Thermal Contact Resistance of Non-Conforming Rough Surfaces Part 2: Thermal Model

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CONTENTS

INTRODUCTION

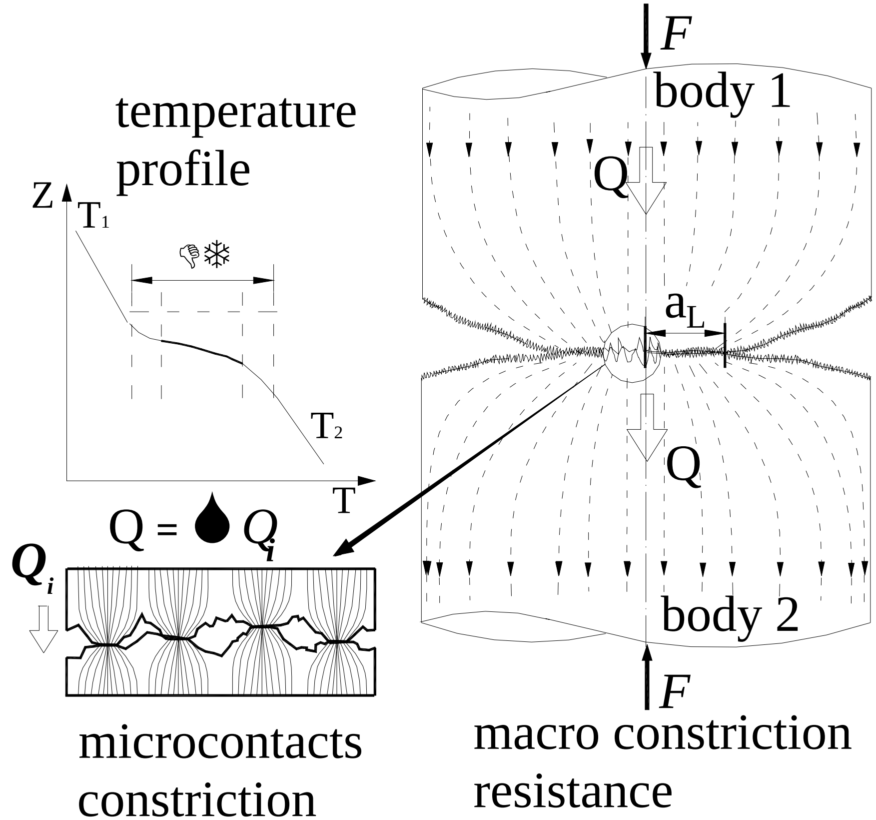
- conduction (microcontacts)
- conduction (interstitial fluid)
- radiation across the gap

- two sets of resistances in series represent TCR in a vacuum

- many researchers assumed

$$R_j \qquad R_{mic} \qquad R_{mac}$$

- Bahrami et al. (2003) reviewed existing non-conforming rough models



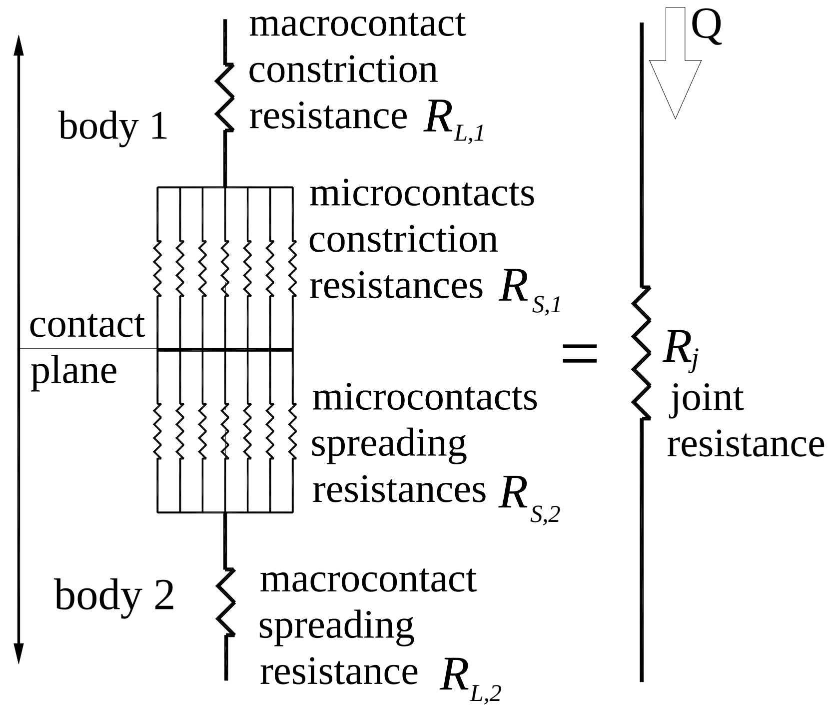
THERMAL RESISTANCE NETWORK

thermal resistance is defined as,

$$R \quad \Delta T/Q$$

$$R_j \quad R_{L,1} \quad R_{s,1} \quad R_{s,2} \quad R_{L,2}$$

$$\left(\frac{1}{R_s}\right)_{1,2} \quad \left(\sum_{i \;\; 1}^{n_s} \frac{1}{R_{s,i}}\right)_{1,2}$$



