1st International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI 2000)
July 13/14 2000 - Paul Scherrer Institut, Würenlingen/Villigen, Switzerland

Thermal Contact Resistance Measurements for Indirectly Cooled SR Optics

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Abstract

Indirectly cooling components by using an intermediate thermal transfer material is desirable in ultra high vacuum (UHV) systems for synchrotron (SR) optics applications, as it largely eliminates the need for expensive integrally cooled optic systems and in-vacuo seals . Such intermediate materials act to fill in the small voids between the actively cooled plate and the optic that arise from microroughness, asperities and other machining/finishing imperfections, and so aid heat transfer by conduction. These materials must be UHV compatible and offer effective thermal transfer, which greatly limits the range of materials for selection. Liquid metals such as gallium have been used successfully but have their own particular problems. Solid interfaces such as indium and gold foils are also employed but the efficiency of the thermal heat transfer, directly related to the so called thermal contact resistance, has not been measured and cannot be estimated theoretically or empirically.

We report on a method for measuring the thermal contact resistance in vacuum and also present the results of measured resistance values for likely combinations of optic/cooled surfaces and thermal interfaces. Particular attention is paid to candidate materials to be used for the Phoenix XUV beamline 6.1 first mirror (which is subject to a high heat load from a 2T multipole wiggler). Candidate materials are copper, silicon and indium.

Keywords: Thermal Contact Resistance, Contact Cooling, High Heatload, SR Optics

1. Introduction

The measurement of thermal contact resistance was initiated after a series of FEA thermal analysis for the cooling of the PHOENIX-UV mirror M1. The heatload from higher energy X-ray absorption in the mirror is considerable (approx 1kW into a beam footprint 900x2mm) and the analysis suggested that contact side cooling would be the most cost-effective in limiting tangential slope errors due to thermal bowing (Fig. 1,2). Thermal deformation is managed by appropriate placing of the cooling geometry. Deformation is related to thermal gradients in the mirror and therefore not greatly dependent on the cooling efficiency, which governs the absolute base temperature of the mirror, rather than gradients. This is extensively explained in the FEA report [1].

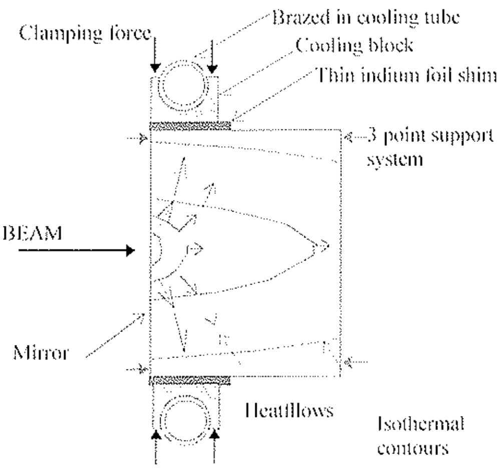


Fig 1. Concept visualisation of contact cooling scheme for phoenix mirror (end-on)

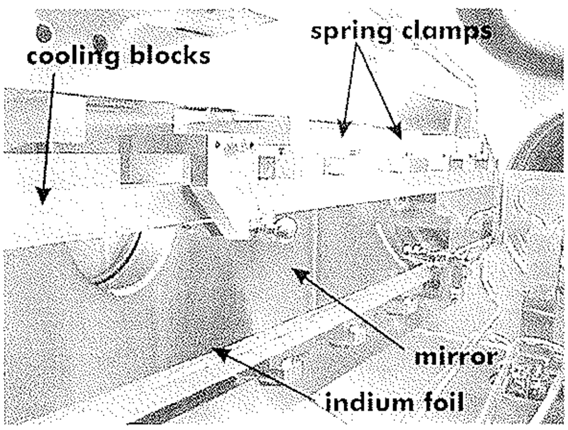


Fig 2. Photo of Phoenix-UV 1st Si Mirror as installed early Jan 2000.

Nevertheless, it important that cooling efficiency is effective enough to limit base temperatures to reasonable levels, otherwise, at elevated temperatures, the mirror would start to re- radiate heat (in the infrared) back onto external mechanisms in an uncontrolled manner that may potentially give rise to serious thermal problems in mirror control. An absolute base temperature rise of perhaps 10 to 20 °C is permissible.

