Combined Loads and Mechanisms

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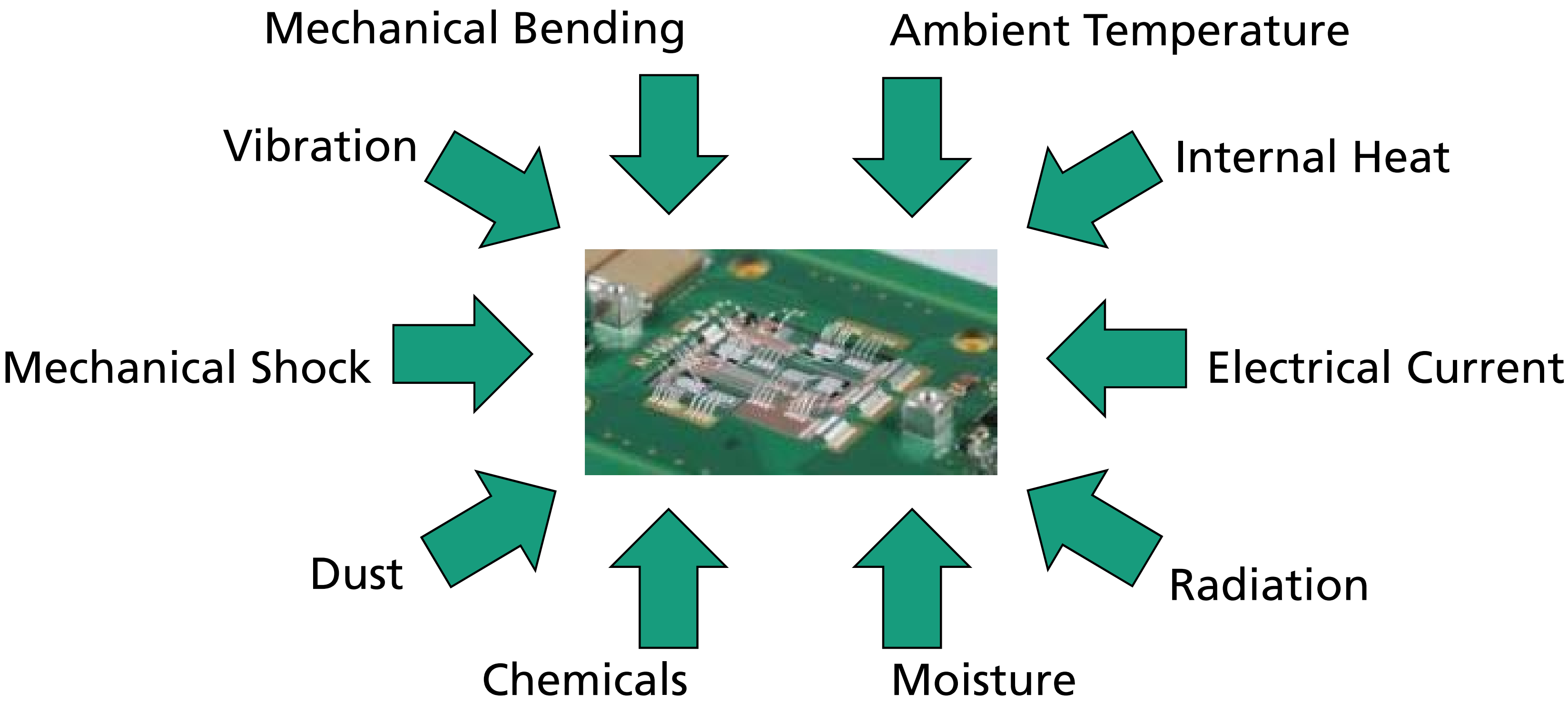

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Combined Loads and Mechanisms
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INTRODUCTION

Complex Use Profiles for Power Modules

- There is a combination of passive und aktive thermal cycles in use conditions (i.e. E-Mobility, Windenergy)
- Passive ones are due to the environmer
- Active ones are due to self-heating

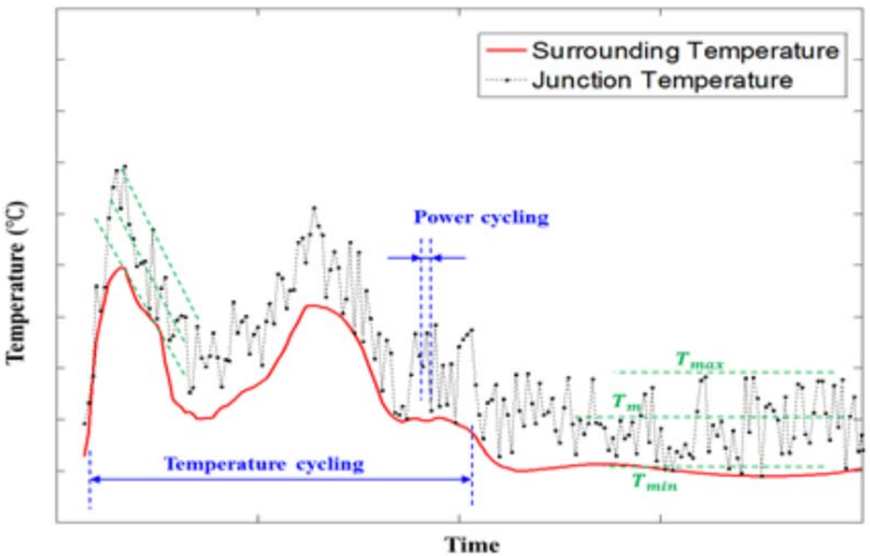


Fig. 2. Thermal cycling and Power cycling for IGBT module

Multi-Objective Design of IGBT Power Modules Considering Power Cycling and Thermal Cycling, Bing Ji et al.

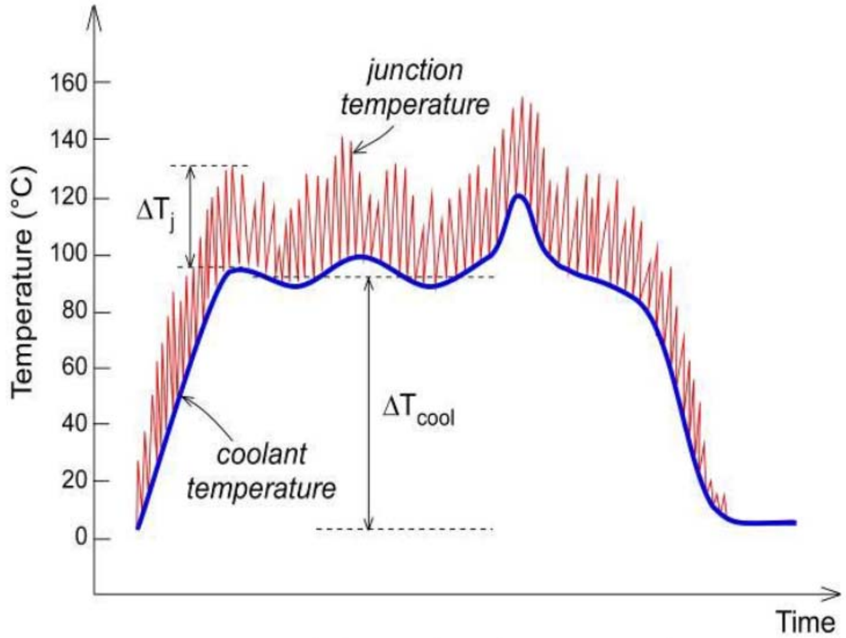


Fig.1 : Typical thermal and power cycling in automotive environment

Comparison of stress distributions and failure modes during thermal cycling and power cycling on high power IGBT modules, M. Bouarroudja et al.

