Experimental Study of the Transient Heat Transfer Across Periodically Contacting Surfaces

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This study experimentally examines the heat transfer across surfaces which contact and separate at regular intervals. The results are presented for the case of low contact pressure, moderate interface temperature, equal contact and separation times during a cycle, and identical materials on either side of the contact interface. The results are presented in two basic areas: 1) the behavior of the thermal contact resistance during the quasi-steady state; and 2) the length of time required for the temperature distribution in the material to approach the temperature distribution observed in the quasi-steady-state condition. The results indicate that the thermal contact resistance should not be considered a constant for contacts of short duration; and that relatively few cycles are required for the temperature distribution in the material to approach that observed in the quasi-steady state.

Nomenclature

A = cross-sectional area, m^2
Bi = contact conductance parameter = $h_c L/k$, dimensionless
Fo = Fourier number $\alpha t/L^2$, dimensionless
h_c = thermal contact conductance = $1/R_c$, $W/m^2 C$
$h_{c,ss}$ = steady-state thermal contact resistance, $W/m^2 C$
h_0 = convective coefficient at $x = 0$, $W/m^2 C$
h_{2L} = convective coefficient at $x = 2L$, $W/m^2 C$
k = thermal conductivity, W/mC
L = specimen length, m
L^* = dimensionless length = x/L
n = number of cycles required to reach the quasi-steady state, dimensionless
Q = heat transfer at the contact interface, W
R_c = thermal contact resistance, $m^2 C/W$
$T(x,t)$ = generalized temperature distribution, C
T_c = heat sink fluid temperature, C
T_H = heat source fluid temperature, C
T^* = dimensionless temperature = $[T(x,t) - T(2L,t)]/[T(0,t) - T(2L,t)]$
t = time variable, s
t_c = contact time, s
x = spatial variable, m
α = thermal diffusivity, m/s^2
ΔT = apparent interface temperature drop, C
τ = dimensionless cycle time parameter = $\alpha t_c/L^2$

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Introduction

THERE has been, over the last three decades, an increasing number of articles concerning heat transfer across contacting surfaces—which have been reviewed by several authors.[1–3] General interest in the subject, however, has been limited to the consideration of transient or steady-state contact across surfaces which are held permanently in contact.

The problem of transient heat transfer across contacting surfaces has been addressed through the use of a variety of techniques. Heasley[4] and Sandal[5] present analytical solutions to transient contact problems by assuming regions of perfect contact interspersed with insulated regions. Schneider and others[6] obtained a numerical solution for the transient thermal behavior in a semi-infinite medium having one surface insulated except for a circular contact area. The problem is then examined by applying various boundary conditions directly to the contact area. An extension of this study by the same authors[7] examines the problem of two semi-infinite solids in continuous contact over a circular area. Of particular interest in this latter study is the determination of the thermal contact resistance as a function of the Fourier number.

These results are also supported by an analytical solution for the same contact problem by Sadhal,[8] although the results of Sadhal indicate a somewhat more complex relationship for the contact resistance than that of the numerical solution of Schneider et al.[7]

Blum and Moore[9] present analytical and numerical solutions for the temperature distribution as a function of distance and time for one-dimensional problems, with particular emphasis on the approach of the solution to its steady-state value. This study was extended by Moore[1] to include an experimental study of the contact phenomena.

Additionally, a wide variety of engineering problems are also of interest which involve intermittent loading conditions once the contact has been established. In particular, the problem of the quasi-steady-state heat transfer across two surfaces coming into regular, periodic contact has been examined analytically by Howard and Sutton,[10] Reed and Mullineaux,[11] and Mikhailov[12] under the assumption of perfect thermal contact at the interface. The analysis has been extended by Howard and Sutton[13] and Vick and Ozisik[14] to include the effects of the thermal contact resistance at the contact interface, with Howard[15] undertaking an additional experimental study.

The present literature is limited to problems where the cycling process of contact and separation has been continued for a sufficient period of time to allow the quasi-steady-state conditions to become established. The current study should provide insight into the periodic contact problem in the time preceding the establishment of the onset of quasi-steady-state conditions. Further application of these results should also be useful in establishing an insight for the approach to and the establishment of quasi-steady-state conditions.