In order to achieve the maximum efficiency of heat transfer from the mirror to the cooling blocks, good thermal contact across the contact junction has to be achieved. This is done by minimising the thermal contact resistance[3]. Thermal contact resistance arises from the micro-surface structure of the material (asperties and roughness), whereby the flow of heat is restricted to highly localised peak to peak contacts (Fig. 3). Under atmospheric conditions thermal resistance is substantially reduced due to the air pockets at the contact points which act as a heat transfer medium, convecting and conducting heat from one surface to the other (Figure1). Under ultra high vacuum conditions this convection process is eliminated. In addition the ultra-clean surfaces have no thin films of grease or other contaminant that may act to further enhance heatflow.

Fig 3. The origin of thermal contact resistance:- With no convection process in vacuum, heat transfer (mostly by conduction) occurs only where asperities are on contact, leading to large thermal contact resistance across surface junctions

With an overall heatload Q of around 1kW and a cooling area A restricted to 900x20x2 = 36000mm^2, it is estimated that applied heat transfer cooling coefficient equivalents of $h \approx 0.003 W/mm^2/°C$ are required to maintain reasonably acceptable absolute base temperature rises ΔT of around 10°C (from $Q = h\ A\ \Delta T$).

The effective heat transfer coefficient, h_{eff}, describes the combined heat transfer action of the contact resistance (which is the inverse of the contact resistance coeff h_c) *and* the normal coolant medium heat transfer coefficient h_w, (in this case for forced water flow). The introduction of h_{eff} is very useful in that it can be directly applied to FEA models, giving reasonable accuracy without having to model cooling blocks and junction interfaces in detail.

For the Phoenix M1 mirror, achievable h_w is defined by the cooling scheme and pump pressure and has been estimated as approximately 0.01 W/mm^2/°C).

$$h_{eff} = \frac{1}{\left(\frac{1}{h_c} + \frac{1}{h_w}\right)} \qquad \text{eqn(1)}$$

From eqn (1) it is apparent that the h_c must be in the region of 0.005 W/mm^2/°C or more to ensure that base ΔT of <10°C are achieved. Thus the contact resistance ($1/h_c$) must be less than 200 mm^2 °C/W (or <0.0002 m^2 °C/W in metre units).

It was apparent from other work [2] that for typical bare copper to copper surfaces in vacuum, contact resistance was typically much higher than this, at > 0.004 m^2 °C/W, although no data existed for copper to silicon. It was thus expected that some means to reduce contact resistance would be necessary.

There are several methods that can be used to eliminate the thermal contact resistance between the two surfaces. The methods include;

1- Applying a large force between both surfaces so that the areas at the micro-contact points are increased due to a 'squashing' effect.
2- Introducing a malleable interface material or fluid between the two surfaces in contact. This would reduce any gaps between the two surfaces causing an increase in the flow of heat.

Further investigation suggested that option 1 would not be sufficient by itself without excessive force being applied.

In the case of option 2, liquid metals such as gallium have been used in UHV with some success but have their own particular problems regarding handling and application. A more versatile solution is to use a soft intermediate solid material which acts to fill in the small voids between contact surfaces. Solid interfaces such as indium and gold foils are often employed in practice but the thermal contact resistance has not been quantitively measured for these materials and cannot be properly estimated theoretically or empirically.

Therefore we undertook to experimentally measure comparative contact resistances for Si-Cu and Si-In-Cu interfaces as employed for the particular cooling solution for the high heat load Phoenix mirror of MPW beamline 6.1, as well as a general study of other combinations of common UHV compatible materials and intermediate 'fillers'.

2. Heat Transfer Measurement - Background Theory

Assuming 1D Fourier conduction only, thermal contact resistance ($1/h_c$) can be determined from eqn(2) where A is cross section area, ΔT_i is the temperature drop (°C) across the contact junction and Q is heat flow (W).

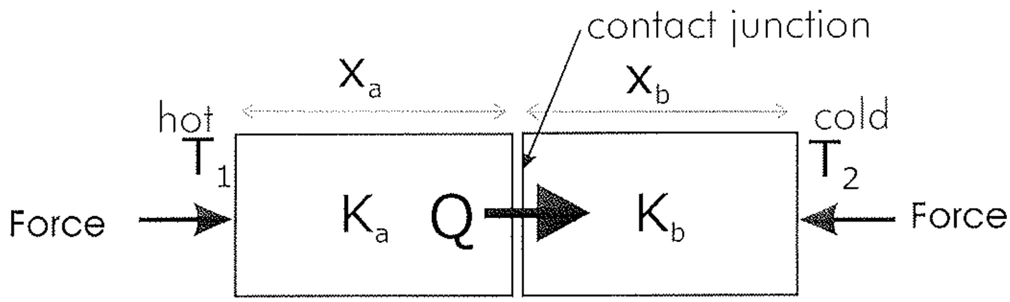


Fig 4 Schematic of set up to measure thermal contact resistance across junctions

$$\frac{1}{h_c} = A.\frac{\Delta T_i}{Q} \qquad \text{eqn(2)}$$

$$Q = \frac{T_1 - T_2}{\dfrac{X_a}{K_a.A} + \dfrac{1}{h_c.A} + \dfrac{X_b}{K_b.A}} \quad \text{eqn(3)}$$

