

THERMAL CONTACT RESISTANCE STUDY

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Abstract

In Synchrotron radiation instruments, many heat load components are cooled by clamping them to a water, liquid nitrogen, or He gas cooled block. For instance, silicon X ray mirrors, monochromator crystals, or the Tungsten back plates of slits are cooled by contact to cooled copper blocks. The value of the thermal contact resistance (TCR) between the two solids is needed in order to estimate the temperature distribution in these heat load components. The TCR depends on many parameters, such as the couple of the two solids, the surface roughness, flatness of the solids, the contact pressure, the environment (vacuum or in-air, temperature), the interstitial materials. This paper presents a testing bench built at the ESRF, some results of TCR between copper and tungsten, between copper and copper, between copper and silicon at room temperature, in vacuum, under different contact pressures, with and without interstitial materials. Influences of the surface state on the value of TCR have also been studied. Some results previously obtained in similar conditions on the CETHIL test bench are also mentioned (CETHIL: Thermal center of Lyon, UMR CNRS 5008, 20, Av. A. Einstein, 69621- Villeurbanne cedex – France)

1. Introduction

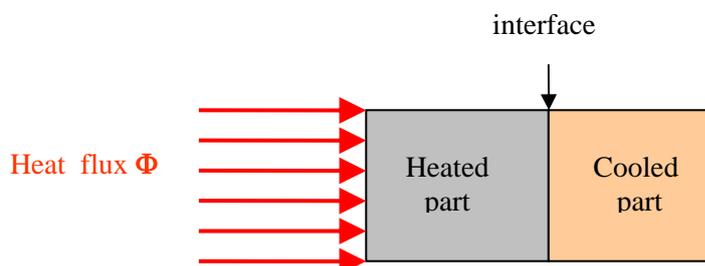
In Synchrotron radiation light sources, an efficient cooling is required for the beam absorbers (beamstops), collimating devices (slits, pinholes,...) and optical components (X ray mirrors, monochromators), which are exposed to intense photon beams (typically several hundred W to a few kW total power and several hundred W/mm² of power density). In the case of beam absorbers and collimating devices, the temperature distribution must be controlled in order to avoid excessive temperatures and also not to reach too high thermal stresses. In the case of optical components, the cooling criteria is imposed by the thermal deformation of the optical surface, which must be kept within acceptable limits to avoid optical distortions. The cooling is ensured by water in most cases, or by helium gas or Liquid Nitrogen when cryogenic temperatures are required. In many cases, the cooling channels cannot be drilled directly into the active part, for technological reasons, and the active part is then linked to the cooled part, either by brazing or by mechanical clamping. When the part receiving the beam power is clamped to the cooled part, this induces a thermal contact resistance (TCR) which results in a local temperature rise at the interface:

$$\Delta T_{\text{interface}} = R \Phi$$

where R = Thermal contact resistance (m².K/W)

$\Delta T_{\text{interface}}$ = Temperature rise at the interface (K)

Φ = Heat flux (W/m²)



For the ESRF Beamlines, several instruments have been designed with their heated part cooled through a clamped contact in Ultra high vacuum atmosphere: Primary slits (Glidcop® / Tungsten or Glidcop® / Tungsten carbide interface), X ray Mirrors (Silicon / copper interface close to ambient temperature), X ray Monochromators (Silicon / copped interface at 80K). The works described in this paper are first intended to provide reliable values of the TCR in conditions similar to those in these Beamline instruments. The second aim of these works is to find solutions to reduce the TCR, by studying the influence of the main contributing parameters: the surface roughness, and flatness of the solids, the contact pressure, the presence of interstitial materials (gold, indium).