Formulation

The experimental results presented here are undertaken for the purpose of providing actual observations of the contact phenomena for periodically contacting surfaces. To this end, an apparatus was developed to simulate, in so far as possible, the following analytical problem for two cylinders, each of length L, as shown in Fig. 1:

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} \quad \text{in } 0 \le x \le L \text{ and } L \le x \le 2L \tag{1a}$$

$$k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} = h_0[T(0,t) - T_H] \tag{1b}$$

$$k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=2L} = h_{2L}[T_C - T(2L,t)] \tag{1c}$$

$$\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=L} = 0 \quad \text{for both cylinders} \tag{1d}$$

$$T(x,0) = F(x) \tag{1e}$$

when the surfaces are separated, and

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} \quad \text{in } 0 \le x \le L \text{ and } L \le x \le 2L \tag{2a}$$

$$k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} = h_0[T(0,t) - T_H] \tag{2b}$$

$$k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=2L} = h_{2L}[T_C - T(2L,t)] \tag{2c}$$

$$k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=L} = h_c[\Delta T_{\text{interface}}] \tag{2d}$$

$$T(x,0) = G(x) \tag{2e}$$

when the surfaces are in contact.

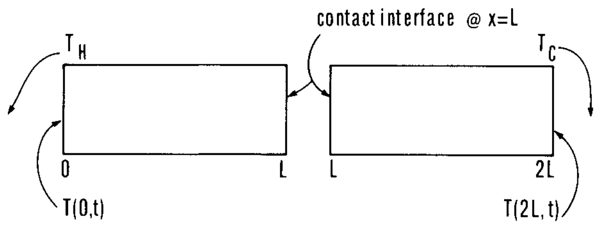

Fig. 1 Mathematical problem geometry.

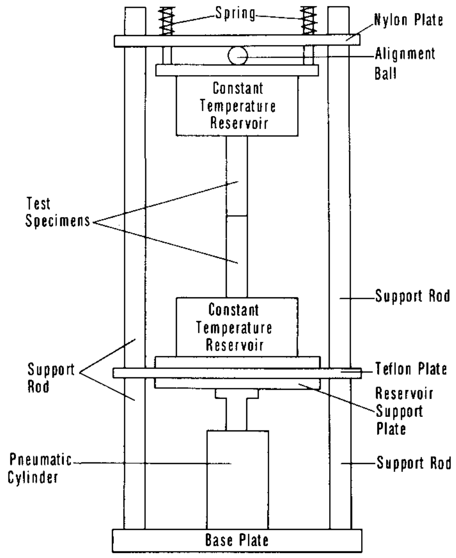

Fig. 2 Experimental apparatus.

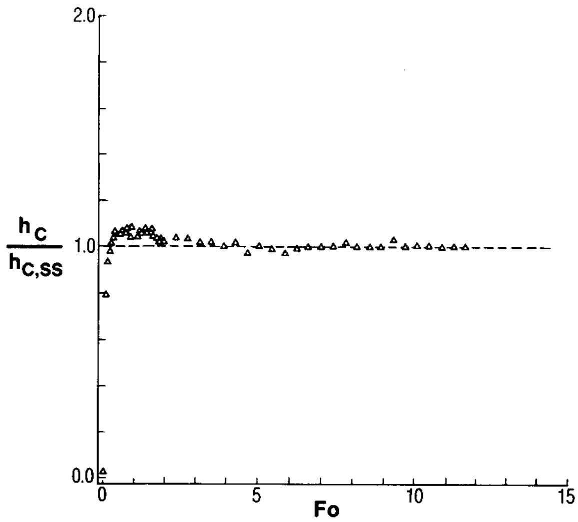

Fig. 3 Contact conductance ratio for aluminum specimens in single contact.

