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Experimental Study and Modeling of Thermal Contact Resistance Across Bolted Joints

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A simple, closed-form model to predict thermal contact resistance of a bolted joint has been developed using a finite element analysis. The plates are of the same thickness and material. The plates are assumed to be smooth and flat. Experiments, using oxygen-free copper plates of various thickness, were performed to study the effects of various parameters on the bolted joint thermal resistance. The comparison between the predicted and the measured resistance shows good agreement.

Nomenclature

a = bolt hole radius
b = bolt head/washer radius
c_1 = correlation constant
E = modulus of elasticity
k = thermal conductivity
L = plate width
P = contact pressure
Q = heat flow rate
R = thermal resistance
r_c = contact radius
T = temperature
t = plate thickness
v = Poisson's ratio

Introduction

PREDICTING heat transfer characteristics across bolted/riveted joints at present remains a largely unestablished area, despite nearly three decades of research effort by various authors.[1] This presents a significant design challenge to thermal packaging engineers, as the contact resistance is often identified as a critically contributing element in the total thermal resistance path.

The difficulty in understanding the bolted joint contact resistance arises mainly from the large number of associated parameters: 1) plate thicknesses; 2) flatness and roughness of plates and washer; 3) plate hole radius; 4) washer radius; 5) bolt hole spacing; 6) mechanical properties of plates, bolt/washer; 7) modulus of elasticity; 8) Poisson's ratio; 9) microhardness; 10) thermal conductivity of plates and interstitial fluid/gas; and 11) mechanical loading/bolt torque.

Some fundamental research effort exists[2–4] where a methodology is outlined (with some specific examples) to bring these parameters together to predict the heat transfer characteristics. While these models provide qualitative understanding of various parametric effects, their accuracy remains to be verified due to the lack of available experimental data. Some of the published experimental works are by Refs. 5–8.

A successful contact resistance research necessitates a clear understanding of two underlying physical phenomena: 1) plastic/elastic deformation of solids necessary in order to predict the macro- and microcontact areas; and 2) thermal constriction/spreading resistance on both macro- and microscopic scales.

There have been some studies performed which deal separately with each of the above two areas for bolted joints; on the analysis of contact pressure and area[9–12] and on the thermal constriction resistance[1,13,14] At present, there exists no simple, closed-form bolted joint contact resistance model which accounts for both the mechanical and thermal aspects. Because of the number and interrelation of the parameters involved, it is difficult to foresee any formulation of general purpose contact resistance model for bolted joints. However, there exists a special case where the analysis is significantly simplified. When the two mating plates are of the same thickness and material, the size of the contact area can be accurately predicted using an existing simple model. The thermal

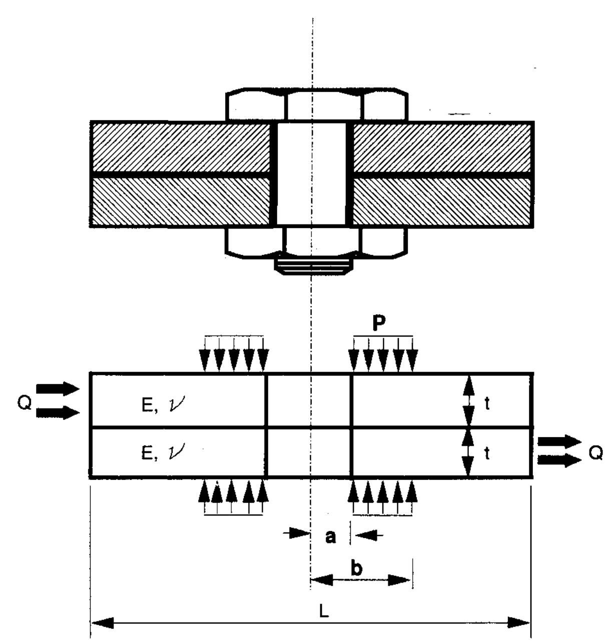

Fig. 1 Bolted joint contact parameters.

