Simple evaluation method for temperature drop at contact interface between rough surfaces under low contact pressure conditions

Toshio Tomimura1,3, Yasuo Takahashi2, TaeWan Do1, Kensei Shigyo1 and Yasushi Koito1

1 Department of Advanced Mechanical Systems, Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto, 860-8555, JAPAN

2 Joining and Welding Research Institute, Osaka University, 2-1Yamada-Oka, Suita, Osaka, 565-0871, JAPAN

3 To whom any correspondence should be addressed.

E-mail: tomi@mech.kumamoto-u.ac.jp

Abstract. For heat removal from systems such as electronic equipment, satellite thermal control systems, and nuclear reactors, reduction of thermal contact resistance (TCR) is the most crucial issue to be addressed. Several studies have attempted to propose evaluation equations for predicting TCR for flat rough surfaces. However, as is well known, there are still wide discrepancies among measured results, even for similar materials. In this study, based on the conventional unit cell model for flat surfaces with roughness and the newly proposed contact surface model for wavy surfaces with roughness, thermal contact resistance under a low contact pressure of 0.1–1.0 MPa is investigated theoretically and experimentally. Comparison of the measured and calculated results shows that the measured temperature drop at the interface (that is, the thermal contact resistance) between flat surfaces with roughness lies between the values evaluated by the unit cell model for the cases with and without the heat flow constriction. Furthermore, when the rough surface has waviness, the introduction of macroscopic constriction resistance is shown to be important for evaluating the temperature drop at the interface.

1. Introduction
In electronic or electric equipment with high heat fluxes, heat transfer modes such as heat conduction, convection, and thermal radiation play an important role in heat removal from the high-temperature regions of the equipment. In addition to these heat transfer modes, thermal contact resistance (TCR) inevitably occurs at the solid–solid contact interface, and these four modes are apt to be coupled intricately.

Several studies have been conducted to propose evaluation equations for predicting TCR for flat rough surfaces. However, as pointed out by Fletcher [1], Torii and Yanagihara [2], Torii [3], Okada and Matsumoto [4], and Madhusudana [5] et al., there are still wide discrepancies among measured TCRs, even for similar materials. In our previous study [6], to investigate the key factors for the
discrepancies, a fundamental analysis was undertaken using a simple contact surface model, which was composed of the unit cell model proposed by Tachibana [7] and Sanokawa [8] and the Hertzian contact model [9]. Based on a series of numerical calculations and measurements, the effects of surface waviness and measured positions of specimen temperatures on TCR measurement were clarified. Furthermore, based on our study using a two-dimensional microscopic surface model, which consists of random numbers and Abbott’s bearing area curve [10], the effects of surface waviness and roughness on the temperature fields near the contact interface have been clarified microscopically.

In this study, to obtain a simple evaluation equation for TCR for flat or wavy rough surfaces, theoretical and experimental investigations were conducted under a lower mean nominal contact pressure of 0.1–1.0 MPa.

2. Physical models for flat and wavy surfaces with roughness

In this section, two types of surface models are investigated theoretically. The first model is the conventional unit cell model for macroscopically flat surfaces with roughness; the resultant equations for evaluating TCR and thermal contact conductance (TCC), which is the reciprocal of TCR, are shown in an organized form. The second model is a newly proposed simple model for macroscopically wavy surfaces with roughness. In this model, by assuming a parallel heat flow through the central solid–solid contact zone and the outer torus-shaped air zone surrounding the central zone, simple evaluation equations for TCC and TCR are derived.

2.1. Unit cell model for flat surfaces with roughness

The unit cell model proposed by Tachibana [7] was introduced according to the process explained in Figure 1. Figure 1(a) shows a magnified image of the solid–solid contact interface. Macroscopically, a discontinuous temperature drop $\Delta T (= T_{ih} - T_{ic})$ is observed at the contact interface; this phenomenon is called the thermal contact resistance. Here, $T_{ih}$ and $T_{ic}$ are the extrapolated interface temperatures obtained based on the measured temperatures for each solid. Microscopically, however, the temperature is supposed to change smoothly in the vicinity of the interface, as indicated at the broken line. On the other hand, Figure 1(b) shows the contact surface model for the interface of Figure 1(a). In this model, the solid–solid contact through the surface roughness is physically expressed by cylinders with the same height of the surface roughness as that shown in Figure 1(a). Furthermore, these cylinders are assumed to be uniformly distributed over the solid surface and have the same whole contact area as the true contact portions. Since TCR based on the heat flow rate per unit area (that is, the heat flux) is equivalent to that of the unit cell shown in Figure 1(c), it is sufficient to consider the heat flow through the unit cell.

