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Thermal Contact Conductance in Vacuum

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Abstract

In this study the macroscopic thermal contact conductance between metallic surfaces of different kind and materials is investigated. Aim of the analyses is to find an effective heat transfer coefficient between the surfaces, to aid in thermal modelling of such contacts. A setup is created in which two metallic samples can be pressed together at contact pressures ranging from 0.2 – 25 MPa with contact sizes of 50 mm^2.

Although, the results show good overlap with literature, it also shows a poor match (deviations can grow as large as 600 %) for certain test settings, with some often-used models (such as the model by Yovanovic [1,2] and Garimella [5]). This establishes the need for a proper understanding of the validity ranges of these models and the phenomena involved in heat transfer over contacts in vacuum, rather than applying readily existing models. Moreover, in some cases a non-reproducibility for re-contacts of up to 100 % is observed (in-line with literature sources), which should be considered when analysing models with dominant thermal contact resistances.

Thermal Contact Conductance, Measurements, Vacuum, Modelling,

1. Introduction

The thermal contact conductance (TCC) between various materials, both in vacuum and atmosphere, has been addressed in many literature studies. An overview is provided in [1]. See Figure 1 for the timeline of the various application areas investigating contact conductance. Further investigation of [1] immediately provides the difficulty in modelling the TCC as the spread on values found for only small deviations in test conditions and materials is immense, see Figure 2.

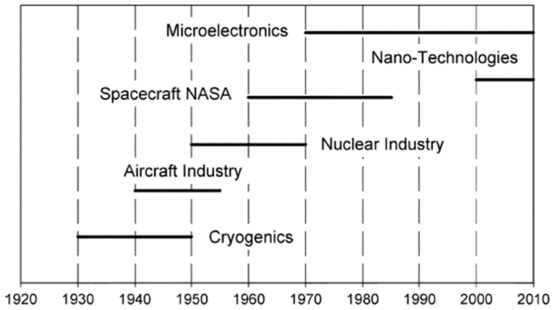

Figure 1. Timeline for thermal contact resistance research, from [1].

This is caused by the huge number of parameters on which the thermal contact conductance is dependent. Hence, the tools to model TCC developed in literature take material and geometric properties and boundary conditions into account. Due to the large number of inputs and sometimes difficult to obtain properties (e.g. Vickers hardness) usage of these tools is difficult.

Moreover, since, these tools have been developed for different application areas ((micro)electronics, cryogenics, aerospace and automotive) in many instances they must be used for situations that are far from the situation for which the models were developed. The predictive nature of these models generally is sufficient for the cases they were developed for, but quickly deteriorate for situations diverging from the setup they originated from (see for example [2] where errors ranging from 100 – 500 % are reported).

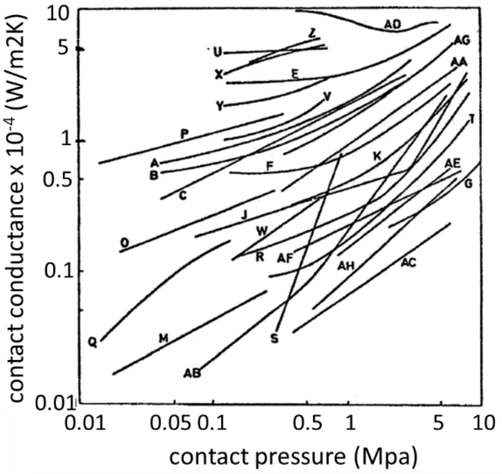

Figure 2. Small impression of the spread in TCC values for very similar experiments, from [Yovanovic2005]: contact conductance of aluminum alloys versus contact pressure.

As a result, in mechatronic applications the predictive accuracy of these models is questionable at best. Therefore, in this study the typical materials, combinations, geometries and contact pressures for high precision vacuum applications are examined.

2. Methodology

2.1. Objective

Objective of this study is to quantify the thermal contact conductance (TCC) in vacuum. This means that a measure for the thermal coupling between two surfaces that are pressed together is searched for. As opposed to most investigations known from literature, here a pragmatic approach is employed. Most perennial studies focus in their research on the difference between microscopic and macroscopic contact conductance in order to define generically applicable models. As discussed in the introduction, here a focus is on test conditions as close to the conditions in high precision vacuum machines as possible.

