AIAA'83

AIAA-83-1434

An Accurate Universal Contact Conductance Correlation for Conforming Rough Surfaces with Different Micro-Hardness Profiles

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AIAA 18th Thermophysics Conference

June 1-3, 1983
Montreal, Canada

AN ACCURATE UNIVERSAL CONTACT CONDUCTANCE CORRELATION FOR CONFORMING ROUGH SURFACES WITH DIFFERENT MICRO-HARDNESS PROFILES

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Abstract

Experimental contact conductance data for Nickel 200, Stainless Steel 304 and Zircaloy conforming, rough surfaces obtained by three, researchers employing nominally similar test equipment and procedures are nondimensionalized and compared with the theoretical contact conductance correlation developed by Yovanovich. The contact pressure is normalized with respect to the effective surface micro-hardness calculated by means of the Direct Approximate Method which employs correlations of Vickers indentation data. The agreement between the 45 experimental points and the theory is excellent; the overall RMS percent difference is 5.53 over a broad range of the geometric characteristics, thermophysical properties and contact pressure used to obtain the data.

Nomenclature

$\bar{a}$	= mean contact spot radius, μm
BH	= Brinell hardness number
c_1, c_2, c_3	= correlation constants
C_c	= $\sigma h_c/k_s$, dimensionless contact conductance
C_c^*	= C_c/m, dimensionless contact conductance
DAM	= direct approximate hardness model
H	= hardness, kg/mm^2
H_b, H_e, H_{mn}, H_{mx}	= bulk, effective, minimum and maximum hardness, kg/mm^2
h_c	= contact conductance, W/m^{2}K
k_1, k_2	= conductivities of contacting asperities W/mK
k_s	= harmonic mean conductivity W/mK
m_1, m_2	= mean absolute surface slope of contacting surfaces, radians
m	= $\sqrt{m_1^2 + m_2^2}$ effective absolute surface slope, radians
$P, \bar{P}, P_{mn}, P_{mx}$	= contact, mean, minimum and maximum pressures, kg/mm^2
RH	= Rockwell hardness number
$T, \Delta T_c$	= temperature and contact temperature drop, K
T_m	= mean interface temperature, K
$t, \bar{t}$	= penetration and mean penetration depth, μm
t_o, t_b	= penetration at maximum and bulk hardness, μm
VH	= Vickers hardness
σ	= effective surface roughness ($= \sqrt{\sigma_1^2 + \sigma_2^2}$), μm

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Introduction

During the past three decades numerous researchers from several countries have published empirical thermal contact conductance results which appear to be in conflict with the contact conductance models developed during this period. Snaith et al [1] also report that there are very large variations in published experimental results for apparently similar contacts. They further state that in many cases, published papers do not contain adequate information for a fellow researcher to perform a truly critical assessment of the reported experimental work.

It is the purpose of this paper to present in some detail geometric characteristics, thermophysical properties, test conditions and empirical contact conductance data for several materials, and to compare the data with the theoretical values determined by means of the conforming, rough surface correlation and the Direct Approximate Method (DAM) developed by Yovanovich and his co-workers [2-4]. The data was obtained by three groups of researchers in two countries. The research was conducted within University, government and industrial laboratories using nominally similar test equipment and experimental techniques.

It will be shown that the nondimensional test results are consistent within themselves and are in excellent agreement with the predictions provided the appropriate surface parameters and the effective surface micro-hardness are used to nondimensionalize the measured contact conductances and the contact pressure.

Thermal Contact Conductance Experimental Results

Test Specimens

The experimental conductances for Ni200[5], Zircaloy surfaces [6,7] and SS304 [8] will be considered. All test specimens were fabricated from bar stock. The nominal contact area of the speciments were 641.0, 490.9 and 506.7 mm^2 for the Ni200, SS304 and Zircaloy, respectively. Their surfaces were carefully lapped smooth and flat after turning. The specified surface roughness was obtained by subsequent glass bead blasting of the lapped surface. The above surface preparation produced the surface characteristics reported in Table 1. The effective RMS surface roughness σ and the effective absolute surface slope m are reported for the seven pairs. It can be shown that the surface parameter σ/m which is essential to the contact conductance correlation and the DAM ranges between 8.71 and 24.65 for the Ni200 pairs; lies in the range 33.7 to 37.9 for the SS304 pairs; and is equal to 31.1 for the Zircaloy pair.

