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THERMAL CONTACT CONDUCTANCE IN A TYPICAL SILICON CRYSTAL ASSEMBLY FOUND IN PARTICLE ACCELERATORS

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Abstract

Every mirror at Diamond Light Source (the UK's Particle Accelerator) has been installed with the premise of clamping the cooling copper manifolds as lightly as possible to minimize distortion. The problem with this approach is that the Thermal Contact Conductance (TCC) depends on the applied pressure among other factors. The assembly is usually a symmetric stack of Copper - Indium Foil - Silicon Crystal - Indium Foil - Copper. Variables that interest the most are those that are easily adjustable in the set-up assembly (number of clamps, pressure applied and cooling water flow rate) PT100 temperature sensors have been used along the surface of the crystal and along the surface of the copper manifolds. Custom PCB units have been created for this project to act as a mean of collecting data and Matlab has been used to plot the temperature measurements vs. time. Another challenge is the creation of an accurate model in Ansys that matches reality up to a good compromise where the data that is being recorded from the sensors matches Ansys results within reason.

INTRODUCTION

The set-up (Fig. 1) of a typical Silicon Crystal assembly is comprised of a symmetric stack of Copper - Indium Foil - Silicon Crystal - Indium Foil – Copper.

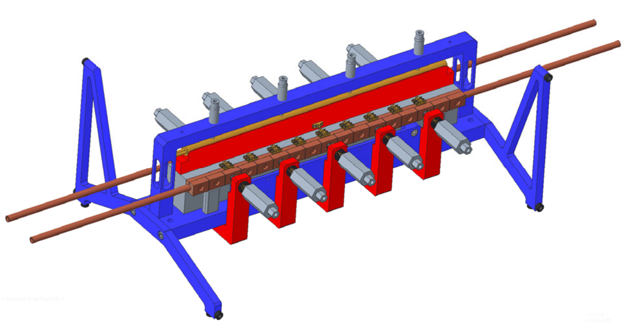

Figure 1: 3D model for the experimental assembly.

A cartridge heater embedded in an aluminium block and located at the top surface of the crystal mimics the input power of the beam that bounces of the silicon mirrors in a particle accelerator. An industrial chiller is used for cooling down the water flowing through the copper manifolds. Temperature is read by PT100 sensors along the surface of the Crystal and at the other side of the interface (along the surface of the copper manifolds) so the drop in temperature across the interface is known. The PT100 sensors have been glued on both surfaces. Custom adjustable spring clamps with a fine thread (0.75mm pitch) along the crystal control the amount of force applied to the interface. Strips of Indium Foil (100µm thick) have been used between the silicon crystal and copper manifolds to cope with surface's irregularities like roughness, waviness and flatness. Spring pushers at the top, screwed into an arch and exerting a force on to the heater to make sure that a good contact among the parts is achieved. A thin layer of oil has been added at the interface between the aluminium block and the silicon crystal to improve the TCC at that interface. The silicon crystal is sat on three sprung stainless-steel balls at the bottom and up against two more at the back. A 4mm insulating layer of Calcium-Magnesium Silicate covers the cartridge heater and aluminium block make sure that most of the power goes into the crystal (Fig. 2).

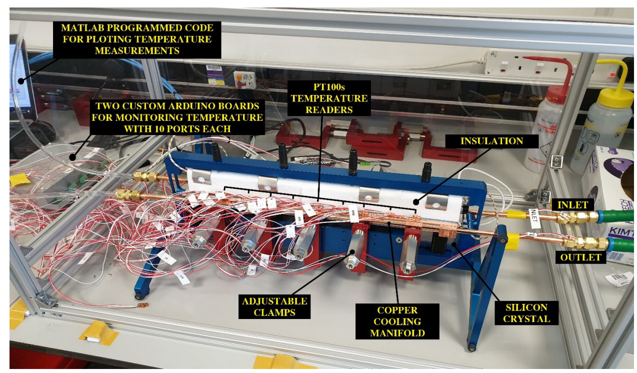

Figure 2: Experimental assembly set-up.

The TCC between two components defines how much heat energy flows through the interface per unit of area and unit of time. The bigger the TCC, the better thermal contact among the parts and thus, more heat flows through the interface. At the microscopic level, only a few discrete points are actually in contact [1]. The TCC depends on many factors [2] (Fig. 3).

