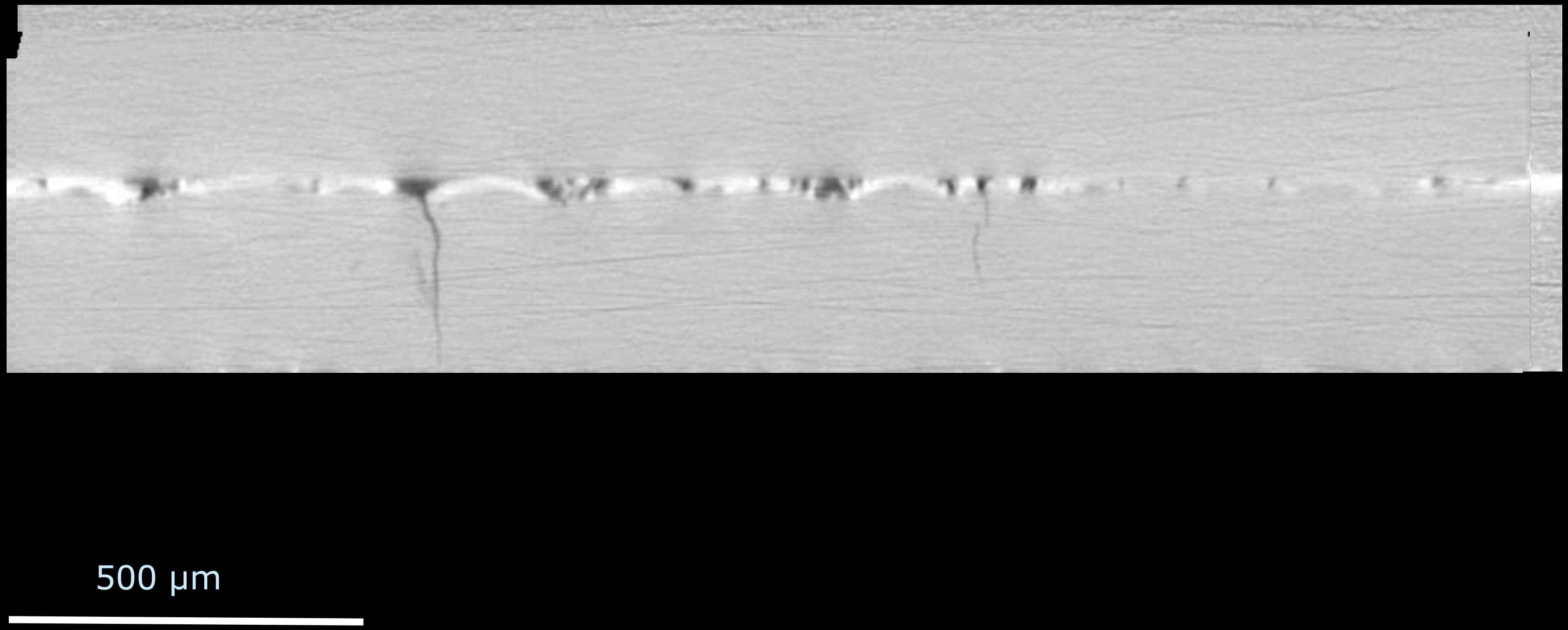


Die side



Crack growth vs time, transfer across material boundary

X-ray CT data: time series in X-Y plane

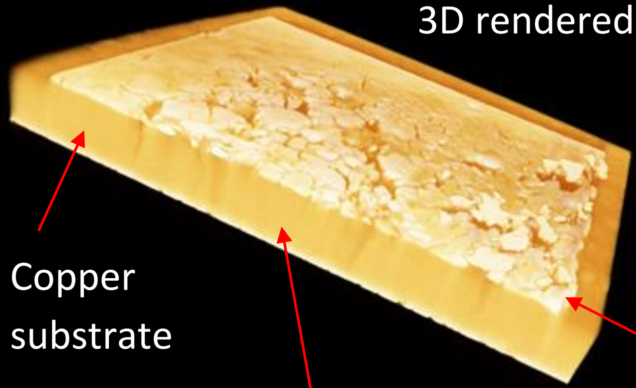


highest pixel intensities right next to widest/most developed cracks

Correlative microscopy

Sample B (low shear strength, high porosity)
>600k thermomechanical fatigue cycles