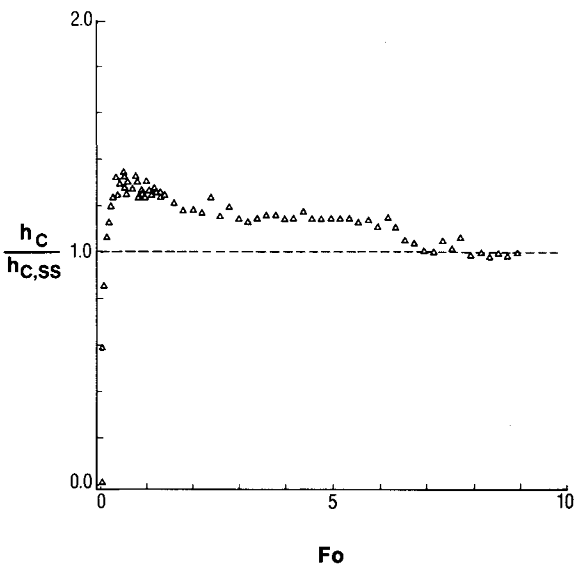

Fig. 4 Contact conductance ratio for brass specimens in single contact.

Experimental Apparatus

The experimental apparatus, shown in Fig. 2, consists of two test cylinders—each held at one end in a thermal reservoir, the supporting frame, and the associated equipment required to bring the test specimens uniformly into and out of contact.

The contact mechanism consists of two main plates, one located directly above the other. The upper plate, made of nylon, is rigidly attached to the support frame. Suspended below this plate, by means of a spring-loaded mechanism, is a smaller nylon plate to which one of the thermal reservoirs is attached. Sandwiched between these two plates is a nylon ball, which, in conjunction with the spring-loaded mechanism, requires the contact force to be transmitted through a single point, thus allowing the entire reservoir assembly (and, therefore, the attached test specimen) to pivot about that point, bringing the contact surfaces of the test specimens into contact over their entire contact face.

The second test specimen and its associated thermal reservoir is attached to the lower plate, which is free to slide along the four PVC rods forming the supporting frame. This plate is made of Teflon to reduce friction and binding in the sliding contact.

The test specimens are caused to contact and separate by driving the lower plate with a pneumatic cylinder. The air flow to the cylinder is controlled by two solenoid valves—one used to drive the pneumatic cylinder up, and the other used to drive the pneumatic cylinder down. The activation of the valves is, in turn, controlled by a microprocessor-based timer.

The fluid reservoirs are constant-temperature baths. Each reservoir circulates fluid supplied by an external bath, which is maintained at a specified temperature.

The test specimens utilized for these experiments are 0.0254 m in diameter and 0.1397 m in total length. On each cylinder 0.0381 m on one end of the cylinder is threaded to fit into the fluid reservoir. Copper-constantan thermocouples are located on the centerline of each specimen at 0.0127 m intervals for the 0.0508 m of each specimen adjacent to the contact surface. Two additional copper-constantan thermocouples are located on the specimen centerline—one at 0.0005 m from the contact surface and the other at 0.1011 m from the contact surface (the point where the specimen enters the thermal reservoir).

Profilometer records of the test specimens show the centerline average surface roughness to be 5.207 μm and 4.750 μm for the aluminum; 0.439 μm and 0.635 μm for the brass; and 2.134 μm and 2.413 μm for the copper specimens. The specimens are otherwise nominally flat and free of coatings or surface oxidation.

The lateral surface of the test specimens is insulated with a Teflon sleeve, which is cut to allow thermocouple access and to allow the thermocouples to move freely in a vertical direction as the surfaces move into and out of contact.

A separate set of experiments was conducted to check for the presence of radial temperature gradients in the test specimens. These results, which are reported by Moses,[16] indicated that, within the accuracy of the recording device, the heat flow down the rod was one-dimensional.

Procedure and Data Acquisition

After allowing the test specimens to come to a steady-state condition while separated, the air pressure regulator was set to provide an applied load at the contact interface of about 85 kN/m^2 and the timer was activated to start the experiment. Temperature measurements were made at 10-s intervals throughout the course of the experiment. All experiments were conducted in air.

Of the two quantities of primary interest, the temperature distribution is available directly from the experimental output. The other quantity, the thermal contact resistance, is computed from the apparent temperature drop and the heat flux across the interface, according to the definition

$$R_c = \Delta T/(Q/A) \tag{3}$$

The apparent temperature drop across the interface is obtained by utilizing a polynomial regression to curve fit the experimental data to a polynomial expression. Examinations of least-squares curve fits of various order, the general shape of the temperature versus location curve itself, and the comments of Moore[1] concerning the application of functional forms other than polynomials led to the selection of a quadratic equation to be fit to the experimental data by means of the polynomial regression scheme.

