A SETUP FOR THE EVALUATION OF THERMAL CONTACT RESISTANCE AT CRYOGENIC TEMPERATURES UNDER CONTROLLED PRESSURE RATES

B.A. Francisco[†], W.H. Wilendorf, V.B. Zilli, G.S. de Albuquerque, D.Y. Kakizaki,
V.C. Kuriyama, A.R. Ribeiro[1], J.H.R. dos Santos[2], M. Saveri Silva
Brazilian Synchrotron Light Laboratory, Campinas, Brazil.
[1] also at Federal University of Uberlândia, Uberlândia, Brazil
[2] also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

Abstract

The design of optical elements compasses different development areas, such as optics, structures, dynamics, thermal, and control. Thermal designs of mirrors aim to minimize deformations, whose usual requirements are around 5 nm RMS and slope errors in the order of 150 nrad RMS.

One of the main sources of uncertainties in thermal designs is the inconsistency in values of thermal contact resistances (TCR) found on the literature. A device based on the ASTM D5470 standard test was proposed and designed to measure the TCR among materials commonly used in mirror systems. Precision engineering design tools were used to deal with the challenges related to the operation at cryogenic temperatures (145 K) and under several pressures rates (1~10 MPa) whilst ensuring the alignment between the specimens. We observed that using indium as Thermal Interface Material reduced the TCR in 10~42,2% for SS316/Cu contacts, and 31~81% for Al/Cu. Upon analyzing the measurements, we identified areas for improvements in the equipment, such as mitigating radiation and improving the heat flow on the cold part of the system that were implemented for an upgraded version.

INTRODUCTION

Thermal contact resistance (TCR) is a parameter that indicates the ratio between surfaces temperature gradients of two bodies in contact and the heat load and exchanged.

A heat exchange measurement setup was developed for improving our database about TCR, especially for cryogenic applications, in which uncertainties become critical for the performance of the instruments.

It is well-known that during mechanical contact between solid bodies, the surfaces typically touch each other from less than 1% to 2% of the nominal contact area [1]. This limited contact area plays an essential role in reducing the heat load exchange. The TCR is also influenced by several variables, encompassing thermal factors (material properties, interface temperature, and heat flow direction), morphological aspects (shape, roughness, finishing), as well as mechanical conditions (applied pressure between the surfaces and potential deformations) in addition to those related to the other heat transfer mechanisms: radiation (emissivity) and convection (fluid characteristics between the surfaces), which is minimized in a vacuum environment.

An experimental approach was chosen since the diversity of models for calculating TCR values are limited to specific configurations. Among the known methods, including T-type, Infrared Thermography, Laser-Flash Method, and 3ω, the one with the lowest uncertainties (2-10%) [2] was selected: the Standard Steady-State Method. This method is comprehensively described in ASTM standard D5470-06 [3], and based on this standard, we developed a setup version for measurements at cryogenic temperatures.

EXPERIMENTAL SETUP

The standard test primarily involves column samples equipped with sensors. These samples are insulated to prevent heat loss through radiation and convection. A heat gradient is generated between the samples by using a heater, which is installed at one end, and a cooling source at the other end. A force actuator can be introduced to vary the stress across the samples. A test schematic is presented in Fig. 1. The temperature acquisition takes place after the system achieves a stationary state, and from this information, the contact region is determined.

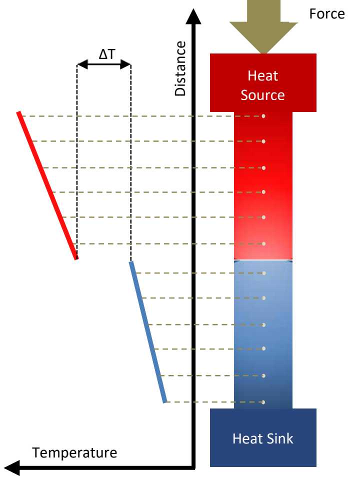

Figure 1: Diagram of how the data related to the standard steady-state method is obtained, from [4].

Thermal Management

Some adaptations were made in response to the cryogenic condition. The system was designed for operation within vacuum chambers, under a pressure level of $1 \cdot 10^{-7}$ mbar

---

[†] barbara.francisco@lnls.br

produced by a turbo pump station. The cooling system employed was a Janis ST-100 open-cycle cryostat with relied on a liquid nitrogen flow and was maintained in contact with the system through copper braids. For a visual representation of the system, please refer Figs. 2 and 3.a).