$$Q = -K.A.\frac{\Delta T}{\Delta X} \quad \text{eqn(4)}$$

ΔT_i is difficult to measure directly, so we measure it indirectly by using an idealised 1D conduction arrangement as shown schematically in Fig. 4.

The contact junction under investigation is formed at the interface between two solid cylinders, of pre-defined lengths x_a x_b, cross section area A, and thermal conductivities K_a and K_b respectively. Temperatures are adiabatically constrained at each end using hot and cold constrained junctions (T_1 T_2). ($1/h_c$) can then be found be re-arranging the overall governing Fourier eqn (3) with only Q as an unknown. By continuity, Q can be found by applying eqn(4) and sampling the temperature gradient ΔT (using strategically placed thermocouples) across any defined length Δx of either cylinder.

3. Experimental Set-up

A thermal test rig was constructed (Fig. 5, 6) that could operate in vacuum. UHV pressures were not essential since any convective processes are negligible beyond 10^{-2}mbar although UHV cleanliness procedures were applied in handling the sample to avoid complications due to contaminants and grease build-up.

The hot plate was pre-set at 80°C by thermo-statically controlled water flow which gave an adequate ΔT for reasonable thermo-couple accuracy, whilst minimising complications due to radiative heatloss (these were further reduced by wrapping each cylinder in reflective foil). Liquid metal was applied between the hot/cold plates and cylinders to eliminate any unwanted contact resistance effects at these surfaces.

Five thermo-couples were attached into small bores on each cylinder using thermal epoxy to sample ΔT across the cylinders and hence calculate the unknown overall heatflow Q, as described.

Pre-defined pressure was exerted across the contact junction by means of a spring assembly, whereby force is calculated from the spring compression given the known spring constant.

Three set-up options were used to measure contact resistance (1) Bare to bare surface contact, (2) with intermediate filler and (3) use of surface disc packer, wherever an entire cylinder of the material proved prohibitively expensive to procure (e.g. silicon and tungsten).

Surfaces were prepared at N6 fine machine finish roughness (RMS 0.8μm) with less than <10μm asperities, whilst Silicon was prepared from both unfinished and etched/polished samples (orientation 211)- the latter denoted as Si* in the results section.

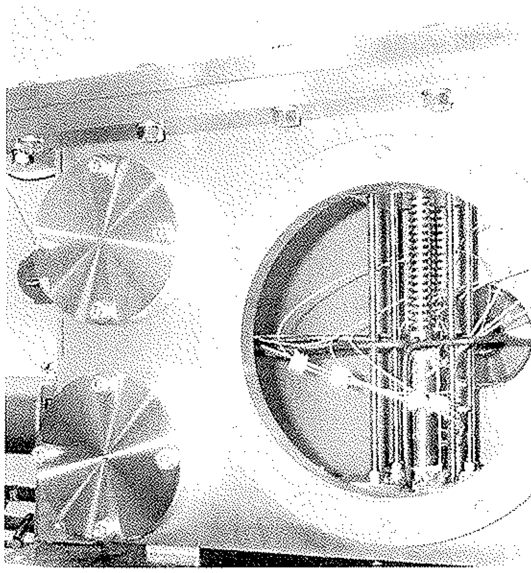


Fig 5 (above) Photo of experimental thermal test rig in vacuum vessel.