Quantification of the contact conductance will be via an effective heat transfer coefficient (HTC) between the two contacting surfaces. To determine the TCC HTC, i.e. h_{TCC}, a setup is built in which two samples with known contact area (A_{con}) are pressed together with a known force. At the one sample a heat flow (Q_{th}) is applied that then flows through the contact to the other sample which is coupled to a heat sink. The temperature of each of the contacting surfaces should be measured to determine the temperature difference over the contact. The effective thermal contact conductance heat transfer coefficient can then readily be calculated via

$$h_{TCC} = \frac{Q_{th}}{A_{con} \cdot \left(T_{surf1} - T_{surf2}\right)} \tag{1}$$

Where T_{surf1} and T_{surf2} are the average contact surface temperature of the surfaces in contact.

2.2. Experimental Setup

A schematical representation of the setup used in this study is provided in Figure 3. The core of the setup consists of a force frame (10), cooling plate (6), sample stack (3) and heating plate (8). This core is placed in a vacuum vessel (1), which is pumped down by a vacuum pump (2) to a pressure level of 1 – 5 Pa.

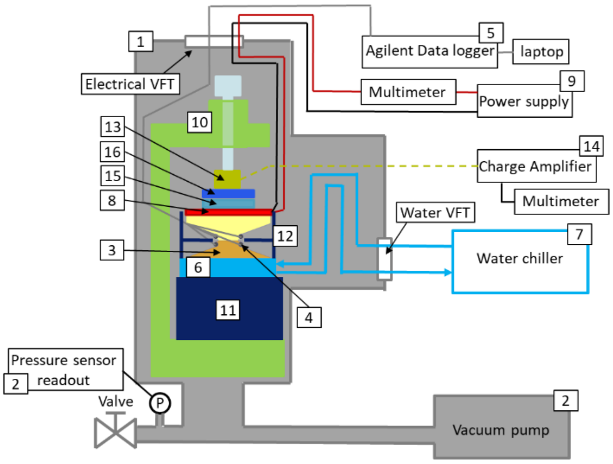

Figure 3. Schematical representation of experimental setup layout

The force-frame is a C-shaped part that holds the test sample stack. This stack, from bottom to top, consists of an elevation block (11) that holds the cooling plate (6). The cooling plate is water-cooled and receives water through a vacuum feedthrough (VFT) from a water chiller (7) that conditions the water to 22 °C. On top of the cooling plate the test samples (3) are placed with their contact surfaces to each other (since the test samples are identical in geometry this means that the top sample is upside down). Together the samples form an hourglass shape.

Near the contact surface each test sample has two temperature sensors of type NTC glued to them (4). The NTCs are wired through a VFT to an Agilent data logger (5) that is connected to a PC that reads out and logs the NTC signals. A radiation shield (12) is placed around the samples to minimize heat leakage towards vessel and force frame. On the top sample the heating plate (8) is placed consisting of an electrical heater to heat up the top sample. Voltage and current to the heater are measured using a multimeter to calculate the total heating power.

On top of the heating plate a PEEK decoupling block (15) is placed to make sure only a small portion of the heat generated in the heater can leak towards the force frame. On top of the decoupling block a force stamp (16) is connected via a rod and a ball-bearing to the bolt of the force frame. In between the stamp and the rod, a load sensor (13) is placed that enables determination of the contact pressure between the samples. The load sensor is read out via its signal conditioner/charge amplifier (14). Unfortunately, the vessel does not contain a VFT for this sensor and the force thus can only be measured prior to the pump down of the setup and after venting.

The alignment between the samples is accomplished via rods that fix the position of the components in the force frame. The alignment of the force frame itself is accomplished via an alignment tool (i.e. a simple rod). As such, the misalignment between samples by design maximally reaches 200µm.

2.3. Data analyses

It must be noted that with this design, some practical limitations need to be addressed when calculating the effective thermal contact conductance HTC. When looking at eqn. (1) three aspects need to be addressed:

1. Misalignment of the contact surfaces
2. Heat leakage
3. Temperature difference between NTC location and contact surface

The first item is dealt with by multiplying the contact surface area, A_{con}, with a factor β that ranges from 0 to 1. For example, a maximal misalignment of 200 µm will lead to a 3.4% reduction in contact area for samples with a 50 mm^2 contact surface area.

