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Thermal contact conductance and its dependence on load cycling

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ABSTRACT

Heat transfer between contacting surfaces is an important factor in the thermal behaviour of engineering components in turbomachinery and various other areas of technology. Thermal contact conductance (TCC) is a parameter that quantifies this heat flow. Any theoretical prediction of TCC should take into account the effects, if any, introduced by repeated loading and unloading. This study aims to add to the limited volume of work available on this topic in the literature. In particular, the focus of this investigation is machined surfaces that typify the mating surfaces in some turbomachinery applications. Experimental work investigating the effect of loading and unloading history for numerous cycles is presented. An instrumented split tube with in line washers, loaded and unloaded under carefully controlled conditions, was used to measure the TCC of washers made of nickel alloy PE16 and 316 stainless steel. The study also examines the load cycle effect on TCC for a variety of interface surface geometries and pressures that are relevant to turbomachinery applications. The results show that load cycling, beyond the first cycle, has a minimal effect on TCC, in disagreement with other studies in the literature. This observation is seen for variety of surface topographies and maximum contact pressures.

1. Introduction

When heat flows across the interface between two contacting bodies, a temperature discontinuity occurs at the interface. Thermal contact conductance (TCC) is the parameter that quantifies the conductive heat flow across such contacting interfaces. An understanding, and measurement, of TCC is necessary in a variety of engineering fields such as the automotive, microelectronics, metalworking and gas turbine industries. The importance of this topic is indicated by the publication of major reviews, see for example [1,2].

The effect of surface roughness, material properties and applied load on the first realisation of TCC is well documented in the literature (see, for example, [3–5]). Numerous amount of work has been carried out to study the deformation analysis of the contacting asperities. Among the pioneers of this study are Greenwood and Williamson [6] and Mikic and Rohsenhow [7]. Based on the deformation theories proposed by Greenwood and Williamson and Mikic and Rohsenhow, numerous theoretical studies have attempted to predict the effect of various parameters on the TCC of flat conforming surfaces [7–9]. Greenwood and Williamson [6] describes the deformation of the asperities based on the elastic theory, while Mikic and Rohsenhow [7], Cooper et al. [8], and Yovanovich [9] predict the contact conductance on the assumption that the deformation mode of the contacting asperities are plastic. Little work is available on the TCC of non conforming wavy surfaces [10–12]. A recent study by Gopal et al. [13] demonstrated the importance of understanding the effect of various length scales on TCC of machined mating interfaces in some gas turbine applications. The study proposed a convenient way to model the surface geometries of a machined surface in a simple yet accurate manner. The finite element modelling approach presented by Gopal et al. offers the possibility of estimating the effect of machined geometry on TCC for gas turbine components during loading.

In real applications, a component is exposed to diverse loads and temperature over time. One specific complication is the subjection of an interface to load cycling and the implications for TCC. From the limited literature available, it appears that TCC is influenced by operational history. Li et al. [14] conducted a study to enhance the TCC of joints. In their study it was argued that there is an increase in TCC with loading history. Stainless steel was loaded and unloaded for numerous cycles between pressures of 0.845–6.425 MPa. Increments in TCC of up to 16% were observed in the first five load cycles and a further 2% up to the 30th cycle. A similar study was conducted by Wahid and Madhusudana [15] and a similar conclusion was made. They reported an increment of 10% in TCC values for the first 25 cycles. Both of these studies argue that the operational effect on TCC is important for at least the first 20 cycles. The load cycle effect was explained in terms

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Nomenclature

C	integration constant
C_c	non-dimensionalised conductance
k	thermal conductivity
m	mean asperity slope
m_a	effective mean asperity slope
n	number of washers
NT	number of thermocouple
q	axial heat flux
T	temperature
TCC	thermal contact conductance
t	thickness of washers
z	location co-ordinate along steel cylinder axis
ΔT	temperature drop
δk	uncertainty of thermal conductivity
δq	uncertainty of heat flux
δT	temperature uncertainty
δT_o	uncertainty of thermocouple reading
δTCC	uncertainty of TCC value
σ	RMS surface roughness
σ_q	effective RMS surface roughness

Subscripts

an	analytical
avg	average value of hot and cold cylinder
cold	lower steel cylinder
ex	experimental
hot	upper steel cylinder
i	the *i*th thermocouple location
TW	tube washer interface
t	steel cylinder
W	washer
WW	washer–washer interface

Superscript

j	the *j*th iteration

of a different deformation mode operating for the contacting asperities during different cycles [14,15]. The current study presents data that contradict these earlier findings.

