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Thermal Contact Conductance in Vacuum

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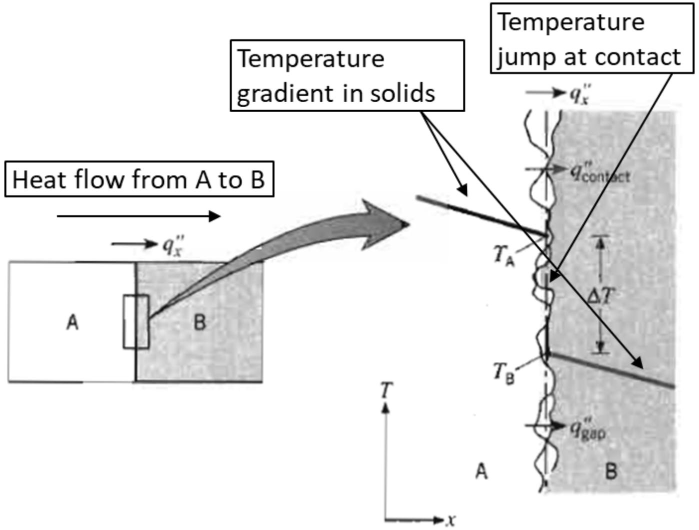
Introduction

Philips Engineering Solutions

- Philips Engineering Solutions
  - Originated from Philips CFT, Apptech, Innovation Services, …
  - “Creates the bridge from idea to market”
  - Innovation support to both Philips businesses as external partners
  - Head quartered in Eindhoven (High Tech Campus)
- Rob van Gils
  - 2002 – 2012: Master/PhD at TU/e, Dynamics and Control
    - Control of a Pool-boiling system
    - Connection between Dynamics, Control and Thermal field
  - 2012 – 2022: Sr. Technologist at Philips Engineering Solutions
    - Competence Leader Thermal & Flow
    - Bridge gap between thermal field and other mechatronics competences

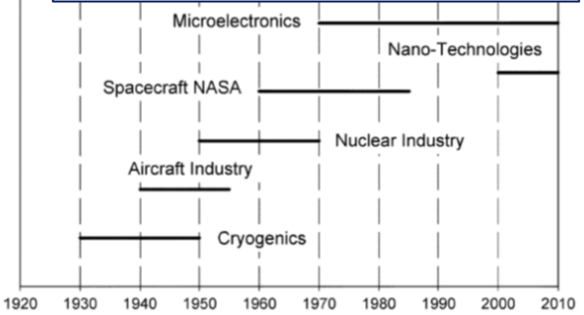
Motivation

- Thermal Contact Conductance (TCC): the thermal resistance between two solids that are pressed together
  - Literature: multiple application areas, see [Yovanovic2005]**
  - Spread in TCC is huge for only small deviations in test conditions
- Tools developed in literature
  - Are complex to use
  - Originate from different applications
- In this study: Test conditions similar to mechatronics applications
  - High precision systems → in vacuum
  - Small contact areas → dominant in heat transfer path
  - Relatively high contact pressures can be achieved

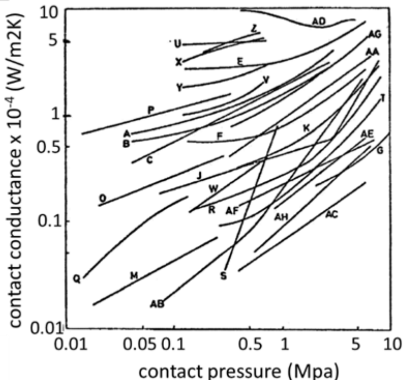


Thermal Contact Conductance; [Incropera2006]

Timeline for TCC research; [Yovanovic2005]



TCC of Al alloys; [Yovanovic2005]



* [Incropera2006]: Fundamentals of heat and mass transfer, *Incropera & DeWitt, 2006, 6th edition*

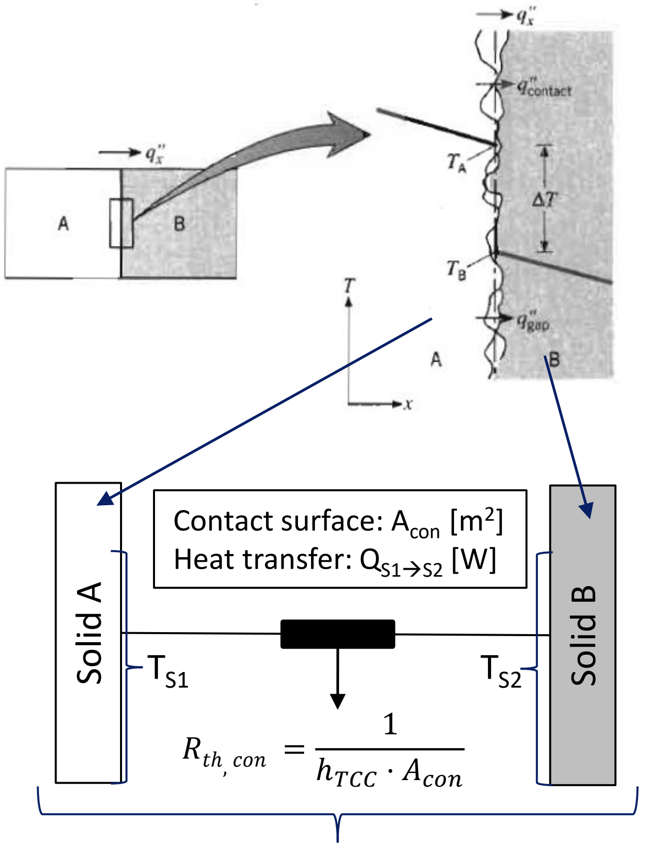
** [Yovanovic2005]: Four Decades of Research on Thermal Contact, Gap, and Joint Resistance in Microelectronics, *M. Yovanovic, IEEE Trans. on components and packaging tech., vol. 28, 2005*

Objective

- Objective is to quantify the thermal contact conductance in vacuum
  - Meaning: a measure for the thermal coupling between surfaces in contact
  - No research on micro/macro-scopic contact in order to define general models
  - Test conditions as close to the conditions in High Precision Machines as possible
- Measure for thermal coupling
  - Expressed as a single heat transfer coefficient: h_{TCC} [W/m^2K]
- Single parameter that quantifies the thermal coupling:

$$h_{TCC} = \frac{Q_{S1\rightarrow S2}}{A_{con} \cdot (T_{s1} - T_{s2})}$$

  - With
  - $Q_{S1\rightarrow S2}$: Heat flow from Surface 1 to Surface 2 in [W]
  - A_{con} the contact area between the solids in [m^2]
  - T_{S1}: The surface averaged temperature of Surface 1 in [°C]
  - T_{S2}: The surface averaged temperature of Surface 2 in [°C]