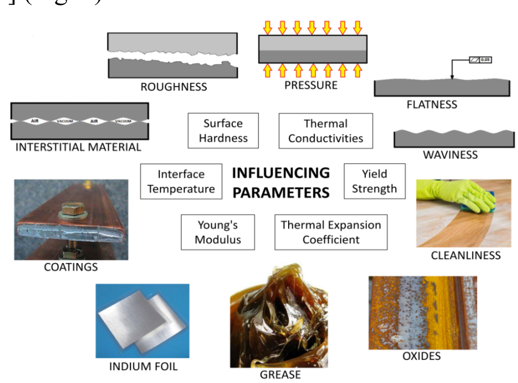

Figure 3: Variables of thermal contact conductance.

ANALYSIS

The following studies have been performed in this project:

- Comparison between a perfect TCC vs actual value (Fig. 4 and Fig. 5).
- Temperature comparison using different Power Inputs (100W, 150W & 200W).

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- Temperature comparison using different fluids (Fig. 6) at the interface between the cartridge heater and the aluminium block and between the latter and the silicon crystal (Oil, Thermal Paste and Bear Surfaces).
- Effect of pump speed (Fig. 7) on the temperatures (Pump speed 3[2l/min] and 5[20l/min]).
- Measurement of the temperature Drop across 7mm of the top surface of the silicon crystal.
- Temperature measurement at the front surface of the silicon crystal near the copper manifold.
- Temperature measurement along the length of the Cartridge Heater.
- Effect of the insulation with different Input Power (100W, 150W & 200W).
- Effect of clamping pressure (Fig. 8) on the TCC (45, 60, 75, 90N).
- Temperature comparison between Ansys and measurements (Fig. 9).
- Analysis of the Thermal Contact Conductance for different clamping forces and input powers (Fig. 10).
- Calculation of power loss by convection and radiation in every case.

An ideal scenario is checked for comparison where all the contacts are set to Program Controlled (Perfect TCC). This is very unrealistic but interesting nevertheless as it highlights the importance of adding the thermal contact conductance in the simulations in order to get accurate results. In addition, Heat Transfer Coefficients (HTC) for most surfaces have been manually calculated using the appropriate correlations and fed in to Ansys.

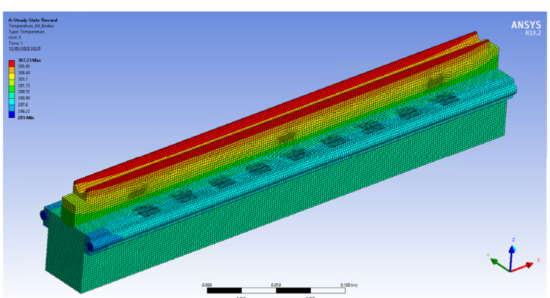

Figure 4: Temperature distribution with perfect TCC.

As we can see the temperature distribution is not realistic as the maximum temperature (307K) is way below that of the PT100s sensor readings (358.5K) On the other hand, by using a TCC at the interfaces, the results are very close to reality.

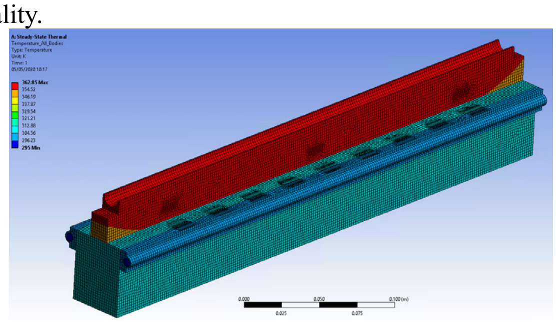

Figure 5: Temperature distribution with actual TCC.

To find out the Thermal Contact Conductance in Ansys, a Response Surface Optimization is used to create iteration analyses based on the temperature measurements from the actual experiment test. To create this iteration analysis the TCC needs to be set as a parameter. Ansys Mechanical doesn't have an automatic way to make the TCC a parameter but to get around this problem an APDL Command (Ansys Parametric Design Language) can be used [3].

The following charts show some of the results from the measurements.