![Figure 1. Unit cell model.](image-url)
As shown in Figure 2, the TCR of the unit cell model $R$ is obtained by taking into account the parallel connection of the thermal resistances caused by the cylinder and the intervening substance (in this study, the air), denoted by $R_c$ and $R_i$, respectively. In the figure, $Q$, $Q_s$, and $Q_i$ are the heat flow rates through the unit cell, cylinder and intervening substance, respectively; $A$ and $a$ are the cross-sectional areas of the unit cell and cylinder, respectively; $\lambda$ is the effective thermal conductivity of the contacting portion surrounded by the broken line; and $\lambda_i$ is the thermal conductivity of the intervening substance. In addition, $\lambda$, $\delta$, $T$ and $H$ are the thermal conductivity, maximum surface roughness of the solid surface, surface temperature, and hardness (Brinell or Vickers [11]) of the solid, respectively, and the subscripts 1, 2, and $i$ denote Solid 1, Solid 2 and the contacting portion of the cylinders, respectively. Here, the relation between the maximum surface roughness of the solid surface $\delta$ and the center line average roughness $Ra$ is given by $\delta \cong 4Ra$ [11].

Based on Fourier’s law of heat conduction and the energy conservation law, which should be satisfied for $Q$, $Q_s$, and $Q_i$, and under the assumption that all the isothermal lines are parallel to the solid–solid contact interface, Tachibana [7] obtained the following evaluation equation for the TCR $r$ [m²·K/W] for flat surfaces with roughness.

$$\frac{1}{r} = \frac{1}{\delta_1 + \delta_2} \frac{a}{A} + \frac{\lambda_i}{\lambda_1 + \lambda_2} \frac{A-a}{A}$$

(1)

Here, the relation between the TCR $R$ [K/W] and the resistance $r$, which is derived based on the heat flux (that is, $Q/A$, $Q_s/a$ and $Q_i/(A-a)$) is given by

$$r = AR.$$  

(2)

On the other hand, to take into account the increase in the thermal resistance due to the contraction and expansion of heat flow through the cylindrical portion of the unit cell, Sanokawa [8] proposed the following equation. In this equation, the additional thermal resistance $1/h_0$ caused by the constriction of the heat flow is introduced in the denominator of the first term on the right-hand side of equation (1).

$$\frac{1}{r} = \frac{1}{\delta_1 + \delta_2} \frac{a}{A} + \frac{\lambda_i}{\lambda_1 + \lambda_2} \frac{A-a}{A}$$

(3)

Here, based on a series of theoretical and experimental studies, the additional term $1/h_0$ is given by

$$\frac{1}{h_0} = 2.3 \times 10^{-3} \left( \frac{1}{\lambda_1} + \frac{1}{\lambda_2} \right).$$

(4)

The ratio of the true contact area to the apparent contact area $a/A$ included in the right-hand side of equations (1) and (3) can be replaced with the following equation [7, 8].

$$1/R \text{ (Whole)} = 1/R_c \text{ (Cylinder)} + 1/R_i \text{ (Interface material)}$$

Figure 2. Thermal contact resistance of unit cell model.
Here, \( p_m \) is the mean nominal contact pressure defined by dividing the axial load \( f \) by the apparent contact area \( A \), and \( H_{\text{min}} \) denotes the smaller of the hardness values of Solid 1 and Solid 2. Based on the above discussion, the following equations can be obtained for the TCC \( k \), which is the reciprocal of the resistance \( r \).

\[
\frac{a}{A} \approx \frac{p_m}{H_{\text{min}}} \tag{5}
\]

Furthermore, with the introduction of the three types of thermal conductance with regard to the cylindrical portion without and with heat flow constriction, denoted by \( k_{TE,s} \) and \( k_{SE,s} \) respectively, and the intervening substance, denoted by \( k_t \), equations (6) and (7) can be expressed by the following equations, respectively.

\[
k_{TE} = k_{TE,s} + k_t \quad \text{(Tachibana’s equation)} \tag{8}
\]

\[
k_{SE} = k_{SE,s} + k_t \quad \text{(Sanokawa’s equation)} \tag{9}
\]