The heat flux at the contact interface is also computed by using the equation obtained from the curve fit of the temperature distribution. The quadratic equation obtained from the regression scheme is differentiated and evaluated at the contact interface for each specimen. The heat transfer in the test specimen is then obtained by multiplying the result by the thermal conductivity.

An alternative, more rigorous method for determining the heat flux or the temperature drop across the contact interface is to utilize the measured temperature distribution to reconstruct the heat transfer problem. This problem—that of determining the boundary conditions for a body from an internal temperature history—is called the inverse heat conduction problem.

Beck et al.,[17,18] Alnajem and Ozisik,[19] and Flach and Ozisik[20] have discussed the solution of the inverse problem in a variety of situations, including applications to thermal contact conductance. This solution method is not chosen for use here due to the proximity of the temperature measurement to the actual contact interface and after a comparison of the subsequent computations obtained for each test specimen.

The overall uncertainty analysis for the results of the experiments, based on the method of Kline and McClintock,[21] indicates an uncertainty of 21% for the aluminum specimens, 14% for the brass specimens, and 11% for the copper specimens. A more detailed discussion of the experimental uncertainty is given by Moses.[16]

Results

The results presented are for the case of identical materials contacting with equivalent times for length of contact and length of separation in any cycle, and are presented in terms of the dimensionless variables, T^*, Bi, τ, and L^*. Further, since the temperature during any cycle is always a function of time, a true steady state is never attained. However, as a reference condition, the quasi-steady state will be defined as the condition where $T(x,t)$ for cycle n is the same as $T(x,t)$ for cycle $n+1$ (and succeeding cycles), where t is the time from the initiation of the cycle.

Results for the Thermal Contact Conductance

Figures 3, 4, and 5 are included to demonstrate the effects of the contact conductance for single contacts which are maintained until steady-state conditions are attained. For each case, the value of the parameter $h_c/h_{c,ss}$ approaches a value of 1 from below, overshoots the value of 1, and then returns. The value of $h_c/h_{c,ss}$ is relatively stable for each specimen near the value of unity by the time the Fourier number, Fo, has a value of 3. As the data presented in the figures represent a variety of values for h_c and $h_{c,ss}$, the value to which the ratio overshoots unity appears most strongly governed by the material properties, with the least deviation being demonstrated by the copper specimen and the greatest deviation from unity being demonstrated by the brass specimen.

The nature of the relationship indicated by the figures is further confirmed by examining the contact conductance for the quasi-steady-state experiments. These results are given in

Fig. 6. For each of these cases, the value $h_{c,ss}$ is obtained by using h_c for the last contact measurement in the cycle. Since the value of h_c at this point in the cycle is consistently higher than a value of $h_{c,ss}$ for a similar single contact measurement, this characterization suppresses the approach of the contact conductance ratio to unity for the quasi-steady-state experiments. Nevertheless, for all of the quasi-steady-state cases—each with a value of $Fo < 1$—the contact conductance increases throughout the contact period, thus contributing to the overshoot phenomena observed at shorter times.

The results of Moore[1] are also consistent with the above observations on the variation of contact conductance with time. The sharp variations in contact conductance at very short times, which Moore[1] attributed to his calculation procedure, are not observed in the present experiments due to limitations on minimum data recording time. The small rise in the contact conductance at later times noted by Moore[1] is observed in the current experiments on the copper and aluminum specimens (Figs. 3 and 5). This particular phenomena is not strongly indicated by examination of the brass experiment presented (Fig. 4).