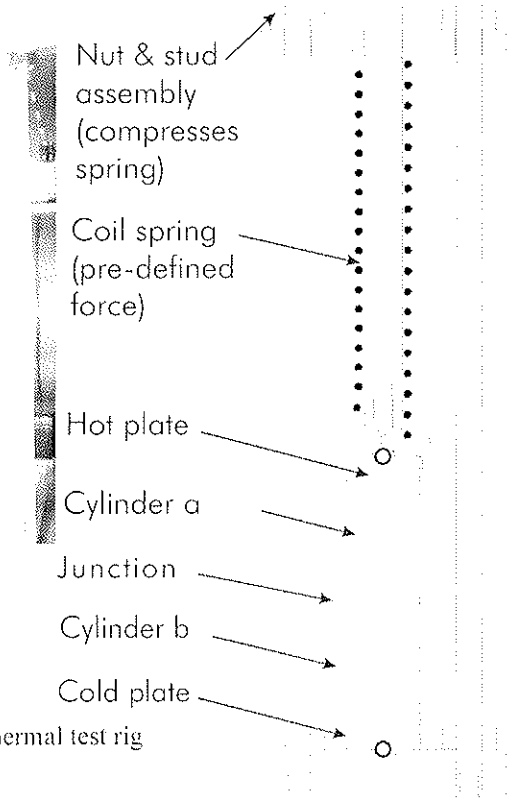


Fig 6 (right) Assembly draiwngs of experimental thermal test rig

4. Results

Data was collated into sets and thermal contact resistance calculated in units of m^2 °C/W as defined in section 2. Results for various junction combinations are displayed graphically against applied pressure in graph (1) and (2), below.

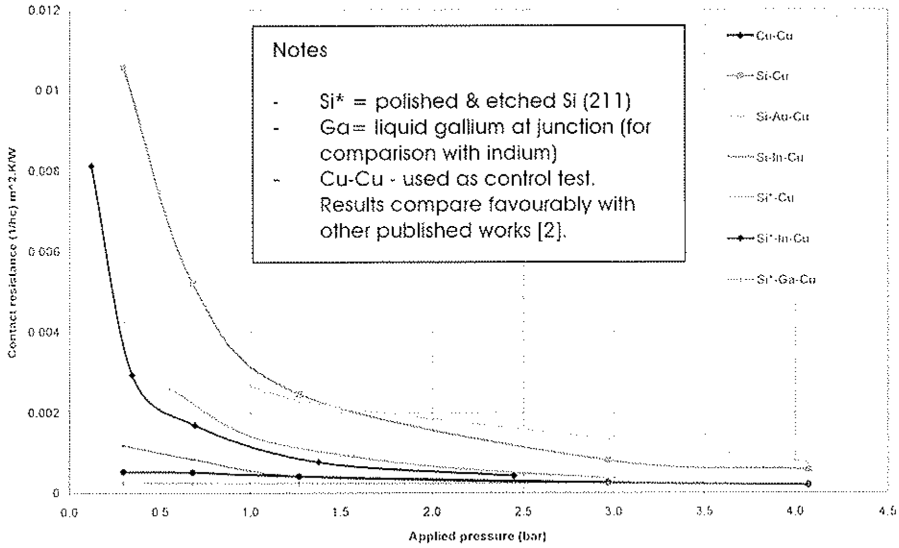
Graph (1) shows the data of most interest to the Phoenix beamline supporting the research, in that combinations of polished and unpolished silicon samples are shown pressed against OFHC copper, for bare surface contacts and with various filler materials, including indium, gold foil and liquid metal (gallium eutectic).

The control experiment, copper to copper junction, agrees well with other reported work [2] which gives us overall confidence in the accuracy of our results.

Graph (2) shows some combinations of other SR UHV compatible materials, by no means exhaustive, but incorporating a tungsten di-sulphide hard coated copper. Further combination experiments were curtailed due to time limits as each dataset took considerable time to obtain, (mostly due to the need to manually adjust force load on the rig, vacuum pump down the system and wait for thermal equilibrium to be established).