For the second and third item, part of the experimental setup is analysed using a FEM modelling approach. The model then is used to quantify the amount of the heat dissipation by the heater (Q_{th}) that actually flows through the contact between the test samples. To include this heat leakage in eqn. (1), Q_{th} is multiplied by yet another factor, α, also ranging from 0 to 1. The model is used iteratively to determine α for the different settings (sample material, contact pressure etc.) used.

Finally, the model is used to find a thermal resistance between the NTC location of the samples and its actual average contact surface temperature. This is done for each sample material used.

As such, the model puts forth the calculation parameters to tune the heat flow (based on the electrical heat dissipation in the heater plate), the contact area and the temperature difference over the contact. The obtained formula for calculating the h_{TCC} as function of these parameters and measurements then yields

$$h_{TCC} = \frac{\alpha \cdot Q_{th}}{\beta \cdot A_{con} \cdot \Delta T_{corrected}} \tag{2a}$$

With

$$\Delta T_{corrected} = \left(T_{NTC,top} - T_{NTC,btm} - \left(R_{top} + R_{btm}\right) \cdot \alpha \cdot Q_{th}\right) \tag{2b}$$

Furthermore,

- h_{TCC} is the thermal contact conductance heat transfer coefficient in [W/m²K]
- Q_{th} is the heat dissipated in the heater plate in [W]
- α is the (assumed) portion of that heat that flows through the contact surface in [-]
- A_{con} is the contact area of the sample in [m²]. In this abstract only samples with A_{con} = 50 mm² are used.
- β is the (assumed) portion of that area that is actual in contact with the other sample in [-]
- $T_{NTC,top}$ is the measured temperature at the top sample in [°C]
- $T_{NTC,btm}$ is the measured temperature at the bottom sample in [°C]

- R_{top} is the (assumed) thermal resistance between the measurement location of the top sample and the actual average surface temperature in [K/W]
- R_{btm} is that for the bottom sample in [K/W]

Next to determination of the parameters in Eqn. (2), the model is employed to quantify the identified error contributions to an overall measurement uncertainty. The RSS of these contributions leads to an estimated total uncertainty of the methodology of approximately 20% for the 50mm² contact area.

3. Results

In this section the measurement results will be presented. Firstly, however, an accuracy quantification test to establish the accuracy of the setup will be discussed.

3.1. Accuracy quantification measurement

To establish the accuracy provided in the previous section, an accuracy quantification experiment is performed. To that end a piece of Corning Eagle XG glass is used. The thermal conductivity of the piece of glass is accurately known and equals 1.09 W/mK. It's thickness can be easily measured with a calliper and equals (coincidentally) 1.09mm. This results in an effective heat transfer coefficient through the glass plate of

$$h_{eff,glass} = \frac{\lambda_{glass}}{t_{glass}} = 1000\ \mathrm{W/m^2K} \qquad (3)$$

Which is somewhat lower compared to the expected TCC values but is in the right range to quantify the measurement accuracy. By placing this piece of glass between two aluminum 5083 samples the effective HTC between the samples is approximately known. Since, a contact resistance will also be present between the samples and the glass, still a small uncertainty in the thermal resistance between the contact surfaces remains, though. The contact pressure applied equals 10 MPa. Assuming a TCC of 10 kW/m²K, the expected effective heat transfer coefficient between samples equals

$$h_{eff,cal} = \frac{1}{1/h_{eff,glass} + 2/10000} = 833\ \mathrm{W/m^2K} \qquad (4)$$

To also correlate the simulation results with the measurement results, the current case is modelled. The model shows a heat loss of 8.1 %, therefore the value for $\alpha = 0.925$ will be considered in the analyses of the measurement data. Furthermore, the model shows similar R_{top} and R_{btm} as determined for the aluminum samples in direct contact: $R_{top} = 0.190$ K/W and $R_{btm} = 0.181$ K/W. Finally, for the 50 mm² samples the value of $\beta = 1$ is considered.

The temperature evolution logged during the measurement is provided in Figure 4. Comparing the results with the model shows a good correlation. The temperature difference measured at the NTCs is 3.4 % larger than the simulated temperature difference. Hence, the α-value and R_{top} and R_{btm} extracted from the modelling results can be used in the analyses of the measurement data.