3D rendered views of sintered attachment

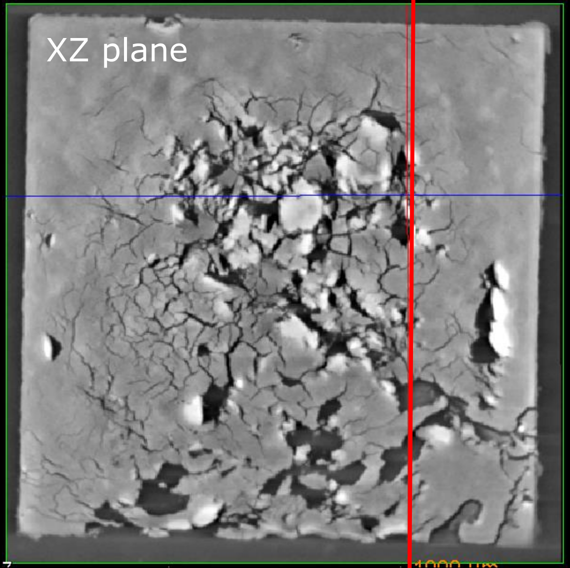


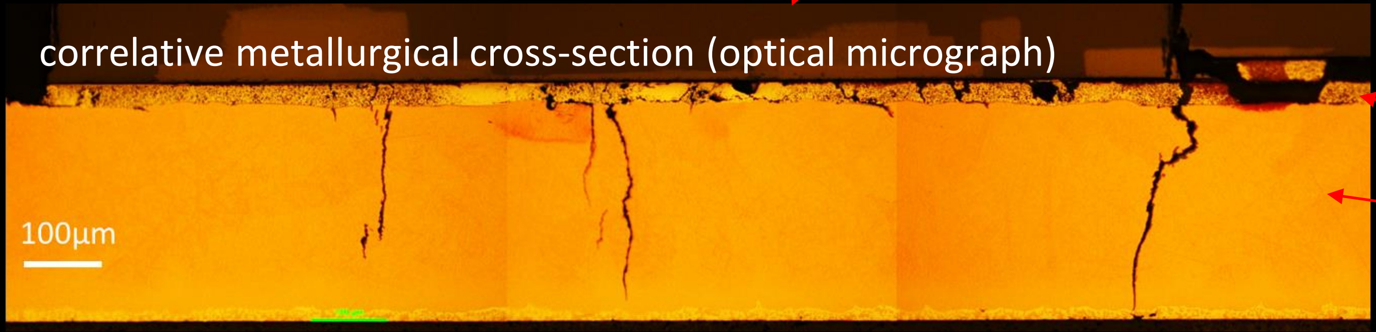
Copper substrate

Sintered layer

This face (right on the edge) was previously cross-sectioned

Virtual slice (XY plane) corresponding to metallurgical cross-section below



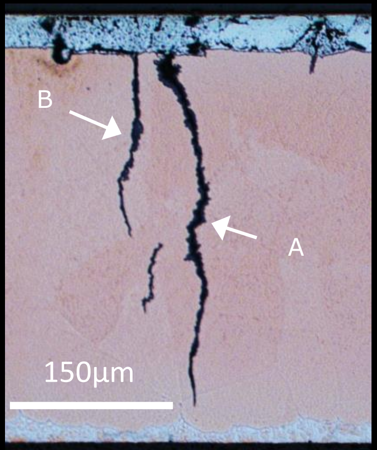


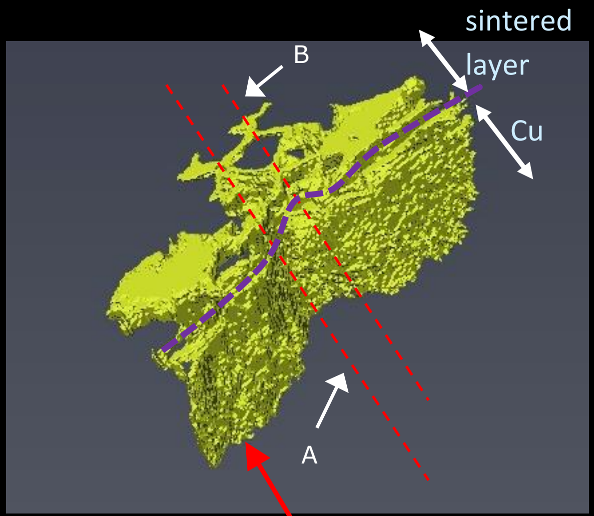
Sintered layer

Copper substrate

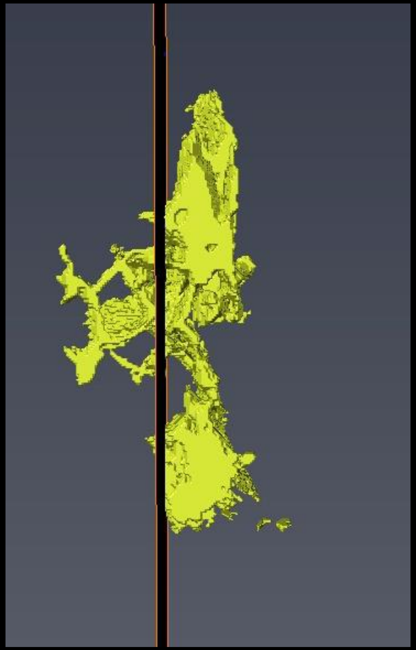
Correlative visualisation of crack morphologies

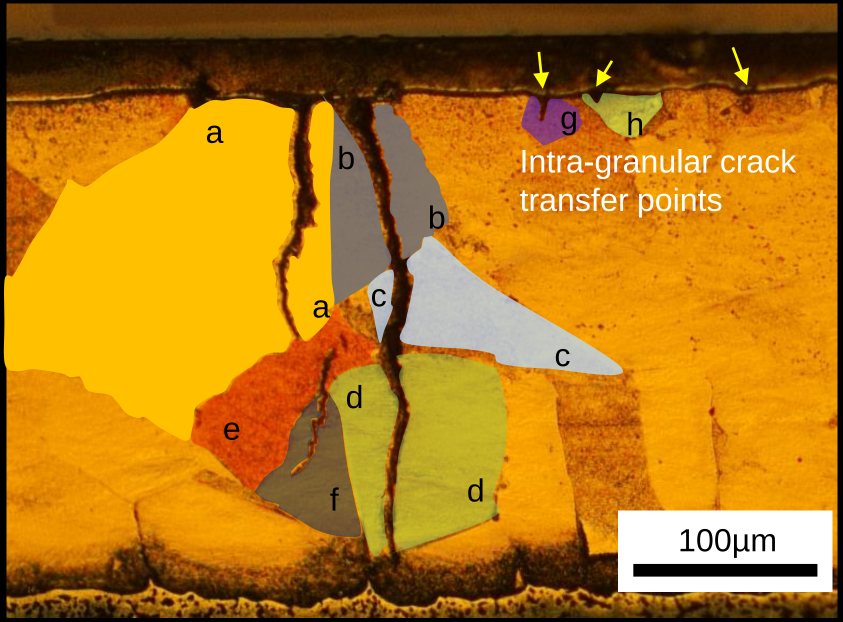
Crack facets/texture may be due to different orientation of cleavage planes in grains?

