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Review : Thermal contact problems at cryogenic temperature

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Abstract

This paper addresses technical problems of thermal contact conductance or resistance which inevitably occurs in most cryogenic engineering systems. The main focus of this paper is to examine what kind of physical factors primarily influences the thermal contact resistance and to suggest how it can be minimized. It is a good practical rule that the contact surface must have sub-micron roughness level with no oxide layer and be thinly covered by indium, gold, or Apiezon-N grease for securing sufficient direct contact area. The higher contact pressure, the lower the thermal contact resistance. The general description of this technique has been widely perceived and reasonable engineering results have been achieved in most applications. However, the detailed view of employing these techniques and their relative efficacies to reduce thermal contact resistances need to be thoroughly reviewed. We should consider specific thermal contact conditions, examine the engineering requirements, and execute each method with precautions to fulfil their maximum potentials.

Keywords: thermal contact resistance, conduction cooling, interstitial material, indium, Apiezon-N grease

1. INTRODUCTION

In various cryogenic applications where the cooling target is conductively cooled at vacuum insulation environment, thermal contact resistance can be a serious problem if proper precautions are not made. The inadvertent assembly procedure sometimes may create large temperature difference between two contact surfaces which shall require excessively long cool-down time from room temperature to cryogenic temperature before its normal operation can start. The insufficient thermal bridging design may also result in unnecessarily large cryogenic cooling system.

In modern superconducting magnet applications, more and more magnets are conduction-cooled for operational convenience of not using cryogens. As we use more HTS (high temperature superconducting) devices than LTS (low temperature superconducting) ones, this tendency is increasing and thermal contact problem is more frequently recognized. Since the overall thermal resistance between the cooling target such as a superconducting magnet and the cooling source such as a cryocooler must be minimized, it is of utmost importance to reduce the thermal contact resistance as much as possible. In the case of conduction cooling mode for a superconducting device, the temperature jump in imperfect contacts between metals creates additional entropy generation that is associated with finite temperature-difference heat transfer and results in the increased cooling load to a cryogenic refrigeration system.

Temperature sensors are usually exploited to provide valuable information in most cryogenic experiments. When they are installed at the surface under vacuum condition, however, some tricky situations often occur. The temperature reading can be erroneous unless they are properly mounted as suggested by the manufacturer's guide. Poor thermal contact with non-negligible self-heating effect is the main source of cryogenic thermometry error. As the mundane problem of heating something at vacuum, we may also experience strangely large temperature difference between the heater and the target material due to poor thermal conduction associated with thermal contact resistance.

The surface of solid has always some irregularity depending on the preparation method. When two solid surfaces meet for contact, the thermal or electrical contact resistance inevitably occur due to this surface condition. Fundamental mechanism of thermal contact resistance is phonon scattering when two dissimilar materials meet each other. The boundary can be considered as a barrier to reflect thermal wave to create additional thermal resistance. There are numerous cryogenic situations where thermal contact resistances are visibly serious problems.

This review paper deals with fundamental aspects of thermal contact phenomenon occurring two solid surfaces. Although it is an interesting research topic to deal with theoretical consideration of phonon dynamics, it is beyond the scope of this paper. We will focus on practical and experimental results to identify, summarize, and show how to improve thermal contact resistance.

Fig. 1 illustrates the physical contact of two solids in a magnified view. Although two mated surfaces look geometrically matched, the true contact area inside the apparent contact region can be only about 1-2 % [1]. The micro-scale asperities comprised of small peaks and valleys cause relatively large temperature jump at the interface