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analysis for this case is relatively simple due to the symmetry condition.

In the present work, bolted joints formed by two smooth and flat plates of the same thickness and material are considered. Figure 1 shows the configuration studied and the related parameters where a, b, and t are bolt hole radius, bolt head/washer radius, and plate thickness, respectively. The material properties E and υ are modulus of elasticity and Poisson's ratio. The plates are overlapped covering a common area of $L \times L$. The bolt torque is assumed to result in a uniform pressure p distributed over the area under the bolt head/washer. Q enters the left edge of the top plate and exits from the right edge of the bottom plate.

A simple closed-form model is developed to predict thermal resistance of the bolted joint. An extensive experimental study was also conducted to show the dependence of thermal resistance upon loading pressure/bolt torque, loading area/washer radius, and the plate thickness. The results of these tests are compared with the model predictions.

Thermal Contact Resistance Model Development

For the configuration shown in Fig. 1, the radius of contact area for flat and smooth plates can be accurately estimated by[15,16]:

$$r_c = b + (t/2) \tag{1}$$

This equation is particularly accurate for $b/t > 0.5$. It is important to note from the equation that, for plates of the same thickness and material, the contact radius is independent of the material type. Furthermore, if the plates are flat and smooth, the size of the contact area does not depend upon the contact pressure (or the bolt torque level). The size of the bolt hole does not significantly affect the contact radius for b/a greater than about 1.5.

A thermal model for which a solution is sought is shown in Fig. 2. Isothermal boundary conditions are imposed on the top left and the bottom right edges covering the areas $t \times L$. Midplane of the model is insulated, with exception of the center annular area of radius r_c, where perfect contact is assumed. Because this model involves both circular and rectangular geometries, it is very difficult to obtain an analytical solution. Instead, finite element modeling (FEM) analysis was used to solve for the thermal resistance over ranges of the contact radius and the plate thickness. A correlation based on the FEM results was then developed to predict the bolted joint thermal resistance.

Table 1 Overview of FEM analysis parameters

Parameter	Range
L	25.4 mm
t	1.59–12.7 mm
a	2.0 mm
r_c	3.0–12 mm
k	398 W/m-K

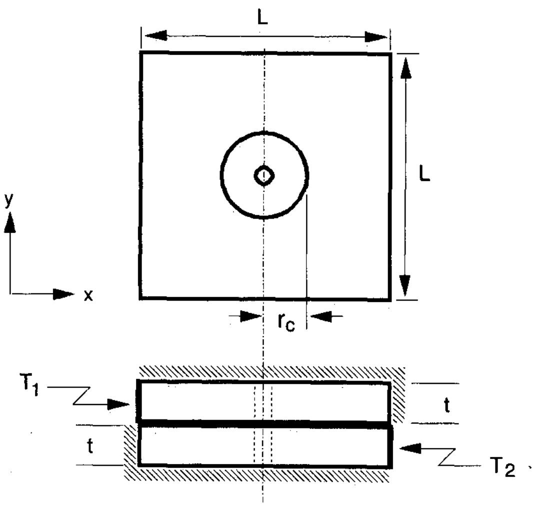

Fig. 2 Bolted joint thermal resistance model.