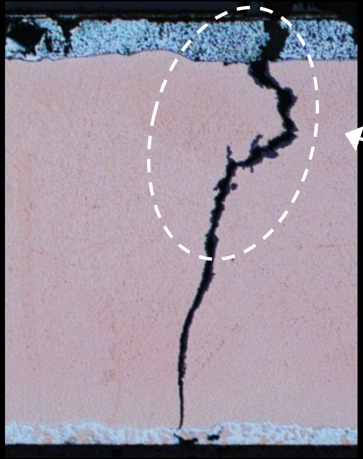


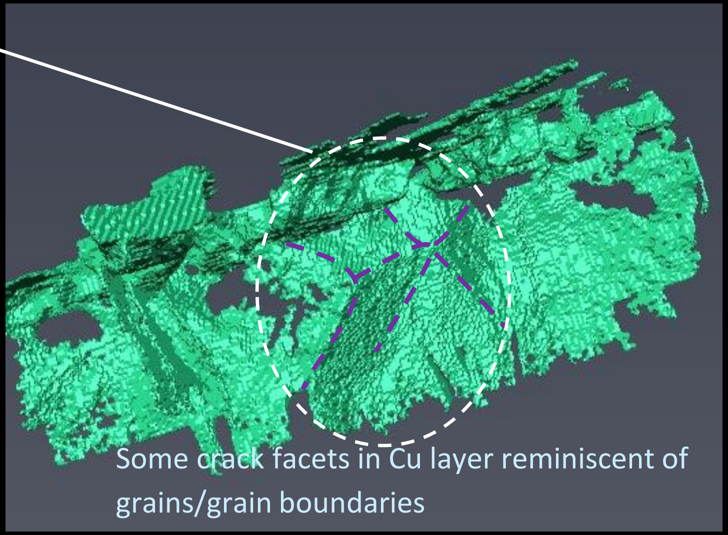


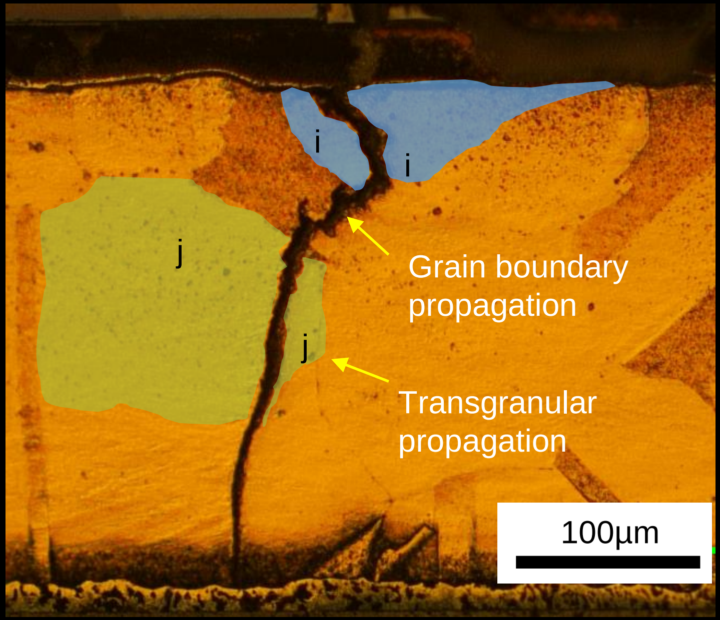
Crack tip in Cu substrate









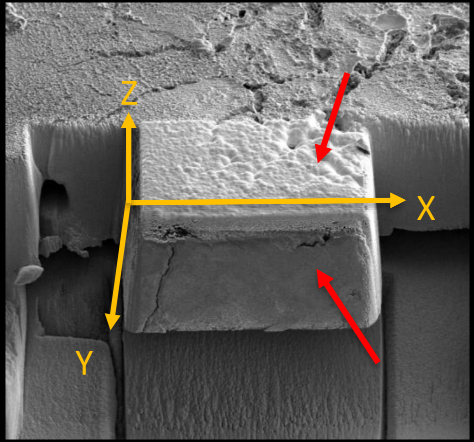


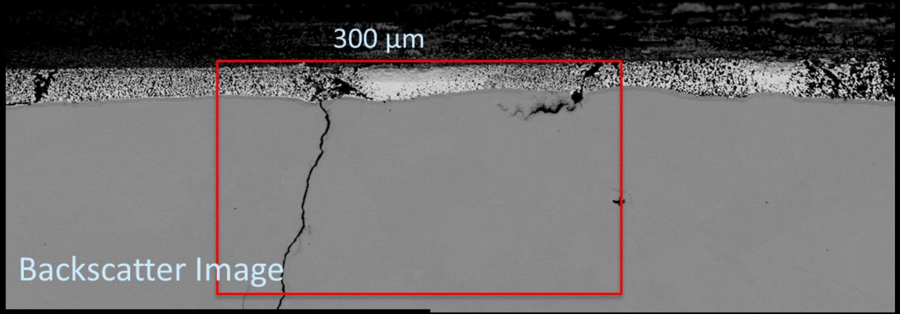
Further investigation of orientation relationship between the crack surfaces and crystallographic planes of grains: EBSD/DCT?