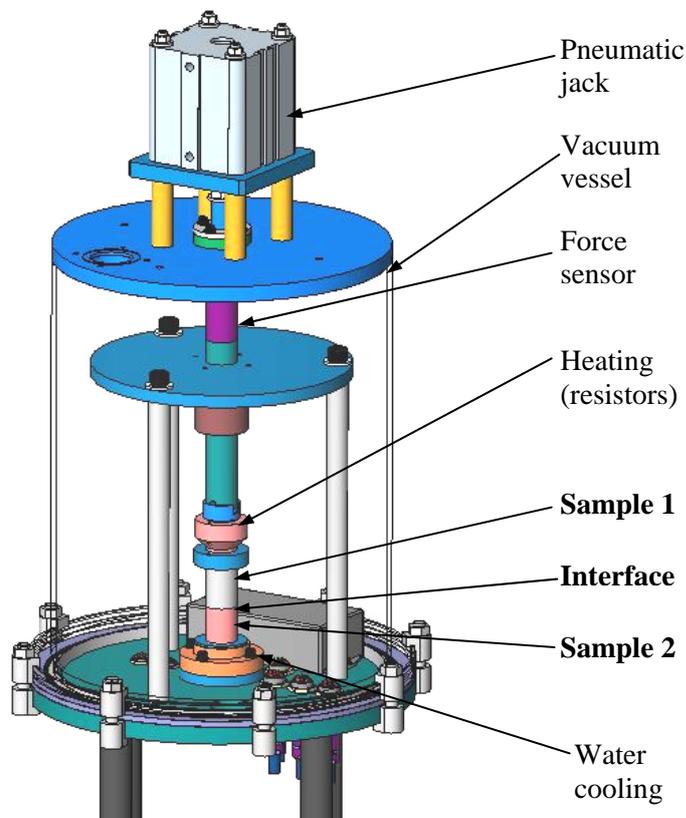
Several experimental values can be found for the TCR [1-5], but only a few values have been measured in conditions similar to ours and, moreover, the available results show a large dispersion due to the influence of the experimental conditions and also to the surfaces history.

Our works on the TCR have been possible thanks to a collaboration with the CETHIL (Thermal center of Lyon, UMR CNRS 5008, 20, Av. A. Einstein, 69621- Villeurbanne cedex – France). First measurements were taken in 2002 [6] in Villeurbanne on the CETHIL test bench, on Glidcop®/ Tungsten carbide samples with and without gold and Indium foil at the interface. In 2003, a test bench based on the same principle as the CETHIL one [7] was built at the ESRF and measurements were done on Cu/Cu and Cu/Si samples with various surface finishes and interstitial materials.

2. The test bench

The set up is shown on fig1.

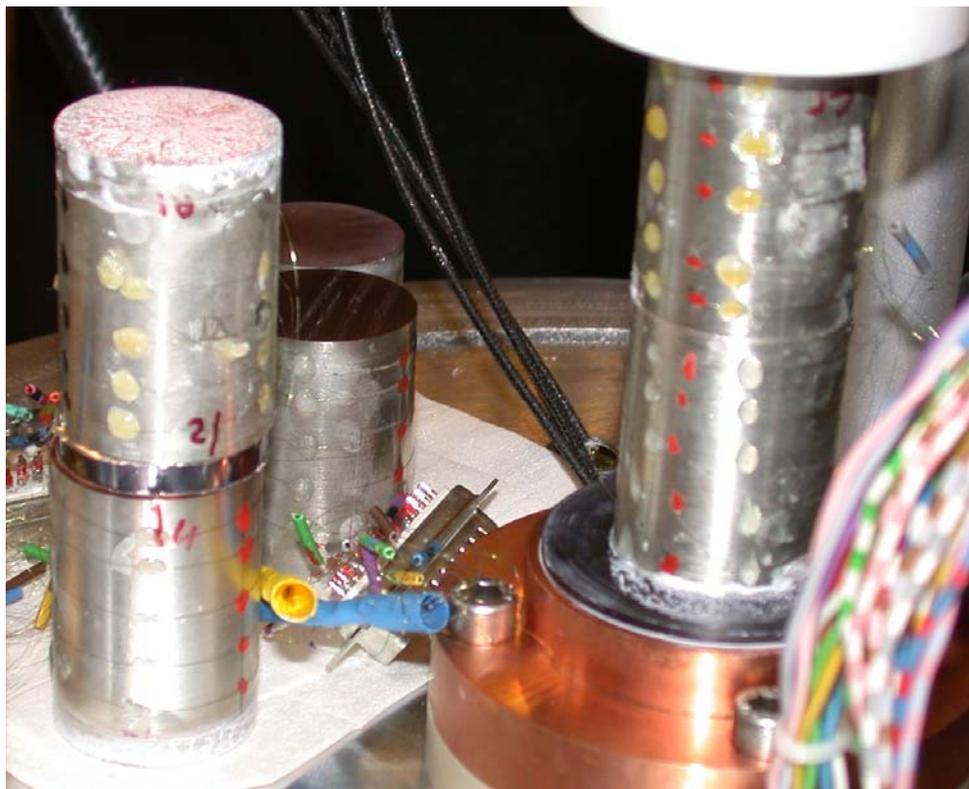
Fig 1: Schematic description of the TCR measurement bench built at the ESRF