Table 1 Test samples with range of geometric and thermophysical properties

Specimen	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Solid	Ni200	Ni200	Ni200	Ni200	Ni200	Ni200	Ni200	Ni200	SS304	SS304	SS304	SS304	Zr-2.5wt% Nb	Zr-4
σ_1 (μm)	1.19	0.19	4.27	0.17	4.29	0.16	8.48	0.14	3.37	3.38	2.72	3.08	2.11	2.41
$10^3 m_1$	137	24	236	24	239	25	344	18	85	93	86	87	69	77

Pair	1	2	3	4	5	6	7
σ(μm)	1.21	4.27	4.29	8.48	4.77	4.11	3.20
$10^3 m$	139	237	240	344	126	122	103
P_{mn}(kPa)	622	518	698	571	360	360	2219
P_{mx}(kPa)	3510	3215	3636	3433	1280	1007	12792
$\bar{P}$(kPa)	2066	1866.5	2167	2002	823	684.5	7505
Hardness	H = H(t)	H = H(t)	H = H(t)	H = H(t)	H = H(t)	H = H(t)	H = H(t,T)
H_e(kg/mm^2)	362.3	302.0	301.5	277.3	285.9	295.3	232.0
H_b(kg/mm^2)	170.4	170.4	170.4	170.4	150.0	150.0	205.0

The surface micro-hardness profiles shown in Figures 1 to 3 were obtained by means of Vickers, Rockwell and Brinell indentations at room temperature.

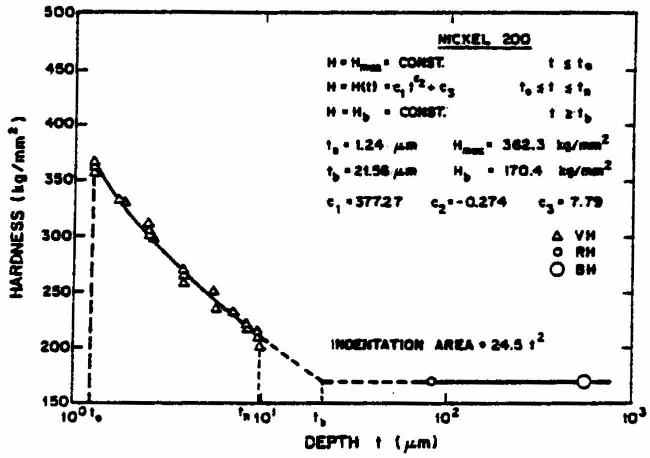

Fig. 1 Micro-hardness profile for Ni200 [5]

The surface micro-hardness correlation equations and the corresponding correlation constants for the Ni200 and the SS304 lapped surfaces are given in Figs. 1 and 2, respectively. Hegazy [8] has developed the following correlation equation for the Zr-2.5wt% Nb surface in the pertinent penetration depth of $4.2 \lesssim t \lesssim 5.25$

$$H(t) = c_1 t^2 \exp (C_2 t) + C_3 \qquad (1)$$

where $C_1 = 148.31$, $C_2 = -0.499$ and $C_3 = -78.00$.

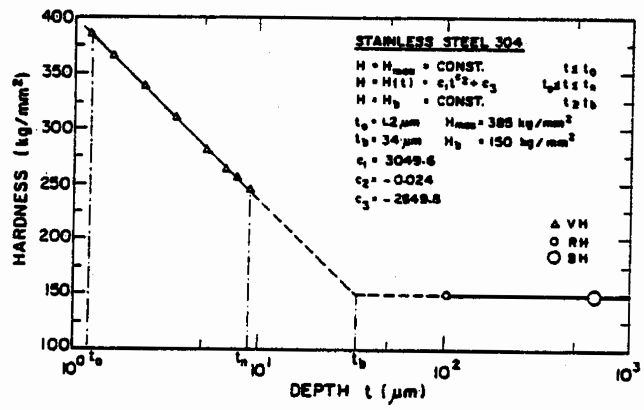

Fig. 2 Micro-hardness profile for SS304 [8]

The units of penetration depth and micro-hardness of Eq. (1) are μm and kg/mm , respectively.