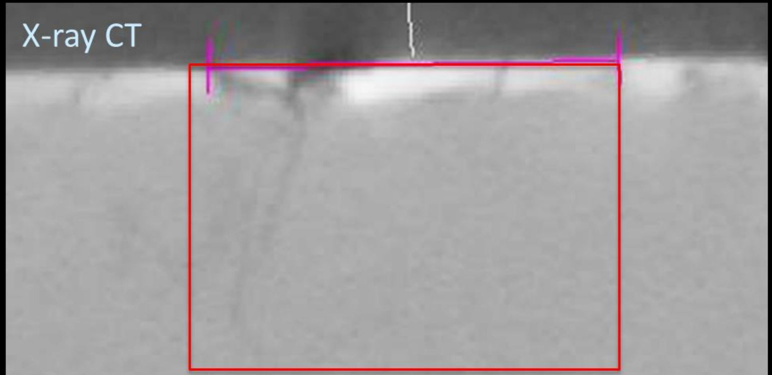
Agyakwa et al., Journal of Microscopy, 277: 140-153 (2019).
https://doi.org/10.1111/jmi.12803

3D reconstruction of serial FIB slices

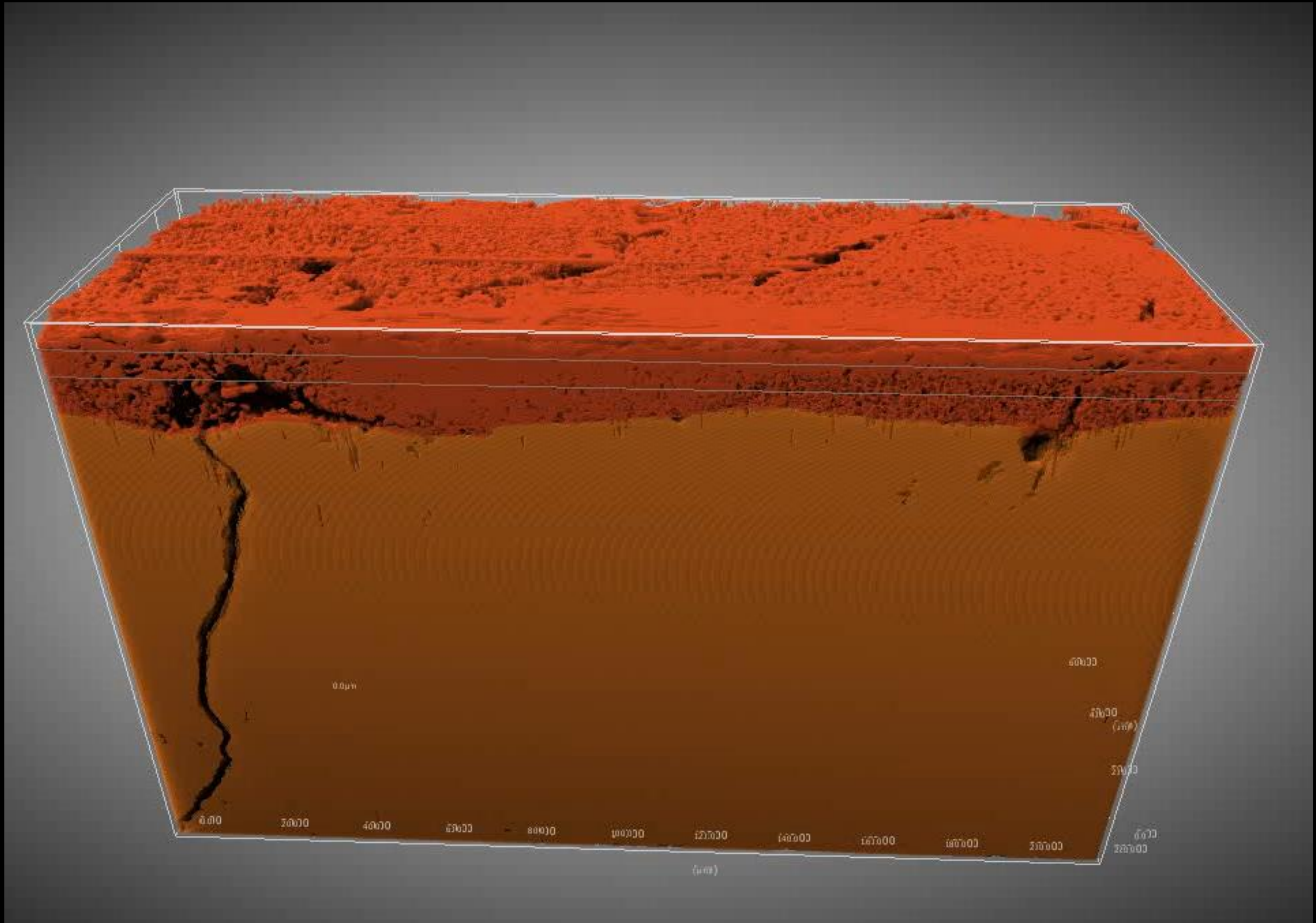
Voxel size X 260 µm @1536 pixel (169 nm / pixel)
Y 173 µm @1024 pixel
Z 100 µm (500 slices @200nm intervals)