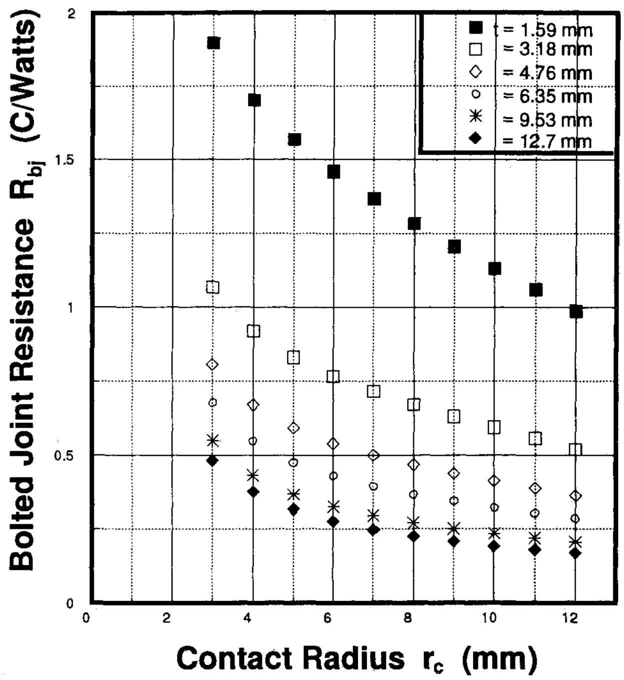

Fig. 3 FEM Computed bolted joint resistance.

Table 1 shows the parameters varied in the FEM analysis. The results from the analysis were reduced to bolted joint resistance defined as

$$R_{bj} = \frac{T_1 - T_2}{Q} \tag{2}$$

where T_1 and T_2 are as shown in Fig. 2, and Q is the total heat flow rate. Figure 3 summarizes the contact resistances, over a range of plate thickness and contact radii, computed from the FEM thermal analysis. These results were used to formulate a simple correlation.

First it was assumed that the thermal resistance consists of the sum of two terms, one representing the bulk resistance in the major direction of heat flow, and the other representing the constriction effect:

$$R_{bj} = R_{constriction} + R_{bulk} \tag{3}$$

The bulk resistance is associated with the x direction (Fig. 2) heat flow, through a rectangular block with dimensions, $L \times L \times 2t$, with perfect contact area, $L \times L$:

$$R_{bulk} = \frac{L}{2ktL} = \frac{1}{2kt} \tag{4}$$

The constriction term involves a ratio of two characteristic dimensions, $\sqrt{tL}$ and r_c. Without any further justification the following functional form was tried to represent the constriction term:

$$R_{constriction} = \frac{1}{c_1} + \frac{1}{kt}\frac{\sqrt{tL}}{r_c} \tag{5}$$

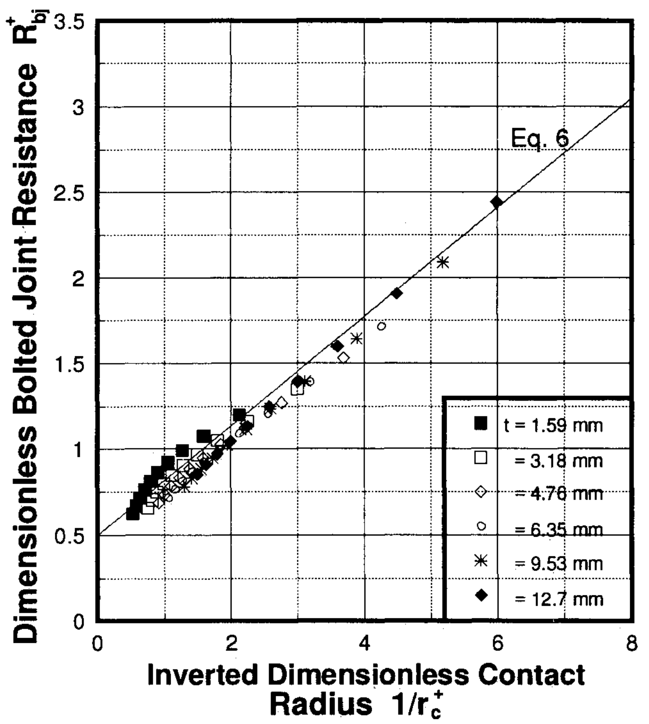

Fig. 4 Correlation of thermal FEM results.

Equation (3) can now be written in a dimensionless form

$$R^+_{bj} = (1/c_1)(1/r_c) + \tfrac{1}{2} \tag{6}$$

where $R^+_{bj} = R_{bj}tk$ and $r^+_c = r_c/\sqrt{tL}$.