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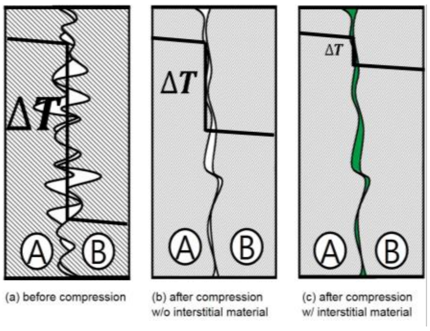
where no interstitial material exists such as in a vacuum condition. This phenomenon is especially noticeable as the amount of heat transfer or the cooling load increases and, therefore, the large temperature difference due to thermal contact resistance may become a serious problem. The temperature jump at the contact can be diminished if the two surfaces are forced to deform by external contact pressure and the true contact area is substantially increased as shown in Fig. 1 (b). The thermal contact problem is further alleviated if an appropriate interstitial material is interposed in the space between two solids. Fig. 1 (c) illustrates that the contact gap is filled with another thermal conductive solid or liquid material to decrease the thermal contact resistance. The selection of this interstitial material is as important as the two contact surface preparations. In general, the inherent properties of materials, the existence of oxide layer, the temperature, and the contact pressure are main influencing components to the thermal contact result. Since there is no thermal superconductor, the thermal resistance circuit for Fig. 1 can be constructed as Fig. 2 which includes an additional thermal resistance, R_{TCR}, due to imperfect contact. R_A and R_B are the inherent thermal resistances originated from two mated material's respective thermal conductivity. The following definition is commonly used to notate the thermal contact resistance. T_A and T_B are temperatures at the interface of the materials A and B respectively.

$$Q = \frac{T_A - T_B}{R_{TCR}} = \frac{T_A - T_B}{\frac{r_{TCR}}{A_c}} = \frac{A_c}{r_{TCR}}\left(T_A - T_B\right) = h_{TCR} A_c \left(T_A - T_B\right)$$

As shown in the above expression, the heat must flow across the contacted cross-sectional area, A_C. This area is the apparent contact area and r_{TCR} is the resistance per unit area, whose inverse is often notated as the thermal contact conductance, h_{TCR}. If the truly contacted area is small due to several factors, the contact resistance is large and so the temperature difference which is indispensable for a certain amount of heat transfer is not negligible. This aspect is clearly not attractive for most cryogenic cooling applications. The physical factors of resulting in much smaller true contact area than the apparently projected area are the roughness of the surface, the poor filling of the interstitial material in the gap, if any, and the inadequate contact pressure. The poor filling is attributed to insufficient initial amount of the interstitial material, but the thermal contraction of too much filled interstitial material can also cause such a problem due to thermal contraction mismatch during cooling. This fact confirms that the atomic bonding through welding, diffusion bonding, soldering, and plating would give rise to the best surface contact condition for heat transfer although some techniques are not permitted in a specific application due to severe physical and thermal conditions for the preparation.

It is generally true that having small thermal contact resistance is desirable in most cryogenic applications. The question is how small it should be! The requirement of the acceptable value of thermal contact resistance depends on the specific application. If the heat flow across the contact surfaces is negligible, thermal contact problem does not draw much attention. The typical example of this is the case of temperature sensor installation where its self-heating effect is negligible and its lead wires are properly selected and thermally anchored to reduce the conduction heat ingress from room temperature to cryogenic temperature. Superconducting magnets operating in DC mode can be also in this category once they are successfully cooled down to the operating cryogenic temperature with an adequate radiation shield. The nominal value of thermal contact resistance per unit area can be relatively high in these situations between 10^{-3} and 10^{-4} m^2K/W. This is equivalent to the thermal resistance of 1 K/W and 0.1 K/W respectively with the contact area of 10 cm^2. In the case of 1 K/W, only 1 K temperature difference occurs with 1 W of heat flow. Even for the same specific thermal contact resistance value, however, a significant temperature jump can occur and cause a problem if the amount of heat across the contact surfaces increases. An order of 10 W of heat transfer can be easily contributed by heat ingress from room temperature environment if there is no proper radiation shielding. Such an amount of heat can be also generated by AC loss during a fast ramping process of magnet. In this situation, the same thermal resistance of 1 W/K may bring a trouble for conduction cooling of superconducting magnet by creating phenomenological 10 K temperature difference. It is highly detrimental if we consider the fact that a magnet is cooled by a cold head of cryocooler. The potential cooling capacity of a cryocooler is simply diminished because of poor thermal bridging technique.

Thermal contact resistance in various cryogenic assembly conditions need to be more specifically quantified. This review paper elucidates some experimental observations to address thermal contact resistance and presents frequently used skills to reduce it by discussing precautions about the specific methods applied.