The samples are cylinders of $\text{Ø}30\text{mm}$, height 40 to 60mm. They are enclosed in a vacuum vessel and pressed together in contact on one of their flat faces. The contact force is generated by a commercial pneumatic jack located outside, controlled by a force sensor located inside the vacuum vessel, and transmitted to the samples by a guided rod with a spherical end, so that the force can be applied without inducing a wrong positioning at the interface. Two resistors are inserted in a copper part of adequate shape to deliver an uniform heat flux to the 30mm diameter top face of sample 1. The bottom face of sample 2 rests on a water cooled copper block fixed on the base of the vacuum chamber via an insulating plastic ring. The vacuum chamber is connected to a turbomolecular pumping group, which enables to reach a vacuum pressure lower than 10^{-4} mbar in the vacuum chamber (pressure measured with a vacuum gauge in the upper part of the chamber).

Four (or five) type K thermocouples are mounted on each sample. The thermocouples are made of two $\text{Ø}50\mu\text{m}$ wires, spot welded on the sample cylindrical face. The positions of the thermocouples along the sample length are measured with accuracy better than 0.15mm. The cold end of the thermocouples are connected inside a temperature controlled insulated box located inside the vacuum vessel (temperature gradient inside the box: less than $0.03\text{ }^{\circ}\text{C}$). All thermocouples are connected to a data acquisition system. The relative error between thermocouples is estimated to less than $0.15\text{ }^{\circ}\text{C}$.

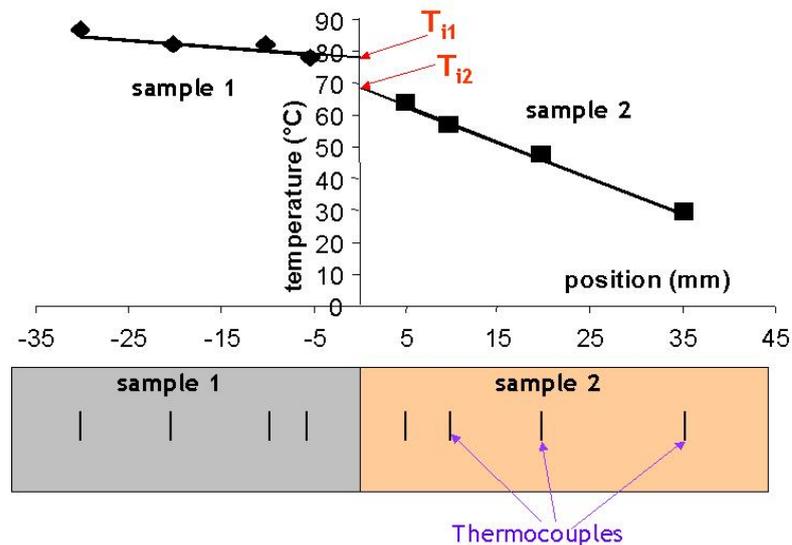
Picture 1: Thermocouple wires spot welded on the samples



3. Determination of the thermal contact resistance

On each sample, the thermocouples give the temperature in four (or five) accurately located points. From these four points, a straight line is determined by the method of the least mean squares, which corresponds to the linear temperature drop along the sample (see fig2).