$$Q_{S1\rightarrow S2} = h_{TCC} \cdot A_{con} \cdot (T_{S1} - T_{S2})$$

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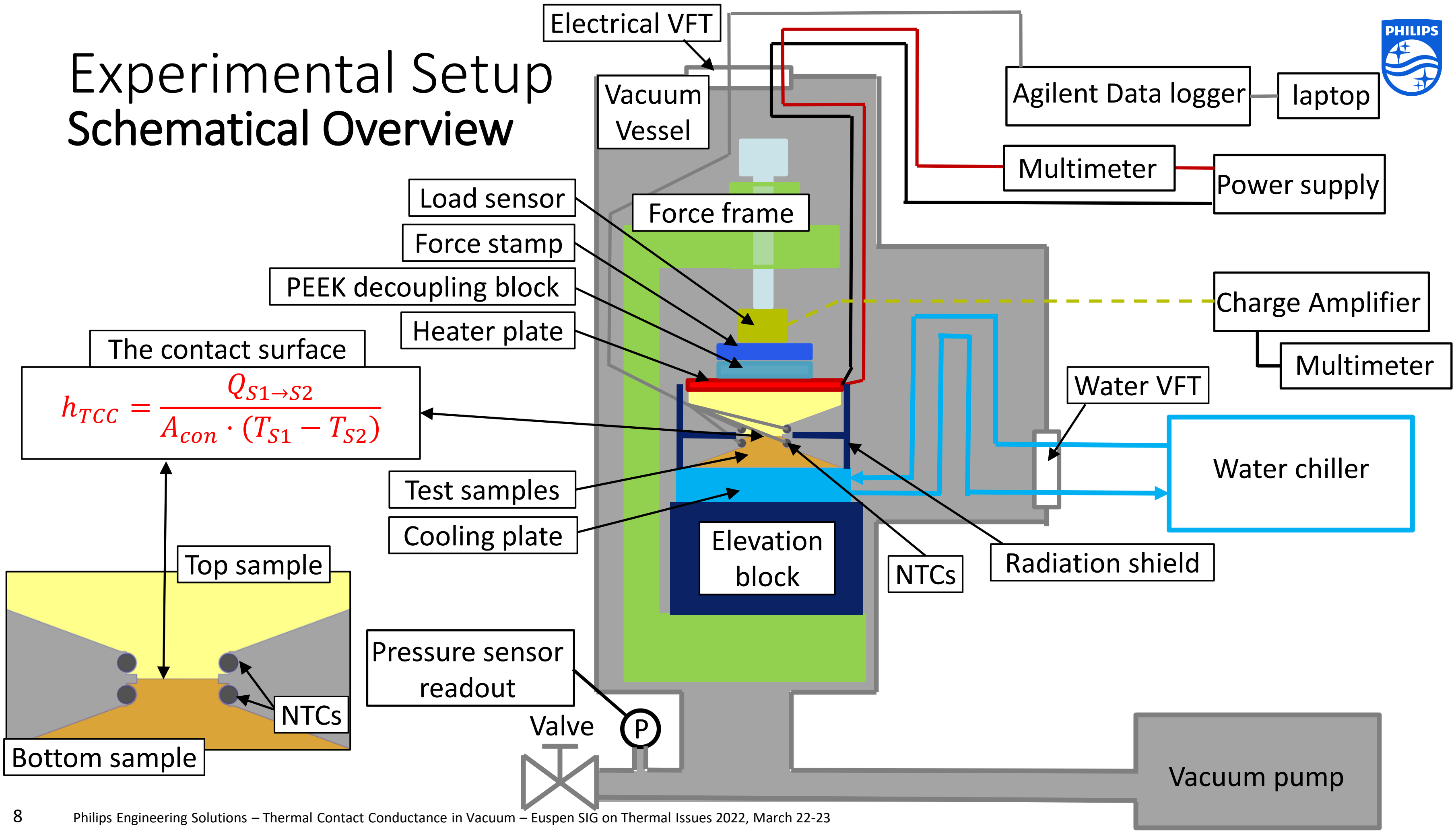
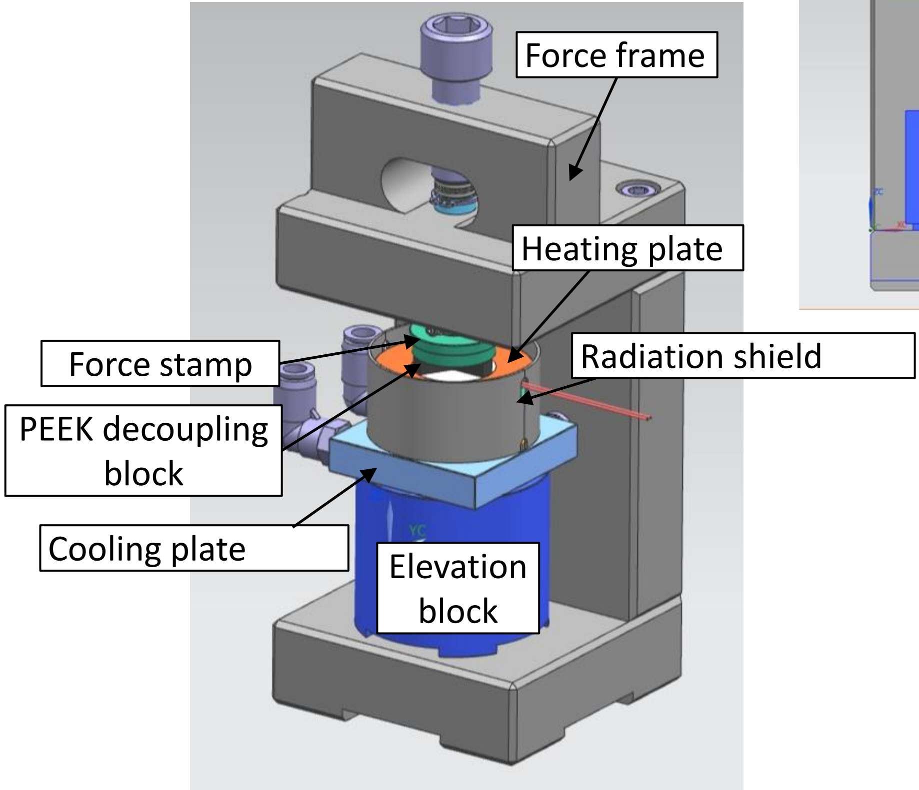
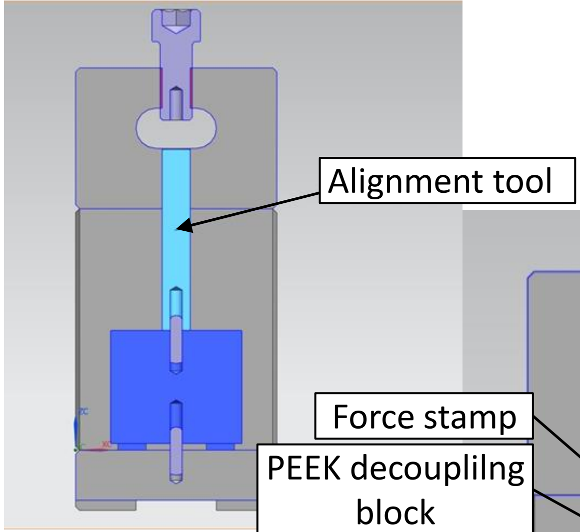
Methodology

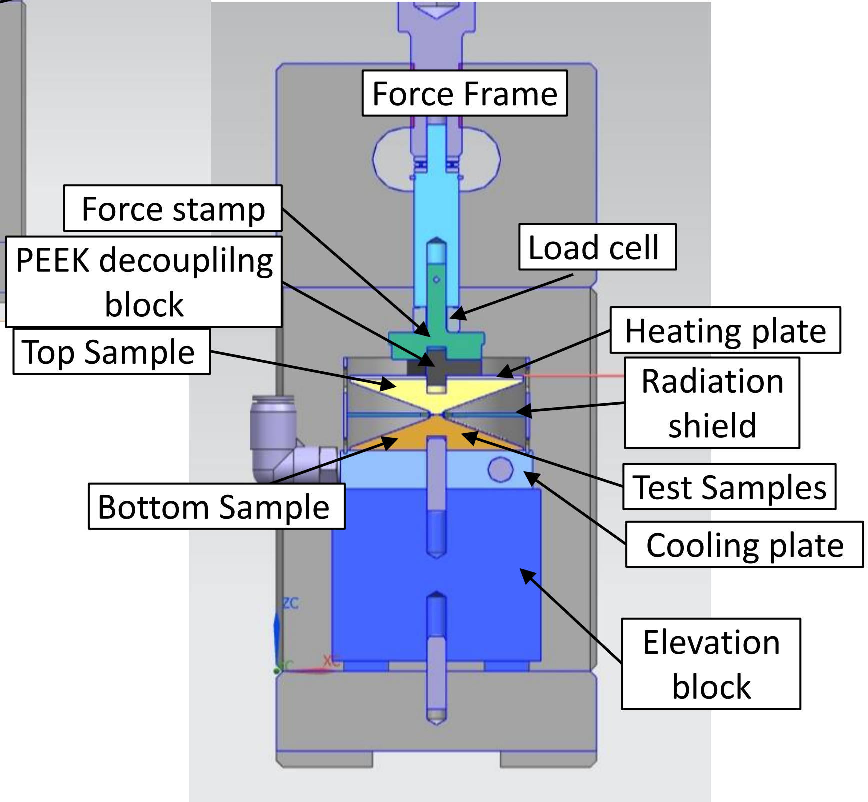
Experimental Setup
Schematical Overview



Experimental Setup
CAD Geometry







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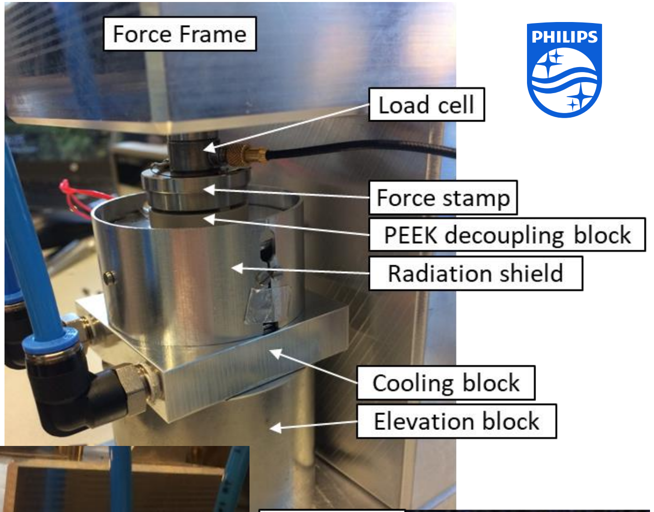
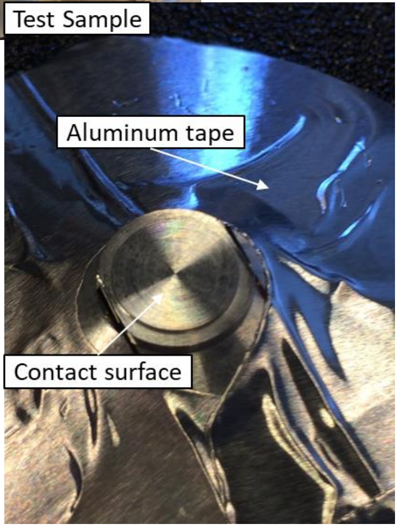
Test settings

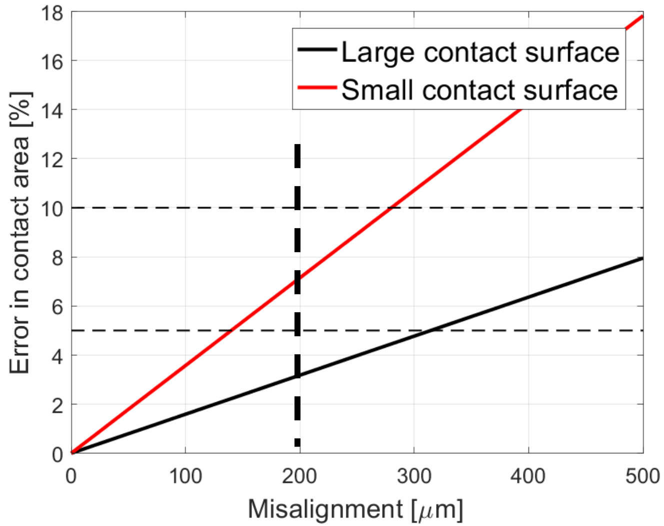
- Sample properties
  - Materials investigated: Aluminum 5083 (Al5), Aluminum 6082 (Al6), AISI316L (StSt), Titanium Grade 5 (Ti5)
  - Contact surface roughnesses: Ra = 0.4µm (nominal), and Ra = 1.6, 3.2 and 6.4µm
  - Contact sizes: 50mm^2 (contact pressure = 0.1 – 25MPa), 10mm^2 (contact pressure = 25 – 100MPa)
- Environmental conditions
  - Vacuum tests: air pressure: 1 – 5Pa air
  - Atmospheric tests: typical Dutch atmospheric pressure: 970 – 1050hPa air
  - Lab temperature: 20 – 24°C