The minimum, maximum and arithmetic mean contact pressures for the seven pairs are listed in Table 1. The SS304 pressures fall into the low to moderate range; and the Zircaloy pressures correspond to moderate to high contact pressures. There is a factor of 21 between the minimum pressure in the SS304 test and the maximum pressure in the Zircaloy test.

The bulk hardness H_b of the test specimens was determined by means of Rockwell and Brinell indenters; these values are also given in Table 1. The SS304 specimens had the minimum value of 150 k_g/mm^2;

Ni200 had a value of 170.4 kb/mm^2; while the Zircaloy specimen had the maximum value of 205 kg/mm^2.

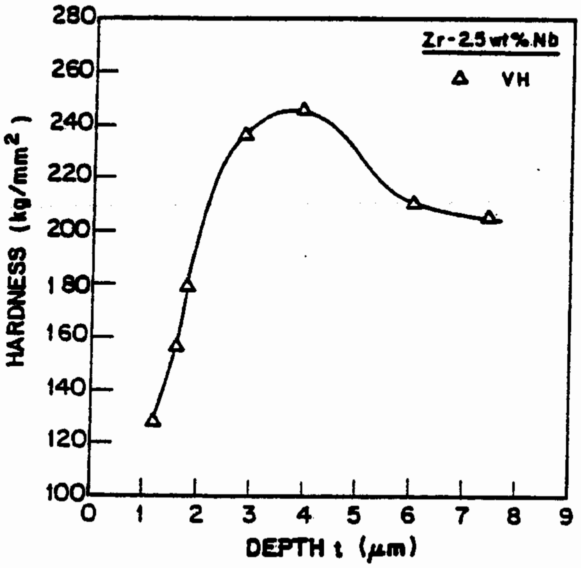

Fig. 3 Micro-hardness profile for Zr-2.5wt% Nb [6]

The values of the effective surface micro-hardness H_e given in Table 1 were computed by means of the DAM developed by Yovanovich et al [3,4]. For each pair compute the mean contact spot radius corresponding to the mean contact pressure and the bulk hardness:

$$\bar{a} = 0.99(\sigma/m)/[-\ln(3.132\ \bar{P}/H_b)]^{0.547} \qquad (2)$$

The relationship between the mean contact spot radius and the mean penetration depth of the Vickers indenter is [3]

$$\bar{t} = 0.358\bar{a} \qquad (3)$$

Substitution of the last expression into the surface micro-hardness correlations give values of H_e listed in Table 1.

It is seen in the above expressions that H_e is a strong function of the surface roughness parameter σ/m and a relatively weak function of the mean relative contact pressure $\bar{P}/H_b$. It is interesting to note that the Zircaloy specimen which has the maximum bulk hardness, also has the minimum effective hardness. The SS304 specimens which have the lowest bulk value possess the highest effective values. The highest effective value occurs in the smoothest Ni200 pair.

The thermal conductivity of the test specimens was measured by running the test apparatus with a single specimen, measuring the temperature gradient, and requiring that the difference between the input electrical power and the ARMCO heat meter heat flow rate be less than 5 percent. Over the temperature range of interest the thermal conductivity was determined to be a function of temperature T($^\circ$C):

For Ni200 [5]

$$k = 73.1 - 0.0553T \qquad (4)$$

For Zr-2.5wt% Nb [6]:

$$k = 18.39 + 0.00843T \qquad (5)$$

For Zr-4 [6]:

$$k = 14.05 + 0.0171T \qquad (6)$$

The thermal conductivity of SS304 was found to be 18.44 W/mK [8] independent of temperature. The thermal conductivity values calculated by Eqs. (4) - (6) are in good agreement with published data.