(a) before compression (b) after compression w/o interstitial material (c) after compression w/ interstitial material

Fig. 1. Physical contact surfaces of two solids in a magnified view.

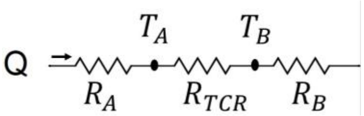


Fig. 2. Schematic diagram of thermal resistance circuit.

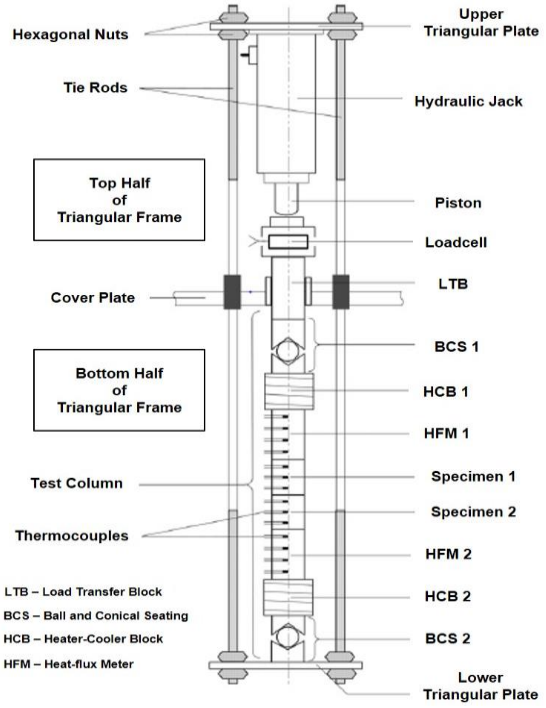


Fig. 3 (a). Experimental apparatus for room temperature measurement of thermal contact resistance [2].

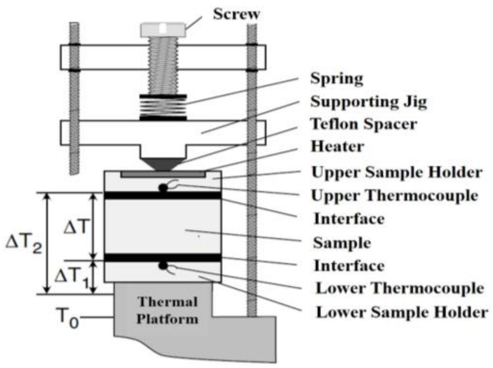


Fig. 3 (b). Experimental apparatus for measurement of thermal contact resistance between 4 K and 300 K [1].

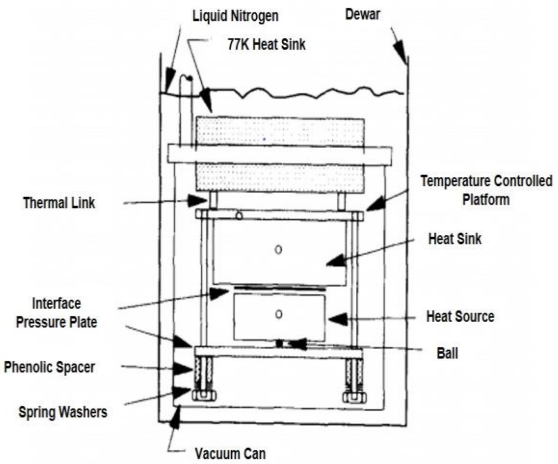


Fig. 3 (c). Experimental apparatus for measurement of thermal contact resistance using liquid nitrogen (N_2) between 77 K and 300 K [4].

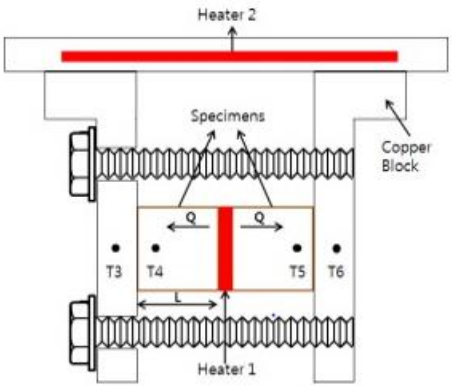


Fig. 3 (d). Experimental apparatus for measurement of thermal contact resistance with horizontally exerted contact force under symmetric situation [5].