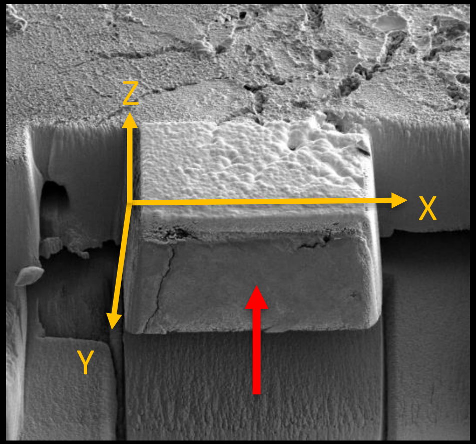
Based on the micro CT tomographic reconstruction an area was interest was selected and identified in the P-FIB
A 3D sample was then prepared



Dr Stuart Robertson, LMCC Loughborough

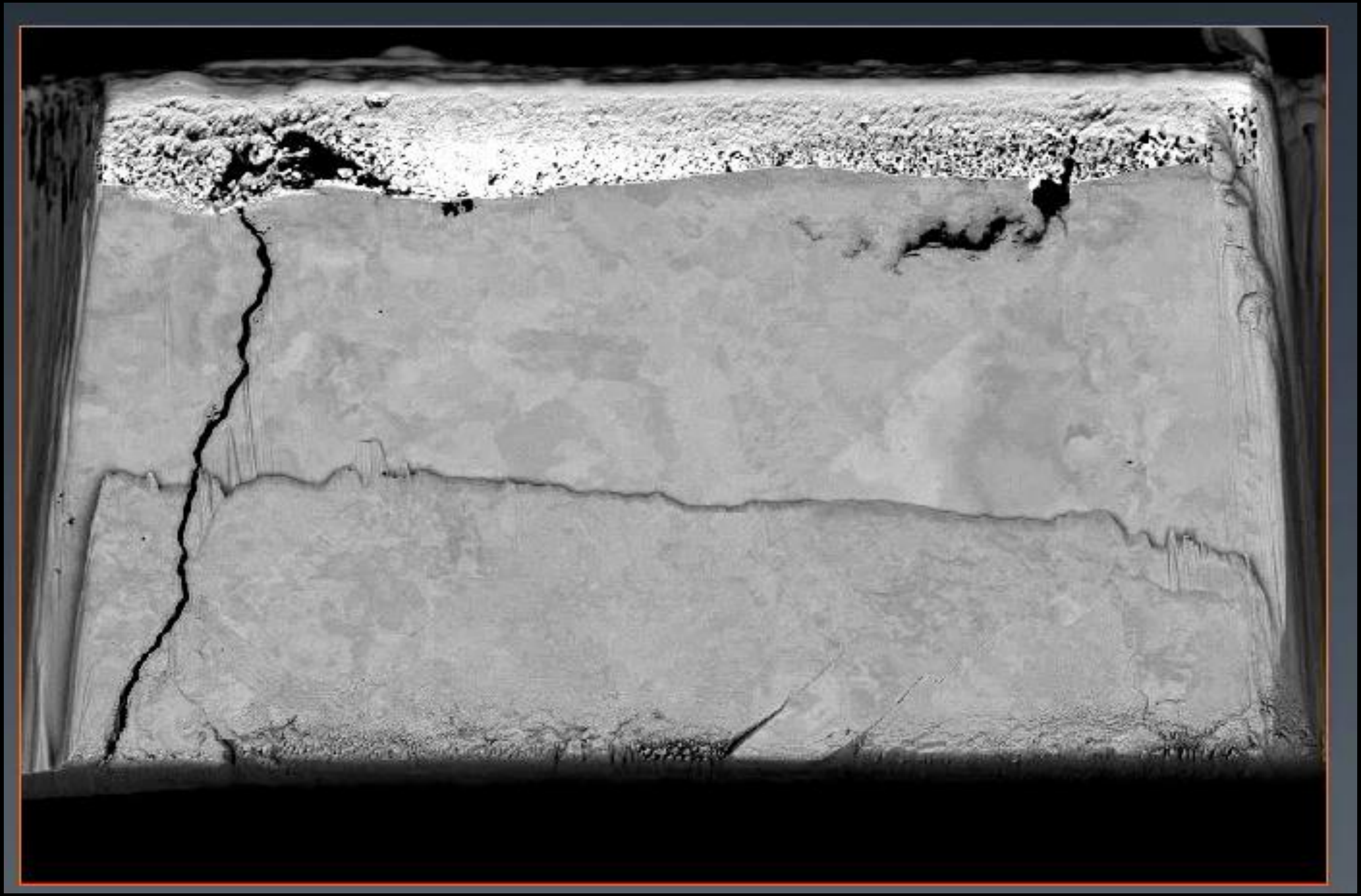
Crack transfer across material boundaries (3D FIB)