Test Procedure and Conditions

All tests were conducted in vacuum systems in which the gas pressure ranged from 10^{-4}mmHg [5] down to 10^{-6}mmHg [6-8]. All test data pertain to clean, dry, conforming, rough surfaces possessing negligible oxide films. The loading is static and only first loading data is reported. Heat transfer is steady.

The normal load applied to the nominal contact area was achieved by a pneumatic cylinder [5], lever arm system [6] and dead weights [8]. The contact pressure ranges are given in Table 1.

For details of the specific test procedure, the number, size and location of thermocouples, heat flow rates, temperature levels and temperature drops, etc., one should consult the research of Antonetti [5], DeVaal [6] and Hegazy [8].

The mean interface temperature in the three tests were observed to be

Ni200:	$85.1 < T_m < 188$
SS304:	$71 < T_m < 123$
Zircaloy:	$115.3 < T_m < 134.2$

At these temperature levels radiation heat transfer across the interface is negligible relative to conduction through the contact spots.

The contact temperature drop determined by extrapolation of the least squares fit of the thermocouple readings were observed to be

Ni200:	$9 < \Delta T_c < 49.7$
SS304:	$31 < \Delta T_c < 67$
Zircaloy:	$3.8 < \Delta T_c < 19.6$

These temperature drops assure reasonable experimental values of the contact conductances.

Experimental Results

Antonetti [4,5] measured contact conductances for Ni200 and found values that ranged from 101 to 1311 W/m^{2}K. The nondimensional contact conductances and the relative contact pressure for pairs 1 through 4 are given in Tables 2 through 5.

Table 2 Comparison between theory and test results for pair 1

P(kPa)	$10^4 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
622	1.750	0.357	0.337	5.93
980	2.757	0.558	0.519	7.51
1624	4.569	0.861	0.839	2.62
2105	5.923	1.166	1.074	8.57
2837	7.982	1.494	1.425	4.84
3510	9.876	1.815	1.745	4.01
		RMS% Difference		5.94

Table 3 Comparison between theory and test results for pair 2

P(kPa)	$10^4 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
518	1.748	0.335	0.337	-0.59
1150	3.882	0.673	0.719	-6.40
1457	4.918	0.878	0.900	-2.44
1827	6.167	1.083	1.116	-2.96
2150	7.257	1.143	1.302	-12.21
3215	10.852	1.981	I.908	3.83
		RMS% Difference		6.05

Table 4 Comparison between theory and test results for pair 3

P(kPa)	$10^4 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
698	2.360	0.468	0.448	4.46
1194	4.037	0.731	0.746	-2.01
1559	5.271	1.045	0.961	8.74
1925	6.508	1.153	1.174	-1.79
2450	8.283	1.369	1.476	-7.25
2890	9.771	1.769	1.727	2.43
3636	12.293	2.312	2.148	7.64
		RMS% Difference		5.61

Table 5 Comparison between theory and test results for pair 4

P(kPa)	$10^4 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
571	2.099	0.372	0.401	-7.23
976	3.588	0.611	0.667	-8.40
1591	5.849	1.061	1.061	0.00
2080	7.646	1.333	1.368	-2.56
2719	9.995	1.814	1.765	2.78
3433	12.620	2.118	2.203	-3.86
		RMS% Difference		5.03

Hegazy [8] measured contact conductances of SS304 and found values that ranged from 125 to 431 W/m^2K. The nondimensional contact conductances and the relative contact pressure for pairs 5 and 6 are reported in Tables 6 and 7, respectively.

DeVaal [6] measured contact conductances of the Zr-2.5wt% Nb/Zr-4 pair and found valves that ranged from 1,270 up to 6,260 W/m^2K. The test results are shown in Table 8 as a function of contact pressure. Also shown are the extrapolated temperatures, and the computed thermal conductivities corresponding to these temperatures.