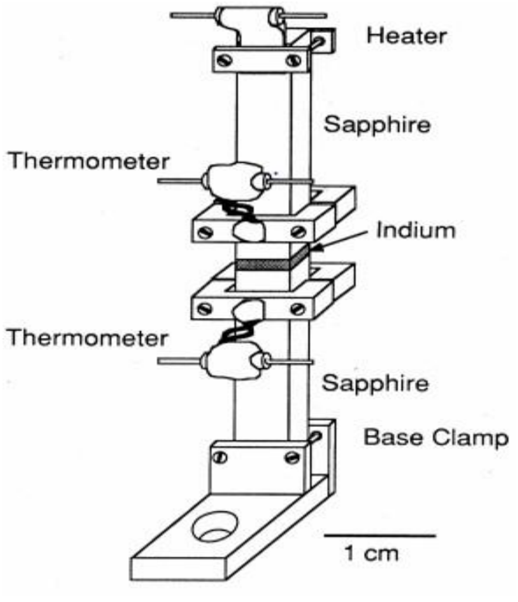


Fig. 3 (e). Experimental apparatus used for measuring thermal contact resistance between indium and sapphire below 5 K [6].

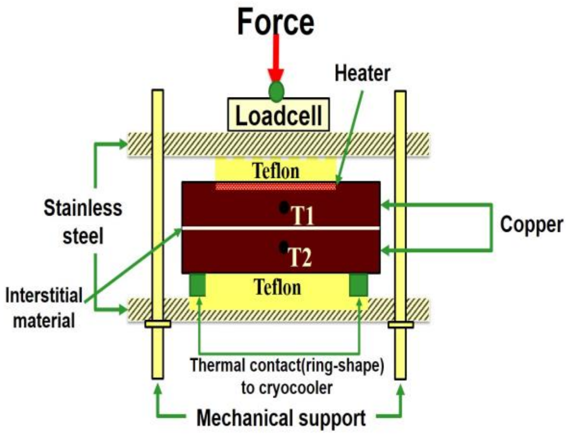


Fig. 3 (f). Experimental apparatus including an in-situ force measurement component for measuring thermal contact resistance.

2. EXPERIMENTAL APPARATUSES

By and large, the quality of metal surfaces is characterized by various factors in view of thermal contact resistance. The complex physical situation makes the theoretical prediction of thermal contact resistance, particularly difficult and inaccurate. Experimental assessment is, therefore, necessary and more useful for practical applications. For the purpose of quantifying the thermal contact resistance values of various cases and evaluating the effect of physical parameter, many experimental apparatuses have been utilized for the measurements as shown in Fig. 3 [1-6]. Fig. 3 (a) is the set-up for room temperature measurement of thermal contact resistance under very high contact pressure (up to 15 MPa) by using a hydraulic jack. Fig. 3 (b) is the sample arrangement with the thermal platform between 4 K and 300 K. The sample temperature is actively controlled by the thermal platform. Fig. 3 (c) is the rather simple experimental set-up using liquid nitrogen for the measurements between 85 K and 300 K. Fig. 3 (d) is the measurement device with horizontally exerted contact force under symmetric situation. All heater power is consumed to raise the temperature of the samples without leak. Fig. 3 (e) is the experimental apparatus used for measuring thermal contact resistance between indium and sapphire below 5 K, but with much small contact pressure compared to the other experiments. Since the contact pressure of the sample at cryogenic temperature is usually created by mechanical screws rather than a hydraulic jack like the room-temperature set-up, the exact value of the contact pressure is uncertain due to thermal contraction and possible change of tightening force of screw. Most experiments have been carried out without measuring the actual contact pressure in the cryogenic experiments. The compressing force is usually estimated by the screw-torque at room temperature assembly. It is, therefore, recommended to include an in-situ force measurement component as shown in Fig. 3 (f) to enhance the accuracy of the contact resistance associated with the pressure. Being similar to Fig. 3 (a), the compressing force is directly measured by a load cell which is preferably located near cryogenic sample.