Courtesy of Dr Stuart Robertson, LMCC Loughborough

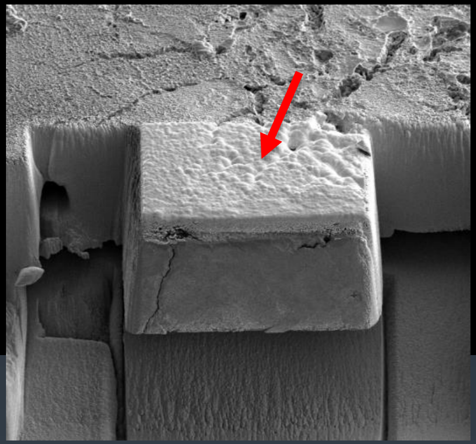


3D reconstruction of serial FIB slices

Through-thickness view



Dr Stuart Robertson, LMCC Loughborough

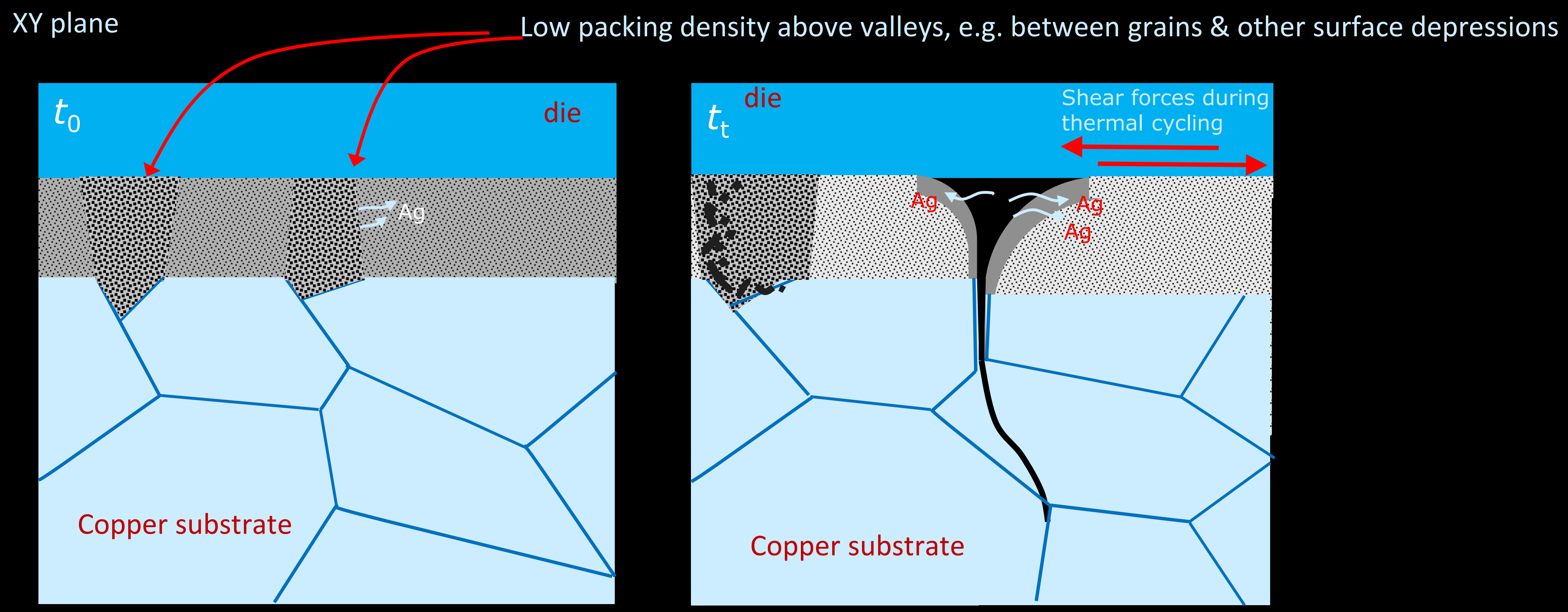


Lateral view

3D reconstruction of serial FIB slices

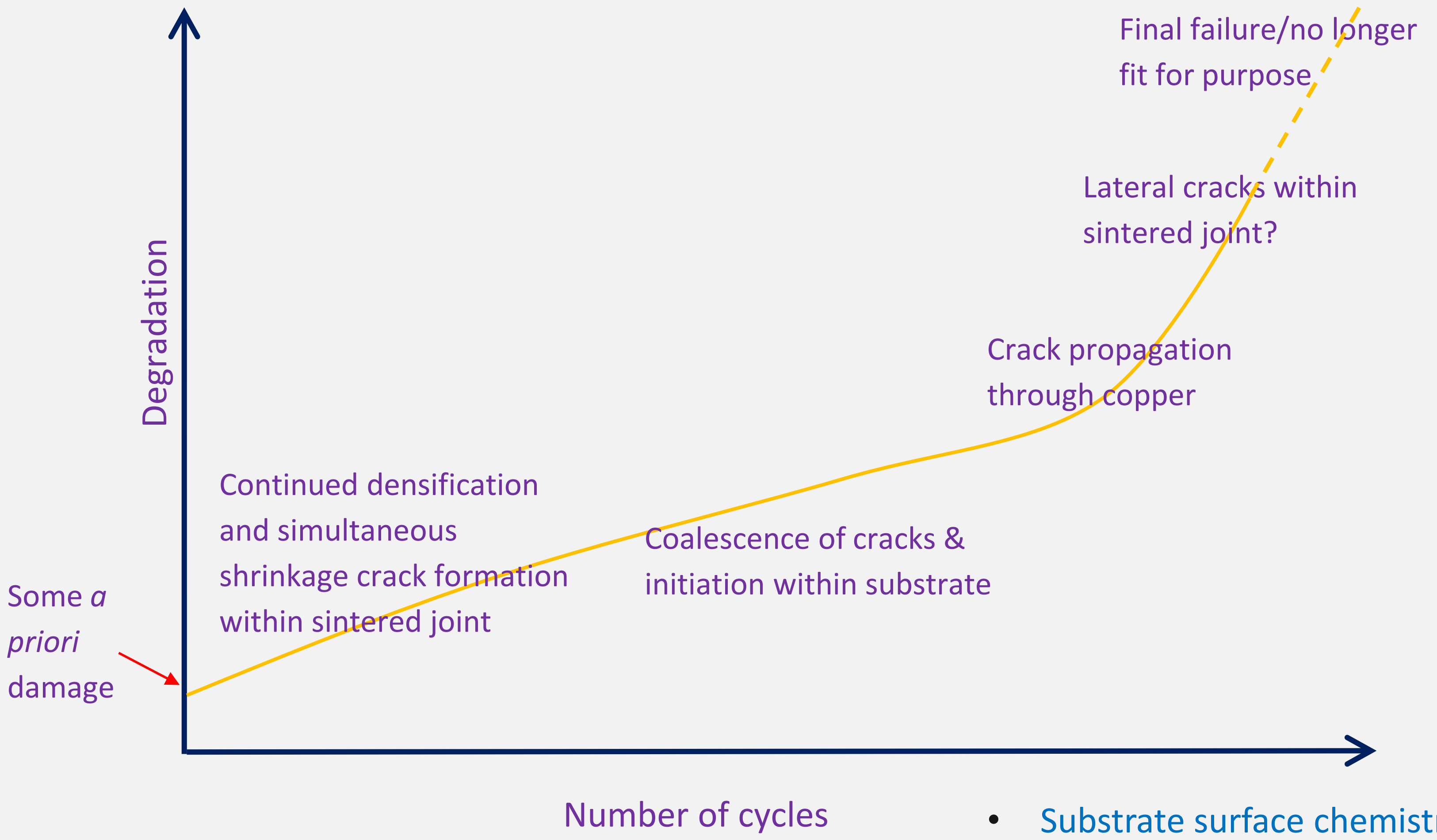