Results for the Approach to the Quasi-Steady State

Examination of the experimental data for the periodically contacting specimens during the transient portion of the development of the temperature distribution and the approach to the quasi-steady state (as defined above) indicates several trends. The data for each experiment were evaluated by comparing the temperature distribution at the same time in each cycle with the distribution in succeeding cycles and with the last temperature measured in each experiment. To account for fluctuations in the data record caused by the recorder, the temperature distributions for successive cycles were not required to match exactly for the determination of the quasi-steady-state condition. Rather, the quasi-steady state was assumed when not more than 3 of the 12 temperature measurements made on the specimen varied from previous and succeeding measurements by not more than $\pm 0.1°C$, with the additional restriction that no long-term trend in the distribution was indicated. Trends in the distribution, more than three measurements having changed by $\pm 0.1°C$, or any single measurement in variance by more than $\pm 0.1°C$ were taken as evidence that the quasi-steady-state condition had not been achieved.

The number of cycles required to reach quasi-steady-state are presented in Table 1 and plotted in Fig. 7 as a function of the product $\tau * Bi$. As shown in the figure, small values of $\tau * Bi$ are associated with larger numbers of cycles required to reach quasi-steady state, while larger values of the $\tau * Bi$ product require fewer cycles to reach the quasi-steady-state condition.

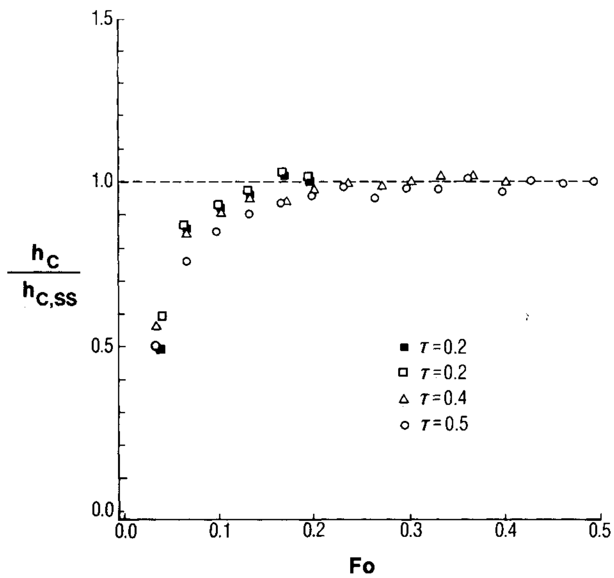

Fig. 6 Contact conductance ratio for brass specimens in the quasi-steady state.

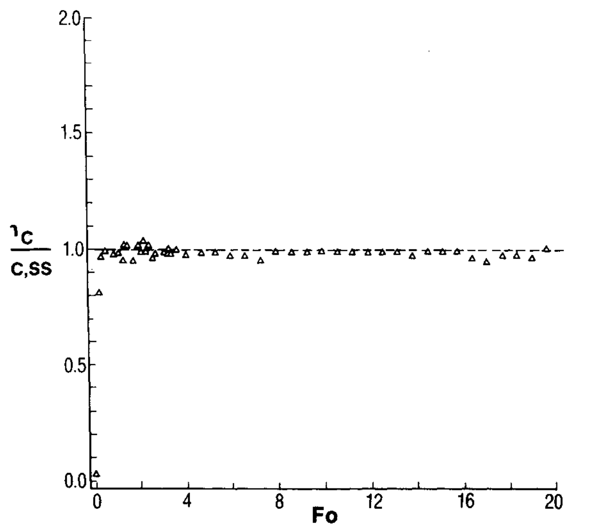

Fig. 5 Contact conductance ratio for copper specimens in single contact.

Table 1 Cycles required to achieve the quasi-steady state

Specimen designation	Cycles to quasi-steady state	$\tau * Bi$
Br019	58	0.321
Al017	41	0.382
Br009	40	0.384
C012	38	0.539
Br025	23	0.704
Br020	24	1.432
Br022	22	1.885