3. RESULTS

Fig. 4 shows the compilation results of numerous thermal contact resistance measurements under various conditions. The data are presented in terms of thermal conductance so that the values being multiplied by the contact area become the inverse of thermal contact resistance. In this paper, we limit our focus only on the metal contacts of copper in the temperature range higher than 4 K. Although pure aluminum is often used, copper is the most commonly used thermal bridge material for LTS and HTS magnets of conduction-cooling systems. It is interesting that the measurement data are widely scattered due to different preparation protocols as well as diverse techniques applied. Since some experimental data are obtained without specific physical descriptions in detail, we should only refer these values as nominal representative ones. Nevertheless, the data can present the essential characteristics of thermal contact resistance and suggest a practical way to overcome thermal contact problems in general.

The followings are essential physical factors to be considered and investigated for further research to determine thermal contact resistance values of the surfaces.

- Effect of oxide layer
- Contact pressure
- Surface roughness
- Interstitial material
- Cooling temperature
- Amount of filled interstitial material
- Filling of interstitial material before or after pressing

Since it is desirable to minimize thermal contact resistance in most conduction-cooling applications, we will discuss in detail what mechanism can effectively play a key role to reduce unnecessary thermal resistance.

4. DISCUSSION

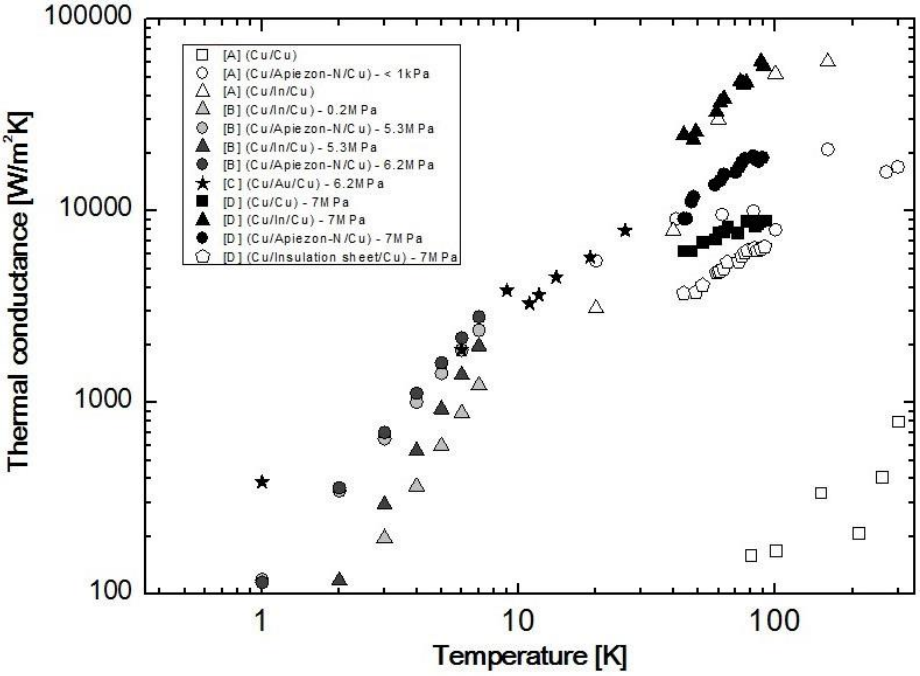
In this section, we would like to point out how to decrease thermal contact resistance in general by explaining some practical sources of the problem. One can avoid undesirable temperature difference between two contacted surfaces by following the suggestions described in this section. Careful and meticulous preparation of the contact surfaces will mitigate most problematic thermal contact issues.