TCR PROBLEM STATEMENT

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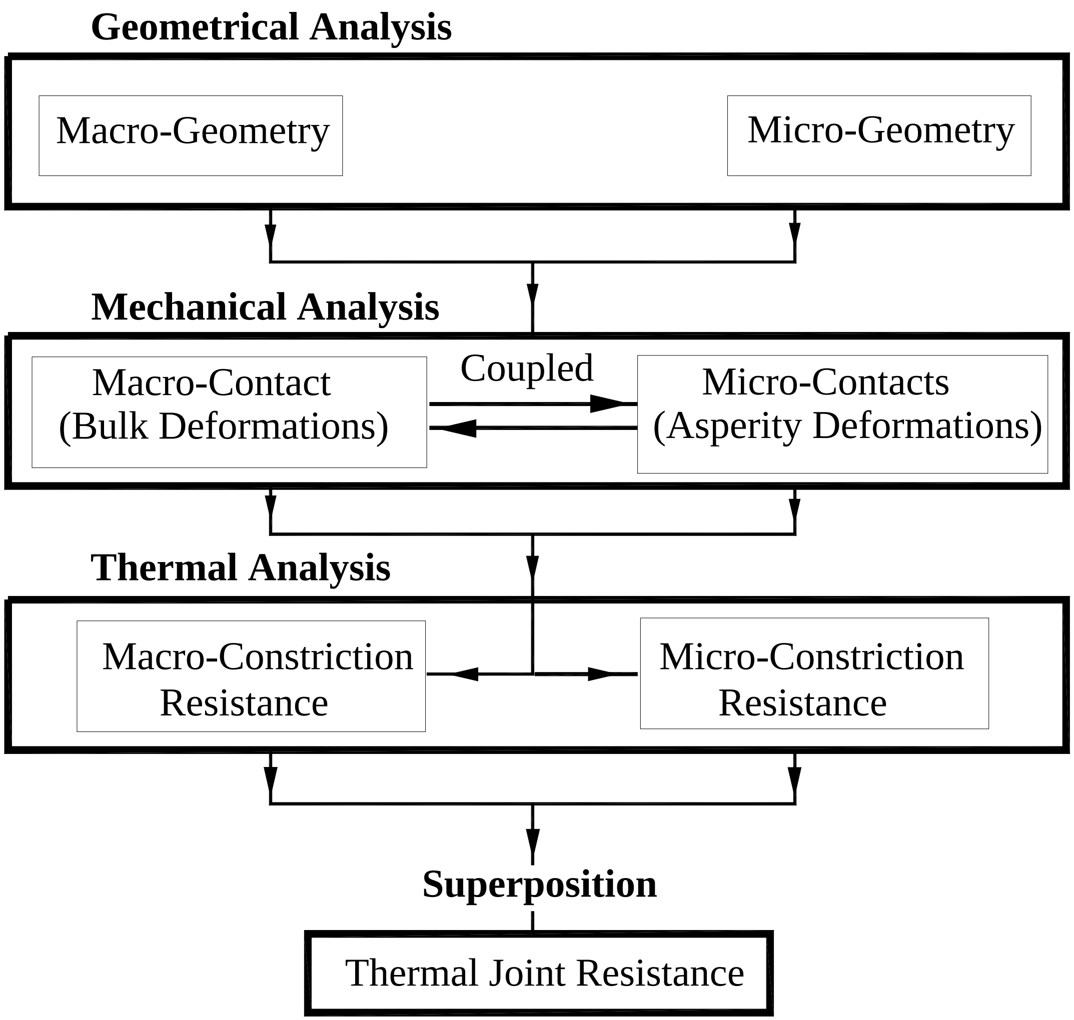
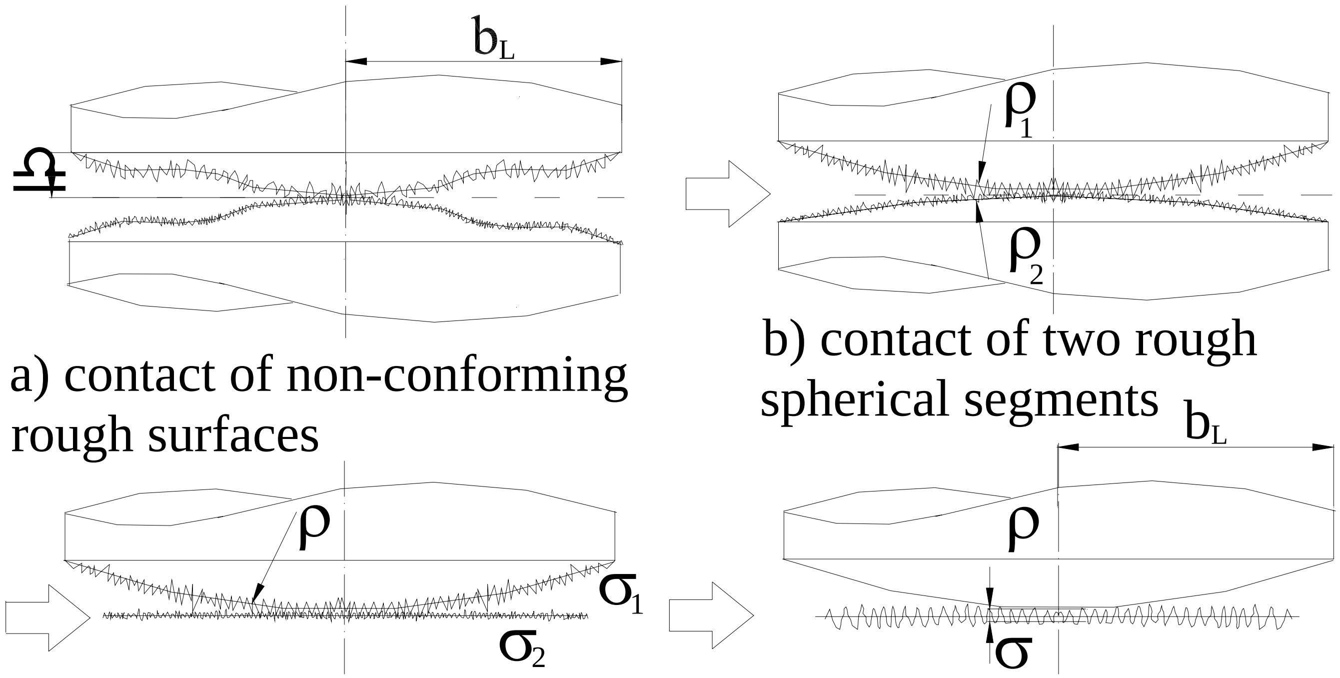


