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Modelling the effective thermal conductivity of compressing structures including contact resistance

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ABSTRACT

A multi-physics simulation-based methodology for estimating the effective conductivity of single or repeated arrays of mechanically deforming structures being compressed between solid planer surfaces is detailed in this work. The proposed methodology utilises Finite Element (FE) simulations to determine the mechanical environment and resulting shape of the deforming structures together with its effective bulk thermal conductivity by simulating the heat transfer through the structure(s). Importantly, the FE model also incorporates the constriction thermal resistance as well as the contact thermal resistance associated with the contact region between the deforming structure(s) and the rigid planer surfaces. The latter is endemically problematic to predict and an approach is proposed which combines accurate multi-physics simulations with precision experiments to estimate the contact resistance in terms of contact pressure on the deforming structure(s). The thermal-mechanical simulation results are compared with experiments for one exemplar geometry verifying the efficacy of the approach. Although illustrated here for determining the effective thermal conductivity, the method is equally valid for determining effective electrical conductivity of deforming electrically conductive structures undergoing compression between rigid planer surfaces.

1. Introduction

Many engineering applications involve the compression of structures between rigid surfaces. In some instances, such as mechanically-attached fins on heat sinks, Thermal Interface Materials (TIMs), solder balls, thermal vias or thermoelectric modules, it is desired or necessary that heat be transferred across the intermediate material. When significant deformation occurs, the effective conductivity of the intermediate material will depend on a complex interaction of the mechanical behaviour of the material and its related thermal behaviour. In particular, the shape of the deformed structure within the compound structure will influence its effective thermal resistance to heat transfer as will the manner in which the material mechanically and thermally interacts with the surface within which it is being compressed. For the latter, constriction and contact thermal resistance can significantly influence the overall thermal resistance.

Surface irregularities are present in nearly all solid surfaces. When two surfaces are brought into contact with each other, these asperities limit the amount of actual contact area between the two objects. The amount of actual contact area depends on the topology of the mating surfaces, the contact pressure and the material properties. For many engineering surfaces, this

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area can be as little as 2% of the apparent contact area [1]. At the macroscopic level, surface issues such as waviness and co-planarity also contribute to the amount of area in actual contact. If the thermal conductivity of the interstitial medium is low compared with that of the contacting solids, then the heat preferably flows through the contact points, causing the low actual contact area. In certain instances, such as mechanically attached fins on heat sinks or attached heat sinks high powered electronic devices, this will result in a non-negligible and undesired thermal contact resistance. This has motivated over a century's worth of basic research into contact resistance in order to gain a fundamental understanding of the phenomenon [1–10], whose estimation is touted as one of the most difficult in the area of heat transfer [8,9]. Additionally, the issue of thermal contact resistance has spawned a global effort towards the development of novel thermal TIM technologies [11–14] creating a global market that reached $715.9 million in 2014 [15].

At the microscale, the contact resistance is due to both the low area of intimate contact area as well as the constriction thermal resistance [16], which is the effective blockage to heat flux associated with the scenario where heat flows from a region of low cross sectional area to one of a larger cross sectional area. The term constriction refers to the narrowing of the iso-flux lines when heat flows into a narrower region. Related to this is the spreading resistance which is the expanding of the iso-flux lines when heat flows from a narrow region to a larger cross sectional area region. However, the constriction/spreading resistance (heretofore referred to as constriction resistance) is not isolated to the microscale and is an important consideration whenever there is a large mismatch between the cross sectional areas thermally communicating bodies. Many studies exist aimed at approximating the constriction resistance for various scenarios [e.g. [16–24]]. In many instances of practical importance, such as electronics cooling, the constriction resistances may in fact be greater than that offered by the intermediate material, and this represent an important component of the overall effective thermal resistance of the compound structure or thermal system. Heat spreaders, aimed at mitigating the constriction resistance, are thus commonplace in many technologies, especially high power density electronic packages and systems [25,26].

When dealing with the issue of contact and constriction resistances, elastic and plastic deformation of the mating surface structures plays a major role in the heat transfer [8,26,27]. The regions of deformation between the contacting bodies not only define the regions of intimate contact and thus the true contact area, but the resulting shape of the deformed structure will determine the effective resistance to heat transfer through the structure itself i.e. a flattening structure will have progressively larger cross-sectional area and thus lower thermal resistance. However, there is much less known about larger scale deformation in composite structures, especially those with multiple contact points e.g. thermoelectric modules, ball grid arrays, solid state TIMs. For the latter, Kempers et al. [28] recently reported a new high performance TIM technology that relied on the plastic deformation of arrays of small scale raised feature that were formed on metallic foils. The determination of the effective thermal conductivity relied on information about the bulk thermal resistance of the TIM material during compression as it plastically deformed, which required simulation of the deformation mechanics of the structures [29]. However, it was not possible to theoretically predict the contact resistance with applied contact pressure so an empirical approach, using the electrical contact resistance, was used [28,30,31] which is not ideal.

The discussion above indicates that significant knowledge exist with regard to contact and constriction resistance, the former being one of the more difficult heat transfer processes to approximate when considering mechanical design of thermal packages and systems. Furthermore, there is very limited literature on the topic of the thermal characteristics of composite 'sandwich-type' structures which are formed by compressing and deforming an intermediate material with multiple contact points with the compressing structures. In the context of the effective thermal resistance of the composite structure, each the contact resistance, constriction resistance and that associated with the deformed shape of the material must be considered. Considering this, the objective of the present work is to propose a new methodology for predicting the effective thermal resistance of composite structures where the intermediate material undergoes significant mechanical deformation.

2. Analytic and multi-physics finite element models of simple structures

Initially, a simple analytical model is discussed as an exemplar which demonstrates the relevant features of a thermal model that accounts for the deformation of an array of compressed features and is able to estimate the effective thermal conductivity throughout the deformation process. The simple model also serves as an initial validation model for the multi-physics FE modelling approach.

2.1. Analytical thermal model formulation

Consider an array of identical small solid cylinders being compressed between rigid solid structures with a fluid in the interstitial spaces. Since array consist of identical repeating features, the model can be simplified by considering a single unit-cell of the larger array, as shown in Fig. 1.

Assuming one-dimensional heat conduction, the thermal resistance, R_{total}, of this unit-cell is independent of heat flux direction can be modelled as two resistances in parallel and is given by:

$$\frac{1}{R_{total}} = \frac{1}{R_{fluid}} + \frac{1}{R_{solid}} \tag{1}$$