When Eq. (6) is correlated to the results of the FEM analysis, a value very close to π for the constant c_1 provides an excellent fit. Figure 4 shows the comparison between Eq. (6) with $c_1 = \pi$ and the FEM results of Fig. 3.

Our final equation for predicting a bolted joint thermal resistance is obtained by substituting Eq. (1) for r_c in Eq. (5) with $c_1 = \pi$:

$$R_{bj} = \frac{1}{kt}\left\{\frac{\sqrt{tL}}{\pi[b + (t/2)]} + \frac{1}{2}\right\} \tag{7}$$

The accuracy of this model will be verified by experimental data in a subsequent section.

Experimental Program

The purpose of this experiment was to study the effect of various parameters upon the bolted joint thermal resistance. The ranges of the parameters studied are listed in Table 2.

The experiment itself was performed in a vacuum chamber. The test assembly consisted of a heater block, cold plate, load cell, and upper and lower specimens (Fig. 5). The heater block contained a single heater cartridge providing an output power of up to 80 W. The cold plate consisted of a copper block cooled by a closed loop water recirculation unit. The pressure applied to the washer by the bolt torque was monitored using a piezoelectric load cell. Six "T-type" thermocouples, three on each specimen, were used to measure the temperature distributions.

The test specimens were prepared from oxygen-free copper bars (thermal conductivity, 398 W/m-K, yield strength, 34.7 MPa). The bars were machined into single plates 76.2-mm long, 25.4-mm wide; the thickness was varied from 1.6 to 6.4 mm. An M4 clearance hole (4 mm in diameter) was drilled through each plate for the bolted connection and three thermocouple holes were drilled 9.65-mm apart. The flatness of the plates was within 5 μ, and the rms roughness within 0.5 μ as measured with an interferometer and a surface profilometer. Special bolts were prepared from stainless steel. Washers, 6.35-mm thick and varying in diameter, were prepared from tungsten to produce evenly distributed pressure on the test plates.

A typical thermal measurement is shown in Fig. 6. Temperature measurements on each specimen were fitted to a straight line. Then projected temperatures at points 1 and 2 were obtained from the fitted lines of the two specimens. The difference between the two projected temperatures was divided by the heat flow rate to yield the bolted joint resistance R_{bj}. The heat flow rate was taken as the average of two estimates calculated using the temperature gradients and the thermal conductivity of two plates. Typical temperature range in the experiments for points 1 and 2 in Fig. 6 was between 30–50°C.

The source of greatest experimental uncertainty was with estimating Q. The comparison of heat flow rate measurements between two independent means, one using the electrical power input to heater cartridge, and the other using the temperature gradient of copper plates, showed maximum difference of about 10% for the experiment with 1.59-mm-thick plates. This translates into maximum R_{bj} measurement uncertainty of about 10%.

Table 2 Overview of experimental parameters

Parameter	Range
L	25.4 mm
t	1.59–12.7 mm
a	2.0 mm
b	3–6 mm
P	6.9–27.6 MPa
Plate yield strength	35 MPa
k	398 W/m-K

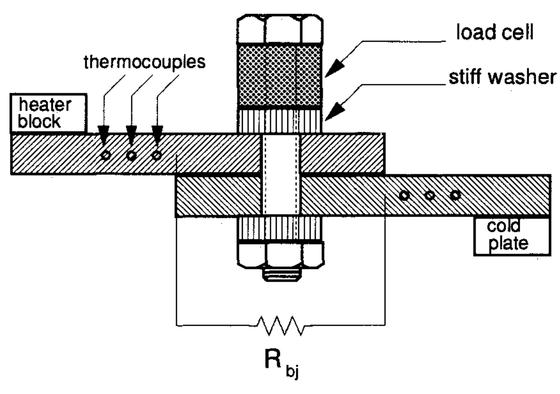

Fig. 5 Experimental setup.