Sate of the Art Evaluation

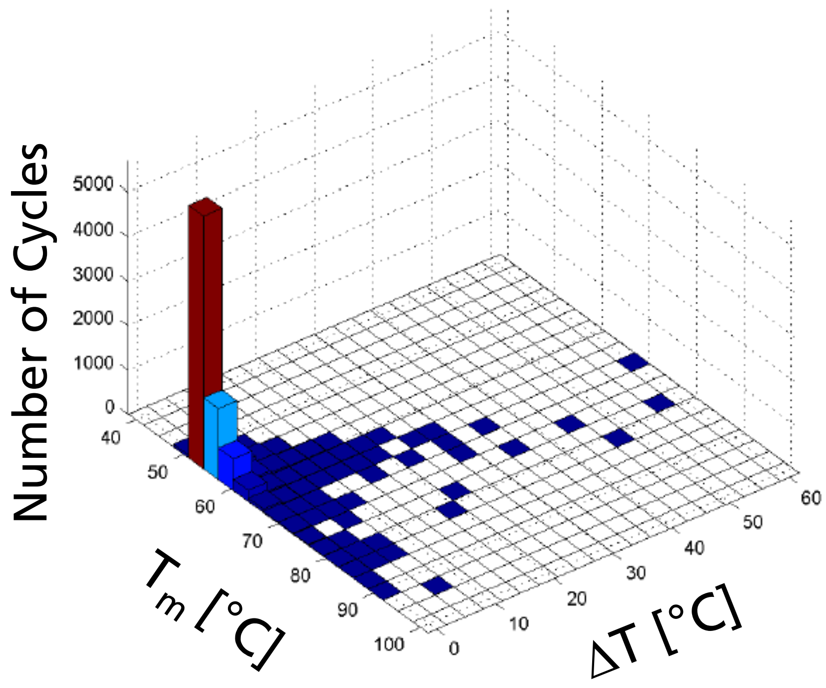


Figure 4.12: Cycles found in the IGBT chip temperature in the wind turbine within a 24 hour period.

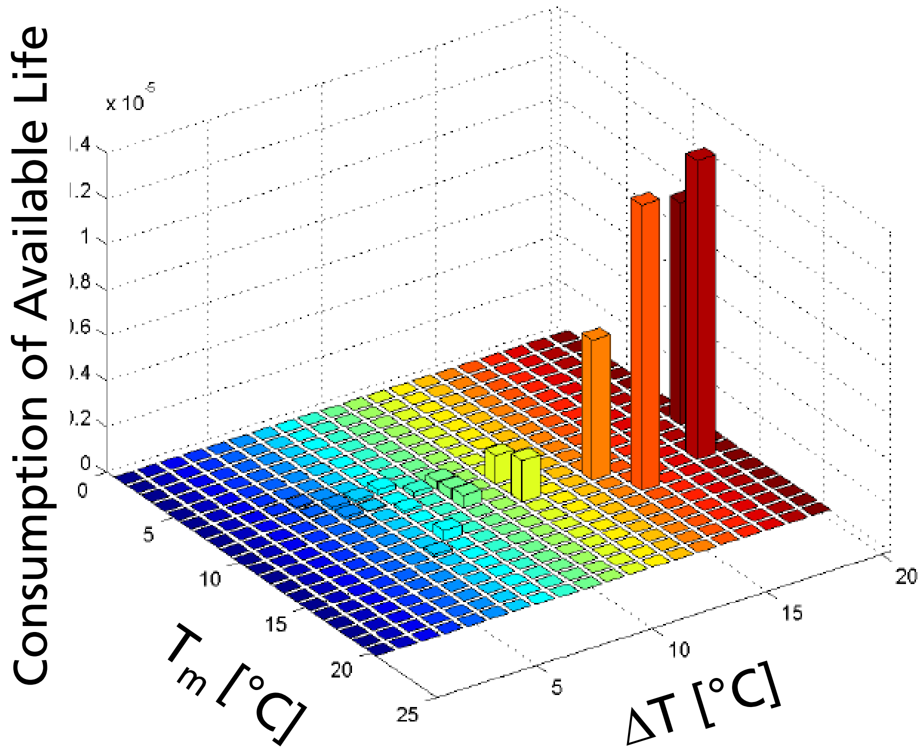


Figure 4.13: Consumption of available life in percents for each bin.

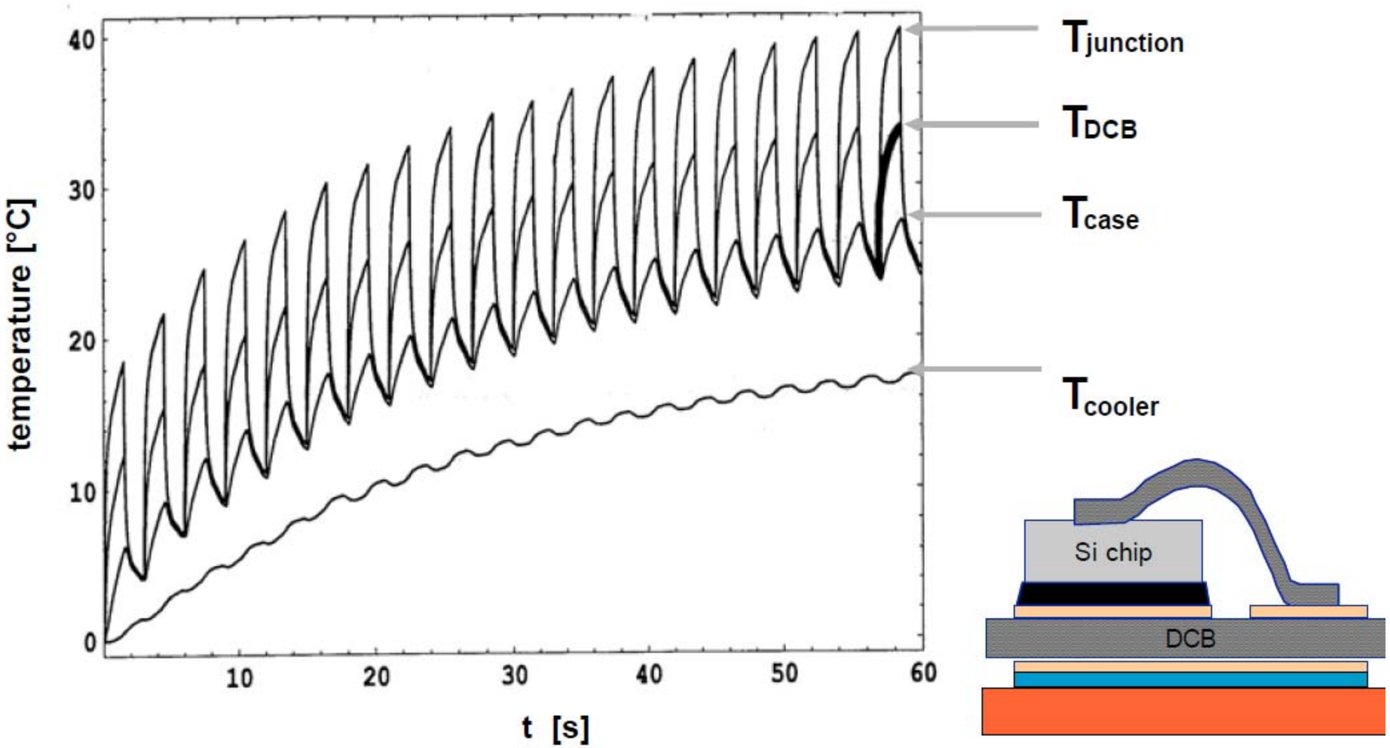
- Application of Miner‘s Rule (Linear Damage Superposition)
- Application of Lifetime Models combining module lifetime in one simplified model:

$$N_\mathrm{f} = A \cdot (\Delta T_\mathrm{j})^{\alpha} \cdot e^{\left(\frac{E_\mathrm{a}}{k_\mathrm{B} \cdot T_\mathrm{m}}\right)}$$

Source: POWER CYCLING LIFETIME ESTIMATION OF IGBT POWER MODULES BASED ON CHIP TEMPERATURE MODELING, Mika Ikonen

Motivation

- Active cycles (short time constant) cause a varying ΔT inside the module
- Passive cycles (large time constant) cause a general off-sett
- Therefore they have a different effect