Fig2: Determination of the temperature distribution in the samples



For sample 1: $T_{\text{sample1}}(x) = a_1 x + T_1$ (1)

For sample 2: $T_{\text{sample2}}(x) = a_2 x + T_2$ (2)

where x is the position along the sample

From these equations, the heat flux Φ can be determined (since the thermal conductivity of each sample material k_1 and k_2 are known, either from preliminary measurements, or from catalog data):

$$\Phi = -k \, dT/dx \Rightarrow \Phi_1 = -k_1 a_1 \text{ and } \Phi_2 = -k_2 a_2$$

Assuming the thermal losses between the samples and the outside (radiation, conduction through Thermocouple wires) are negligible, Φ_1 and Φ_2 should be equal (within measurement errors). The flux Φ is then calculated as $\Phi = (\Phi_1 + \Phi_2)/2$.

From equations (1) and (2), the temperatures at the interface on samples 1 and 2 T_{i1} and T_{i2} can be extrapolated (see fig 2). The RTC is then deduced by:

$$\text{RTC} = (T_{i1} - T_{i2}) / \Phi$$

Case of the Silicon:

Thermocouples cannot be welded on the Silicon. To measure the RTC between Copper and Silicon, a silicon disk $\varnothing 30\text{mm}$ thickness $t = 5.6\text{mm}$ was used, clamped between two copper samples equipped with thermocouples.

$$(T_{i1} - T_{i2}) / \Phi = 2 \text{RTC}_{\text{Copper-Silicon}} + t/k_{\text{Si}} \text{ which enables to extract } \text{RTC}_{\text{Copper-Silicon}}$$

4. Results

4.1 TCR measurements between Glidcop and WC without and with Gold / Indium interstitial foil on the CETHIL test bench

TCR values measured between Glidcop® A115 and Tungsten carbide samples are shown on graph 1. These values were measured on the CETHIL test bench in the following conditions:

Glidcop® grade A115 Lox is a copper alloy (Cu 99.7%, Al₂O₃ 0.3%) developed by SCM Metal

products and distributed by OMG Americas.