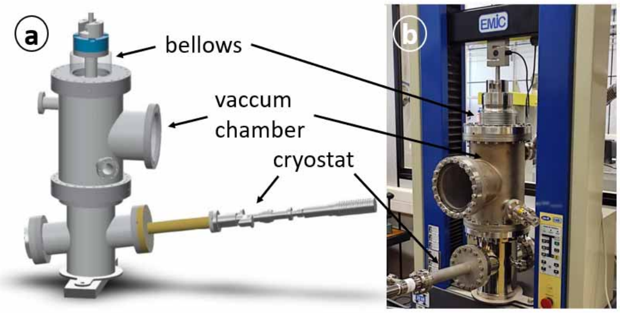

Figure 2. CAD representation (a) and photo (b) of the setup.

The support bases of the coldest temperature sample are depicted in Fig. 3.b). They were designed after a lumped-mass analysis to isolate the cold parts from the external environment, whose temperature remained above the dew point (~15 °C).

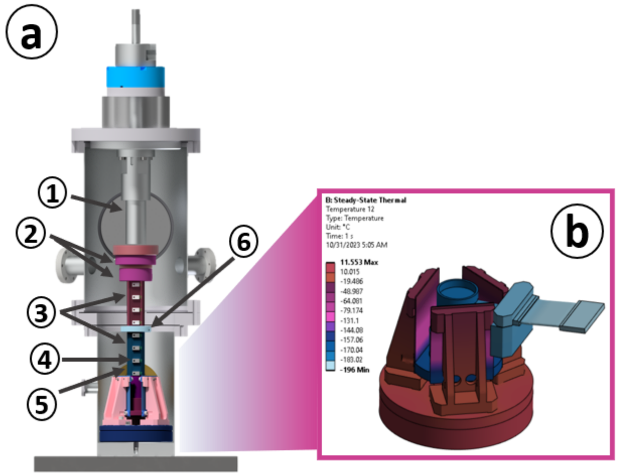

Figure 3: (a) CAD representation of internal view of the setup: 1. Piston; 2. Heaters Placement; 3. Samples; 4. Sensor; 5. Copper Braid; 6. Alignment Ring. (b) Thermal steady-state simulation of down part.

Testing Apparatus

The system was installed in an EMIC machine [5] (Fig. 2.b)). The force was transmitted unidirectionally to the samples in-vacuum through a specially designed bellows-piston feedthrough containing fittings to ensure the alignment and polymeric insulators to minimize heat leaks (Fig. 3.a)).

Samples with 35 mm diameter were selected to ensure that the range and resolution of forces provided by the EMIC actuator would result in pressures consistent with those applied in optical instruments at beamlines such as mirrors and monochromators. Additionally, this choice allowed for the accommodation of sensors with a significant temperature gradient between them.

Data Acquisition and Actuation

A CompactRio 9045 [6] device equipped with 9226 module was employed to monitor the temperatures from the Pt-2k thermal sensors whereas a 9403 module was used to regulate the 0~10 W heaters by sending the signal to an in-house designed amplifier [7]. Vacuum levels were read using a MKS cold cathode gauge [8] distinct from the pump station.

The heat load can be calculated from the heater current or from the slope of the curve using thermal conductivities from literature.

Force measurements were obtained via a script developed specifically for the EMIC machine, considering displacement inputs.

PRELIMINARY RESULTS

The prototype was applied for the determination of TCR of two contacts frequently present in thermal paths of optical instruments: Cu-SS and Cu-Al, both with and without indium as TIM (Thermal Interface Material).

Loads were incrementally applied, ranging from 0 to 12 kN, and subsequently returned to 0, with such cycle being repeated three times. The repetition aimed to ensure reproducibility of the data while also considering that, during the initial steps, under low loads, indium is not subject to plastic deformation.

The results for Cu-Al and Cu-In-Al when 1 kN (0.331 MPa) is applied are shown on in Fig. 4. The markers refer to the readings of the temperature sensors, which are interpolated to the contact region to calculate the temperature gradient and, consequently, the TCR.

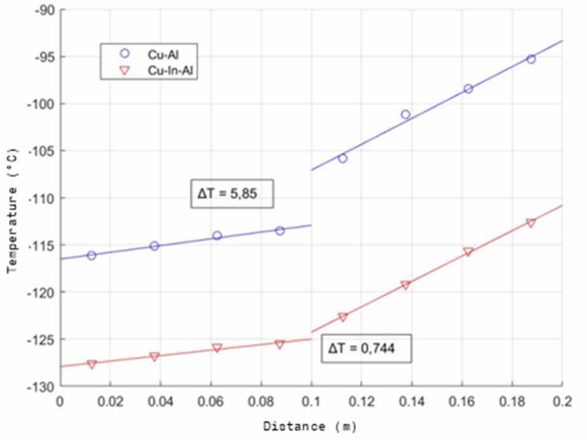

Figure 4. Temperature sensors positions vs temperatures for Cu-Al samples under 1 kN.