OBJECTIVES

- develop analytical TCR model for entire range of contacts:
  - conforming rough
  - elastoconstriction
  - transition region
- study effects of input parameters on TCR
- derive simple correlations for determining TCR

GEOMETRICAL MODELING



a) contact of non-conforming rough surfaces

b) contact of two rough spherical segments

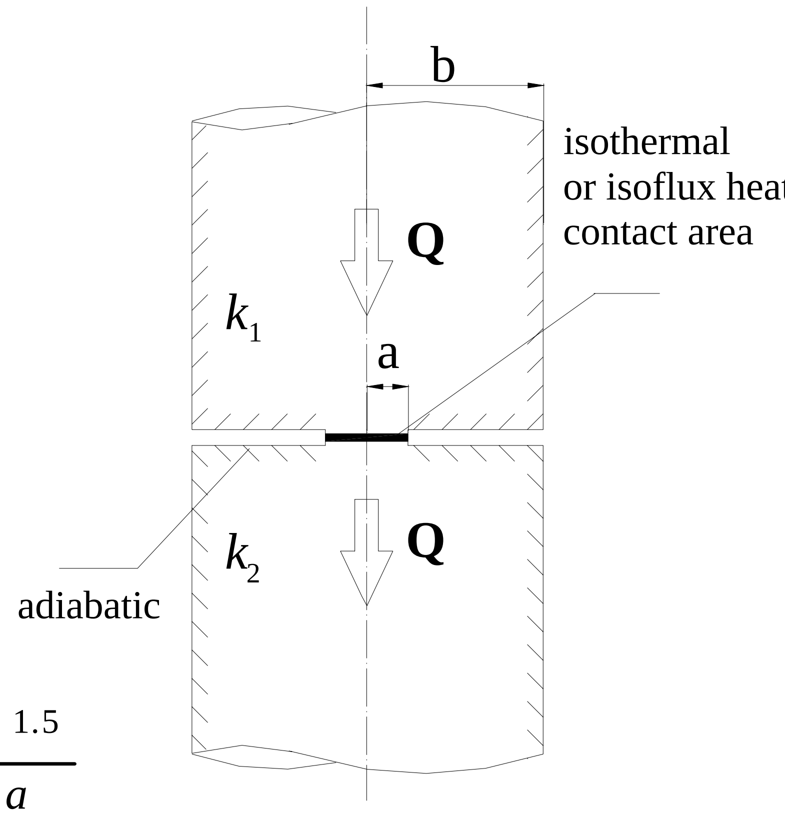
c) rough sphere-flat contact, effective radius of curvature

d) equivalent sphere-flat contact, effective radius and roughness

$$\frac{b_L^2}{2}$$

FLUX TUBE SOLUTION

- inside macrocontact area a number of parallel cylindrical heat channels exist
- basic element for macro and micro thermal analysis
- Cooper et al. (1969)



$$R_{\text{flux tube 1}} \quad R_{\text{flux tube 2}} \quad \frac{\quad}{2k_s a} \quad \frac{1- \quad^{1.5}}{2k_s a}$$

$$a/b \qquad k_s \quad \frac{2k_1 k_2}{k_1 \quad k_2}$$

PRESENT MODEL (ASSUMPTIONS)