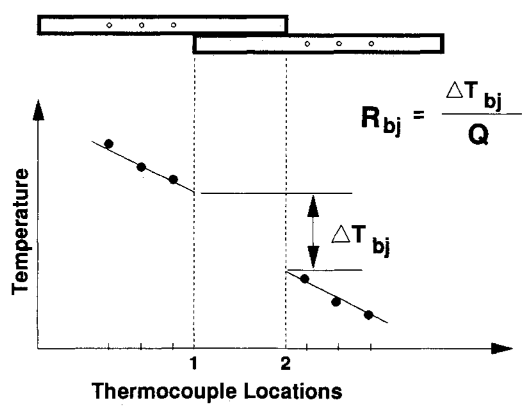

Fig. 6 Data reduction.

Experimental Results

Figure 7 shows the bolted joint resistance measurements over the load pressure and washer radius ranges. Experiments were performed for four different pairs of plate thicknesses (1.59, 3.18, 4.76, and 6.35 mm). For the purpose of clarity, measurements for only three different thicknesses are shown in the figure.

It is seen from the figure that, as predicted, the bolted joint thermal resistance is nearly independent of the contact pressure. At a light contact pressure ($P < 15$ MPa), however, a trend is observed that the resistance slightly decreases with the increase in pressure. This trend is more visible for thicker plate pairs. It is speculated that since the test specimens are not perfectly flat, some level of pressure is required to force the plates to come to an initial contact.

Figure 8 shows the bolted joint resistance measurements over washer radius range for all four different plate thicknesses. It is clearly shown that the resistance decreases with an increase in the washer size, likely due to the increase of contact area. Also shown in the figure are bolted joint resistance predictions made by Eq. (7). The agreement between the predicted and the measured values of the thermal resistance is good. However, the measured resistance values are consistently lower than the model predictions. The greatest difference between the measured and the predicted resistance values is observed with the thinnest plate pair (t = 1.59 mm) and with the smallest washer radius (b = 3 mm). This trend appears to be due to the fact that the plates are not perfectly smooth. The roughness of plates results in the effectively larger macroscopic contact area than that assumed with smooth plates, thus resulting in the lower macroscopic constriction resistance. The roughness of plates also plays an important role in the microscopic contact area, in which case one observes dependence of contact resistance greatly upon the contact pressure. However, in the present experimental scope, there is no significant contact pressure effect upon the bolted joint resistance (Fig. 7), and therefore, it is concluded that there appears to be no significant roughness effect related to microscopic contact area.

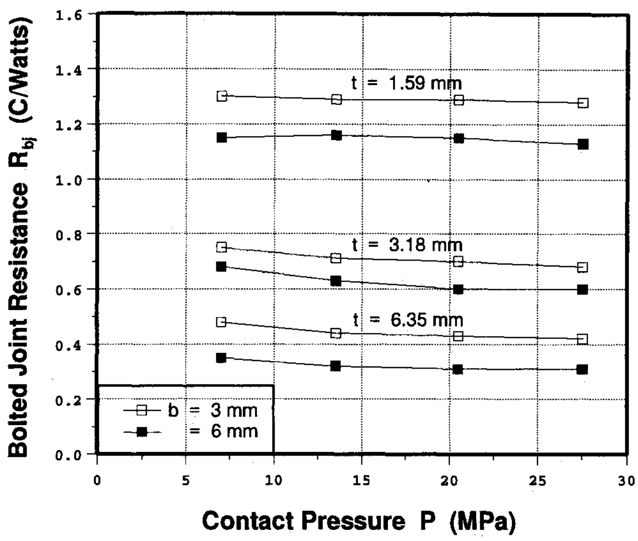

Fig. 7 Bolted joint resistance measurements.