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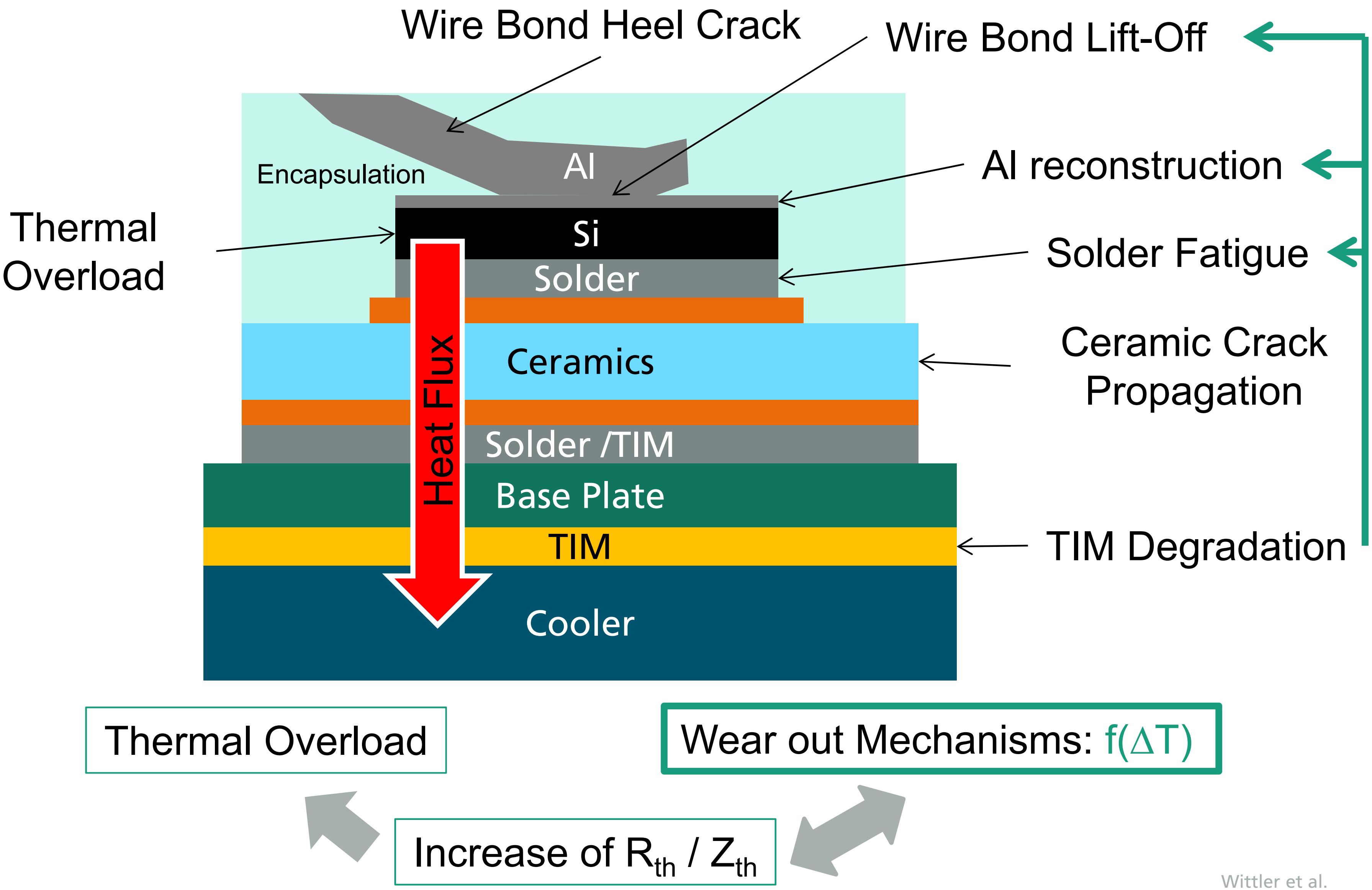
Typical Failure Mechanisms in Power Electronics



Conclusion on State of the Art

- Complex load histories (i.e. active and passive cycling) are highly relevant in power electronic applications.
- Current state-of-the-art lifetime models neglect the existing interaction of failure mechanisms and nonlinearity in damage superposition.
- A prediction of life time for complex load histories is not possible

→ Large safety margins or improved liftime models needed

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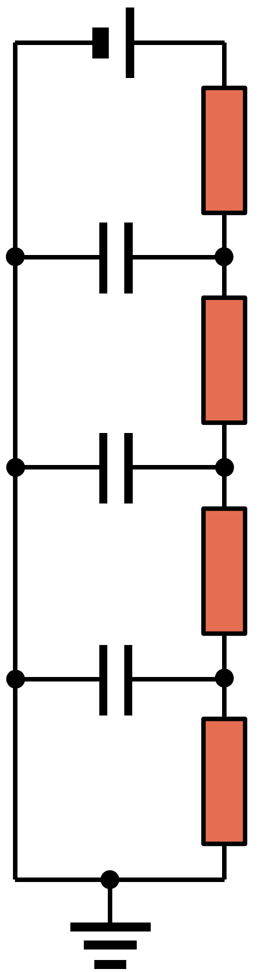
Thermal and Combined Damage Model



- Power loss and thermal resistance directly depend on the current temperature cycle
  $$P = P(T_{cyc}), R = R(T_{cyc})$$
- Damage also increases thermal resistances due to material degradation and/or interface reduction
  $$R = R(D)$$
- The damage progression again a function of temperature
  $$\dot{D} = D(T_{cyc})$$
- The calculation is done for each thermal cycle, so that ongoing damage is considered

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Requirements for Damage Parameter D

- Can be attributed to a specific failure mechanism
- Is being described based on the local temperature history
- Is being described by a lifetime model

→ Quantification damage vs. local temperature load in model an experiment

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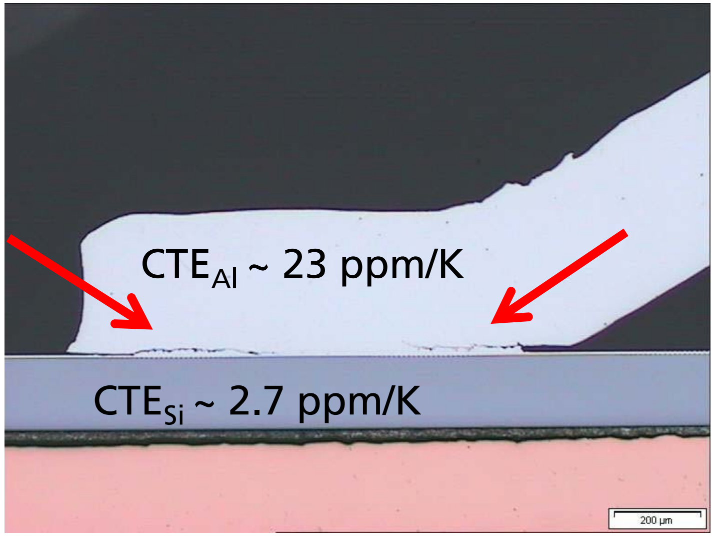

TEST APPROACH FOR WIRE BOND

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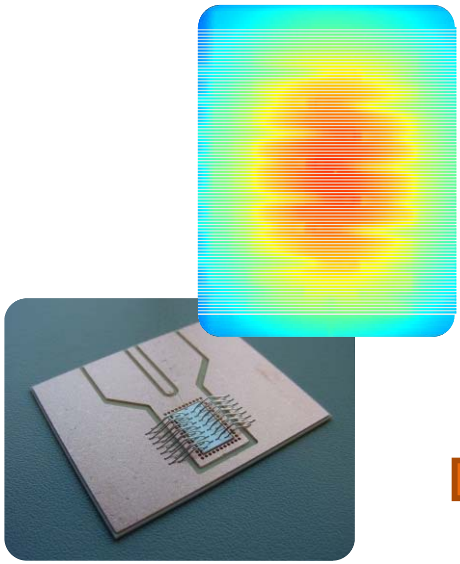
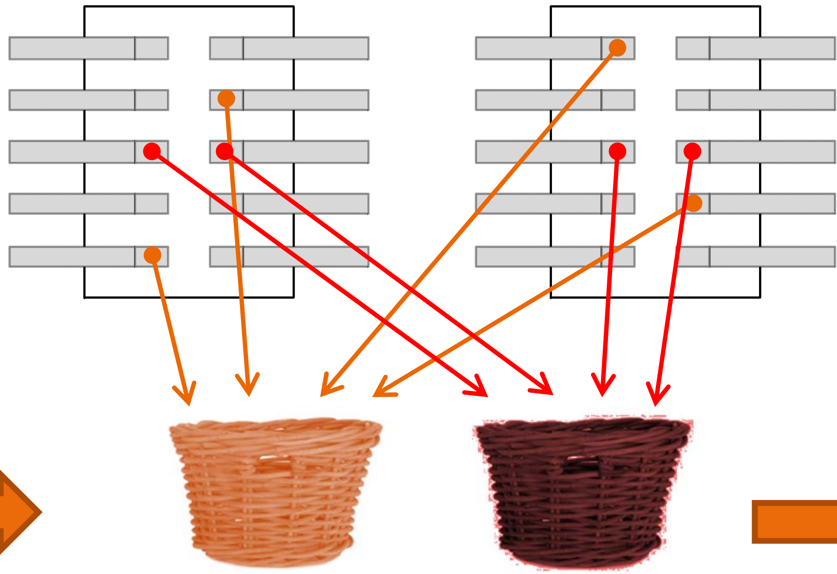
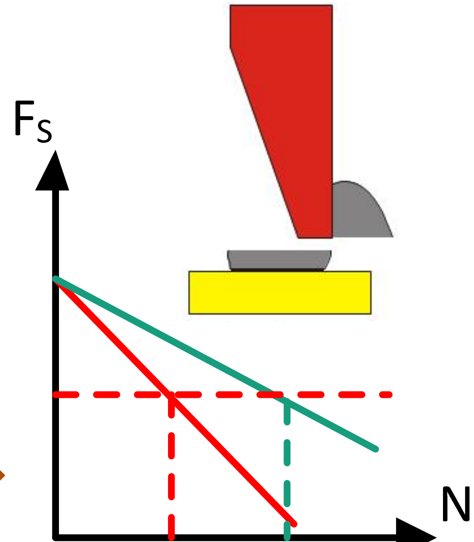
Reliability Investigations