Procedure to determine h_{TCC}

- Contact conductance is calculated via
  - $h_{TCC} = \frac{Q_{S1\rightarrow S2}}{A_{con}\cdot(T_{S1}-T_{S2})}$
- Determination of Q_{th}
  - Electrical input to heater is measured
  - Heat might leak to environment
  - Assumed heat flow through contact: $Q_{S1\rightarrow S2} = \alpha \cdot Q_{th}$
- Determination of A_{con}
  - Test samples with A_{con} = 50mm^2 and with A_{con} = 10mm^2
  - Misalignment of samples leads to $A_{con} = \beta \cdot A_{con}$
  - Maximal misalignment of 200µm between samples
- Determination of T_{S1} and T_{S2}
  - Measurement of NTCs is not at the contact
  - Model-based adjustment of the measurements needed
  - $T_{S1} = T_{NTC,top} - R_{top} \cdot \alpha \cdot Q_{th}$
  - $T_{S2} = T_{NTC,btm} + R_{btm} \cdot \alpha \cdot Q_{th}$

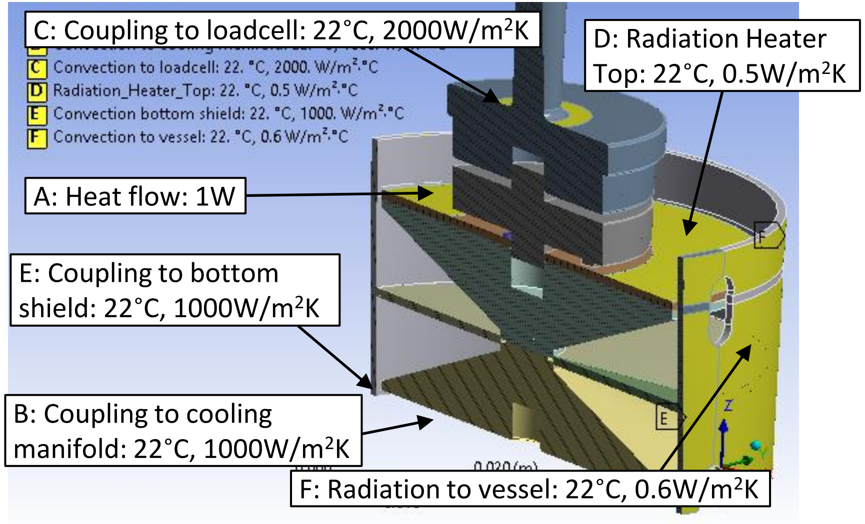


- The adjustment parameters α, β, R_{top} and R_{btm} are defined per sample pair
- The Contact Conductance can then be obtained via

$$h_{TCC} = \frac{\alpha \cdot Q_{th}}{\beta \cdot A_{con} \cdot \left(T_{NTC,top} - T_{NTC,btm} - \alpha \cdot Q_{th}\left(R_{top} + R_{btm}\right)\right)}$$

Thermal modelling
Of part of the setup

- Thermal model set up in ANSYS Mechanical
  - Boundary conditions: heat sink, radiation, heat load
  - Contact between samples: h_{TCC}
  - Other contacts: $h_{con} \approx 1000 - 2000 W/m^2K$ (subjected to full contact surface)
- Model used to determine the adjustment parameters α, β, R_{top} and R_{btm} per sample pair
- Model used to define error budget:
  - Statistical sum of contributions: +/-20%



Error source	Error contribution 50mm² contacts
Heat load uncertainty due to voltage and current uncertainty	6.0%
Heat flow uncertainty due to heat losses	10.0%
Contact area uncertainty	3.2%
NTC measurement error	2.5%
Additional error due to temperature measurement adjustment	
Heat flow uncertainty	0.8%
Misalignment	6.1%
Uncertainty in thermal conductance	12.3%
Uncertainty in emissivity samples	5.3%
Uncertainty in emissivity heater top	5.4%
Statistical sum:	**20.2%**

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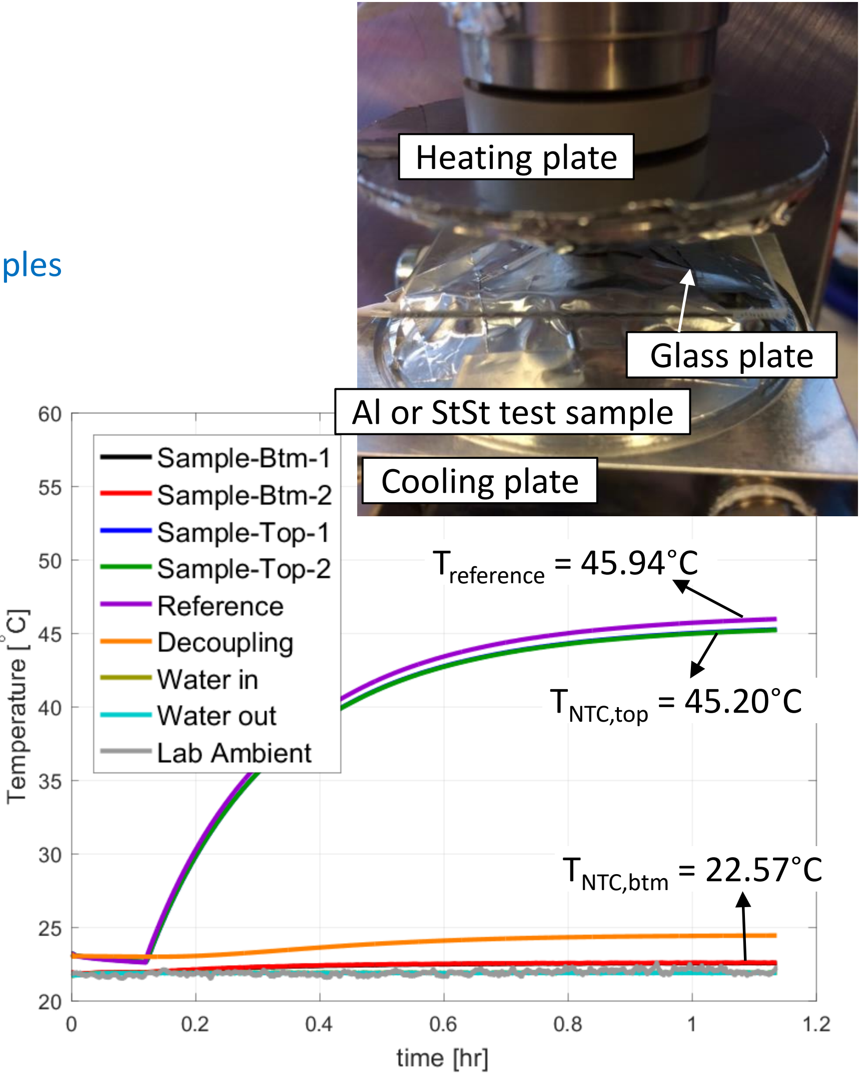
Results

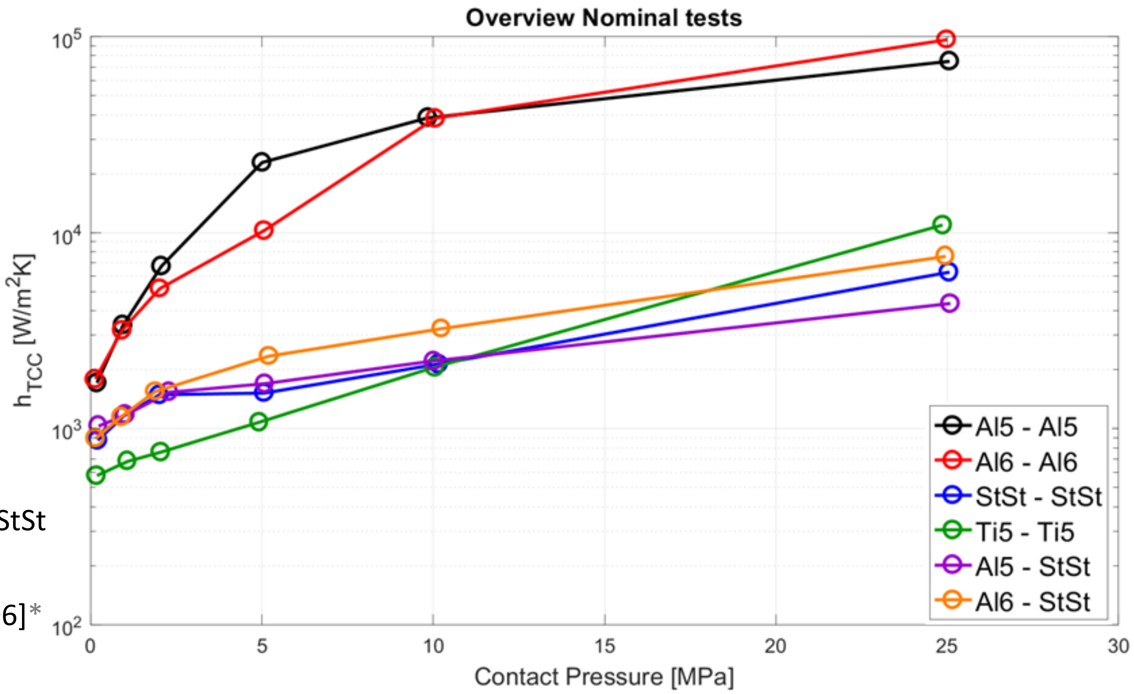
Accuracy quantification

- Accuracy test: measure h_{TCC} with glass plate between samples
- Effective HTC:
  - Conduction through glass: h_{eff} = 1000W/m²K
  - Contact Conductance Al to glass: h_{con} = 10000W/m²K
  - Total effective HTC: $h_{eff} = \frac{1}{t/\lambda+2/10000}$ = 833W/m²K
- Measurement
  - Al samples: h_{TCC} measured: 847W/m²K
  - StSt samples: h_{TCC} measured: 765W/m²K
- **Conclusion: Measured h_{TCC} in line with expected h_{TCC}**