Proposed densification & cracking model

(1) Densification-driven shrinkage and crack formation within sintered joint



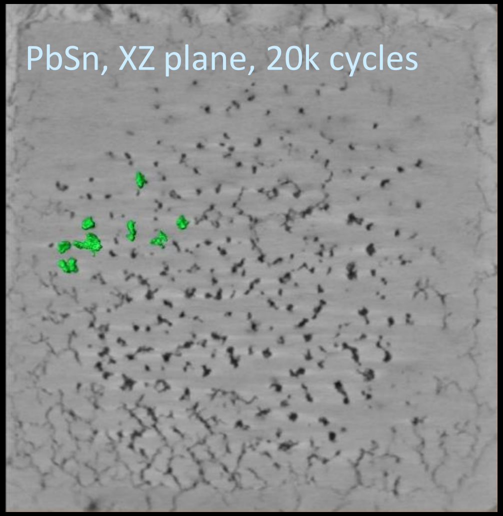
(2) Intergranular/transgranular propagation of crack through copper substrate

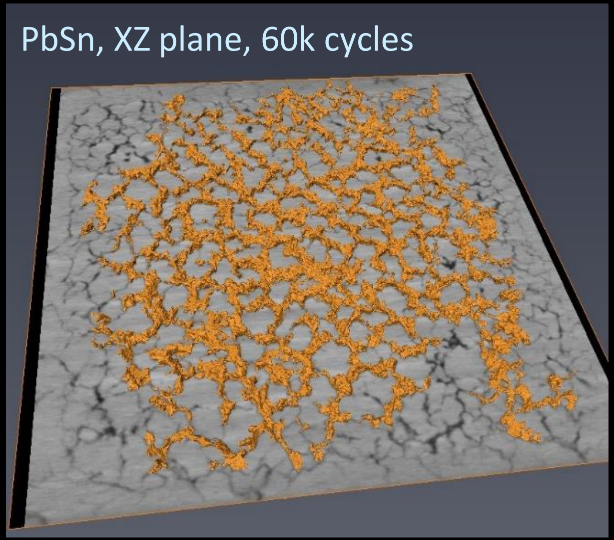
Proposed damage model for sintered attachments