Data-analysis is done by determining the temperature difference between the top and bottom sample. Which equals dT = 22.63K. The effective heat transfer coefficient can now be calculated using Equation (2). Implementation of the parameters ($\alpha = 0.925$, $Q_{th} = 1.02$ W, $\beta = 1.0$, $A_{con} = 50\text{e-}6$ m², $R_{top} = 0.19$ K/W and $R_{btm} = 0.181$ K/W) and the measured temperature difference, yields a value of 847 W/m²K.

Taking into account the contact resistances of 10 kW/m²K at both contacts (i.e. from top sample to glass and from glass to bottom sample) the h_{eff} of the glass equals 1020 W/m²K. Which leads to a measured thermal conductivity of the glass of 1.11 W/mK. Clearly, this is fine-tuned based on the choice for the contact conductance between samples and glass of 10 kW/m²K. However, increasing that value to an unrealistically high value of 100kW/m²K would still result in a very decent thermal conductivity measured of 0.94 W/mK (≈14 % error). Similarly reducing it to an unrealistically low value of 5 kW/m²K would lead to a conductivity of 1.4 W/mK (≈28 % error).

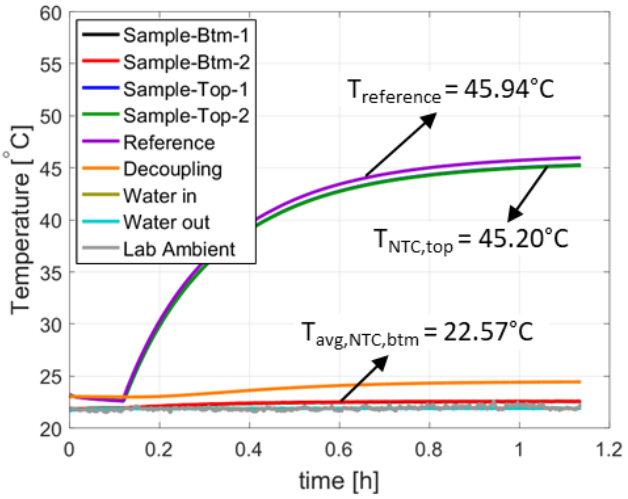

Figure 4. Measurement data for the accuracy quantification.

Based on this accuracy quantification measurement the following can be concluded:

1. A good correlation between model and experiment is observed. Hence, model results can be used to determine values for α, R_{top} and R_{btm}.
2. The uncertainty determined in the uncertainty analysis provided in the previous section is established by at least one accuracy quantification test. Further validation of it would require a vast amount of these measurements which are out of scope for the current study.

3.2. Effect of contact pressure

Using the above procedure, multiple sample combinations are measured at multiple contact pressures. The following materials are considered: aluminum 5083 (Al5), aluminum 6082 (Al6), stainless steel AISI316L (StSt) and Titanium Grade 5 (Ti5). For these measurements the surface roughness of the contact surfaces equals Ra = 0.4 µm. Only samples with a contact area of 50mm² are considered and the contact pressure range considered equals 0.2 – 25 MPa (for each sample pair going from low to higher pressure). The obtained results are provided in Figure 5.

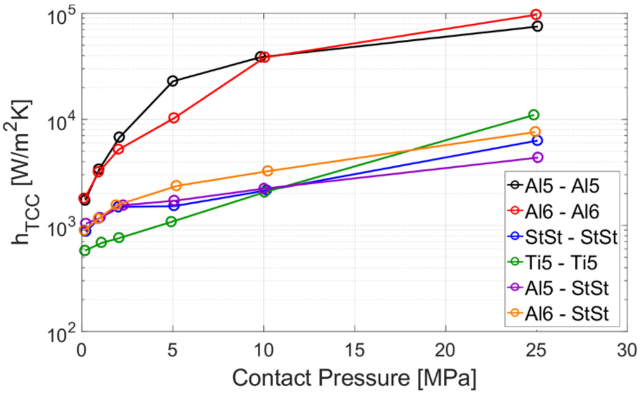

Figure 5. TCC values for several material combinations for contact roughness of Ra = 0.4 µm.

The results clearly show a significantly higher TCC value for aluminum to aluminum contacts than for contacts with stainless steel or titanium involved. Moreover, a somewhat linear trend with contact pressure (note the logarithmic y-scale) is observed.

3.3. Effect of Surface Roughness

Next to the effect of contact pressure also the effect of surface roughness was investigated. In this abstract only the results on surface roughness changes for Al5 to Al5 contacts are discussed.