Here, \( k_{TE,s}, k_{SE,s} \) and \( k_t \) are given as follows:

\[
k_{TE,s} = \frac{1}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} \frac{P_m}{H_{\text{min}}}} \quad \text{(Cylindrical portion without heat flow constriction),} \tag{10}
\]

\[
k_{SE,s} = \frac{1}{\frac{\delta_1}{\lambda_1} + 2.3 \times 10^{-5} \left( \frac{1}{\lambda_1} + \frac{1}{\lambda_2} \right) + \frac{\delta_2}{\lambda_2} \frac{P_m}{H_{\text{min}}}} \quad \text{(Cylindrical portion with heat flow constriction)} \tag{11}
\]

and

\[
k_t = \frac{\lambda_t}{\delta_1 + \delta_2} \left( 1 - \frac{p_m}{H_{\text{min}}} \right) \quad \text{(Intervening substance).} \tag{12}
\]

Equation (4), which gives the additional term \( 1/h_0 \) is obtained under a mean nominal contact pressure of approximately 1.0–10 MPa. This pressure range is almost one order of magnitude higher than that targeted here. Therefore, in this study, the extension and applicability of Tachibana’s equations (6) or (8) and Sanokawa’s equations (7) or (9) to a pressure range of 0.1–1.0 MPa have been investigated by comparing them with the measured results obtained from the experiments with flat rough surfaces.

### 2.2. Solid–solid contact model for wavy surfaces with roughness

A pair of solids, Solid 1 and Solid 2, corresponding to the present cylindrical test specimens with radius \( r_o \); radius of curvature \( r_{s1}, r_{s2} \); maximum surface roughness \( \delta_1, \delta_2 \); and the same spherical waviness \( A \), are placed face to face, as shown in Figure 3(a). The solids have thermal conductivity \( \lambda_1, \lambda_2 \); harness \( H_1, H_2 \); Young’s modulus \( E_1, E_2 \); and Poisson’s ratio \( \nu_1, \nu_2 \). After the two solids are pressed together with axial load \( f \) or mean nominal contact pressure \( p_m (= f / (\pi r_o^2)) \), the system is deformed elastically, as shown in Figure 3(b). From a geometrical consideration, the thickness of the intervening substance \( z_r \) with thermal conductivity \( \lambda_t \) at an arbitrary radial position \( r \) is expressed using the following equation.
Here, \( r_1 \) is the radius of the contact surface and is expressed by
\[
\left[ \frac{3}{4} f \frac{\left(1-v_1^2\right)E_1 + \left(1-v_2^2\right)E_2}{r_{s1} + r_{s2}} \right]^{\frac{1}{3}}
\]  
(14)

from the Hertzian analysis [9].

In the present study, as the first step for developing a simple evaluation equation for the macroscopically wavy contact surfaces with roughness under lower pressure conditions, Tachibana’s equations (6) or (8) and Sanokawa’s equations (7) or (9) have been applied at the central solid–solid contact zone \( (0 \leq r \leq r_0) \) by introducing the following modified mean nominal contact pressure \( p_{ma} \), evaluated using the central contact area \( \pi r_1^2 \).

\[
p_{ma} = \frac{r_1^2}{r_0^2} p_m
\]  
(15)

On the other hand, in the case of the outer intervening substance surrounding the central solid–solid contact zone similar to that shown in Figure 4(a), an equivalent thickness \( \delta_t \) of the intervening substance has been introduced as the first step for clarifying the effect of the macroscopic waviness on the overall thermal resistance. The value of \( \delta_t \) shown in Figure 4(b) is obtained from
\[
\delta_t = \frac{1}{S} \int_0^S z_i 2 \pi r dr.
\]  
(16)

Here, \( S \) is the annular projected area of the outer intervening substance and is expressed as
\[
S = \pi (r_2^2 - r_1^2).
\]  
(17)

Accordingly, by substituting equations (13) and (17) into equation (16), and then performing the integration, the following equation for the equivalent thickness \( \delta_t \) is obtained.
\[
\delta_t = \frac{A}{\pi^2} \left[ 1 - \left( \frac{r_1}{r_0} \right)^2 \right]
\]  
(18)

From the equations derived so far, and by assuming a parallel heat flow through the central solid-solid contact zone and its outer intervening substance, the thermal contact conduction of the present
wavy surfaces with roughness is obtained as follows, based on the equation applied at the central contact zone, that is, Tachibana’s equation or Sanokawa’s equation.

\[
k_{\text{WTE}} = \left(\frac{r_k}{r_0}\right)^2 k_{\text{CTE}} + \left[1 - \left(\frac{r_k}{r_0}\right)^2\right] k_{\text{Of}}
\]