Results
Nominal tests

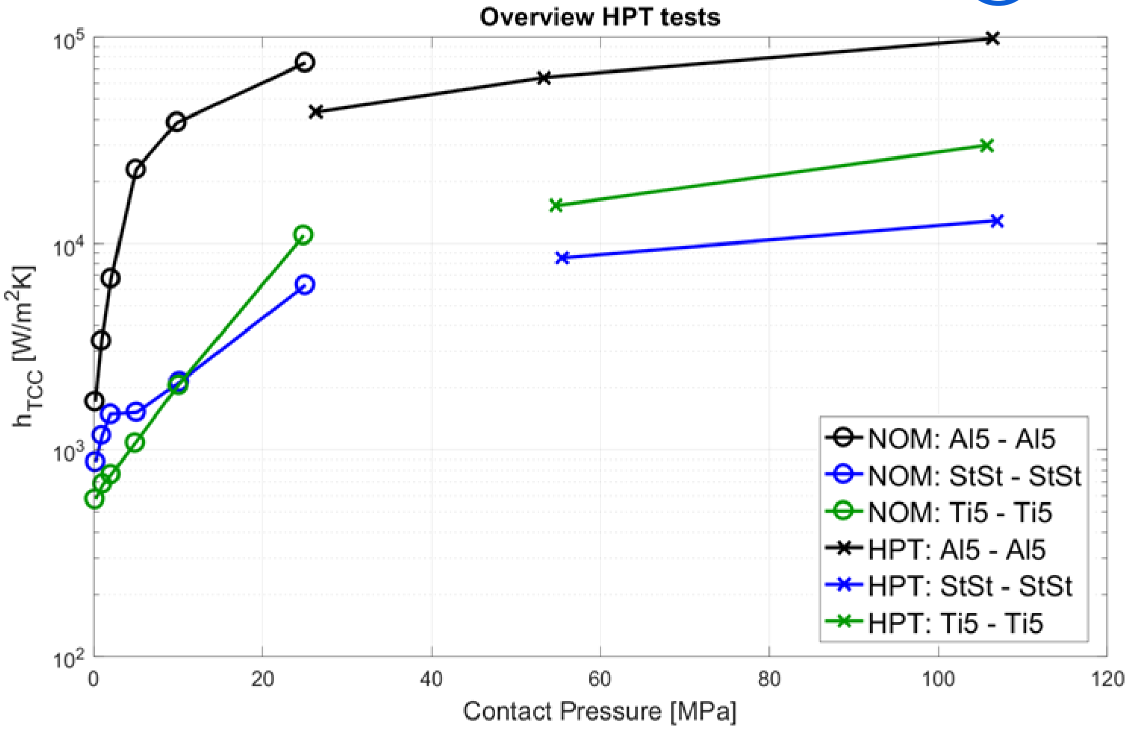
- Nominal tests are employed with
  - Samples with a Ra of 0.4µm
  - Contact pressure: 0.1 – 25MPa
- Observations
  - Some measurement points are not in line with the trend observed → this is assumed to be the nature of the TCC
  - TCC values for Al lie considerably higher than those for StSt and Ti
  - TCC for Al – StSt not much higher than StSt – StSt
- Correlations with literature
  - Good overlap with values from [Incropera2006]*
  - Good overlap with earlier found values in different test setup
  - Poor correlation with Yovanovic** and FVV models***



* [Incropera2006]: Fundamentals of heat and mass transfer, *Incropera & DeWitt, 2006, 6th ed.*
** [Yovanovic2005]: Four Decades of Research on Thermal Contact, Gap, and Joint Resistance in Microelectronics, *M. Yovanovic, IEEE Trans. on components and packaging tech., vol. 28, 2005*
*** [FVV2011]: Modellentwicklung für den kontaktdruckabhängigen ärmeübergang, *72.Jahrgang pp142-147, 2011*

Results
High contact pressure

- High contact pressure tests are employed with
  - Samples with a Ra of 0.4µm
  - A_{con} = 10mm^2
  - Contact pressure: 50 – 100MPa
- Observations
  - TCC values seem to plateau towards an asymptotic value
  - Large variance between test with large contact surface and small contact surface @ 25MPa
- Correlations with literature
  - Poor correlation with Yovanovic model**, but it is only valid up to 10MPa
  - Poor correlation with FVV models*** which are based on atmospheric tests and for >5 Re-contacts



* **[Incropera2006]**: Fundamentals of heat and mass transfer, *Incropera & DeWitt, 2006, 6th ed.*

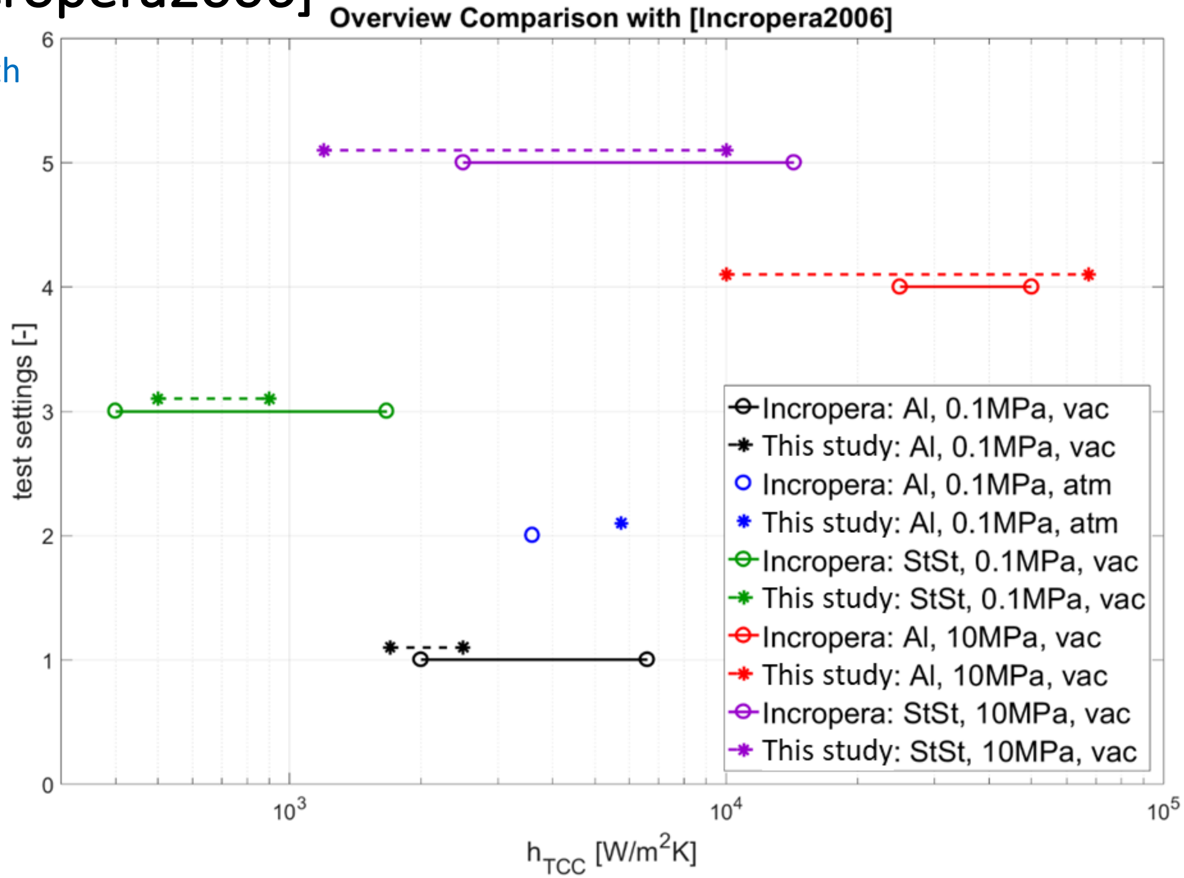
** **[Yovanovic2005]**: Four Decades of Research on Thermal Contact, Gap, and Joint Resistance in Microelectronics, *M. Yovanovic, IEEE Trans. on components and packaging tech., vol. 28, 2005*