- Bonding Parameter Optimization
- Active Power Cycling
  - Constant temperature swing -20/+100°C (ΔT= 120K, center of chip)
- Thermography
  - Extraktion of local temperature swing for each bond
  - Classification of bonds by their temperature swing (± 2,5K)
- Shear testing in regular intervals

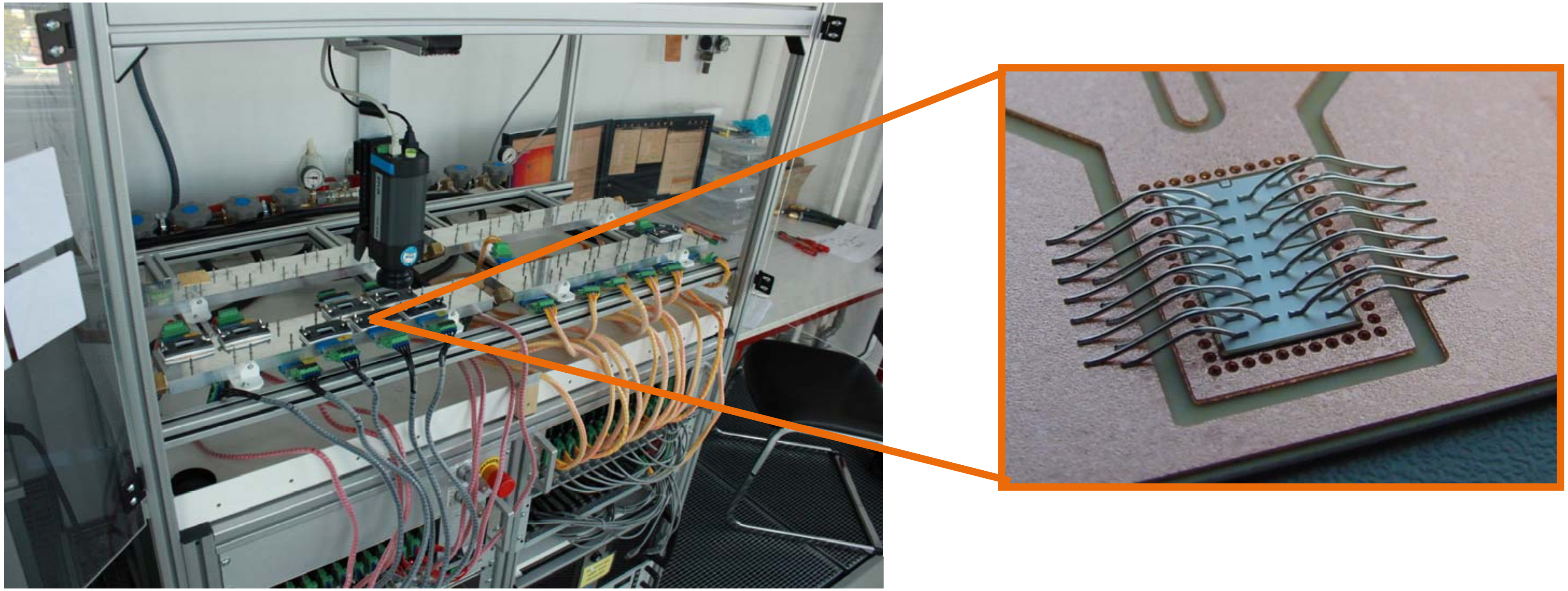






Wittler et al.

Active Power Cycling



- Regular temperature measurement by use of reverse diode in MOSFET
- Control for constant temperature swing by use of control of gate source voltage

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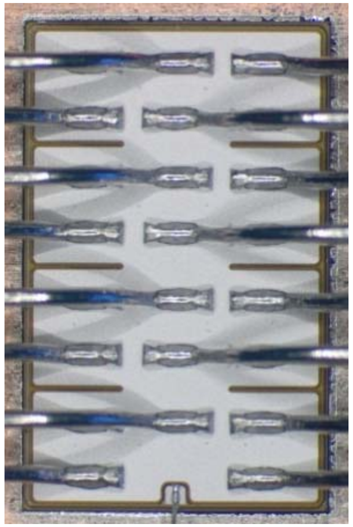
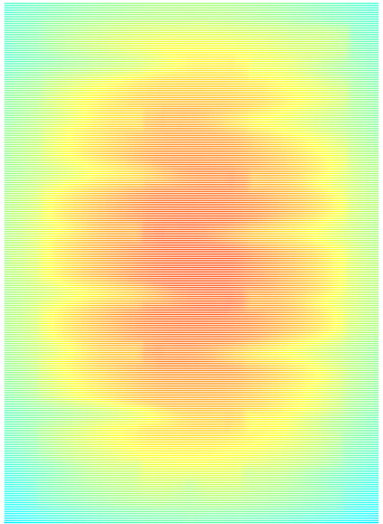
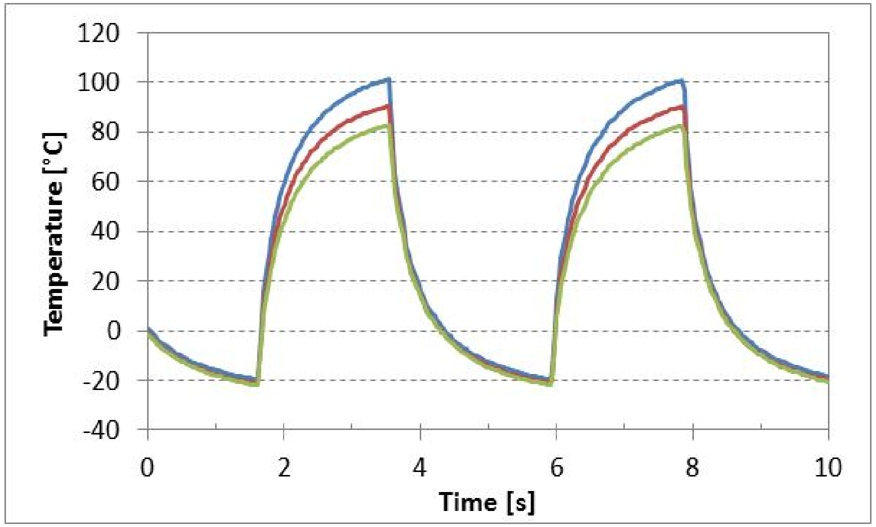
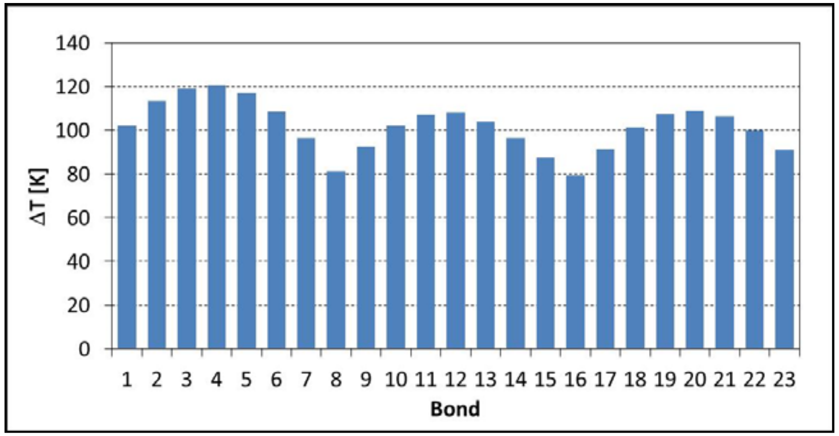
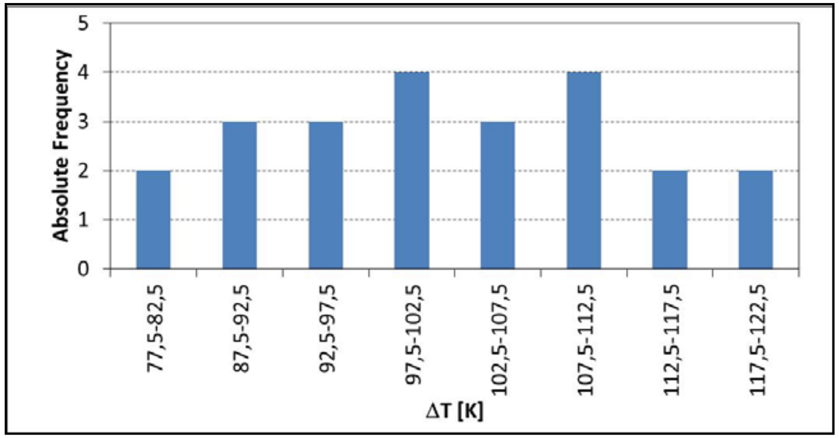
Temperature Distribution on Power Semiconductor