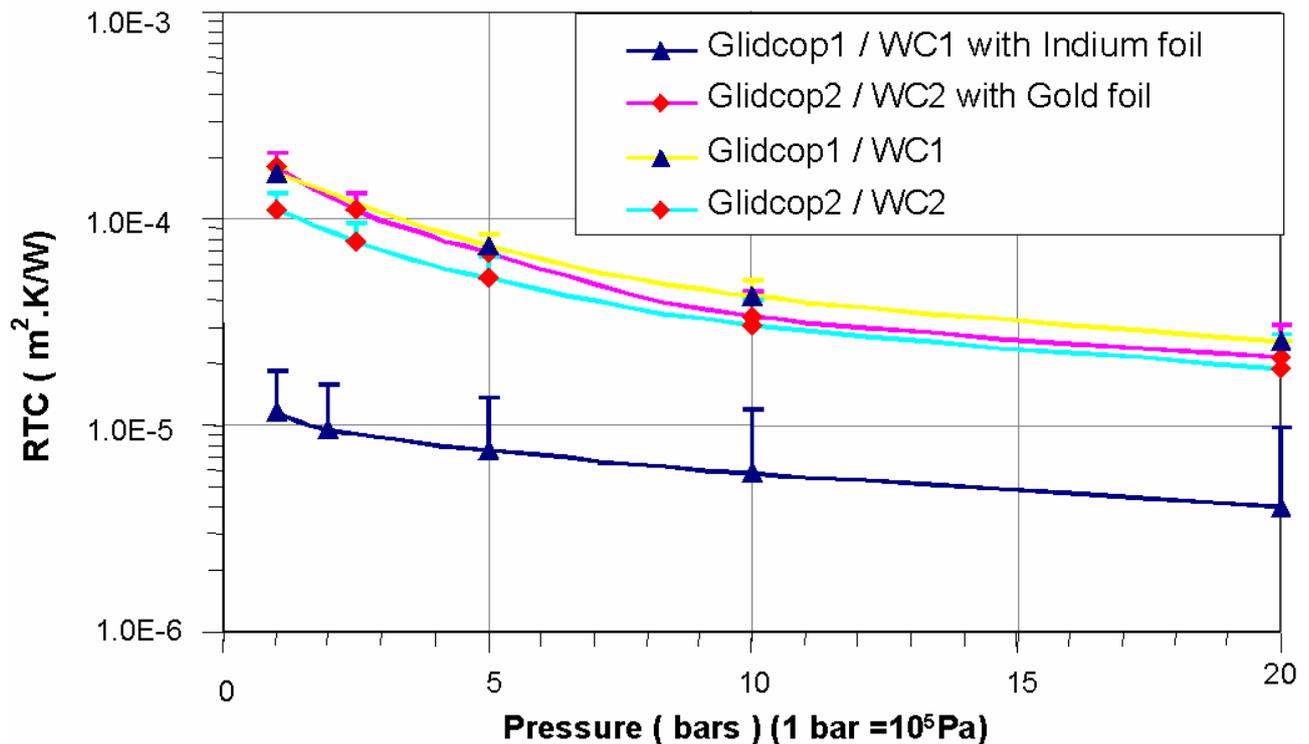
The Tungsten carbide used is the TSM 30 grade from Plansee Tizit (www.plansee.com).

Surface roughness of samples: 0.2 to 0.4 μm ; Surface flatness of samples: 0.002 mm

Interface temperature: 60 to 80 $^{\circ}\text{C}$; Vacuum pressure: 10^{-2} mbar

Gold foil and Indium foil thickness: 100 μm . In an attempt to soften it, the gold foil was annealed at 830 $^{\circ}\text{C}$ before inserting it between the samples.