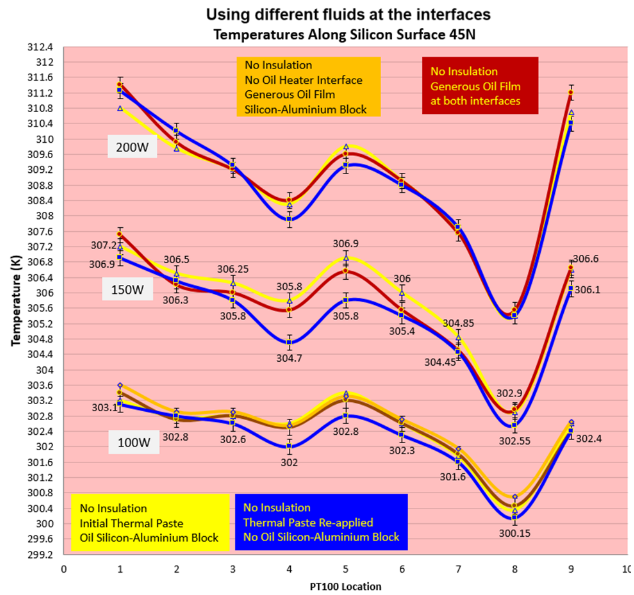

Figure 6: Temperature along the Si top surface using different fluids at the interfaces.

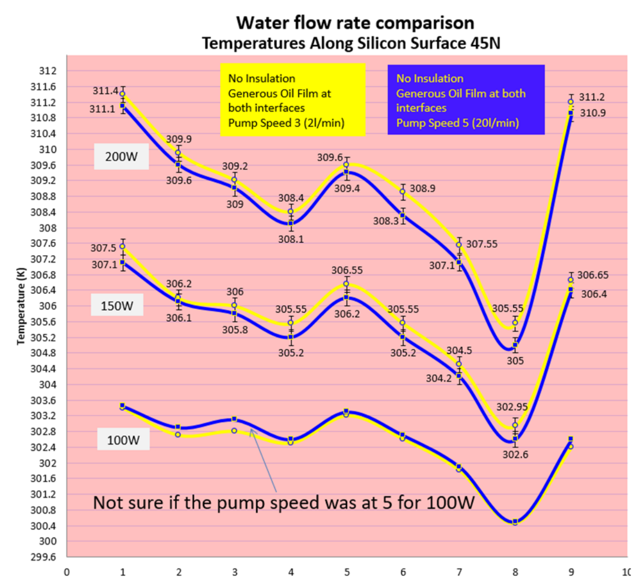

Figure 7: Temperature along the Si top surface using different cooling water flow rates.

All data has been taken using 3 different input powers (100W, 150 and 200W) as can be noted in the charts.

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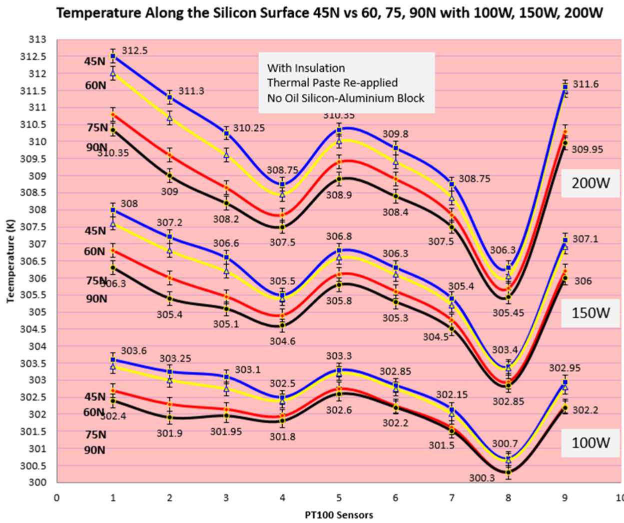

Figure 8: Temperature along the Si top surface using different clamping forces for the copper manifolds.