The effective surface micro-hardness values corrected for temperature level are given in Table 9. The temperature correction is applied to the micro-hardness profile given by Eq. (1) and shown in Fig. 3. The temperature correction coefficient is [6]

$$c(T) = 1.054 \exp(-0.00239T) \quad (7)$$

where T is the extrapolated temperature T_1 in degrees Celsius.

The nondimensional contact conductances and relative contact pressures are listed in Table 9.

Table 6 Comparison between theory and test results for pair 5

P(kPa)	$10^4 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
360	1.284	0.257	0.251	2.39
573	2.043	0.436	0.391	11.51
793	2.827	0.544	0.532	2.26
1007	3.590	0.693	0.667	3.90
1157	4.125	0.821	0.761	7.88
1286	4.585	0.886	0.842	5.23
		RMS% Difference		6.43

Table 7 Comparison between theory and test results for pair 6

P(kPa)	$10^4 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
360	1.243	0.262	0.244	7.38
573	1.978	0.386	0.379	1.85
793	2.737	0.489	0.516	-5.23
1007	3.476	0.609	0.647	-5.87
		RMS% Difference		5.47

Table 8 Test results for pair 7

P MPa	T_1 °C	T_2 °C	k_1 W/mK	k_2 W/mK	h_c kW/m^2K	$10^4 C_c^*$ test
2.22	144.0	124.4	19.60	16.17	1.269	2.292
2.86	137.9	122.0	19.55	16.13	1.555	2.815
2.88	136.2	120.6	19.54	16.10	1.602	2.904
3.52	132.3	119.2	19.51	16.08	1.890	3.431
4.18	128.3	117.3	19.47	16.05	2.240	4.074
5.46	125.3	116.3	19.45	16.03	2.674	4.869
6.76	121.4	113.9	13.41	16.00	3.252	5.933
8.06	117.9	112.0	19.38	15.96	4.085	7.468
10.28	117.6	113.0	19.38	15.97	5.168	9.444
12.79	117.1	113.3	19.38	15.98	6.263	11.442

Table 9 Comparison between theory and test results for pair 7

P(MPa)	H_e(MPa)	$10^3 P/H_e$	$10^3 C_c^*$ test	$10^3 C_c^*$ theory	% Diff.
2.22	1700	1.306	2.225	2.275	-2.20
2.86	1725	1.658	2.733	2.854	-4.24
2.88	1732	1.663	2.819	2.863	-1.54
3.52	1748	2.014	3.331	3.434	-3.00
4.18	1765	2.368	3.955	4.005	-1.25
5.46	1777	3.073	4.727	5.130	-7.85
6.76	1794	3.768	5.760	6.226	-7.48
8.06	1809	4.455	7.250	7.300	-0.07
10.28	1811	5.676	9.169	9.189	-0.02
12.79	1813	7.055	11.109	11.297	-1.66
		RMS% Difference			3.95

Comparison of Experimental and Theoretical Results

Experimental and theoretical nondimensional contact conductances $C_c^* = (\sigma/m)(h_c/k_s)$ for all seven pairs are given in Tables 2 through 9 as a function of the relative contact pressure P/H_e.

The 45 experimental values and the theoretical curve are shown in Fig. 4. The percent differences between experimental and theoretical values shown in Tables 2 through 9 are relative to the theoretical values which are computed by means of the contact conductance correlation developed by Yovanovich [2]:

$$C_c^* = (\sigma/m)(h_c/k_s) = 1.25\,(P/H_e)^{0.95} \qquad (8)$$

where k_s is the harmonic mean thermal conductivity of the interface.