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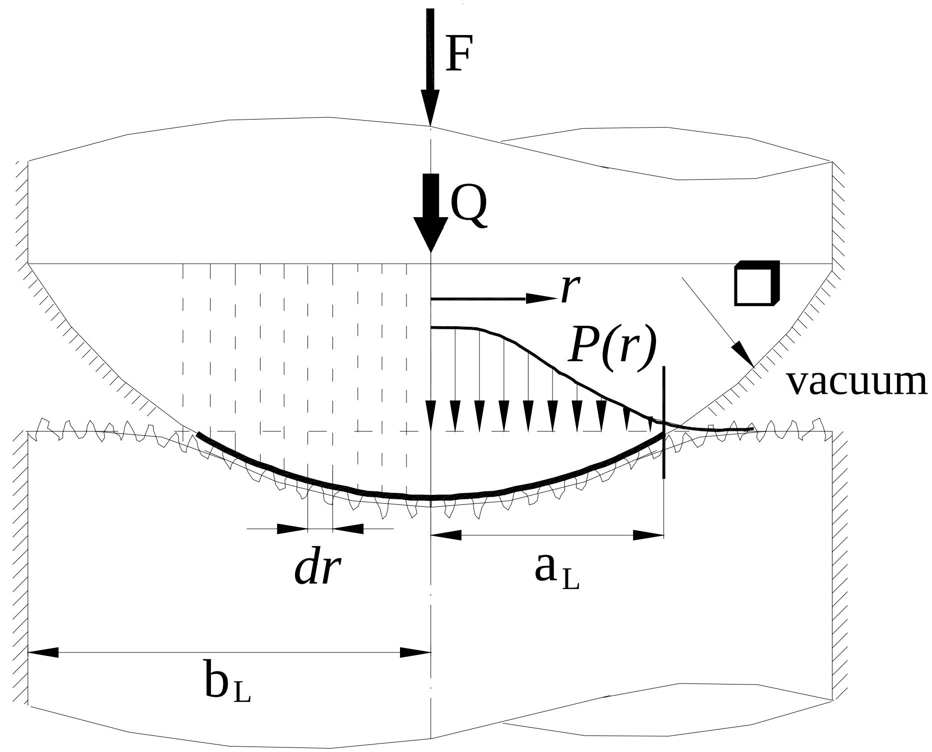
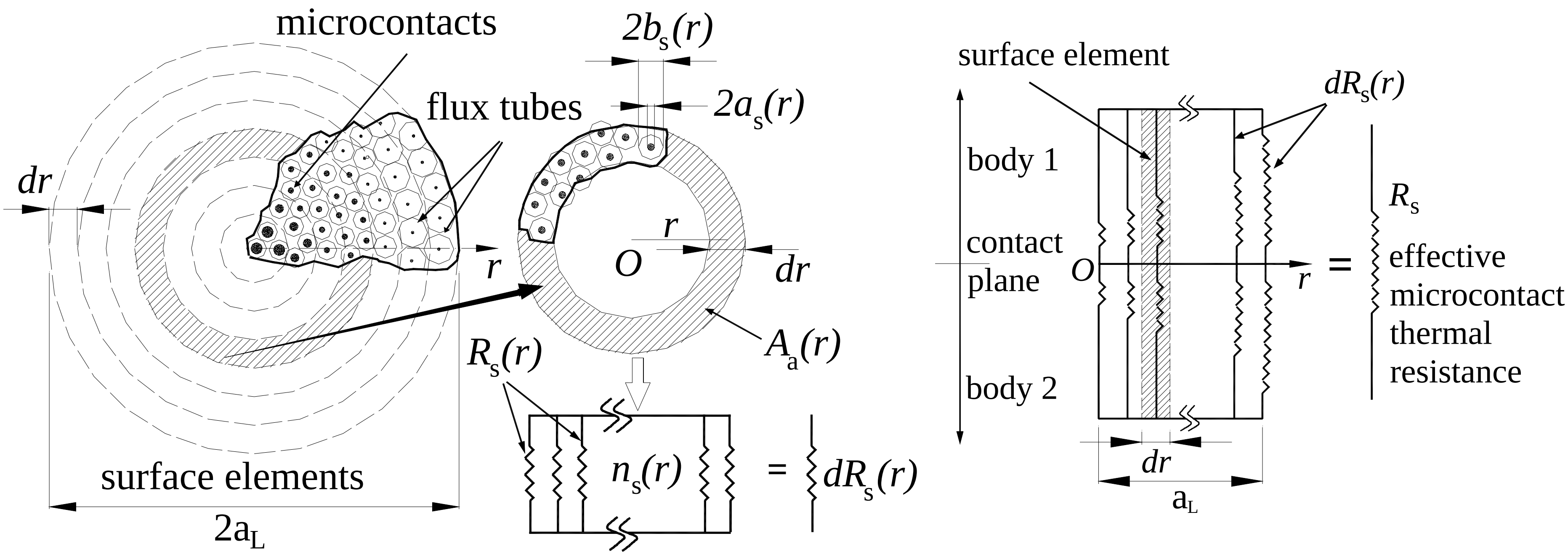
- solids are isotropic
- radiation heat transfer is negligible
- microcontacts are circular and steady-state heat transfer
- isothermal microcontacts
- microcontacts are flat
- surfaces are clean