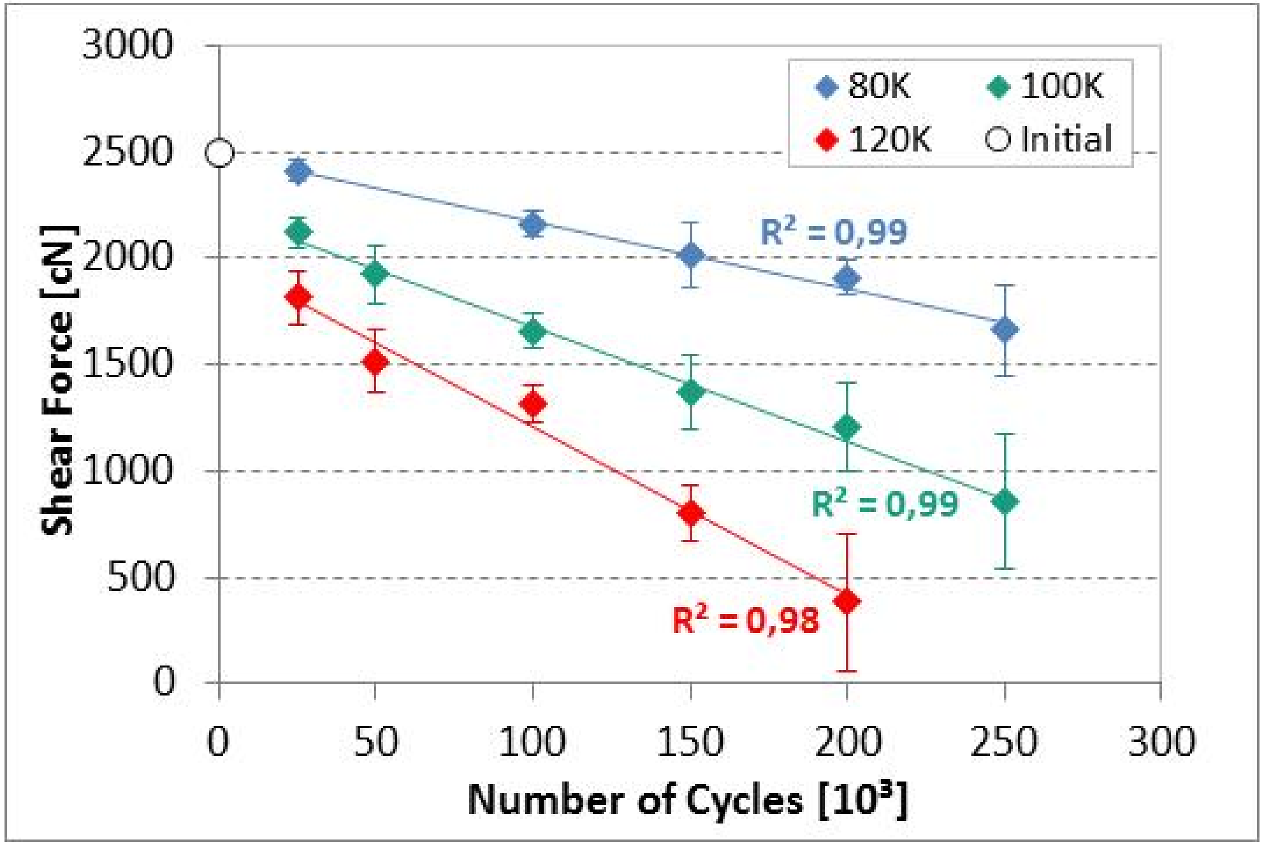


→ Individual temperature swing for each bond!

Göhre et al., CIPS 2008

Results of Power Cycling

Shear Force - high US-power (Q1)



- Decreasing shear force with increasing number of cycles
- Higher ΔT lead to higher degradation rate

Göhre et al., CIPS 2008

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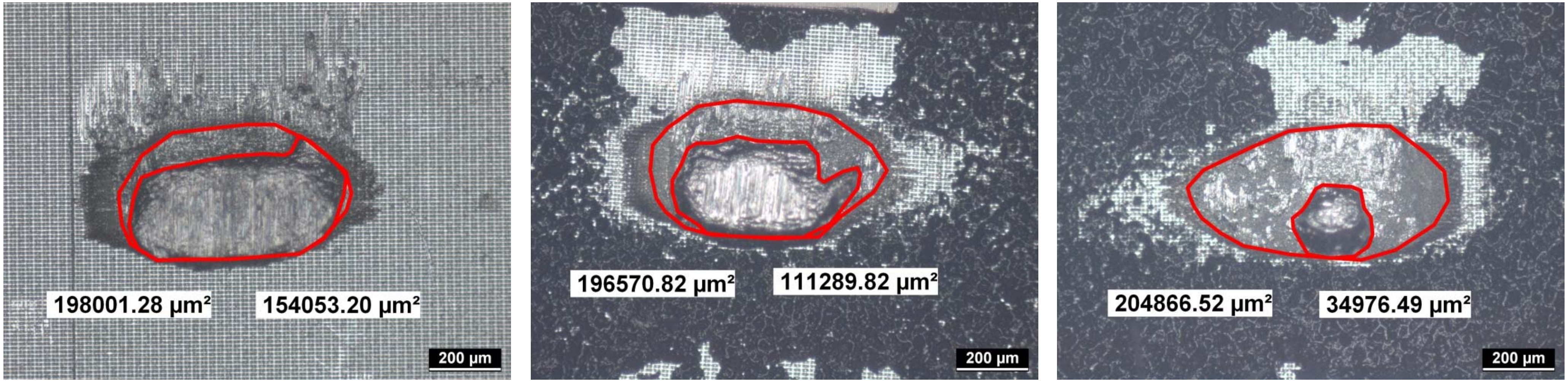
Estimation of Crack Length



Initial → 100.000 Zyklen → 200.000 Zyklen

Göhre et al., CIPS 2008

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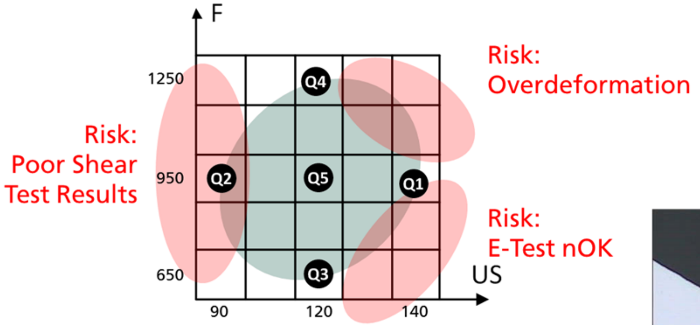
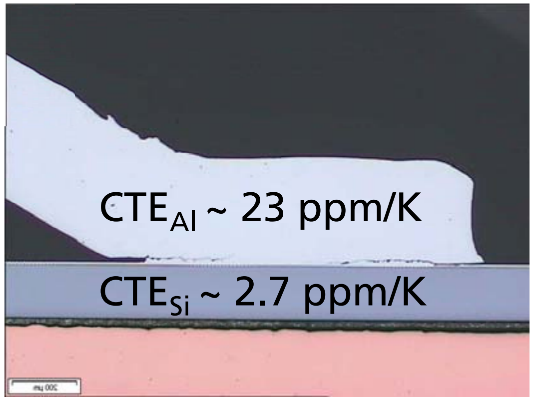
Lifetime Testing and Modelling for Wire Bonds in Power