A summary of the TCR calculations at various pressures is presented in Fig. 5. The values range from 1.7E-5 m²K/W (Cu-In-Al @ 13.2 MPa) to 1.9E-3 m²K/W (Cu-SS @ 0 MPa). As expected, the inclusion of an indium layer results in a significant reduction in TCR, with the TCR decreasing as the applied pressure increases.

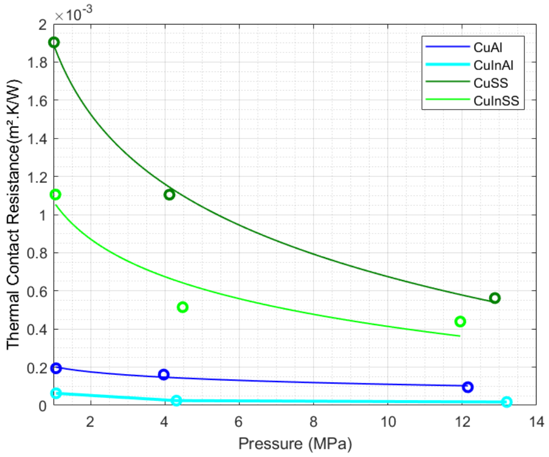

Figure 5: TCR for Cu-Al and Cu-SS pairs with and without indium as TIM as a function of the applied load.

Each point required a considerable amount of time to achieve the steady-state, particularly when dealing with low-diffusivity materials such as stainless steel and titanium. Conversely, due to the high thermal conductivity of copper, small temperature gradients emerged among the sensors, which compromised the data resolution. Besides that, the absence of radiation shielding also compromises the obtained values.

PERSPECTIVES

An upgraded setup is under design with the goal of improving the results accuracy and to shorten the test duration time. The upcoming version is incorporating a radiation shield and the heat exchange between cryostat and samples will be optimized, besides the exchange to a higher power heater.

Silicon samples have been machined for the evaluation of Cu-Si and SS-Si contacts. Moreover, we expect to extend the analysis by investigating varying levels of roughness on some pairs of material.

Finally, the addition of a mathematical analysis of errors and uncertainties associated with the measurements is required for a more accurate estimation of the final values.

CONCLUSION

A setup for the evaluation of thermal contact resistance (TCR) at cryogenic temperatures was proposed. Preliminary studies led to the conclusion that using indium as Thermal Interface Material reduced the TCR in 10~42% for SS316/Cu contacts, and 31~81% for Al/Cu.

We have ongoing plans for equipment enhancements, such as the introduction of a radiation shield, further investigations into contacts with varying surface roughness, and the application of mathematical analysis to refine result accuracy. Our work expects to advance the understanding of TCR and contribute to more effective thermal designs for optical instruments.

REFERENCES

[1] M. Bahrani, J. Culham, M. Yananovich, *et al.*, “Review of thermal joint resistance models for nonconforming rough surfaces”, *Appl. Mech. Rev.*, vol 59, no. 1, pp. 1-12, 2006. `doi:10.1115/1.2110231`

[2] Y. Xian, P. Zhang, S. Zhai, P. Yuan, *et al.*, “Experimental characterization methods for thermal contact resistance: A review”, *Appl. Therm. Eng.*, vol. 130, pp. 1530-1548, 2018. `doi:10.1016/j.applthermaleng.2017.10.163`

[3] ASTM International, “*Standard Test Method for Thermal Transmission Properties of Thermally Conductive Electrical Insulation Materials*”, ASTM D5470-06, 2006.

[4] Z. Bulinski *et al.*, “Determination of the thermal conductivity of solids based on the ASTM D 5470 standard”, *Steel Metals and New Technologies*, vol. 3-4, pp. 57-62, 2019.

[5] `https://www.emic.com.br/`

[6] `https://www.ni.com/pt-br/shop/model/crio-9045.html`

[7] M.M. Donatti, D.H.C. Araujo, F.H. Cardoso, G.B.Z.L. Moreno, L. Sanfelici, and G.T. Semissatto, “Multi-Channel Heaters Driver for Sirius Beamline’s Optical Devices”, in *Proc. ICALEPCS'21,* Shanghai, China, Oct. 2021, pp. 705-709. `doi:10.18429/JACoW-ICALEPCS2021-WEPV026`

[8] `https://www.mks.com/p/104220008`