*** **[FVV2011]**: Modellentwicklung für den kontaktdruckabhängigen ärmeübergang, *72.Jahrgang pp142-147, 2011*

Nominal tests

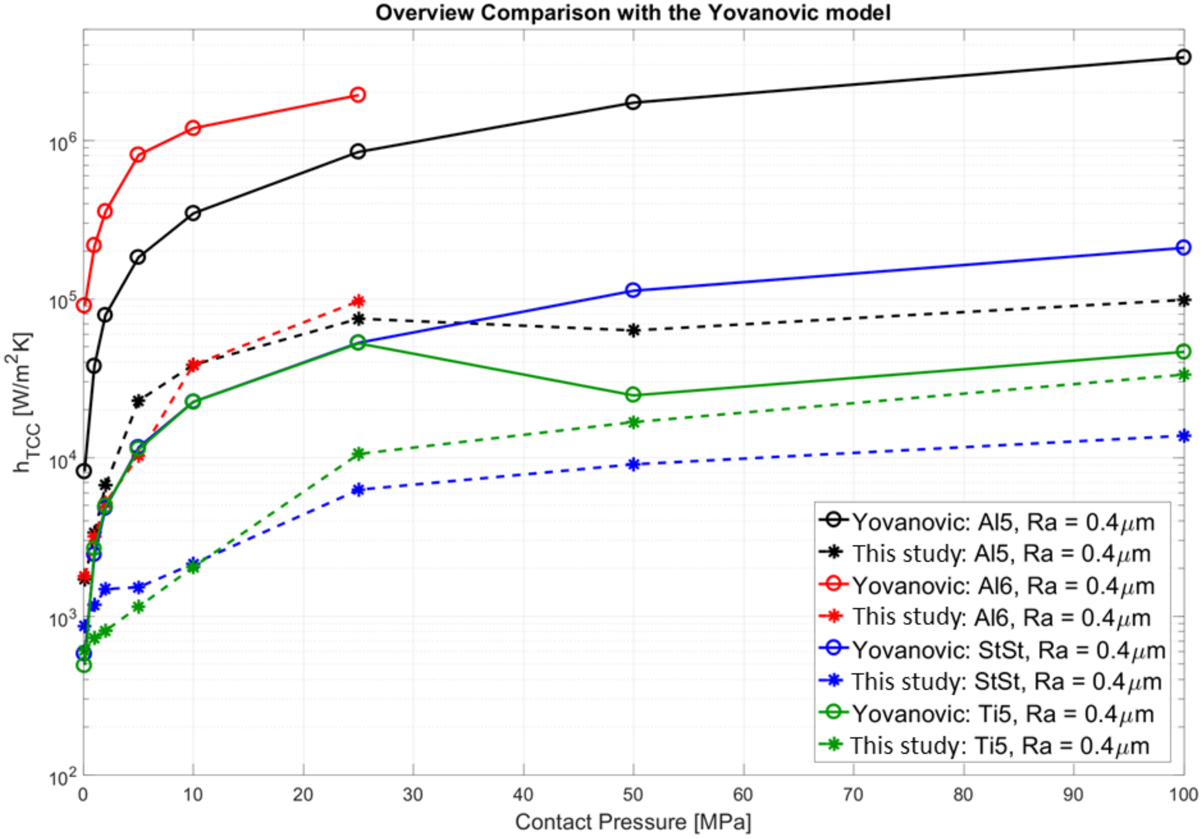
Correlation with [Incropera2006]

- Nominal tests are employed with
  - Samples with a Ra of 0.4µm
  - Contact pressure: 0.1 – 25MPa
- Correlations with literature
  - Good overlap with values from [Incropera2006]



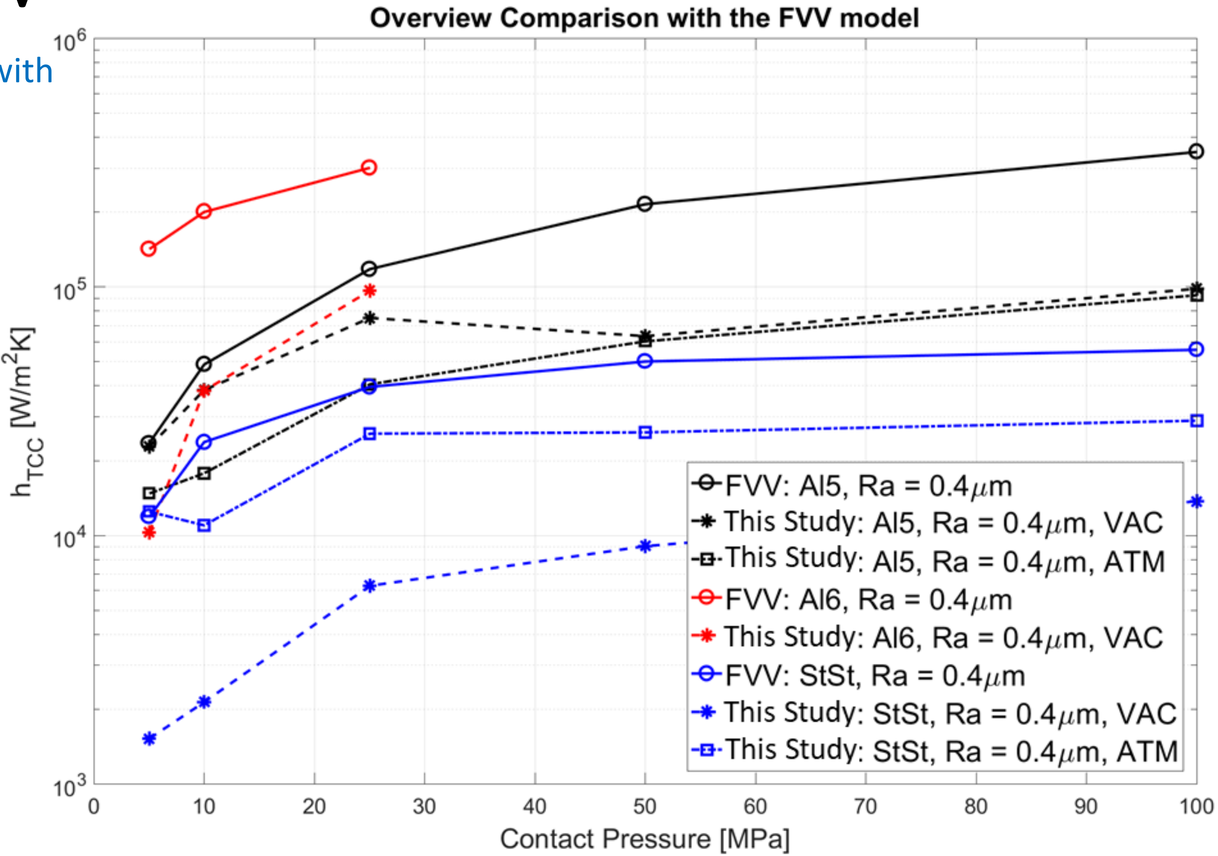
Nominal tests
Correlation with Yovanovic

- Nominal tests are employed with
  - Samples with a Ra of 0.4µm
  - Contact pressure: 0.1 – 25MPa
- Correlations with literature
  - Poor correlation with Yovanovic and FVV models
  - Yovanovic model predicts significantly higher TCC values (up to one order of magnitude)
  - Models are used outside of their validity range
    - Surface roughness Ra < 3µm
    - Contact pressure > 10MPa
    - Aluminum samples



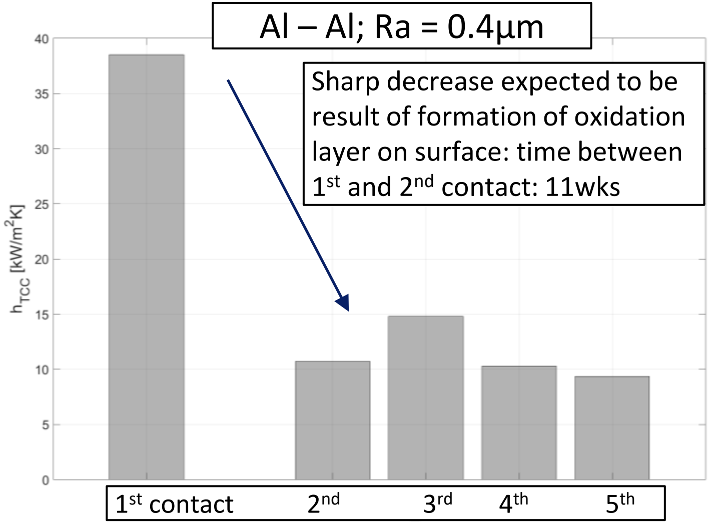
Nominal tests
Correlation with FVV

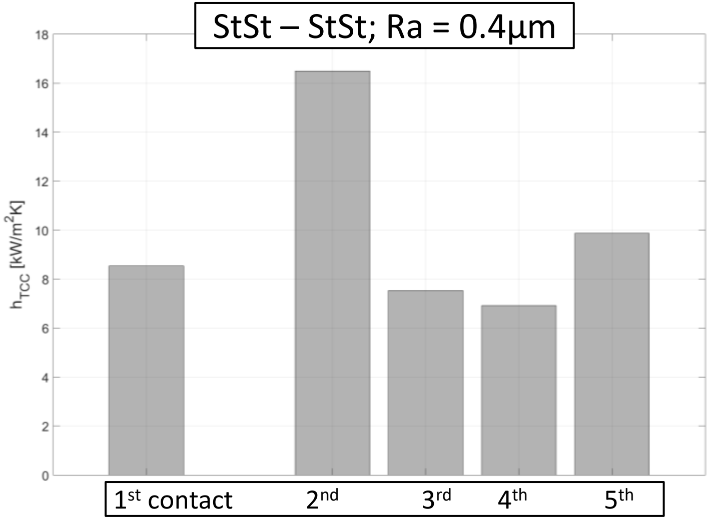
- Nominal tests are employed with
  – Samples with a Ra of 0.4µm
  – Contact pressure: 0.1 – 25MPa
- Correlations with literature
  – Poor correlation with Yovanovic and FVV models
  – FVV models based on atmospheric tests