The results for six different contact pressures with surface roughnesses of Ra = 0.4 µm, Ra = 1.6 µm, Ra = 3.2 µm and Ra = 6.4 µm are provided in Figure 6.

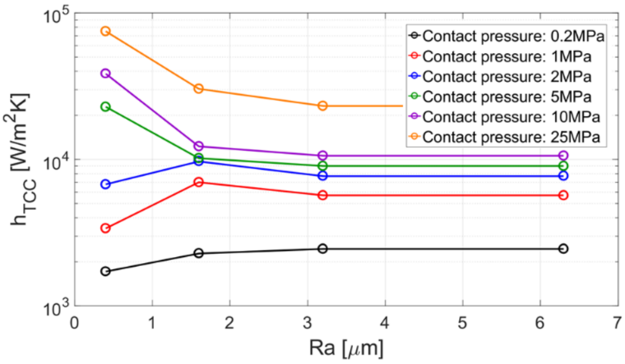

Figure 6. TCC values for aluminum 5083 contacts at several contact pressures.

It can be seen that for high contact pressures the TCC value decreases for increasing roughness. The remarkable thing is though, that at mediocre contact pressures the TCC values first rises for rougher surfaces and then decreases. Moreover, it seems that the TCC values converges on a constant value for surfaces beyond that with Ra = 3.2 µm (at least for values up to Ra = 6.4 µm).

3.4 Re-contacts

Finally, the effect of re-contacts has been investigated as well. The above measurements are taken on the first contact moment after manufacturing. However, from literature it is known that the TCC value might vary considerably under subsequent re-contacts. Therefore, for some sample combinations the TCC value is re-measured after the samples have been dis-assembled and re-assembled.

The results obtained are highly uncorrelated. For Al5 a sharp decrease of 75 % in TCC value was observed. Possibly this is the effect of an oxidation layer having formed on the surface over the 14-week timespan in between. For other combinations sometimes a factor 2 increase or decrease was observed on the second or third contact. For most combinations the TCC value seemed to settle at some constant value at the 4th or 5th contact.

4. Correlation with literature

Comparing the obtained results with literature shows an overlap in found TCC values compered to, e.g., the values provided in [3]. Also, many of the trends observed in literature in a qualitative sense meet the trends observed in this study. For example, the trend discussed in Section 3.3 is discussed in [2] too.

Re-contacts have been measured in literature as well. Sources like [4] and [5] show that the difference in TCC found during first contact and subsequent contacts can be significant, i.e. >100 %. It is even found that a hysteresis effect can be observed during loading (low to high contact pressure) and unloading (high to low). In this study only a loading procedure has been employed.

However, also some non-correlations with data obtained in literature are found. Although, the comparison done here is highly superficial and in many cases to setup conditions that are quite different to those in this study, these should not be neglected. For example, comparison to the model by Yovanovic in quantitative sense, yields very large differences of a factor 10 to 60 for some settings:

- Low surface roughnesses, i.e. Ra < 3 µm
- And high contact pressures, i.e. beyond 10 MPa

Especially considering the values calculated by the model for aluminum render large mismatches. Inspection of relevant Yovanovic sources, however, also indicate that these conditions are outside the validity range of the models and that the model is not based on experiments with aluminum contacts. Which marks the gap in available data and thus the importance of this study.

5. Conclusions

In this study, an experimental setup to determine thermal contact conductance (TCC) in vacuum is discussed. The measurement data obtained is analysed using model-based adjustment parameters to find the effective heat transfer coefficient between two surfaces pressed together. Testing with a glass plate implemented at the contact between two samples established the accuracy of the FEM model and experimental results.

Furthermore, results on several material combinations and geometrical parameters have been discussed. This shows TCC values obtained in the setup are in line with those found in [3]. Also, some particular trends observed in the measurements are in line with observations in literature.

However, the experiments also show that for some settings large differences (up to 600 %) between models from literature and experimental results from this study can appear. It is hypothesised that this is due to the models being applied outside their validity range. However, it does mark the importance of TCC investigations with contact conditions that are common in high precision vacuum applications rather than those in (micro)-electronics or automotive industry.

Moreover, when bringing the same samples in re-contact for a second- or third-time, large variances in contact conductance can be observed. This has a major implication for modelling the thermal contact conductance. Based on this result, it is advisory to always do a sensitivity study on the TCC value rather than only considering a single model-based value.

References

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