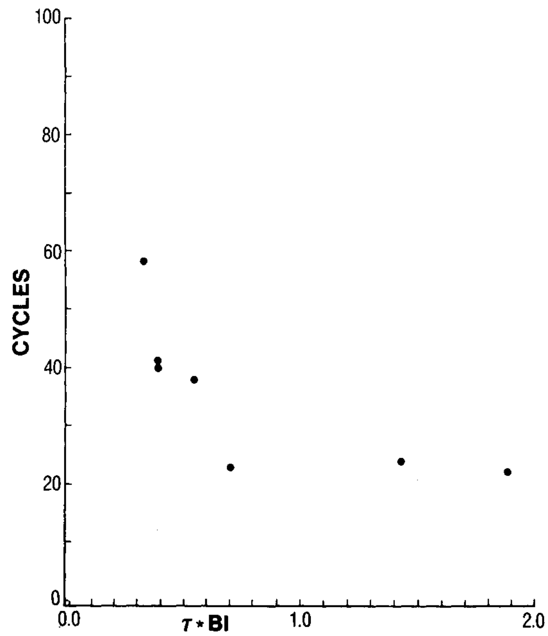

Fig. 7 Cycles required to reach the quasi-steady state.

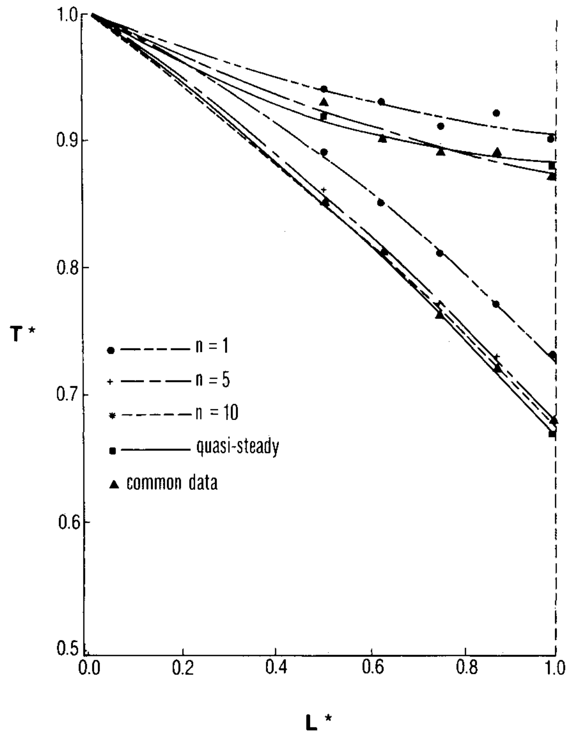

Fig. 8 Approach to the quasi-steady state for copper, $\tau = 0.55$, $Bi = 0.98$.

This observation may be physically related to the $\tau * Bi$ product, since, because the material properties and the specimen length are fixed, the value of $\tau * Bi$ is directly proportional to h_c *(contact time). Therefore, large values of $\tau * Bi$ are related to either a large contact conductance or to a large contact time. If the contact time is large, the temperature distribution is then approaching the single contact steady-state distribution on each cycle, thus requiring a small number of cycles to achieve the quasi-steady-state condition. If the contact conductance value is large, then the temperature distribution in each specimen is forced more directly toward its quasi-steady-state value.

Similarly, if the contact time or the contact conductance is small, then the temperature distributions in each bar remain, relatively, farther apart. Hence, the temperature difference in the bars at the initiation of contact is higher for low values of $\tau * Bi$ and remains so for a longer number of cycles in these specimens than it does in specimens with larger values of the $\tau * Bi$ product.

Additionally, Figs. 8 and 9 show, respectively, the approach to the quasi-steady state for a copper and a brass experiment. Most notable in these figures is the rapidity with which the temperature distributions approach the temperature distributions for the quasi-steady state. In Fig. 8, the quasi-steady state is attained after 38 cycles. Yet, after five cycles, the temperature distribution is within 15% of the quasi-steady-state distribution at the end of both the contact and separation portions of the cycle.

Similarly, while the brass specimens in Fig. 9 reach the quasi-steady state after 23 cycles, the temperature distributions are nearly indistinguishable after only five cycles. This trait of having the temperature distribution approach the quasi-steady-state distribution after a relatively short number of cycles is demonstrated in each experiment. These data are presented in Table 2.

As demonstrated by the table, all of the specimens required fewer than half of the number of cycles required to reach the quasi-steady state to approach the temperature distribution exhibited by the quasi-steady-state condition; and, with one exception, the number of cycles required to match the temperature distribution is 25% or less of the cycles required to attain the quasi-steady state. Consequently, the temperature distribution in the specimens during a large part of the transient portion of the contact problem may be approximated by the quasi-steady-state temperature distribution.