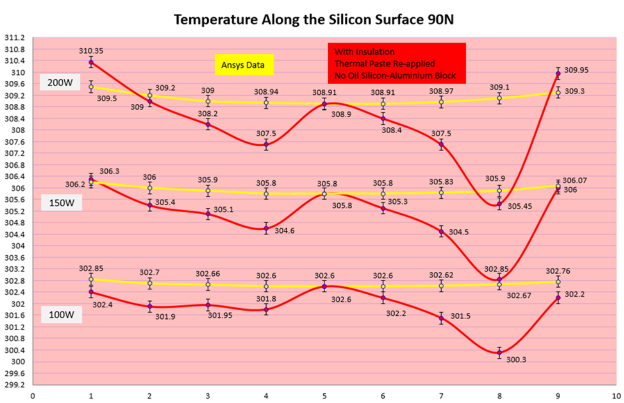

Figure 9: Temperature along the Si top surface compared with Ansys results.

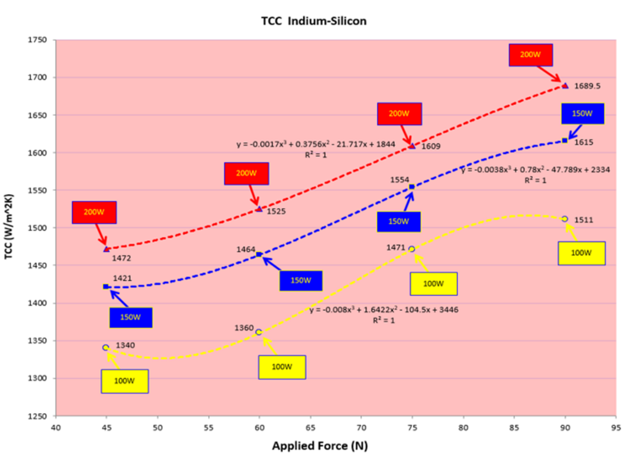

Figure 10: Thermal Contact Conductance vs applied Force.

CONCLUSION

Finding the Thermal Contact Conductance has proven to be challenging as there are many influencing parameters that affect this coefficient. Furthermore, real experiments show that reality is far from the ideal world of computer simulation despite of creating an FEA as close to reality as possible. Nevertheless, it has been proven that calculating convection and radiation losses was worthy as they play a role in the temperatures and thus on the accuracy of the TCC. In addition, the Ansys simulation calculates the TCC assuming that the clamping force among the parts is evenly distributed over the mating area which has been proven not to be the case in this assembly due to the distortion of the copper manifolds. This highlights the importance of challenging the results regardless of whether we agree or not with them at a first glance and do not blindly trust the simulation.

Vacuum brazing of the copper cooling manifolds play a big role in the flatness of the mating face with the Indium Foil that is up against the Silicon Crystal. This is a typical process in many assemblies that are used under high vacuums environments and it completely distorts the copper blocks. Therefore, it is recommended to get the parts machined afterwards to make sure that distortion is minimized. This may explain the odd behaviour of sensor number 8 as the copper may be distorted in several planes which could produce a very good TCC at discrete locations.

The increase in clamping pressure shows an improvement in the TCC about 13.5% in all cases when comparing the extremes (from 45N to 90N) as well as a reduction of the overall temperatures (up to 2 degrees in some cases).

The increase in water cooling flow rate (pump speed 3[2l/min] to 5[20l/min]) shows a drop in temperature along the Silicon crystal top face up to 0.6 degrees in some cases but with an average of 0.3-0.4 in most readings. Which offers the possibility of reducing the pump speed to get the benefits of low vibration and sharper images without being too detrimental on the Silicon bulk temperature.

The interstitial fluid between the cartridge heater and the Aluminium Block and between the Aluminium Block and the Silicon Crystal doesn't seem to play a big role in the temperatures of the Silicon Crystal as the maximum change is about 1.1 degrees in some locations but with an average of 0.5 degrees in most cases.

The insulation of the cartridge heater and the aluminium block show an average change in temperature up to 1.2 degrees for the 200W analyses whereas for 150W the change is about 1 degree and only about 0.5 degrees for analyses with lower input power like 100W. Therefore, depending on the input power the losses due to convection may be neglected.

Ansys Response Surface Optimization (RSO) has proven to be a great tool for finding the TCC when comparing hundreds of scenarios automatically and allows the user to easily check the influence of the parameters by using the sensitivity analysis tool in the RSO. To lastly iterate accordingly after the best candidates have been found to get the most accurate values.

In addition, a number of hand calculations have been performed to compare them to the Ansys results which show a good agreement among. Furthermore, the energy balance check has been carried out in every analysis as a sanity check.

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