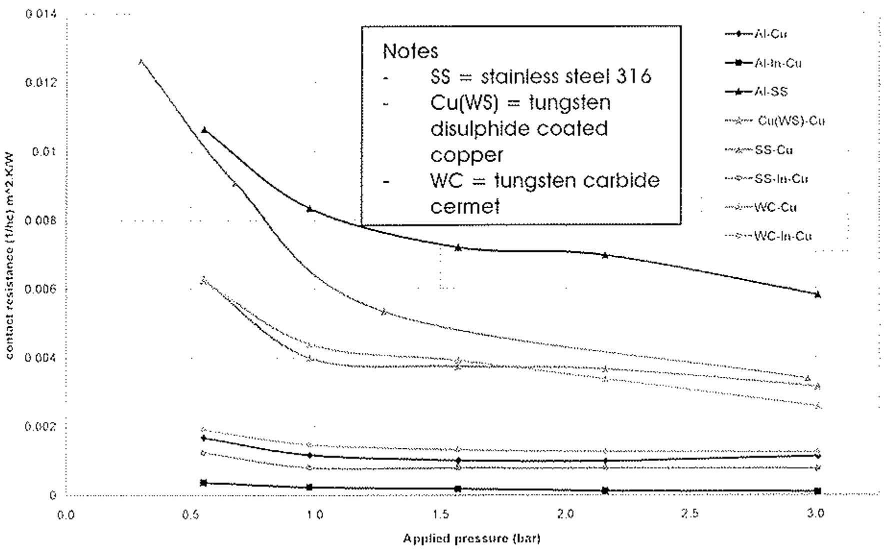
Graph (1) right

Cu-Si junctions - contact resistance vs applied pressure

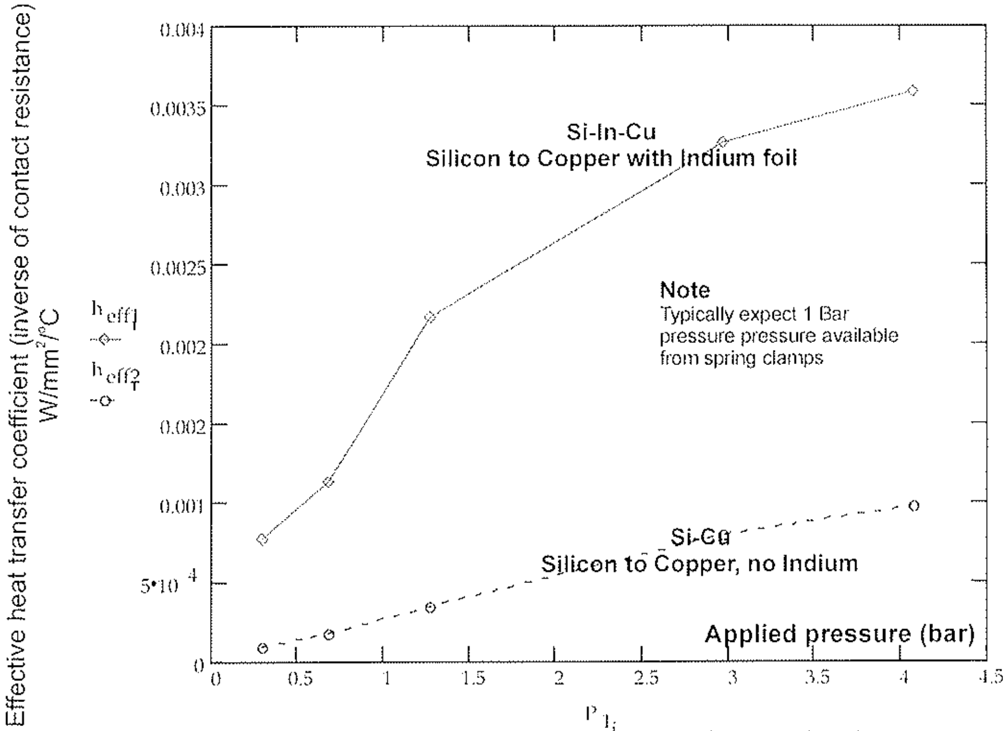


Graph (2) right

Various combination junctions- contact resistance vs applied pressure



Graph (3) below shows the effective heat transfer coefficient calculated from eqn(1) for the phoenix M1 mirror set-up using the experimental data obtained for thermal contact resistance ($1/h_c$), for both with and without indium foil. At applied pressures of between 1 to 1.5 Bar the effective heat transfer with indium is close enough to the desired level of 0.003W/mm^2/°C to give acceptable base temperature rises (in the region of 15°C), whereas without indium base temperatures would rise by an unacceptable 100°C or more.



Graph (3) effective heat transfer coefficient h_{eff} for phoenix mirror vs pressure

5. Conclusions

Experimental measurement of thermal contact resistance has given us more confidence in our predictive thermal modelling of contact cooled optics. It is clear that the use of indium foil with moderate applied pressures reduces contact resistance to acceptable levels in most cases and is even favourable when compared against liquid metal interfaces (except at very low contact pressures). It is also clear that other solid interfaces such as gold foil (and also aluminium - though not reported here) whilst offering some reduction in resistance at low pressures are poor in comparison to indium and actually even marginally *increase* contact resistance at higher contact pressures.

Further work to be done includes measuring contact resistances with different surface finishes and verifying base temperature on the phoenix mirror under full MPW (2Tesla) heatload.

Acknowledgements

Thanks to Roger Lowery for providing technical support and Alexander Snodgrass for carrying out a second set of validation measurements.

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