(19)

\[
k_{\text{WSE}} = \left(\frac{r_k}{r_0}\right)^2 k_{\text{CSE}} + \left[1 - \left(\frac{r_k}{r_0}\right)^2\right] k_{\text{Of}}
\]

(20)

Here, \(k_{\text{CTE}}, k_{\text{CSE}}\) and \(k_{\text{Of}}\) are given as follows:

\[
k_{\text{CTE}} = \frac{1}{\delta_1 + \delta_2} \left(\frac{p_{\text{ma}}}{H_{\text{min}}} + \frac{\lambda_f}{\delta_2} \left(1 - \frac{p_{\text{ma}}}{H_{\text{min}}}\right)\right)
\]

(21)

\[
k_{\text{CSE}} = \frac{1}{\delta_1 + 2.3 \times 10^{-3} \left(\frac{1}{\lambda_1} \left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right) + \frac{\delta_1}{\lambda_2} \left(1 - \frac{p_{\text{ma}}}{H_{\text{min}}}\right)\right) + \frac{\delta_2}{\lambda_2} \left(1 - \frac{p_{\text{ma}}}{H_{\text{min}}}\right)}
\]

(22)

and

\[
k_{\text{Of}} = \frac{\lambda_f}{\delta_f}.
\]

(23)

Furthermore, by substituting equation (18) into equations (19) and (20), the following final equations are obtained.

\[
k_{\text{WTE}} = k_{\text{CTE}} (p_{\text{ma}}) + k_{\text{Of}} (\Delta) \quad \text{(Without heat flow constriction at the contact surface)}
\]

(24)

\[
k_{\text{WSE}} = k_{\text{CSE}} (p_{\text{ma}}) + k_{\text{Of}} (\Delta) \quad \text{(With heat flow constriction at the contact surface)}
\]

(25)

Here, \(k_{\text{CTE}} (p_{\text{ma}}), k_{\text{CSE}} (p_{\text{ma}})\) and \(k_{\text{Of}} (\Delta)\) are given as follows:

\[
k_{\text{CTE}} (p_{\text{ma}}) = \left(\frac{r_k}{r_0}\right)^2 k_{\text{CTE}}
\]

(26)

\[
k_{\text{CSE}} (p_{\text{ma}}) = \left(\frac{r_k}{r_0}\right)^2 k_{\text{CSE}}
\]

(27)

\[
k_{\text{Of}} (\Delta) = \frac{\lambda_{\text{Th}}}{\Delta}
\]

(28)

3. Experiment

The validity of the evaluation equations (8) and (9) for flat rough surfaces and equations (24) and (25) for wavy rough surfaces, derived in the previous section, was experimentally confirmed using two pairs of cylindrical brass specimens.

3.1. Experimental apparatus

Figure 5 shows a schematic of the experimental apparatus. A film heater of 40 mm (= 2\(r_0\)) diameter, 0.5 mm thickness and 20 W (= \(Q\)) heat output is attached on the top surface of the upper test specimen. A copper cooling block, which is maintained at 20 °C by circulating water from a constant temperature water bath, is placed under the bottom surface of the lower test specimen. The test specimens are placed in a hollow cylinder with a 50-mm-thick styrene foam wall. Under the bottom of the film heater, an acrylic resin block of 20 mm thick is placed for thermal insulation. The axial load \(f\) is applied to the test specimens via a lever and hanging weight arrangement. Here, a balancing weight is set at the opposite end of the lever to obtain the no-load condition.
3.2. Test specimen

In the present study, two pairs of brass specimens are tested in still air and at room temperature. One specimen has a flat rough surface, and the other has a wavy rough surface. As shown in Figure 6, the diameter $d (=2r_o)$ and length $l$ of each specimen are 40 mm and 45 mm, respectively. Each specimen has four small holes of 0.6 mm diameter and 10 mm depth, located at 15, 22, 29, and 36 mm from the contact surface, for temperature measurements. Copper–constantan–sheathed thermocouples of 0.5 mm diameter are inserted in each hole by applying a thermally conductive silver paste.

The contact surface of the specimen is finished by polishing after being turned by a lathe turning machine. Figure 7 shows examples of the center line average surface roughness $Ra$ and the macroscopic waviness $\Delta$ of such a finished surface, measured using a stylus profilometer. The mean values of $Ra$ and the maximum values of $\Delta$, measured at four sections by rotating the specimens in steps of 45°, are listed in Table 1.