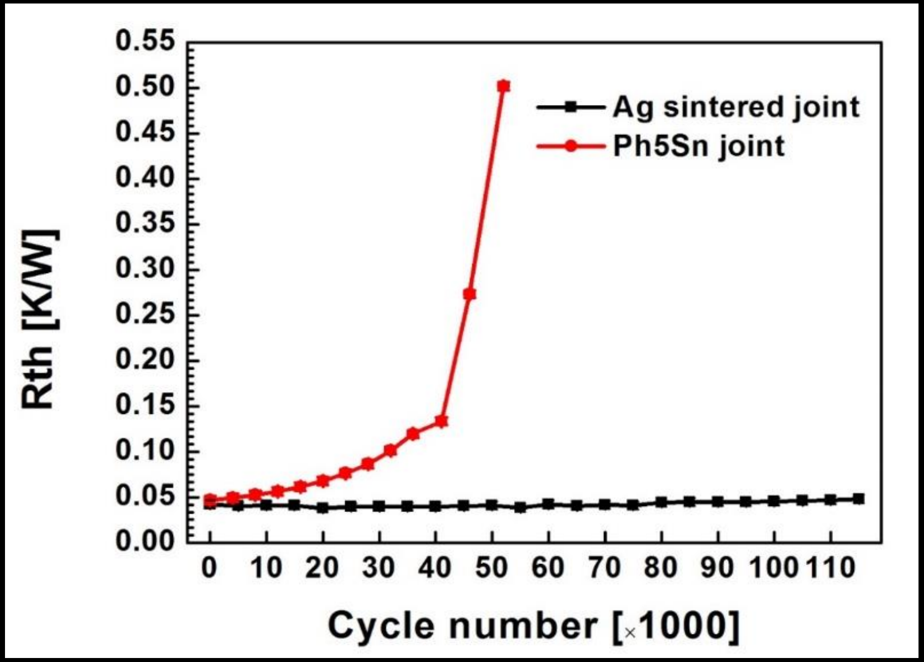
- Substrate surface chemistry
- Substrate surface roughness
- Sintering parameters (degree of densification)
- Other existing damage

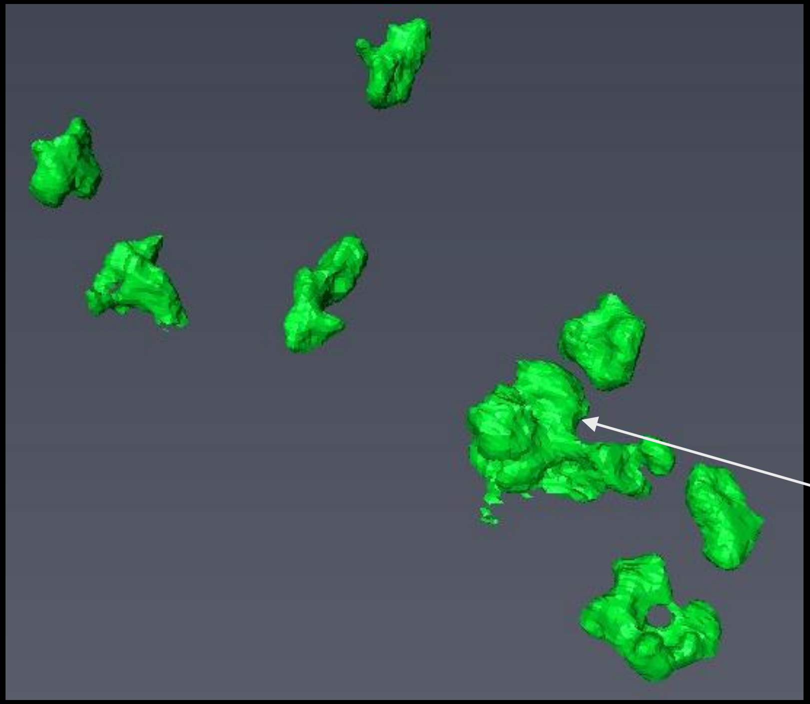
Effect of damage morphology on reliability?





Comparing thermal performance under power cycling with PbSn solder joints





Damage accrues more rapidly in the PbSn solder under the same conditions

Could their morphological differences in damage may play a role? e.g. greater sphericity of PbSn damage
– lateral discontinuities have greater influence on the thermal path in the package

Thank you

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Dr Jingru Dai, Dr Bassem Mouawad, Dr Chris Parmenter, Dr Martin Corfield, Dr Li Yang, Dr Paul Evans, Dr Elaheh Arjmand, Dr Jianfeng Li, Dr Fang Xu, Prof Mark Johnson, Dr Imran Yacqub, Dr Yun Wang, Dr Rob Skuriat (University of Nottingham)

Dr Stuart Robertson, Dr Zhaoxia Zhou (Loughborough University LMCC)

Dr Lisa H. Chan, Dr Hrishikesh Bale, Dr Jun Sun (Carl Zeiss Microscopy & XNovo Tech)

Prof Chris Bailey, Prof Hua Lu (University of Greenwich)

Sincere thanks to Oscar Khaselev and Mike Marczi of Cookson Electronics for providing Ag nanoparticle paste, and to Dr Kim Evans & Dr Mumby-Croft, Dynex Semiconductor Ltd. for the provision of Al and Cu wire bond samples

The work was supported by Mentor Graphics, the UK Engineering and Physical Sciences Research Council projects EP/K035304/1 & EP/R004366/1 through the Centre for Power Electronics, the Innovative Electronics Manufacturing Research Centre (IeMRC) EP/H03014X/1, the Engineering and Physical Sciences Partnered Access Fund (2017) and the EU Commission's 7th Framework Programme Cleansky2 JU EMINEO

pearl.agyakwa@nottingham.ac.uk

world-changing research
from The University of Nottingham