Results
Re-contact tests

- Re-contact tests are employed with
  - Samples with a Ra of 0.4 and 1.6µm
  - Contact pressure: 10MPa
- Observations
  - The Al – Al contacts drop significantly after the first contact → due to changing surface conditions?
  - No real trend due to re-contacts can be determined
- Correlations with literature
  - In literature re-contacts are known to have an effect on the TCC value between surfaces





Conclusions & Future Work

Conclusions

- Experimental Setup
  - A test setup to measure the thermal contact conductance between metallic surfaces in vacuum is designed
  - Measurement data is used together with model-based parameters to determine the h_{TCC}
  - An accuracy test with a known thermal resistance and model-based error budgeting establishes an accuracy of 20 and 30% for the $50mm^2$ and $10mm^2$ contacts, respectively
- General observation on the TCC value
  - The TCC of metallic surfaces is rather unpredictable and non-reproducible
  - Fresh Al – Al contacts provide highest TCC values
  - Al – Al contact conductance can significantly reduce when an oxidation layer has formed on the surfaces → the resulting h_{TCC} is the same order of magnitude as those for StSt and Ti contacts
  - Comparison with TCC models from literature shows that very large mismatches can occur when models are used outside their validity range
- Advice for systems where performance is dominated by TCC behavior
  - Be aware of the large non-reproducibility that can occur upon recontact and/or changing surface conditions (e.g. oxidation)
  - Be aware of the validity ranges and quick deterioration outside these ranges of TCC models from literature
  - Do elaborate sensitivity studies on thermal models to investigate the impact of this
  - **But if possible: Design such that performance is not impacted by changes in the TCC between surfaces**

Future Work

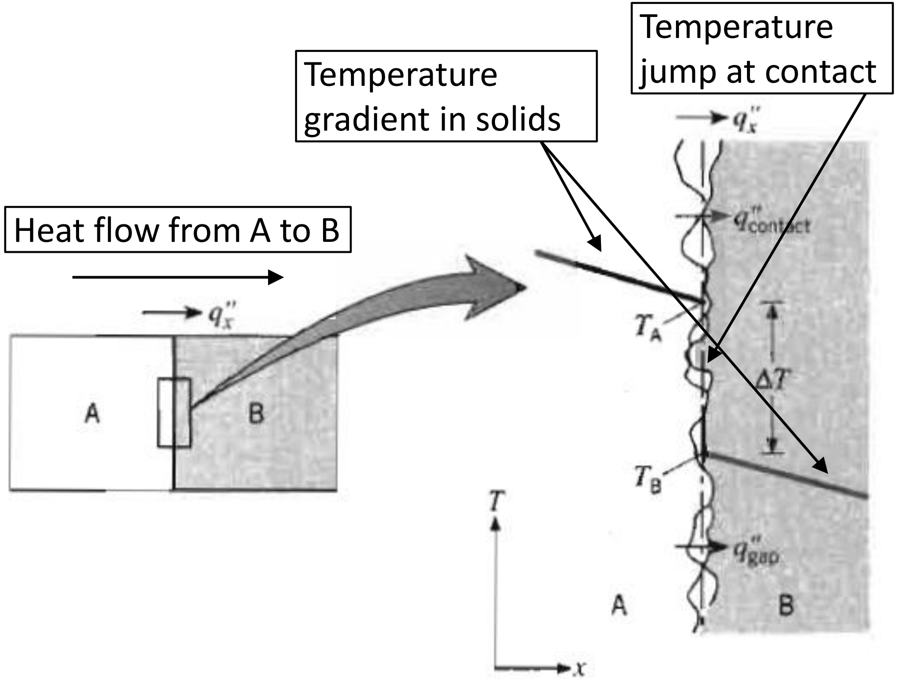
- Currently we are continuing this study as part of an MSc-assignment
  - Reproducibility of test setup using glass plate
  - Experimentally qualifying heat losses in the setup
  - Surface topology investigation (using microscopes) to investigate changes in surface roughness/topology after re-contacts & their effect on the TCC value
- Research directions for future studies can be
  - Further investigate impact of orientation of surfaces on TCC
  - Investigate further combinations between materials and surface roughnesses
  - Investigate the use of fillers

Questions & Answers

References:
* **[Incropera2006]**: Fundamentals of heat and mass transfer, *Incropera & DeWitt, 2006, 6th ed.*
** **[Yovanovic2005]**: Four Decades of Research on Thermal Contact, Gap, and Joint Resistance in Microelectronics, *M. Yovanovic, IEEE Trans. on components and packaging tech., vol. 28, 2005*
*** **[FVV2011]**: Modellentwicklung für den kontaktdruckabhängigen ärmeübergang, *72.Jahrgang pp142-147, 2011*

Thermal Contact Conductance

- Thermal Contact Conductance: the thermal resistance between two solids that are pressed together
- Typical order of magnitude
  - Highly variant under conditions, especially contact pressure
  - Low contact pressure (<1 Mpa): 100 – 5000W/m^{2}K
  - High contact pressure (>10MPa): 10 000 – 100 000W/m^{2}K
- In high precision applications
  - Often vacuum
  - Small contact areas → dominant in heat transfer path
  - Relatively high contact pressures can be achieved



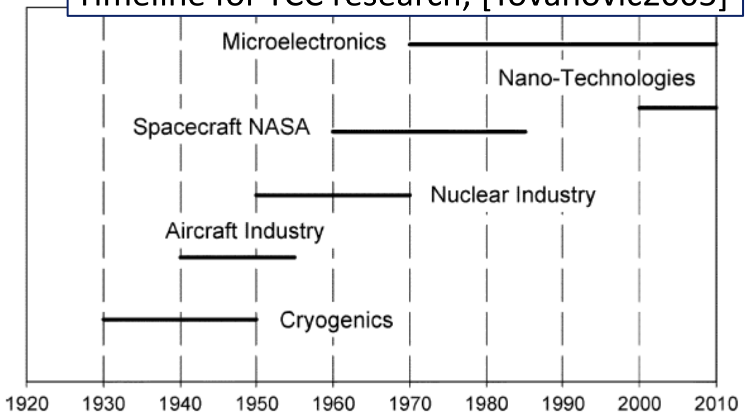
Thermal Contact Conductance; [Incropera2006]

* **[Incropera2006]**: Fundamentals of heat and mass transfer, *Incropera & DeWitt, 2006, 6th edition*

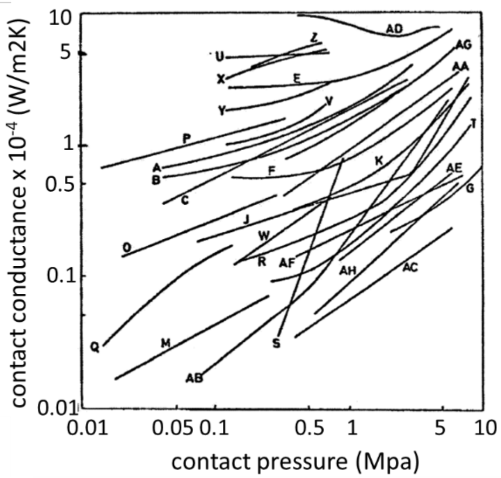
Motivation

- Thermal Contact Conductance (TCC) in vacuum
  - High precision systems → in vacuum
  - Dominant phenomenon in thermal modelling
- TCC has been addressed in literature
  - Overview presented in [Yovanovic2005]**
  - Multiple application areas
  - Spread in TCC is huge for only small deviations in test conditions
- Tools developed in literature
  - Are complex to use
  - Originate from different applications
- In this study:
  - Vacuum conditions
  - Test conditions similar to mechatronics applications

Timeline for TCC research; [Yovanovic2005]



TCC of Al alloys; [Yovanovic2005]



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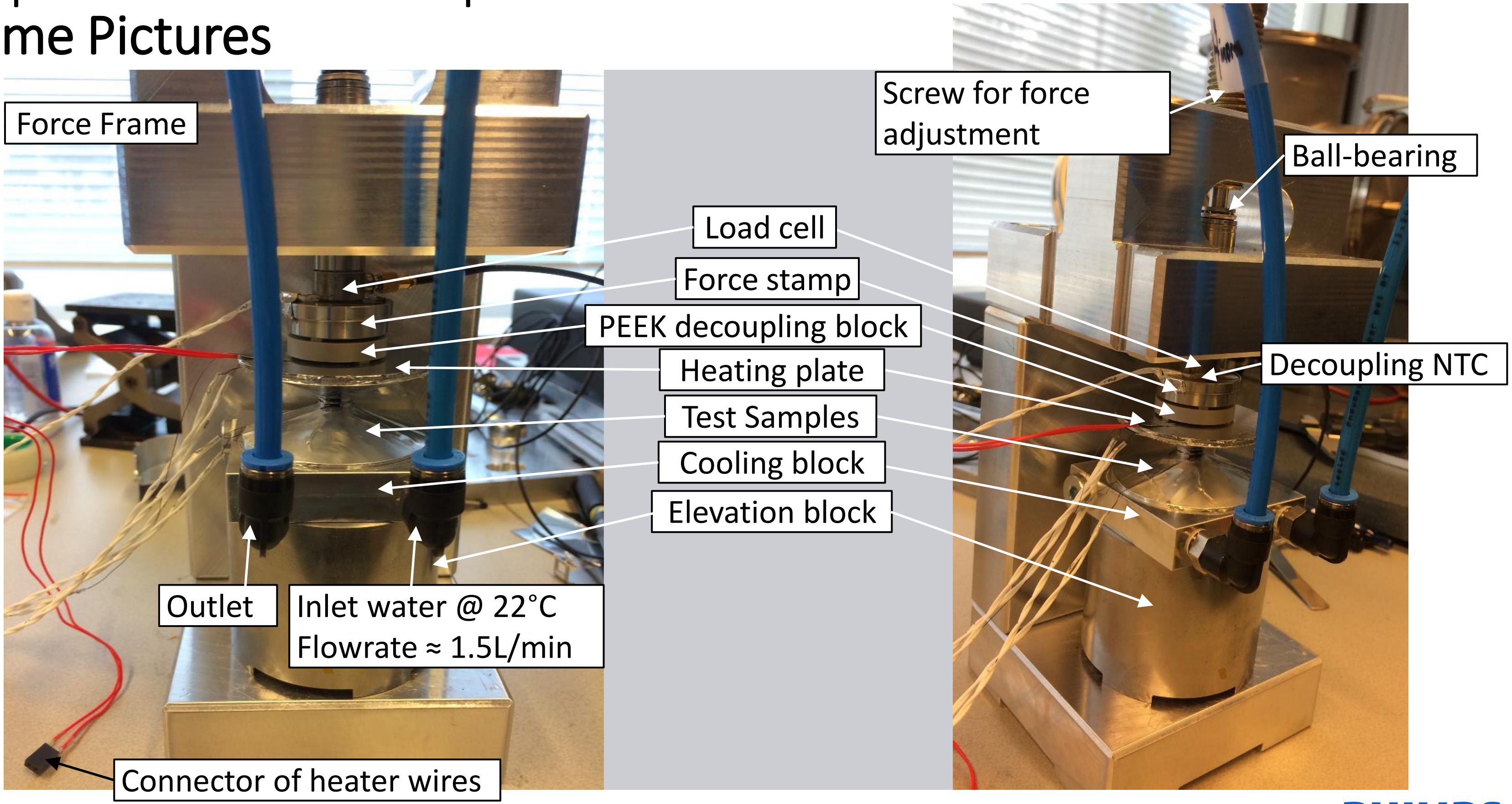
Experimental Setup
Some Pictures