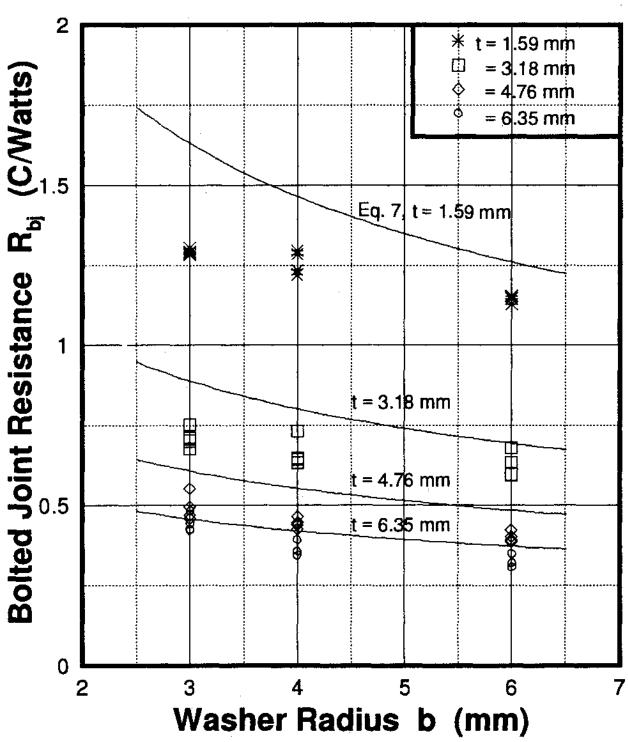

Fig. 8 Comparison of resistance predictions and measurements.

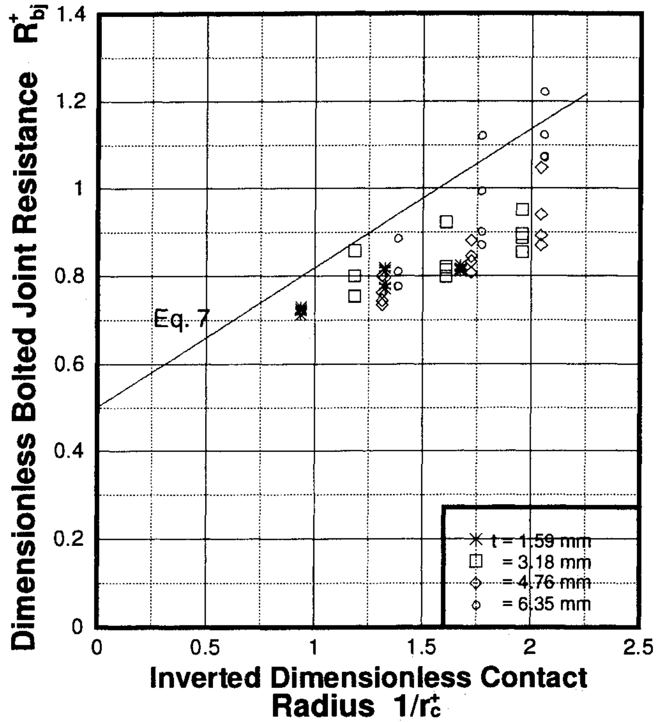

Fig. 9 Dimensionless resistance predictions and measurements.

Figure 9 shows the comparison between the measured and predicted bolted joint resistances in terms of dimensionless parameters. Again, the model tends to overpredict (and therefore, is conservative for design purposes) the bolted joint resistance, with the maximum difference of about 30% from the measurements.

Summary

A simple, closed-form model has been developed which predicts the bolted joint thermal resistance of two flat, smooth plates of the same thickness and material. According to the model, the contact resistance, under the currently assumed conditions, depends upon four parameters; the width, thickness, and the thermal conductivity of the plates, and the size of the bolt head or washer. The model indicates that the resistance is independent of the bolt torque and material properties other than the thermal conductivity.

Experiments were performed to study the effects of various parameters on the bolted joint thermal resistance. The comparison between the measured and the predicted resistance shows good agreement.

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