$$R_j \qquad R_L \qquad R_s$$

$$R_L \qquad \frac{1-a_L/b_L \quad ^{3/2}}{2k_s a_L}$$

MICROCONTACTS RESISTANCE



$$R_s \ r \qquad \frac{r}{2k_s a_s \ r}$$

$$dR_s \ r \qquad \frac{R_s \ r}{n_s \ r}$$

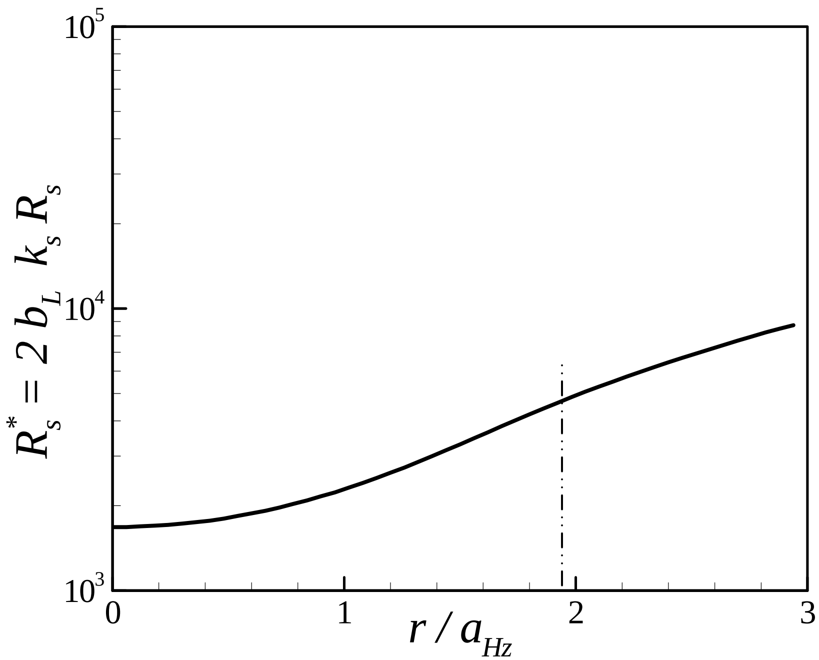
$$r \qquad \sqrt{\frac{A_r \ r}{A_a \ r}} \qquad \sqrt{\tfrac{1}{2}\,\mathrm{erfc} \quad r}$$

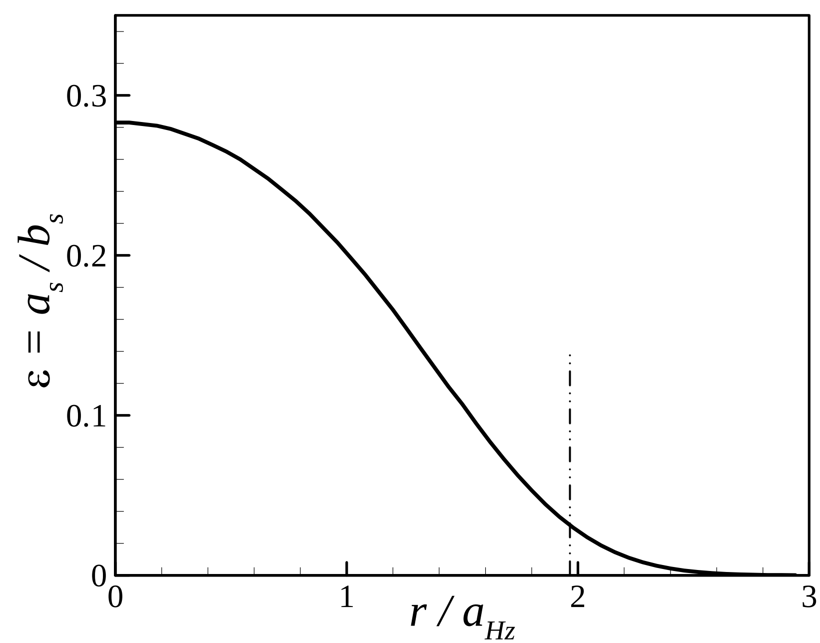
$$R_s \qquad \frac{1}{\sum \ 1/dR_s \ r}$$

$$n_s \qquad \frac{1}{16} \quad \frac{m}{\ } \quad ^{2} \ \frac{\exp\left[-2 \quad r^{\ 2}\right]}{\mathrm{erfc} \quad r} A_a$$