Graph 1:TCR measured between Glidcop® and WC samples on the CETHIL test bench



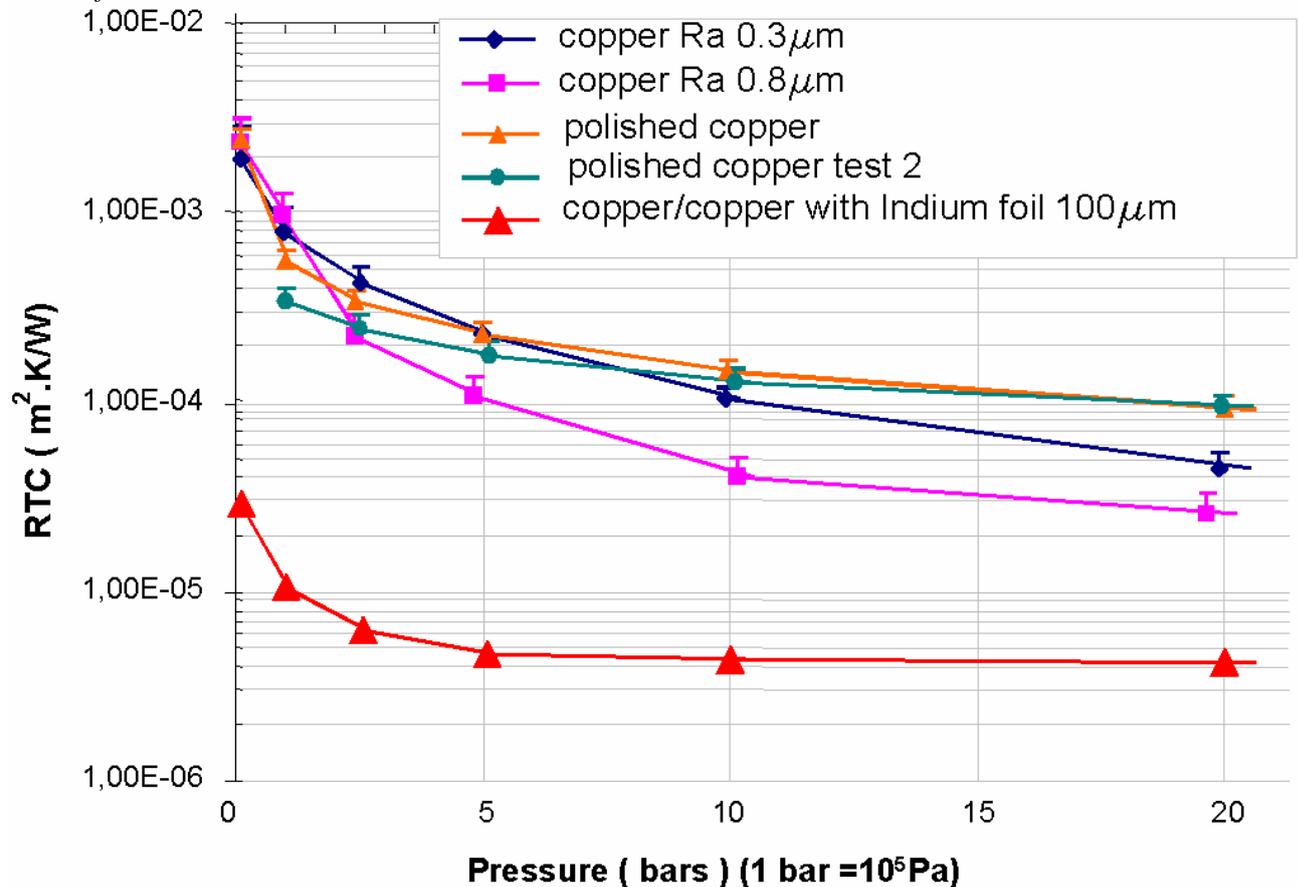
4.2 TCR measurements between Copper and Copper without and with Indium interstitial foil on the ESRF test bench

TCR values measured are shown on graph 2. These values were measured on the ESRF test bench, using three sample sets with different surface roughness: Ra 0.8 μm , machined by a lathe; Ra 0.3 μm , machined by a lathe; Polished surface finish. The other conditions of this test were:

Interface temperature: 20 to 100 $^{\circ}\text{C}$; Vacuum pressure: 10^{-4} mbar

Indium foil thickness: 100 μm .

Graph 2: TCR measured between 2 Copper samples of different surface roughness without and with Indium foil