Table 2 Cycles required to approach the quasi-steady state

Specimen designation	Cycles to quasi-steady state	Cycles to approach quasi-steady state
Br019	58	9
Al017	41	6
Br009	40	10
C012	38	7
Br025	23	4
Br020	24	6
Br022	22	10

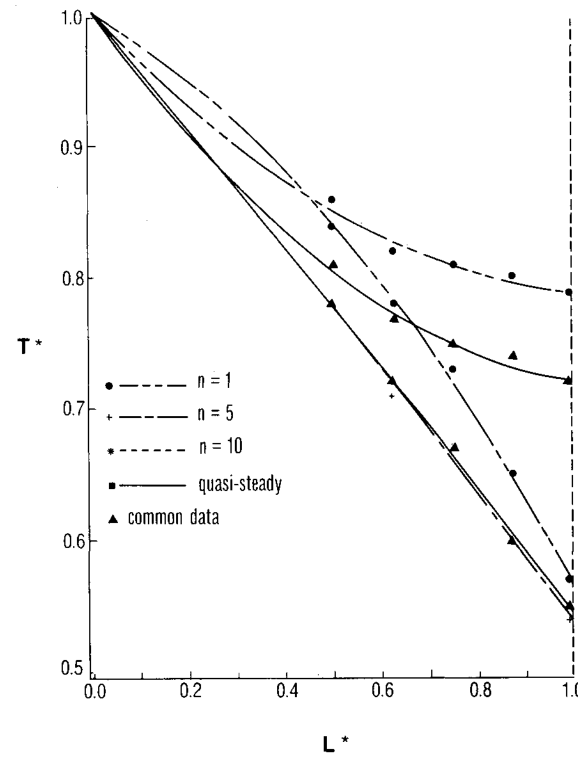

Fig. 9 Approach to the quasi-steady state for brass, $\tau = 0.20$, $Bi = 3.52$.

Summary and Conclusions

Observations are presented for an experimental evaluation of the heat transfer and temperature distribution across periodically contacting surfaces. The results are limited to the case of low contact pressures, moderate interface temperatures, identical materials across the contact interface, and equal contact and separation times in any cycle.

One family of results concerns the behavior of the thermal contact resistance during both single contact and quasi-steady-state experiments. These results demonstrate that the contact resistance decreases with time from the initiation of contact, eventually falling below the steady-state value of the thermal contact resistance, and finally rising back to the steady-state value. These results call into question the common practice of considering the thermal contact resistance constant throughout a contact period. While from a mathematical perspective there is indeed such a constant value of contact resistance for which the heat flux is the same as that actually encountered, the proper selection of such a parameter is not resolved by the experimental analysis. For long contact times the contact resistance value in the steady state may be a justifiable parameter. However, at shorter contact times, where the actual value of the contact resistance is never equivalent to the value of the contact resistance at steady-state conditions, a more selective procedure is required to approximate the contact resistance.

The second set of observations concerns the length of time required for the periodically contacting surfaces to reach the quasi-steady state. These results indicate a relationship between the number of cycles required to achieve the quasi-steady state and the product of the contact time and the thermal contact conductance (as nondimensionalized in τ and Bi), which may be expected from the general form of transient conduction problems.

An additional aspect of the approach to quasi-steady-state concerns the observation that the temperature distribution in the material does not approach the quasi-steady-state distribution uniformly with time. Rather, the temperature distribution in the material approaches the quasi-steady-state distribution after relatively few cycles have elapsed. Hence, a general knowledge of the quasi-steady-state distribution may be used to provide insight to the truly transient temperature distribution over a large portion of the periodic contact problem.

References

[1] Moore, C.J. Jr., "Heat Transfer Across Surfaces in Contact: Studies of Transients in One-dimensional Composite Systems," PhD. Dissertation, Southern Methodist University, 1967.

[2] Madhusudana, C.V. and Fletcher, L.S., "Contact Heat Transfer—The Last Decade," *AIAA Journal*, Vol. 24, No. 3, March 1986, pp. 510–523.