To make valid conclusions about the various factors affecting TCC, it is critically important that the inevitable errors in measurement are calculated realistically. The common experimental set up uses a steady state method with thermocouples embedded in cylindrical bars. The major source of errors associated with this set up is the measurement of the temperature difference between the interfaces in contact. Accuracy of the experiment improves with larger temperature drop across the interface. Another common source of error with this set up is the simplifying assumption that the thermal conductivity is constant across the entire assembly. Large quantities of experimental work available in the literature assume constant thermal conductivity across the entire assembly, for example see [3–5,14,15].

This paper makes use of a rigorous uncertainty analysis and uses a data reduction technique developed originally by Chen [16] to account for the variation of thermal conductivity with temperature. Having addressed these two issues, this paper then investigates the variation of TCC with load cycling for both 316 stainless steel and nickel alloy PE16. Various surface geometries are examined in order to facilitate comparison with previous studies and to extend the work to machined surfaces, which typify those found in some turbo machinery applications.

2. Data reduction technique for calculation of TCC

A detailed description of the experimental procedure, including the methodology for TCC calculation and the surface characterisation of the specimens has been reported by Gopal et al. [13]. A brief description is given below.

A split tube experimental apparatus as shown in Fig. 1 was used, where washer specimens are located in between two steel cylinders. Thermocouples are embedded in these steel cylinders for temperature measurement. To generate the axial heat flow, a band heater was fitted to the top steel cylinder and a water cooler was fitted to the bottom steel cylinder. This assembly was insulated using foil wrapped glass wool cladding. The entire rig was placed inside an Instron machine for controlled loading and unloading of the samples. For a detailed explanation of the testing procedure see Woodland [17].

Based on this test set up TCC values are obtained by calculating the heat flux across the entire assembly and dividing it by the temperature drop across the interface as shown in Eq. (1). Regression analysis is used to extrapolate the thermocouple measurements to get the steel cylinder interface temperature. This is then used to calculate the temperature drop across the washer interfaces. For a one dimensional steady state heat transfer, without internal heat generation or heat loss, heat transfer can be defined by Eq. (2).

$$\mathrm{TCC} = \frac{q_{avg}}{\Delta T} \tag{1}$$

$$q = k_t\left(\frac{dT}{dz}\right) \tag{2}$$

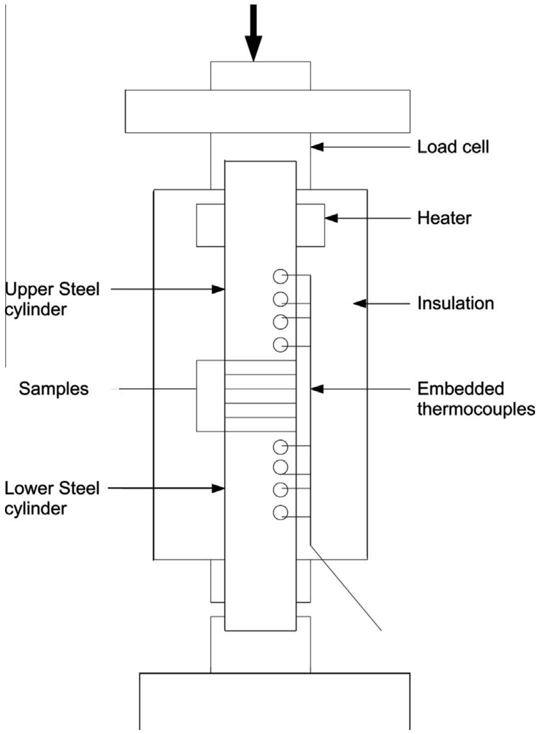

Fig. 1. Schematic of experimental set up.