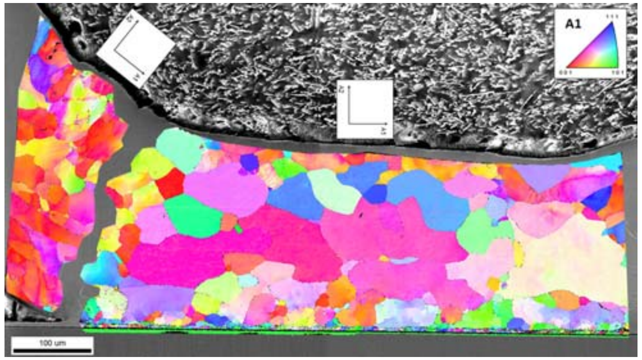
Bonding Process



Advanced Lifetime Test

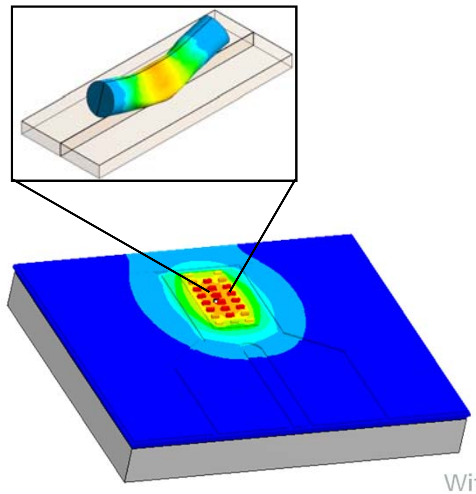


Microstructure



EBSD image after 2000 cycles

FEM based Lifetime Model



Material Data

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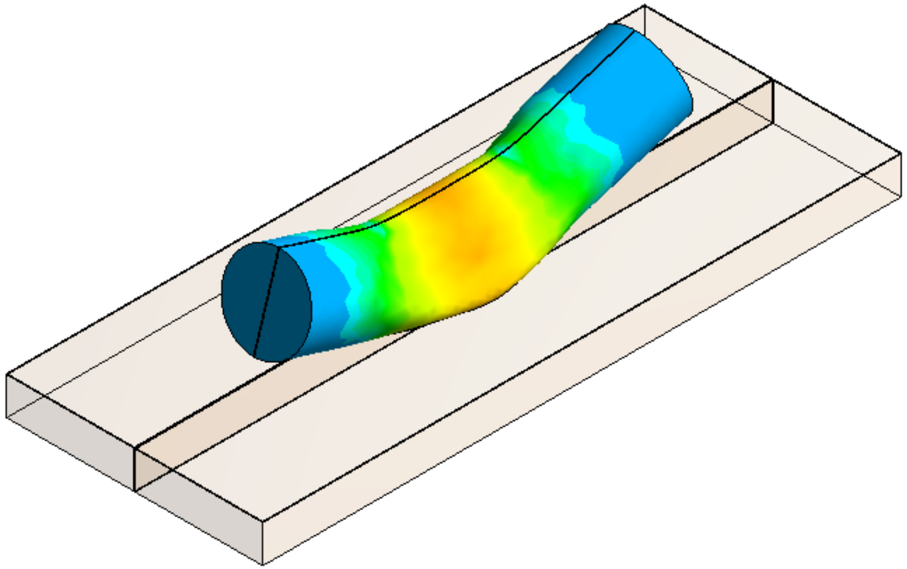

LIFETIME MODELLING

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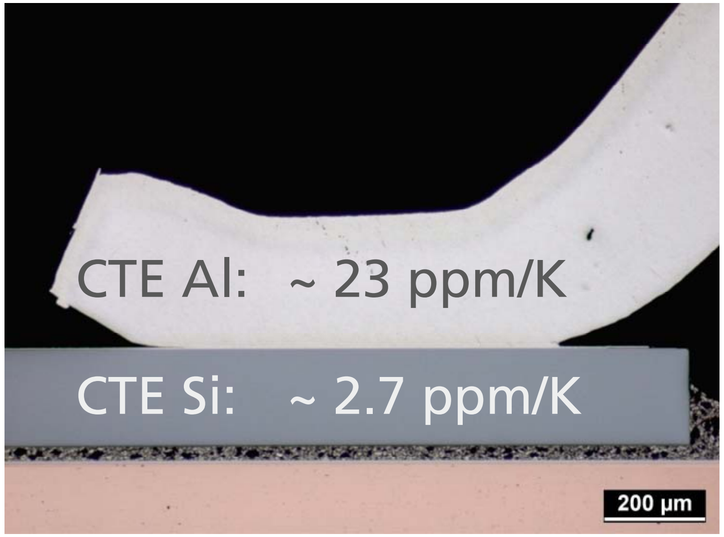
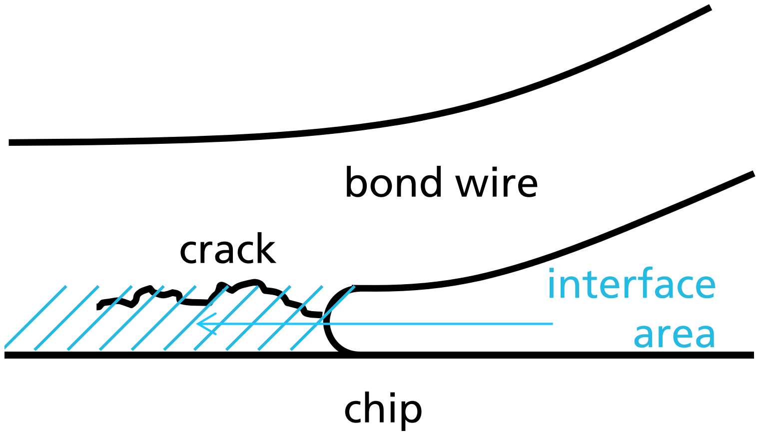
Crack Driving Force

- Temperature difference causes strains in materials

$$\varepsilon_{th} = \alpha_{CTE} \cdot \Delta T$$

- High stresses occur due to different CTEs of adjacent materials
- Plastic deformation during temperature cycling causes fatigue damage in aluminum
- Loop shape and relative movement of bond wedges have only negligible influence





Grams et al., EUROSIME 2014

Lifetime Modelling Approach

- Widest spread among POF approaches is Coffin Manson approach

$$N_f = C_1(\Delta\varepsilon_{\mathrm{pl}})^{-C_2}$$

- Crack growth approach comprises interesting advantages:

Modified Paris law: $$\frac{dA}{dN} = C1(\Delta\varepsilon_{pl})^{C2}$$

- ➢ Validity is independent of interface area
- ➢ Crack-length dependency of damage parameter is taken into account
- ➢ Damage accumulation can be considered by stepwise integration

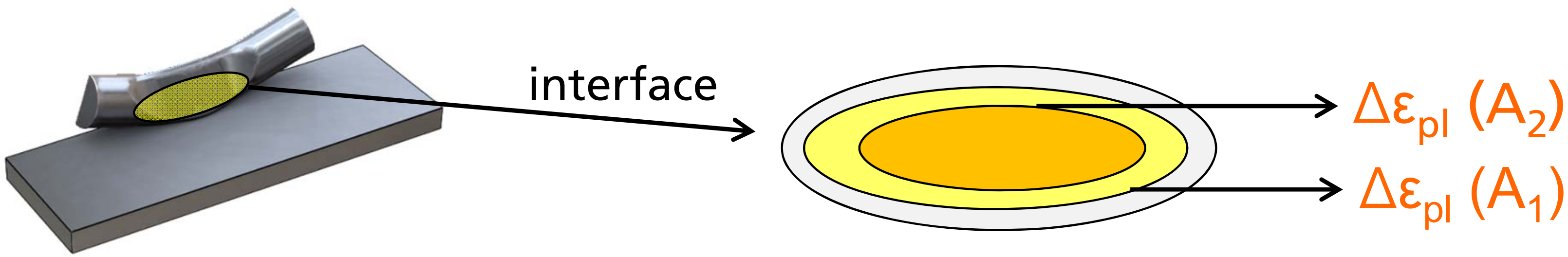
Grams et al., EUROSIME 2014

Lifetime Modelling Approach – Workflow

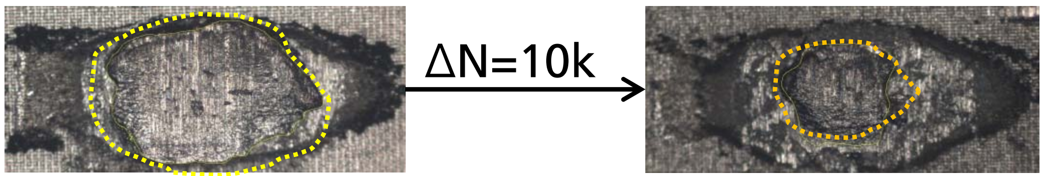
- Goal: Lifetime from integration of crack growth law

$$\frac{dA}{dN}(A) = C1[\Delta\varepsilon_{pl}(A)]^{C2} \longrightarrow N = \int_{A_0}^{A_f} \frac{1}{C_1\,[\Delta\varepsilon_{pl}\,(A)]^{C_2}}\,dA$$