4. Results and discussion

In this section, the thermal contact resistance at the solid–solid contact interface has been discussed by comparing the theoretical and experimental results. First, in the case of the solid–solid contact of flat rough surfaces, the extension and applicability of Tachibana’s equation (6) or (8) and Sanokawa’s equation (7) or (9) to the low pressure range has been investigated. Next, for wavy surfaces with...
In general, the relationship among $\Delta T$ at the solid–solid contact interface, the heat flux flowing through the interface $q (= Q/A$, $Q$: heat rate flowing through the interface, $A$: cross-sectional area of the solid), the thermal contact resistance $r$, and the thermal contact conductance $k$ is given by the following equation.

$$q = \frac{\Delta T}{r} = k \Delta T$$  \hspace{1cm} (29)

In the present study, the heat output of the film heater attached on the top surface of the upper test specimen $Q$, which can be regarded as the heat rate flowing through the solid–solid contact interface, was kept constant at 20 W throughout the experiments. Hence, for facilitating intuitive understanding of the behavior of the thermal contact resistance $r$ or the thermal contact conductance $k$ at the interface, the temperature drop $\Delta T$, which is proportional to $r$ or inversely proportional to $k$ as can be seen from equation (29), has been used for the comparison between the experimental and theoretical results.

### 4.1. Solid–solid contact of flat surfaces with roughness

Figures 8 and 9 illustrate the effect of $p_m$ on the thermal contact conductance $k_{TE}$ and $k_{SE}$, respectively, calculated under the conditions corresponding to the present experiment. In the figures, $k_{TE,s}$ and $k_{SE,s}$ are indicated by the broken line and the component $k_f$ by the dash-dotted line. The thermal conductivity $\lambda$ of the test specimen was measured by using a 90–mm–long test cylinder, cut from the same cylinder. In addition, the Vickers hardness $H_V$ of the test specimen was also measured with a portable hardness testing machine. In the case of Tachibana’s equation (8), $k_{TE,s}$ by the cylindrical portion is dominant and a higher thermal contact conductance is obtained. On the other hand, in the case of Sanokawa’s equation (9), the component $k_{SE,s}$ of the cylindrical portion is quite low because of the contraction and expansion of the heat flow through the cylindrical portion of the unit cell. As a result, $k_f$ owing to the intervening substance (in this case, the air layer) accounts for most of the conductance, and $k_{SE}$ is several times lower than $k_{TE}$.

| Test specimen | $Ra$ [$\mu m$] | $\Delta$ [$\mu m$] |
|---------------|----------------|------------------|
| Flat rough surface | 0.3 | 0 |
| Upper | 0.3 | 0 |
| Lower | 0.4 | 0 |
| Wavy rough surface | 1.0 | 25 |
| Upper | 1.0 | 25 |

Table 1. Measured $Ra$ and $\Delta$ of test specimen.

**Figure 8.** Thermal contact conductance by Tachibana’s equation (8).

**Figure 9.** Thermal contact conductance by Sanokawa’s equation (9).
In Figure 10, the experimental and theoretical results are shown in terms of $\Delta T$ at the solid–solid contact interface. Here, the symbols (circles, triangles, and squares) denote the measurement results; the closed symbols correspond to the loading process and the open symbols to the unloading process. In each measurement, reassembling and assembling of the lower and upper specimens was repeated. In the figure, the hysteresis phenomenon is observed during the loading and unloading processes, and almost all of the experimental results exist between the results obtained using Sanokawa’s equation extrapolated to the lower $p_m$ and those obtained using Tachibana’s equation.

4.2. Solid–solid contact of wavy surfaces with roughness

Figure 11 shows the effect of $p_m$ on the radius of the contact surface $r_a$ for the present brass test specimen. Here, equation (14) has been rearranged as the following equation using the relations $r_{s1} = r_o/(2\Delta)$, $E = E_1 = E_2$, $\nu = \nu_1 = \nu_2$ and $p_m = f/(\pi r_o^2)$.

$$r_a/r_o = \left[\frac{3}{8}\pi\left(1-\nu^2\right)\frac{r_o}{E} \frac{\Delta}{\nu^3} P_m\right]^{1/3} \quad (30)$$

In the figure, the Young’s modulus $E$ and the Poisson’s ratio $\nu$ are considered as $10.06 \times 10^4$ MPa and 0.350 [12], respectively. As seen from the figure, only a 1–4% macroscopic contact area against the cross-sectional area of the cylinder has been realized under the present lower $p_m$ conditions.