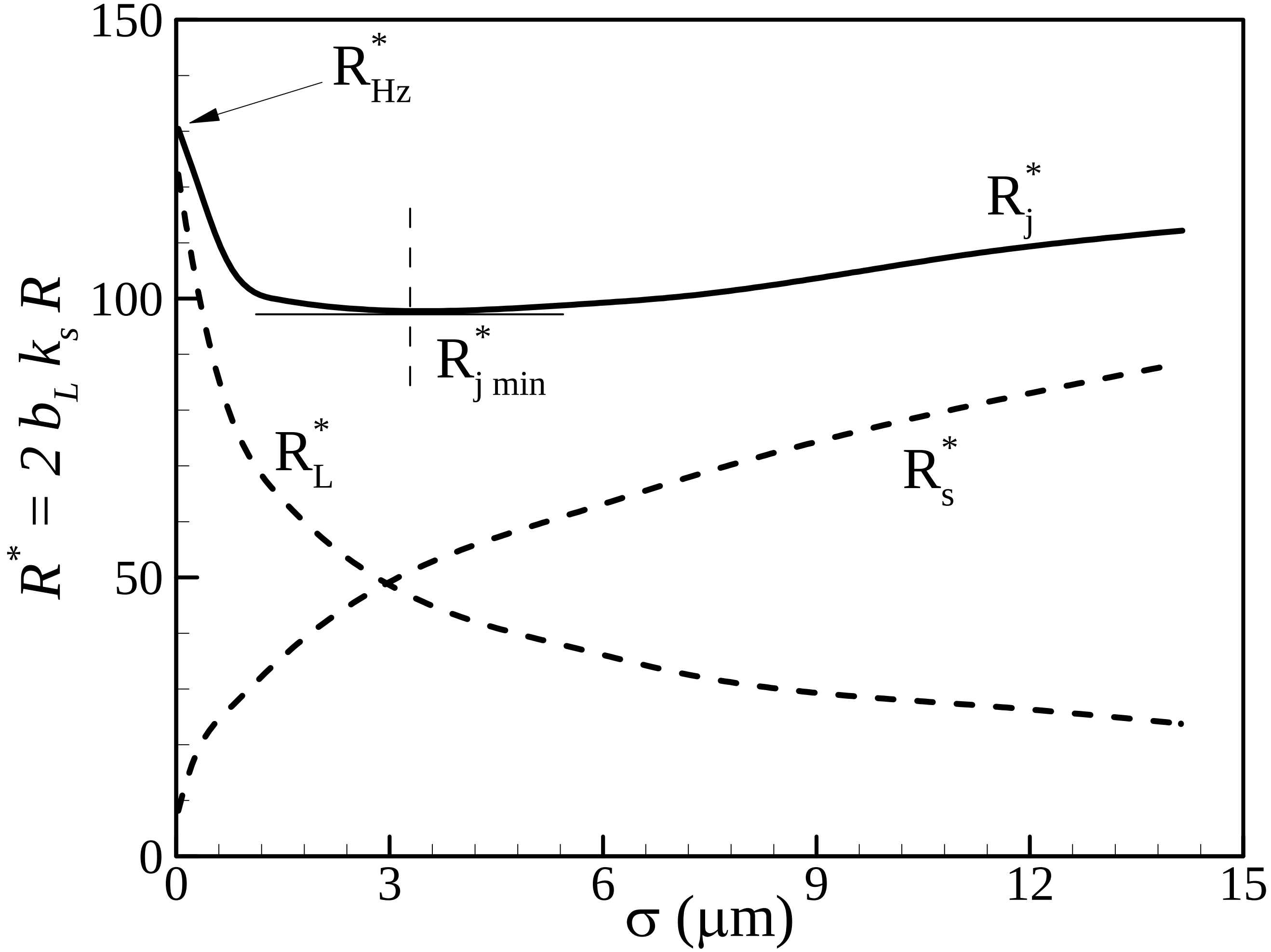
NUMERICAL RESULTS

25 mm	F 50 N
1.41 m	E' 112.1 GPa
m 0.107 −	c_1/c_2 6.27 GPa / − 0.15 −
b_L 25 mm	k_s 16 W/mK