Experimental Setup
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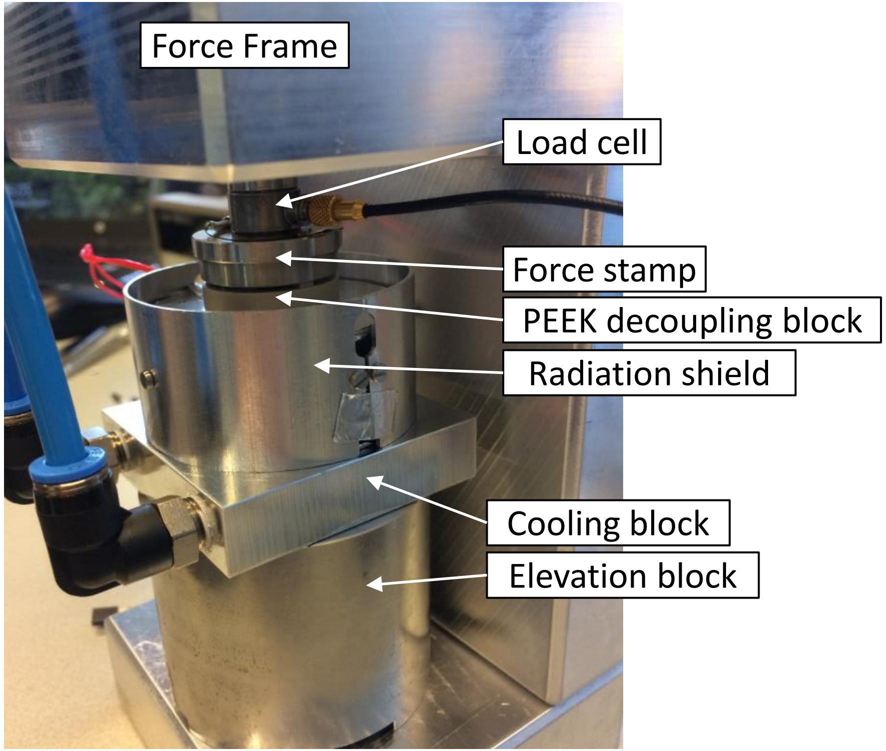

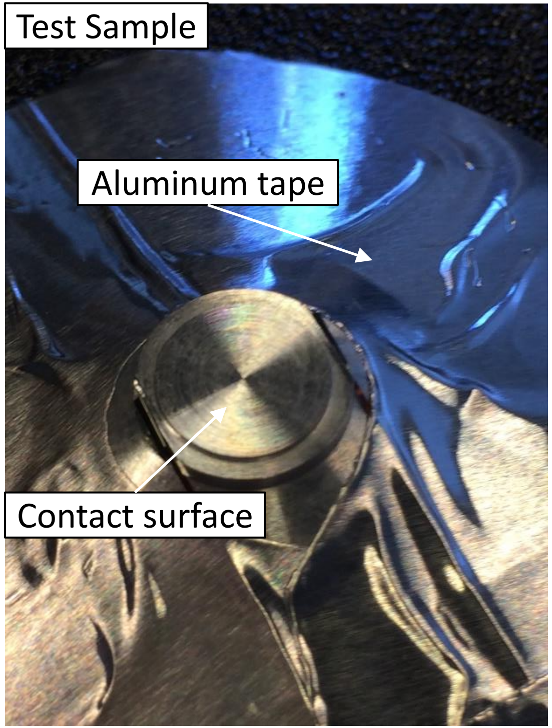

Experimental Setup
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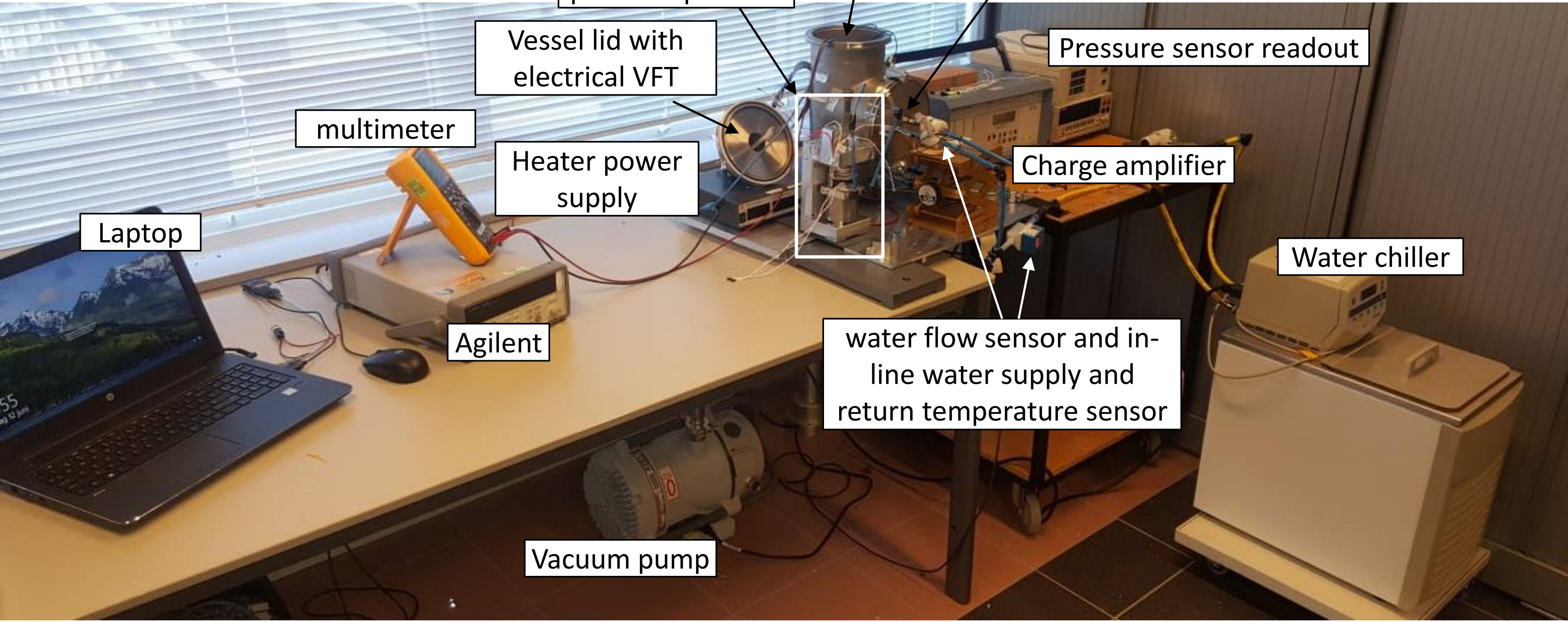


Determined adjustment parameters

- The adjustment parameters α, β, R_{top} and R_{btm} are defined per sample pair

Sample combination	Contact area [mm²]	Contact pres. [MPa]	Percentage of heat input used: α [–]	Percentage of contact area used: β [–]	R_{top} [K/W]	R_{btm} [K/W]
Al5 – Al5	50	0 – 25	1.0	1.0	0.19	0.18
Al6 – Al6	50	0 – 25	1.0	1.0	0.13	0.13
StSt – StSt	50	0 – 25	0.975	1.0	1.36	1.31
Ti5 – Ti5	50	0 – 5	0.90	1.0	3.27	3.17
Ti5 – Ti5	50	6 – 25	0.95	1.0	3.24	3.15
Al5 – Al5	10	25 – 100	1.0	0.95	0.56	0.56
StSt – StSt	10	25 – 100	0.90	0.95	4.14	4.13
Ti5 – Ti5	10	25 – 100	0.85	0.95	9.42	9.42
Al – StSt	50	0 – 25	1.0	1.0	Al5: 0.19 Al6: 0.13 StSt: 1.30	Al5: 0.18 Al6: 0.13 StSt: 1.30