- For a set of crack states the damage parameter is calculated



- Crack propagation rate is obtained from experiments



$$\longrightarrow \frac{dA}{dN}(A)$$

➢ Parameters C_1 and C_2 can be fitted

Grams et al., EUROSIME 2014

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Building the Geometry Model

3D-Laserscan → bond tool CAD model

→ Import →

ANSYS → Deformation analysis

↓ APDL script ↓

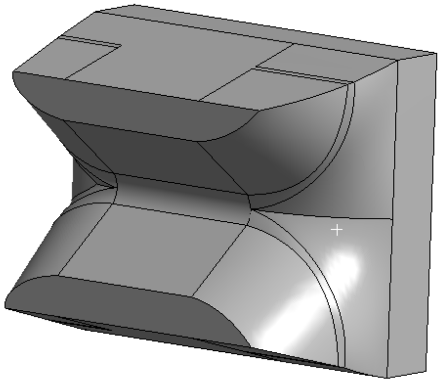
cloud of points, XYZ coordinates

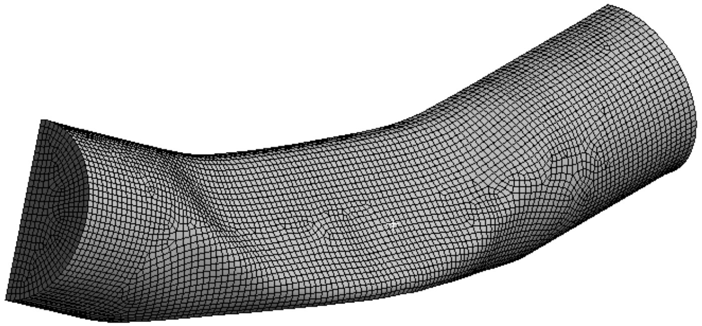
↓ Import ↓

SolidWorks Surface areas, body

↓ Changes to interface area ↓

ANSYS Geometry model





Grams et al., EUROSIME 2014

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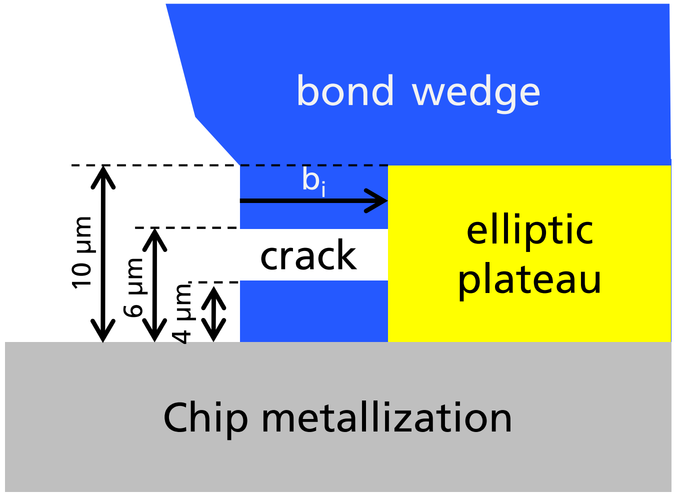
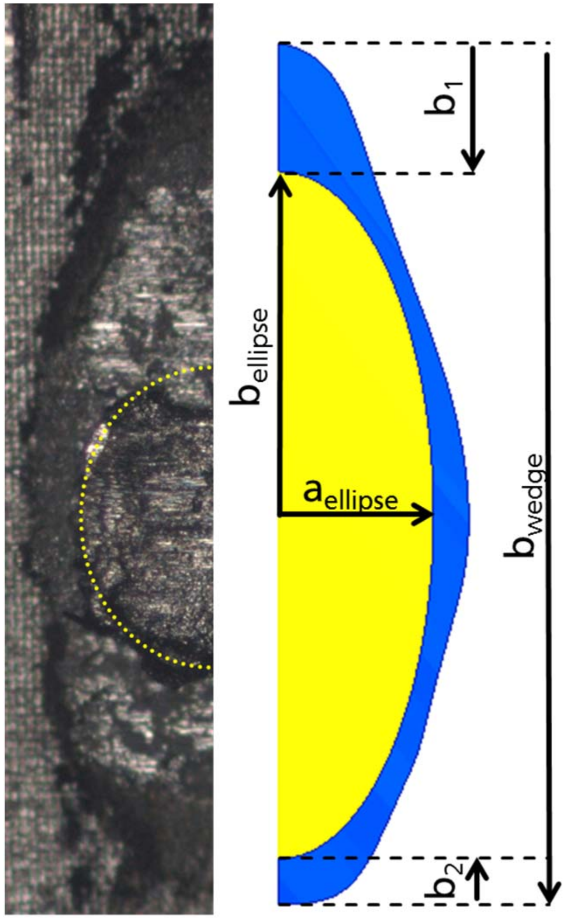
Modelling of Crack States

- Crack is modelled as 2 µm gap, centred 5 µm above the chip



loop side



tail side

- The uncracked area is modelled elliptically
- Ellipse is defined by its length, width and position derived from shear pictures
- Parametric crack generation in dependence of b_2 (distance tail side)

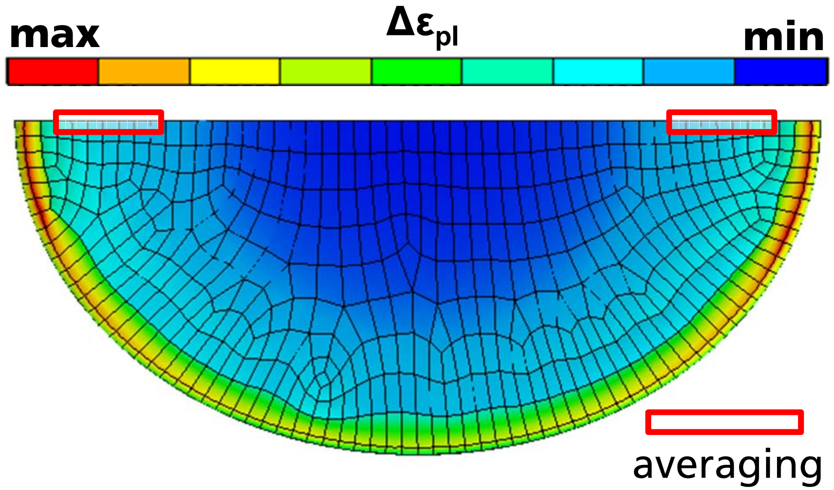
Grams et al., EUROSIME 2014

Evaluation of an Adequate Damage Parameter

- Accumulated plastic strain is representative for damage in the aluminium

$$\frac{dA}{dN} = C1(\Delta\varepsilon_{\mathrm{pl},\, acc})^{C2}$$

- singularities at the crack front are mesh dependent, → $\Delta\varepsilon_{\mathrm{pl},\, acc}$ will be averaged over a volume
- length b is characteristic for cracked area and elliptic geometry →a volume of the crack path along b is selected



- the increase in accumulated strains is evaluated from 3rd to 4th cycle, no change in $\Delta\varepsilon_{\mathrm{pl},\, acc}$ after the 4th cycle

$$\Delta\varepsilon_{\mathrm{pl},\, acc} = \varepsilon_{\mathrm{pl},\, acc,\, 4} - \varepsilon_{\mathrm{pl},\, acc,\, 3}$$