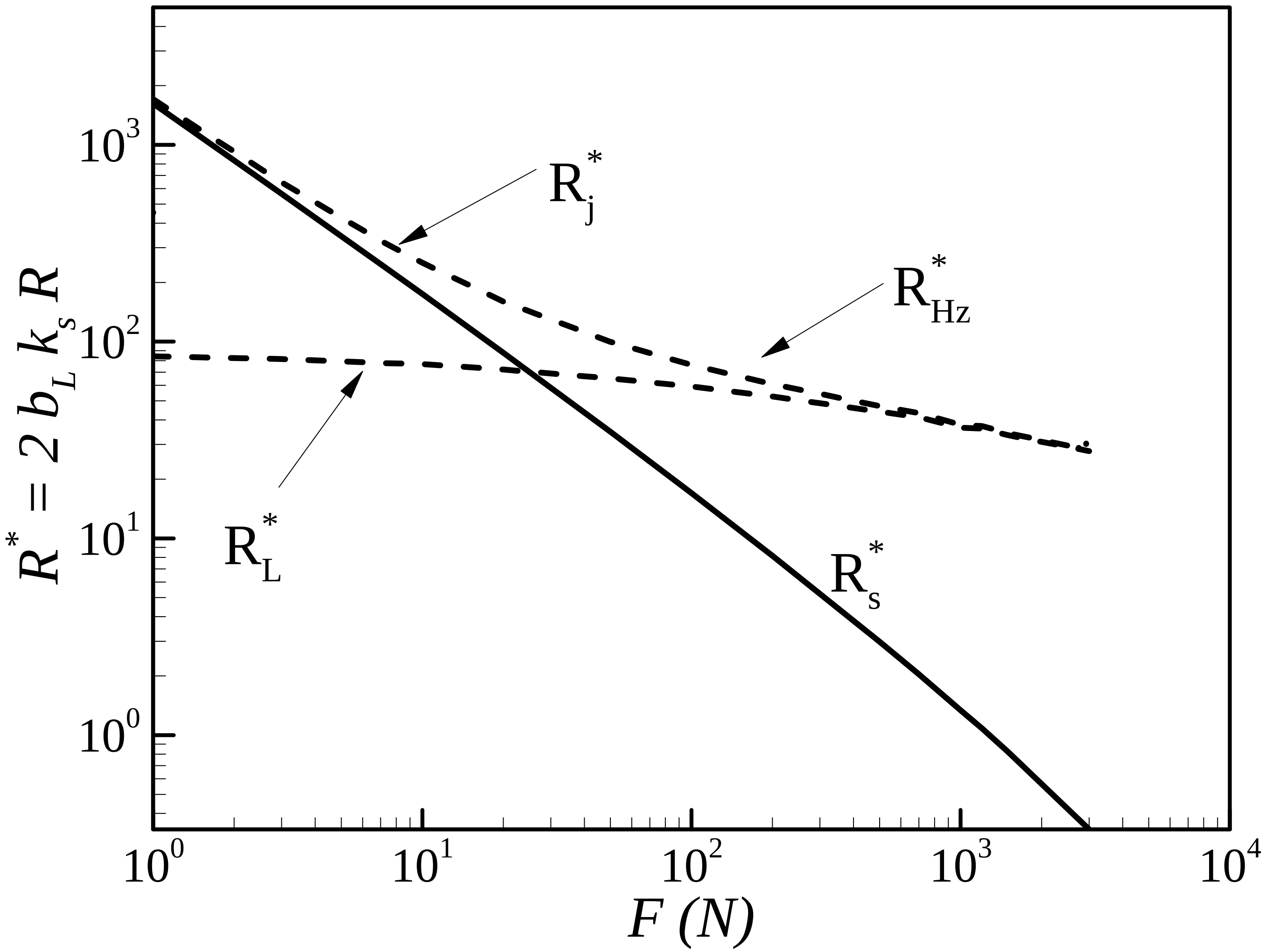




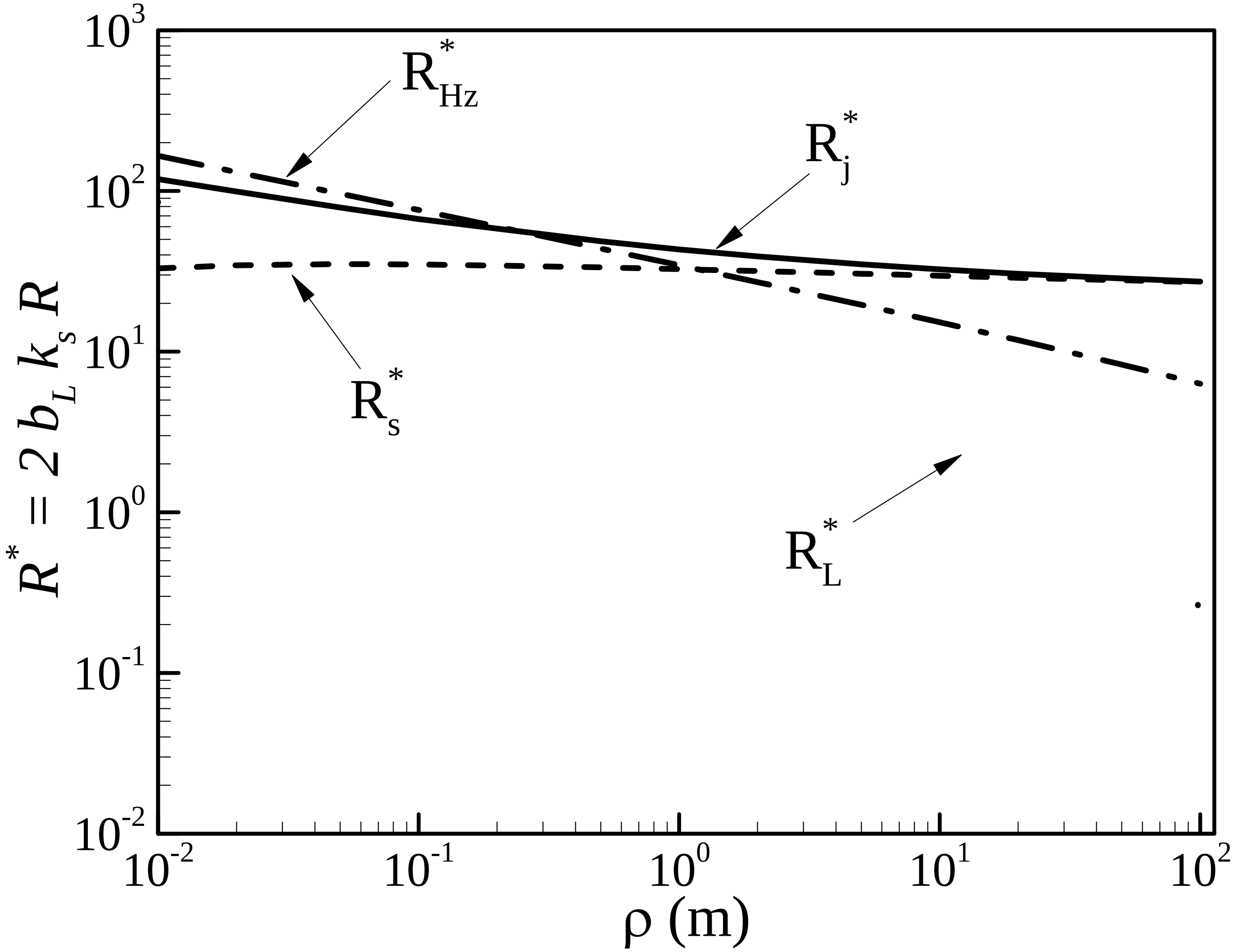
EFFECT OF ROUGHNESS



EFFECT OF LOAD



EFFECT OF RADIUS OF CURVATURE



ALTERNATIVE APPROACH

- conforming rough conductance, Yovanovich (1982)

$$h_s \quad 1.25 k_s \frac{m}{} \left(\frac{P}{H_{mic}} \right)^{0.95}$$

- heat transfer in non-conforming rough contact:

$$Q \qquad \underset{contact\ plane}{} \qquad h_s \ r \ \Delta T_s dA_a$$

- using pressure distribution, Part I and $R \quad 1/ \ hA_a$

$$R_s \quad \frac{1 \ \ s}{1.25 \quad m \, k_s \, a_L^2} \left(\frac{H'}{P_0} \right)^{s}$$

PROCEDURE FOR UTILIZING THE MODEL

If an estimate of microhardness is available, set $c_1 = H_{mic}, c_2 = 0$

m, may be estimated from:

$m = 0.076\sigma^{0.52}$

$\sigma[\mu m]$

Start

Input

F, ρ, σ, m, k_s

E', b_L, c_1, c_2

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$$

$$m = \sqrt{m_1^2 + m_2^2}$$

$$\rho = [1/\rho_1 + 1/\rho_2]^{-1}$$

$$k_s = 2k_1k_2/(k_1 + k_2)$$