Figures 12 and 13 illustrate the effect of $p_m$ on the thermal contact conductance $k_{WTE}$ and $k_{WSE}$, respectively, calculated under the conditions corresponding to the present experiment. In the figures,
k_{CTE} (p_{ma}) and k_{CSE} (p_{ma}) are indicated by the broken line, and the component k_{Of} (\Delta) by the dash-dotted line. In the case of evaluation equation (24) based on Tachibana’s equation (6), k_{CTE} (p_{ma}) at the central solid–solid contact zone is dominant and a high thermal contact conductance is obtained. On the other hand, in the case of evaluation equation (25) based on Sanokawa’s equation (7), k_{CSE} (p_{ma}) at the central solid–solid contact zone is low because of the contraction and expansion of the heat flow through the cylindrical portion of the unit cell. However, in the present model, since the macroscopic constriction of the heat flow at the solid–solid contact interface has not been introduced, k_{CSE} (p_{ma}) shows roughly the same effect as k_{Of} (\Delta) on the whole thermal contact conductance k_{wSE}. On the other hand, as previously shown in Fig. 9, k_{SE,s} for the flat rough surfaces, in which the microscopic constriction of the heat flow is introduced at the contact interface formed by the surface roughness, has a much smaller effect than k_{Of} on the whole thermal contact conductance k_{SE}.

The experimental and theoretical \Delta T values at the solid–solid contact interface are shown in Figure 14. Here, the symbols (circles, triangles) denote the measured results; the closed symbols correspond to the loading process and the open symbols to the unloading process. In contrast to case of the flat rough surfaces, almost no hysteresis is observed during the loading and unloading processes. Equation (24), which does not consider the additional thermal resistance at the cylindrical portion of the unit cell, considerably underestimates \Delta T under the present low pressure range. Unfortunately, however, even if the additional resistance is taken into account as in equation (25), the agreement between the experimental and theoretical results is not so good. This may be due to the absence of macroscopic constriction of the heat flow at the contact interface; this is the major problem for consideration in future research.

5. Conclusions

From the present theoretical and experimental studies, the following findings have been obtained.

(1) It has been shown that, in the case of solid–solid contact of flat surfaces with roughness, almost all of the measured temperature drops caused by the thermal contact resistance at the contact interface exist between the values evaluated by the unit cell model with and without the heat flow constriction. This implies that Sanokawa’s equation can be successfully extrapolated to the lower mean nominal contact pressure of 0.1–1.0 MPa.

(2) When the rough surface has waviness, the newly proposed evaluation equation based on Tachibana’s equation has been proved to underestimate the temperature drop at the contact interface. On the other hand, although another proposed equation based on Sanokawa’s equation is consistent
with the measured results to some extent, the introduction of constriction resistance due to the macroscopic waviness seems to be necessary for a more accurate evaluation of the temperature drop.

References
[1] Fletcher L S 1988 Trans. ASME, J. Heat Transfer 110 1059
[2] Torii K and Yanagihara J I 1989 J. Heat Transfer Soc. Jpn. 28 79
[3] Torii K 1993 J. Jpn. Soc. Mech. Eng. 96 198
[4] Okada M and Matsumoto K 1993 J. Heat Transfer Soc. Jpn. 32 25
[5] Madhusudana C V 1996 Thermal Contact Conductance (New York: Springer) pp 1-8
[6] Tomimura T and Fujii M 1999 Proc. Symp. on Advances in Packaging, APACK ’99 (Singapore: Gintic Institute of Manufacturing Technology) pp 216-219
[7] Tachibana F 1952 J. Jpn. Soc. Mech. Eng, 55 102
[8] Sanokawa Y1967 Trans. Jpn. Soc. Mech. Eng. 33 131
[9] Yamamoto Y and Kaneta M 1999 Tribology (Tokyo: Rikougaku-sha) pp 20-37
[10] Tomimura T, Matsuda Y, Zhang X and Fujii M 2000 Jpn. Soc. Mech. Eng. Int. J. B 43 665
[11] Jpn. Soc. Mech. Eng. 1983 JSME Data Book: Heat Transfer 3rd Edition (Tokyo: The Japan Society of Mechanical Engineers) pp 176-177
[12] National Astronomical Observatory 2013 Chronological Scientific Tables (Tokyo: Maruzen Publishing Co., Ltd.) p 389