Grams et al., EUROSIME 2014

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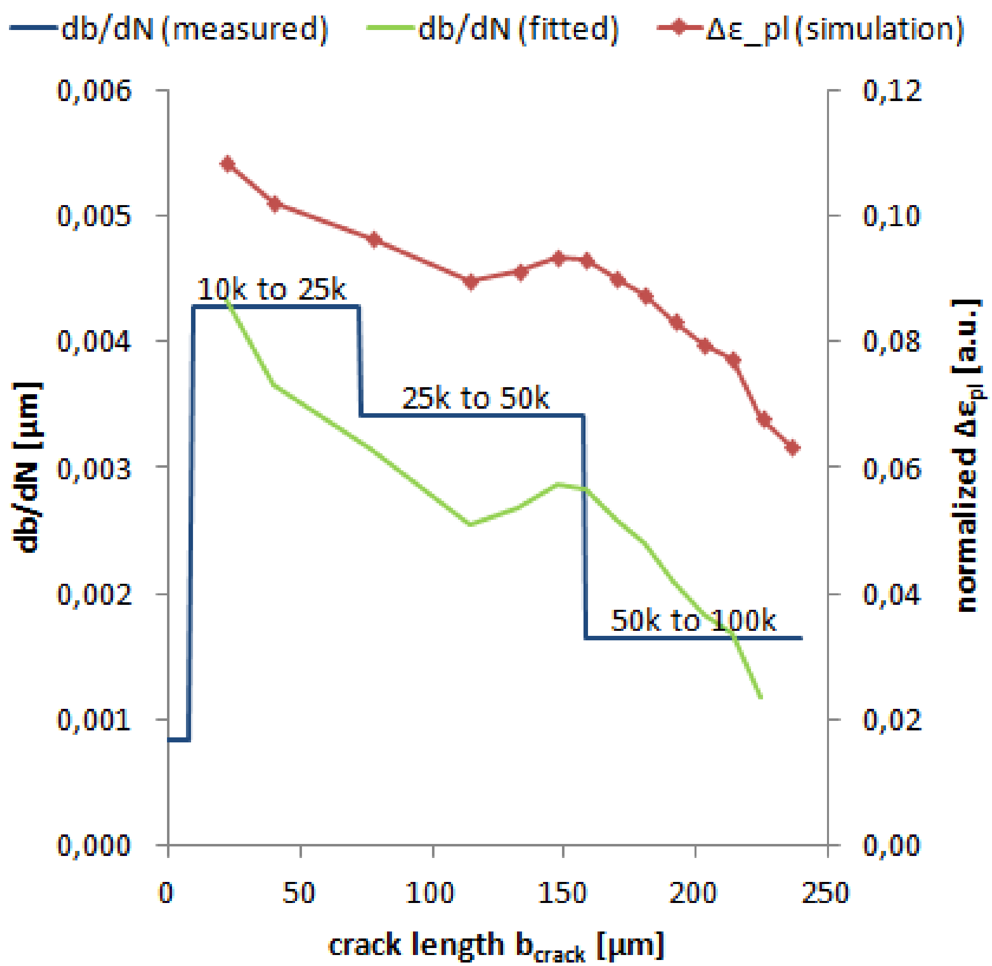
Adjusting the Fit Parameters

- with the collected db/dN data and the calculated $\Delta\varepsilon_{pl}$, fit parameters can be determined

$$\frac{d\boldsymbol{b}}{dN}(\boldsymbol{b}) = C_1[\Delta\varepsilon_{pl}(\boldsymbol{b})]^{C_2}$$

- the early state (N < 10k) of slow crack initiation cannot be described by the approach
- after crack initiation the measured data can be fitted well



Grams et al., EUROSIME 2014

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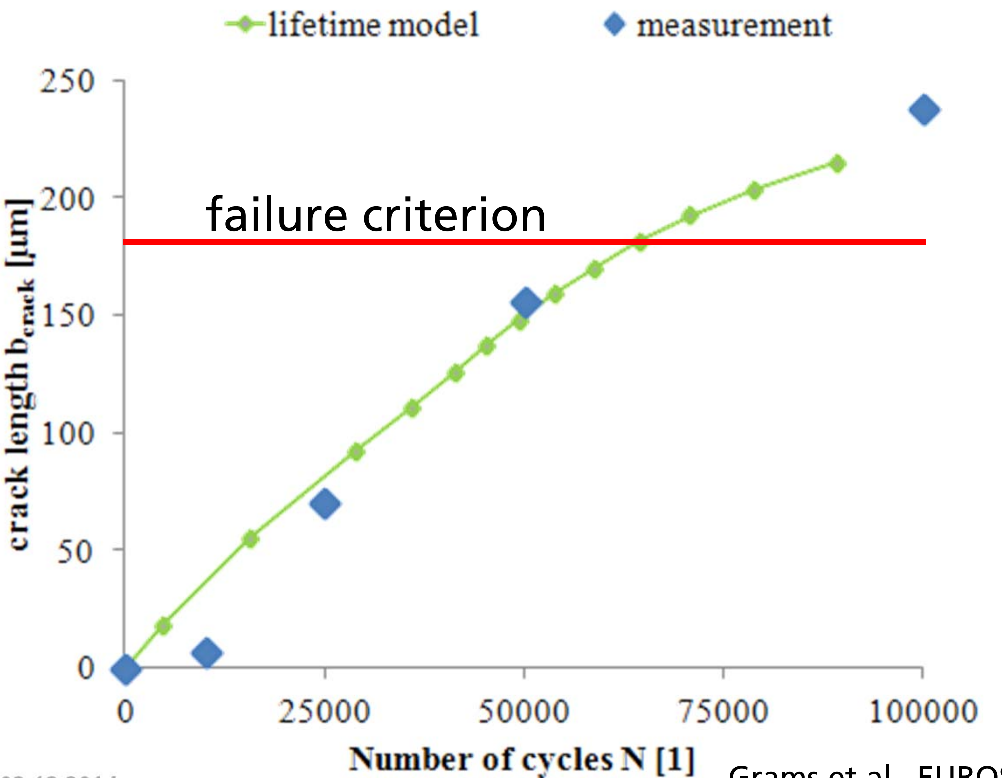
Calculation of Crack Length

- With the crack growth law now also crack lengths can be calculated

$$\frac{dA}{dN}(A) = C_1[\Delta\varepsilon_{pl}(A)]^{C_2} \longrightarrow N = \int_{A_0}^{A_f} \frac{1}{C_1\,[\Delta\varepsilon_{pl}\,(A)]^{C_2}}\,dA$$



Grams et al., EUROSIME 2014

- Crack length results from the integration of the db/dN-fit
- Failure criterion can be chosen, e.g.

$$A_{interface} < A_{wire}$$

Summary

- A modelling approach exists to analyse complex load histories by consideration of interaction of failure mechanisms and nonlinearity in damage superposition

- A unified damage model for Al wire bonds was developed based on
  - … a special power cycling test
  - … a finite element model describing the damage progression and geometrical influences

- Data can be extracted in a simplified form for a damage parameter used in a thermal coupling model.

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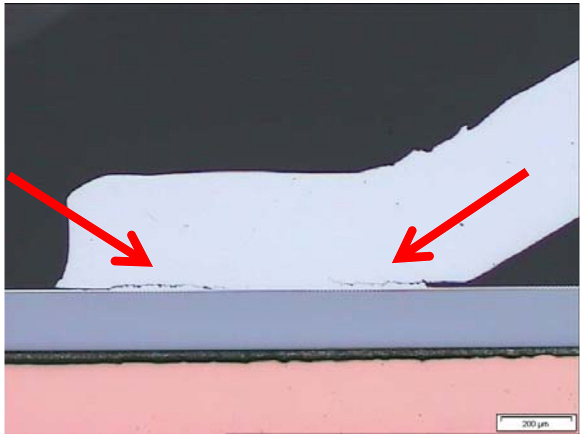
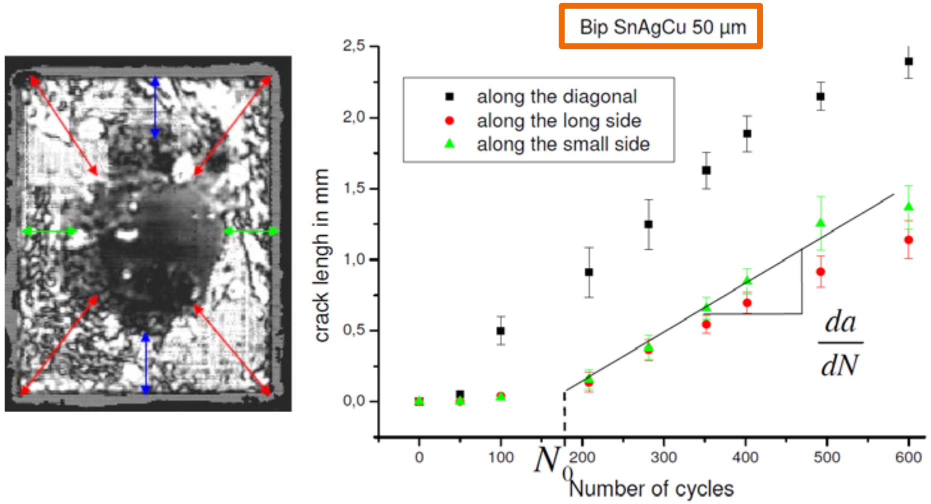
Outlook

- Coupling of Die Attach and Wire Bond degradation





(S. Deplanque et al., EuroSimE 2006)

- Analysis of typical mission profiles

- …

Thank you for your attention !

The recent results are based on research in the BMBF research activity “RoBE” (FKZ 16N11464) supported by the German Federal Ministry of Education and Research in the programme “IKT 2020”. This support is gratefully acknowledged.

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