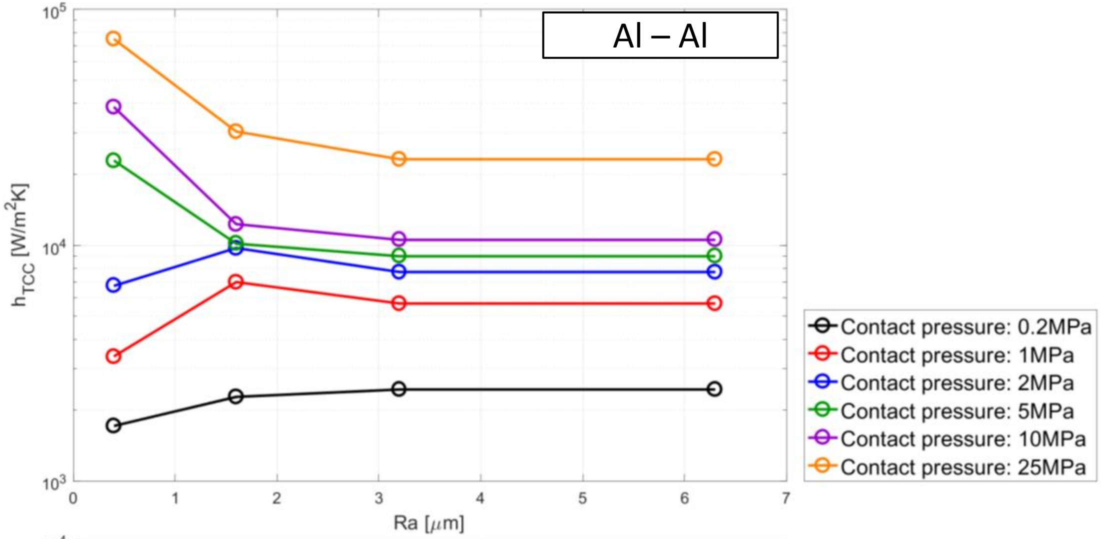
Error Budget

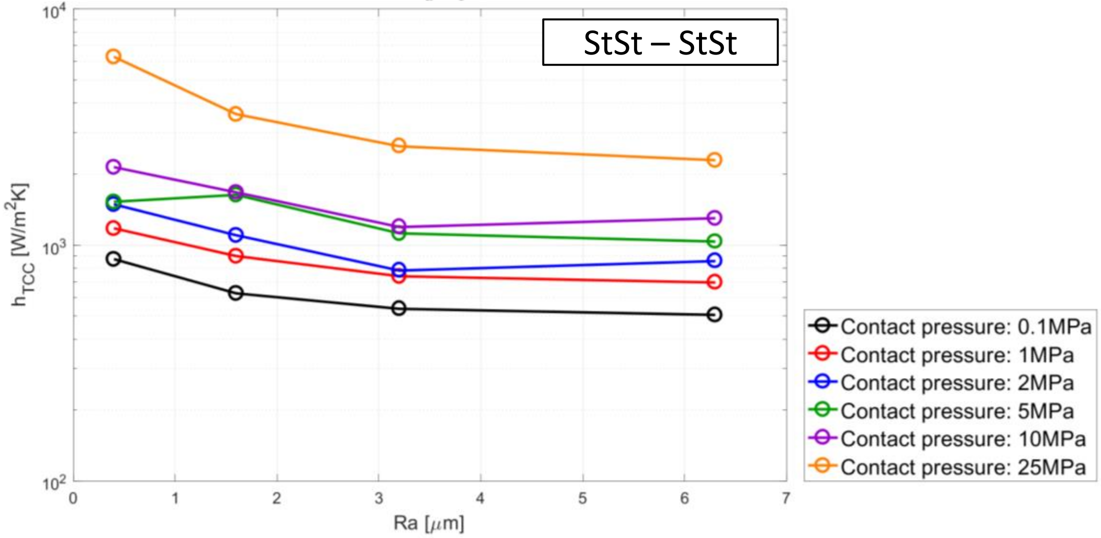
- Types of erros:
  - Physical errors between measured quantity and actual quantity: heat flow, contact area, etc
  - Model errors between
- Magnitude of errors is determined via model and measurement equipment accuracy

Error source	Error contribution	
	Large contacts	**Small contacts**
Heat load uncertainty due to voltage and current uncertainty	6.0%	6.0%
Heat flow uncertainty due to heat losses	10.0%	12%
Contact area uncertainty	3.2%	5%
NTC measurement error	2.5%	1.2%
Additional error due to temperature measurement adjustment		
Heat flow uncertainty	0.8%	2.9%
Misalignment	6.1%	12.1%
Uncertainty in thermal conductance	12.3%	13.1%
Uncertainty in emissivity samples	5.3%	15.1%
Uncertainty in emissivity heater top	5.4%	16.0%
Statistical sum:	**20.2%**	**31.9%**

Results
Surface roughness tests

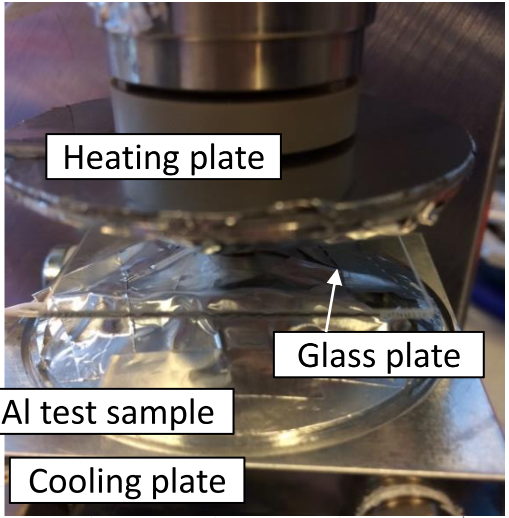
- Surface roughness tests are employed with
  - Samples with a Ra of 1.6, 3.2 and 6.4µm
  - Contact pressure: 0.1 – 25MPa
- Observations
  - At small contact pressures the TCC value can increase with surface roughness
  - Generally (at higher contact pressures) the TCC value drops for higher surface roughness and settles at some asymptote beyond 3µm
- Correlations with literature
  - Same qualitative behavior observed as in literature where rougher surfaces have a higher TCC at low contact pressures

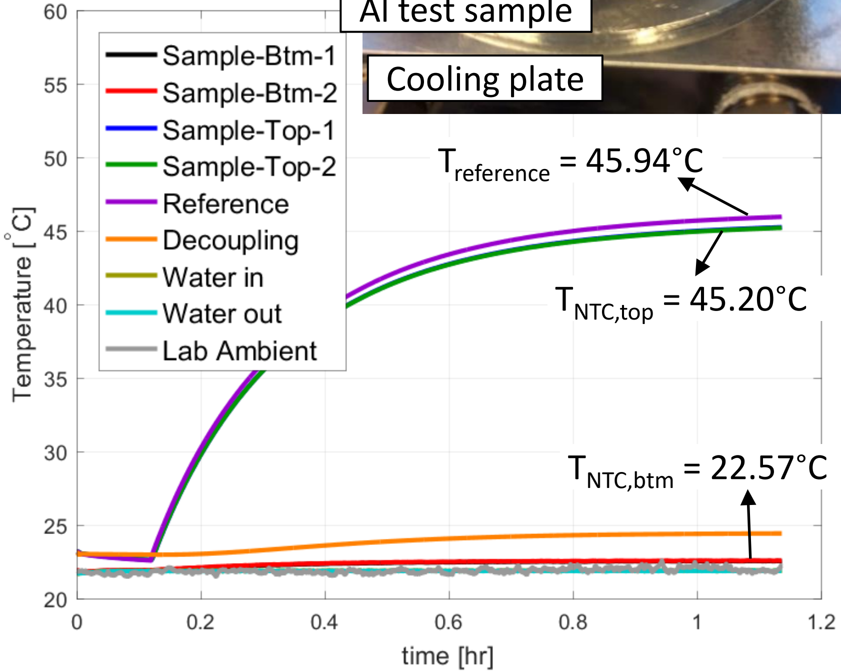




Accuracy quantification
Aluminum samples

- Accuracy test: measure h_{TCC} with glass plate between samples
- Theoretical HTC:
  - Glass plate properties: Thickness: t = 1.09mm, Conductivity: λ = 1.09W/mK
  - Contact Conductance Al to glass: h_{con} = 10000W/m²K
  - Total effective HTC: $h_{eff} = \frac{1}{t/\lambda+2/10000}$ = 833W/m²K
- Measurement
  - α determined model-based: 0.925
  - β, R_{top} and R_{btm} as determined for Al samples
  - Contact pressure = 10MPa
  - Heater power: Q_{th} = 1.02W
  - dT measured: 22.63K
  - dT corrected: 22.28K
  - **h_{TCC} measured: 847W/m²K**
- **Conclusion: Measured h_{TCC} in line with expected h_{TCC}**





Accuracy quantification
StSt samples

- Accuracy test: measure h_{TCC} with glass plate between samples
- Theoretical HTC:
  - Glass plate properties: Thickness: t = 1.09mm, Conductivity: λ = 1.09W/mK
  - Contact Conductance Al to glass: h_{con} = 10000W/m²K
  - Total effective HTC: $h_{eff} = \frac{1}{t/\lambda + 2/10000}$ = 833W/m²K
- Measurement
  - α determined model-based: 0.925
  - β, R_{top} and R_{btm} as determined for StSt samples
  - Contact pressure = 10MPa
  - Heater power: Q_{th} = 0.961W
  - dT measured: 25.60K
  - dT corrected: 23.23K
  - **h_{TCC} measured: 765W/m²K**
- **Conclusion: Measured h_{TCC} 10% lower than expected h_{TCC}**