[3] Minges, M.L., "Thermal Contact Resistance, Volume 1—A Review of the Literature," Wright-Patterson Air Force Base, Ohio, Technical Report AFML-TR-65-375, 1966.

[4] Heasley, J.H., "Transient Heat Flow Between Contacting Solids," *International Journal of Heat and Mass Transfer*, Vol. 8, Jan. 1965, pp. 147–154.

[5] Sadhal, S.S., "Unsteady Heat Flow between Solids with Partially Contacting Interface," *Journal of Heat Transfer*, Vol. 103, No. 1, Feb. 1981, pp. 32–35.

[6] Schneider, G.E., Strong, A.B., and Yovanovich, M.M., "Transient Heat Transfer from a Thin Circular Disk," AIAA Paper No. 75-707, 1975; see also *Progress in Astronautics and Aeronautics, Radiative Transfer and Thermal Control*, Vol. 49, A.M. Smith, ed., AIAA, New York, 1976, pp. 419–432.

[7] Schneider, G.E., Strong, A.B., and Yovanovich, M.M., "Transient Thermal Response of Two Bodies Communicating Through a Small Circular Contact Area," *International Journal of Heat and Mass Transfer*, Vol. 20, April 1977, pp. 301–308.

[8] Sadhal, S.S., "Transient Thermal Response of Two Solids in Contact over a Circular Disk," *International Journal of Heat and Mass Transfer*, Vol. 23, May 1980, pp. 731–733.

[9] Blum, H.A. and Moore, C.J. Jr., "Transient Phenomena in Heat Transfer Across Surfaces in Contact," ASME Paper 65-HT-59, 1965.

[10] Howard, J.R. and Sutton, A.E., "An Analogue Study of Heat Transfer Through Periodically Contacting Surfaces," *International Journal of Heat and Mass Transfer*, Vol. 13, Jan. 1970, pp. 173–183.

[11] Reed, J.R. and Mullineux, G., "Quasi-Steady State Solution of Periodically Varying Phenomena," *International Journal of Heat and Mass Transfer*, Vol. 16, Nov. 1973, pp. 2007–2012.

[12] Mikhailov, M.D., "Quasi-Steady State Temperature Distribution in Finite Regions with Periodically Varying Boundary Conditions," *International Journal of Heat and Mass Transfer*, Vol. 17, Dec. 1974, pp. 1475–1478.

[13] Howard, J.R. and Sutton, A.E., "The Effect of Thermal Contact Resistance on Heat Transfer Between Periodically Contacting Surfaces," *Journal of Heat Transfer*, Vol. 95, No. 3, Aug. 1973, pp. 411–412.

[14] Vick, B. and Ozisik, M.N., "Quasi-Steady State Temperature Distribution in Periodically Contacting Finite Regions," *Journal of Heat Transfer*, Vol. 103, No. 4, Nov. 1981, pp. 739–744.

[15] Howard, J.R., "An Experimental Study of Heat Transfer Through Periodically Contacting Surfaces," *International Journal of Heat and Mass Transfer*, Vol. 19, April, 1976, pp. 367–372.

[16] Moses, W.M., "An Experimental Investigation of the Heat Transfer Across Periodically Contacting Surfaces," PhD. Dissertation, North Carolina State University, 1985.

[17] Beck, J.V., "Surface Heat Flux Determination Using an Integral Method," *Nuclear Engineering and Design*, Vol. 7, Feb. 1968, pp. 170–178.

[18] Beck, J.V., Blackwell, B.C., and St. Clair, C.R., *Inverse Heat Conduction*, Wiley-Interscience, New York, 1985.

[19] Alnajem, N.M. and Ozisik, M.N., "A Direct Analytical Approach for Solving Linear Inverse Heat Conduction Problems," *Journal of Heat Transfer*, Vol. 107, No. 3, Aug. 1985, pp. 700–703.

[20] Flach, G.P. and Ozisik, M.N., "Periodic B-Spline Basis for Quasi-Steady Periodic Inverse Heat Conduction," Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC, 1986.

[21] Holman, J.P., *Experimental Methods for Engineers*, 3rd ed., McGraw-Hill, New York, 1978.