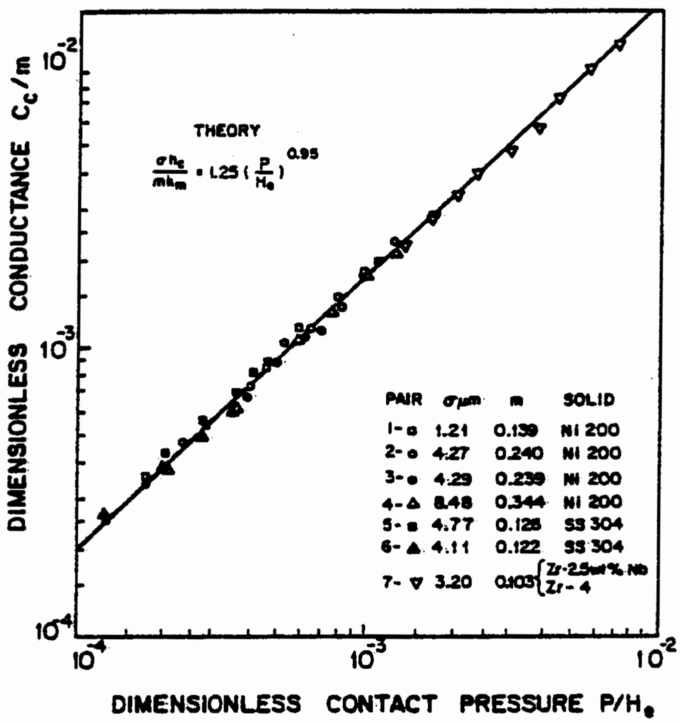

Fig. 4 Comparison of theory and experimental results

Table 2 shows that the experimental values of pair 1, the smoothest pair, exceed the theoretical values for all contact pressures; however, the RMS percent difference is only 5.94.

Tables 3 and 4 pertain to the Ni200 pairs 2 and 3 which are almost identical. It can be seen that the experimental values are slightly below the theoretical values for pair 2 with an RMS percent difference of 6.05; and for pair 3 the experimental values are both above and below the theoretical values with an RMS percent difference of 5.61.

Table 5 pertains to the very rough Ni200 pair 4 specimen. As with pairs 1 through 3, the agreement between the experimental and theoretical values is excellent; the RMS percent difference is only 5.03.

Tables 6 and 7 relate to the SS304 pairs 5 and 6 which are similar specimens. For pair 5, all experimental values exceed the theoretical values with an RMS percent difference of 6.43. On the other hand, for pair 6, the very high load values exceed the theoretical values, while the higher load values are below the theoretical values. Again the agreement between experiment and theory is excellent because the RMS percent difference is 5.47.

Table 9 contains the experimental and theoretical contact conductances of pair 7. It can be seen that all experimental values are below the theoretical values; the RMS percent difference is 3.95.

The agreement between all 45 experimental values and the predictions based upon the contact conductance correlation of Yovanovich and the effective hardness of the DAM developed by Yovanovich and co-workers is excellent; the overall RMS percent difference is 5.53. This excellent agreement between experiment and theory is clearly seen in Fig. 4 where all 45 experimental points are shown plotted against relative contact pressure which ranges over two orders of magnitude.

Summary

The nondimensional contact conductance data of Antonetti [5], DeVaal [6] and Hegazy [8] are shown to be consistent with each other when plotted against relative contact pressure based upon the effective surface micro-hardness which is computed by means of a correlation of the Vickers micro-hardness data versus penetration depth.

The agreement between the experimental and theoretical dimensionless contact conductances is excellent overall. This excellent agreement holds over a broad range of the geometric characteristics, the thermophysical properties, relative contact pressure, and loading device employed to obtain the experimental values.

This study demonstrates that when accurate experimental contact conductance data obtained by different researchers using different materials are reduced to dimensionlize contact conductance and relative contact pressure parameters, the experimental values are consistent and in excellent agreement with the theory, provided the appropriate surface parameters and surface hardness are used in the normalization; otherwise the data will appear to be inconsistent with other data and theoretical values.

It can therefore be concluded that the contact conductance correlation of Yovanovich in conjunction with the Direct Approximate Method of determining the effective surface micro-hardness is an accurate, universal contact conductance correlation for conforming, rough surfaces.

Acknowledgements

The authors acknowledge the financial support of AECL Whiteshell Nuclear Reactor Establishment under contract File A-7662 and the partial support of the National Science and Engineering Research Council of Canada under operating grant A-7445.

The authors also thank Dr. M.H. Schankula and Mr. J. DeVaal for their assistance and advice.

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