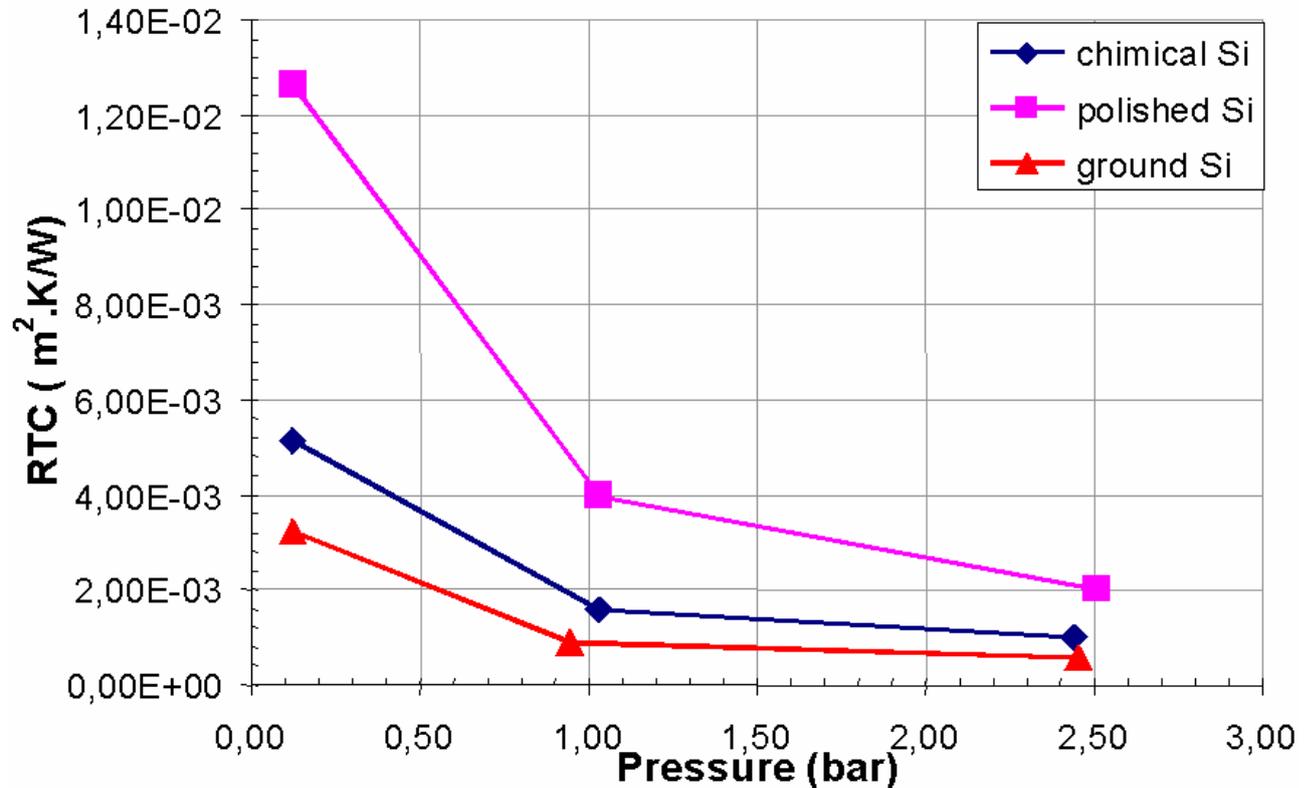
4.3 TCR measurements between Copper and Silicon

TCR values measured are shown on graph 3. These values were measured on the ESRF test bench, using three Silicon samples with different surface finishes: Ground finish; Polished finish; Chemical etching finish. The other conditions of this test were:

Vacuum pressure: 10^{-4} mbar

The mechanical pressure applied was limited to 2.5 bar.

Graph 2: TCR measured between Copper and Silicon samples for different surface finishes



5. Discussion and conclusion

From the results mentioned in the previous section, the following tendencies appear:

- The TCR decreases when the contact pressure increases
- The TCR is drastically reduced by adding an Indium foil at the interface, especially at low contact pressures (factor > 10 on the TCR). Thanks to its very low hardness, Indium penetrates in the surface defects and enables to increase the actual contact area.
- Adding a Gold foil at the interface does not decrease the TCR. Gold is too hard to penetrate deeply in the surface irregularities and the slight gain obtained by this effect does not compensate the fact that adding the gold foil results in two interfaces instead of one.
- No clear variation of the TCR was observed between finely polished samples and machined samples with Ra up to 0.8µm (see graph 2). In the case of Silicon samples, like for copper samples, a fine polishing up to the level which enables the mating surfaces to “stick” by surface forces does not reduce the TCR. For Ra lower than 0.8µm, the surface flatness is probably a more important parameter, since a few microns of flatness error would have a strong influence on the actual surface area. It would be necessary to compare the flatness profiles of the samples with a sub-micrometric resolution in order to confirm this assumption.
- As mentioned in other papers, important dispersions were recorded between similar samples. These discrepancies are probably not due to measurements errors, but to uncontrolled surface effects (oxidization, local flatness defects, ...)

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