- Effect of oxide layer

The metal surface for contact is usually oxidized unless it is assembled immediately after the two surfaces are machined. The oxide layer of copper is typically composed of CuO or Cu_2O depending on how the surface is prepared. Unless the copper surface is heated at oxygen environment, the oxide layer having much less than 1 micro meter thickness [7, 8] does not contribute significant thermal contact resistance. In the case of anodized aluminum, however, the oxide layer of the surface must be thoroughly removed before assembly for thermal contact because the anodized surface has thermal conductivity of merely 1 W/m·K as an approximate value [9]. Regardless of its material, therefore, it is always a good practice to remove any kind of naturally oxidized layer of the bare surface.

- Surface roughness

The surface roughness basically determines true contact area before any contact pressure is exerted. Considering the magnified view of the two contacted surfaces, we can deduce the small roughness would induce better thermal contact because of the large true contact area. In case of copper, sub-micron roughness value can be readily achievable with lapping or polishing. It is clear that the softer material gets inherently more benefit of surface



[A] No information about contact pressure, surface roughness, interfacial material thickness
[B] Surface roughness: $0.8\mu m$, In thickness: $130\mu m$
[C] Surface roughness: $0.4\mu m$, Au thickness: $0.5\mu m$, Ni thickness: $1.3\mu m$
[D] Surface roughness: $0.21\mu m$, In thickness: $100\mu m$

Fig. 4. Results of numerous reports of thermal conductance [1, 5, 10, 11].

finish treatment, but its effect is more noticeable with contact pressure in association with easier plastic deformation [2]. Therefore, when the contact surface is made of pure copper, it is always wise to polish the mating surfaces as smooth as possible so that they can have effective sub-micron root mean square roughness.

- Contact pressure

In a given geometric contact area of the surface, the actual true contact area depends on the smoothness of surface and the contact pressure. The contact pressure on the surface with certain smoothness invokes elastic or plastic deformation of the original micro-asperities of the surfaces. Theoretical analyses and prediction of the true contact area upon the exerted force or pressure have been extensively done by numerous researchers [12, 13]. As the contact pressure increases from 0.6 to 15 MPa, the thermal contact resistance decreases linearly according to the reference [2]. The sensitivity surely depends on the contact material, its hardness, and its yield strength because the amount of deformed area is different for different material properties. The surface roughness value in the range below 3 micro-meter also influences the sensitivity of thermal contact resistance upon contact pressure [2].

- Interstitial material

It is commonly practiced to fill the gap of contact surfaces with soft interstitial material such as indium, InGa, tin, lead, gold, Apiezon-N grease, Cryocon grease, GE7031 varnish, , Polytec (thermally conductive epoxy), Stycast 2850 epoxy, Araldite, Teflon, etc. The fundamental concept of utilizing soft interstitial material as a filler is to fill the unavoidable micro void between the mating surfaces. The interstitial material with its own thermal conductivity contributes extra thermal contact conductance which is better than the dry contact condition. It is, therefore, preferable to use soft malleable materials of high thermal conductivity with minimum amount just to fill the void space without imposing additional thermal resistance. Liquid with small viscosity is an attractive filler because it can easily penetrate and fill the gap between the contacted surfaces. When it is solidified, however, undesirable void space may occur to negate its filling effect. This problem can get worse if the temperature is lowered and the thermal contraction of the filler material exceeds that of the mating solids. In most cryogenic applications, therefore, soft solids are frequently chosen for interstitial materials. Metallic solids are conveniently used in a variety of processes because they usually have higher thermal conductivities than most liquid interstitial materials. Pure indium or gold with their room temperature thermal conductivities of 86 W/m·K and 317 W/m·K respectively are inherently the best materials. Cryocon grease is supposed to lower the thermal contact resistance by containing copper powder. However, since this powder may hinder further reduction of the gap distance, it may result in poor performance than pure Apiezon-N. Depending on the application circumstance, the type of grease has to be carefully selected. If indium is used for the interstitial material, its surface has to be also thoroughly cleaned and chemically etched to remove the oxide layer [18].

- Cooling temperature

Thermal contact resistance decreases as temperature goes down as shown in Fig. 4. This temperature dependence characteristic is different from that of bulk copper which shows maximum thermal conductivity around 20 K. In the case of bulk copper, thermal conduction is dominated by phonon effect below liquid nitrogen temperature and the phonon scattering at bulk is continuously diminished until the mean free path becomes the order of sample length scale [14, 15]. Since the contacted surfaces of solids, however, always exist like a grain boundary, thermal conduction mechanism of governing thermal contact resistance is easily affected by the boundary scattering. The phenomenon of showing no peak in thermal contact resistance is similar to the behavior of nanowire where thermal conductivity decreases monotonically with temperature [16].

The assembled structure at room temperature experiences thermal contraction when it is cooled-down to cryogenic temperature. The exerted contact pressure may change or the gap between the contacted surfaces tends to increase due to thermal contraction mismatch. This problem becomes worse if the interstitial material is composed of polymer such as grease or epoxy. The initially filled void by grease or epoxy at room temperature may recreate an empty pocket at cryogenic temperature. The thickness of the interstitial material has to be optimized because more polymer interstitial material tends to shrink more.

- Amount of filled interstitial material

As described earlier, the interstitial material is useful to fill the void space between the mated contact surfaces. It is indicated, however, that the extra interstitial material may cause extra thermal resistance because of its smaller thermal conductivity than that of copper. The optimum thickness of the interstitial material is approximately twice of the surface roughness [17] to ensure complete covering of the micro-asperities. The extra amount of interstitial material needs to be easily drained out of the contact surface during assembly process.

- Interstitial material filling before or after pressing

There are three practical methods to apply metallic interstitial materials on the bare contact surfaces [18].

(i) Compression between two surfaces without melting : The interstitial material is placed between the two contacted surfaces and pressure is exerted. Malleability and contact pressure are important parameters to determine the final result of interstitial material because it is spread by force and has to fill the gap as a solid phase.

(ii) Soldered between two surfaces : This process involves in-situ heating of two mated surfaces so that the interstitial material is basically melted and fills the gap with capillary force. This method may require a soldering flux to remove oxide layers on the surface. Since some application may not allow direct heating of the contacted surfaces, this method is limitable, but, if possible, it can produce excellent thermal contact conductance value.

(iii) Cold-welding : This method is an intermediate process between (i) and (ii). The mated surface is pre-coated or soldered with the thin layer of interstitial material. Then, both coated surfaces are thoroughly cleaned, deoxidized, and mechanically compressed to form a flux-free solder joint. The amount of coated interstitial material has to be minimized to avoid extra thermal resistance of the interlayer.

For the best result of thermal contact, the contact surface either it is copper or other metal, must be thoroughly cleaned and sufficiently smooth. This process shall ensure no contaminant left between two mated surfaces. There should be only beneficial interstitial material between them. The rough solid surface is inherently not desirable for good thermal contact, but, if it is in the micron-order range, the thermal contact resistance may be effectively reduced by proper interstitial material and adequate contact pressure. The cleaning process sometimes involves not only physical but also chemical so that there is no oxide layer remained. Interstitial material like indium, gold, or Apiezon-N grease can significantly reduce thermal contact resistance when it is minimally applied. The extra amount of interstitial material in the gap of contact surfaces should not produce negative effect against efficient thermal conduction. Repeating the assembly processes in order to correct unexpected errors with careful visual inspection would outcome a satisfactory result.

5. SUMMARY

This review paper intends to provide valuable and practical information about fundamental characteristics of thermal contact of two solids. The poor thermal contact situation is often encountered critically in various cryogenic practices and ruins the whole system performance. The thermal contact resistance may be negligible if the amount of heat transfer across the contact is small. However, in the case of transient cooling or active cooling of cryogenic components where heat is significantly generated, the thermal contact problem becomes conspicuous and every effort should be made to minimize it. Otherwise, the large temperature difference shall ultimately result in demanding a needlessly large cryogenic refrigeration system. This paper discusses some dominant physical factors that influence thermal contact resistance and suggests how one can overcome thermal contact problem. It is commonly recommended that the contact surface must be flat and have sub-micron roughness level with no oxide layer. The surface can be thinly covered by indium, gold, or Apiezon-N grease for securing sufficient direct contact area for best result. In general, the higher contact pressure, if possible, the lower the thermal contact resistance. Soft interstitial material like Apiezon-N grease, however, is not so sensitive to contact pressure.

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