$$E' = \left[\frac{(1-\upsilon_1^2)}{E_1} + \frac{(1-\upsilon_2^2)}{E_2}\right]^{-1}$$

$$F_c = \frac{4E'}{3\rho}\left(\max\left\{0, \left(b_L^2 - 2.25\sigma\rho\right)\right\}\right)^{3/2}$$

$F_c = 0$:

$$R_s^* = \left(\frac{\pi H' b_L^2}{F}\right)^s$$

$a_L = b_L$

Flat surface

$F \le F_c$:

$$R_s^* = \frac{1 + s\gamma}{\left(\frac{a_L}{b_L}\right)^2 \left(\frac{P_0}{H'}\right)^s}, \text{ where}$$

$$R_s^* = 1.25\pi k_s b_L^2 (m/\sigma) R_s$$

$F > F_c$:

$$R_s^* = \left(\frac{H'}{P_{0,c}}\right)^s (1 + s\gamma_c) + \left(\frac{\pi b_L^2 H'}{F - F_c}\right)^s, \; a_L = b_L$$

$$s = 0.95/(1 + 0.071c_2)$$

$$H' = c_1\left(1.62\sigma^*/m\right)^{c_2}$$

$$\sigma^* = \sigma/\sigma_0 \; [\mu m]$$

$$\alpha = \sigma\rho/a_{Hz}^2, \; \tau = \rho/a_{Hz}$$

$$a_{Hz} = (0.75F\rho/E')^{1/3}$$

$$P_{0,Hz} = 1.5F/\pi a_{Hz}^2$$

$$R_L = \frac{(1 - a_L/b_L)^{3/2}}{2k_s a_L}$$

$$R_j = R_L + R_s$$

End

$$P_0' = \frac{P_0}{P_{0,Hz}} = \frac{1}{1 + 1.37\,\tau^{-0.075}\alpha}$$

$$a_L' = \frac{a_L}{a_{Hz}} = 1 - 1.5\ln P_0' - 0.14\ln^2 P_0' - 0.11\ln^3 P_0'$$

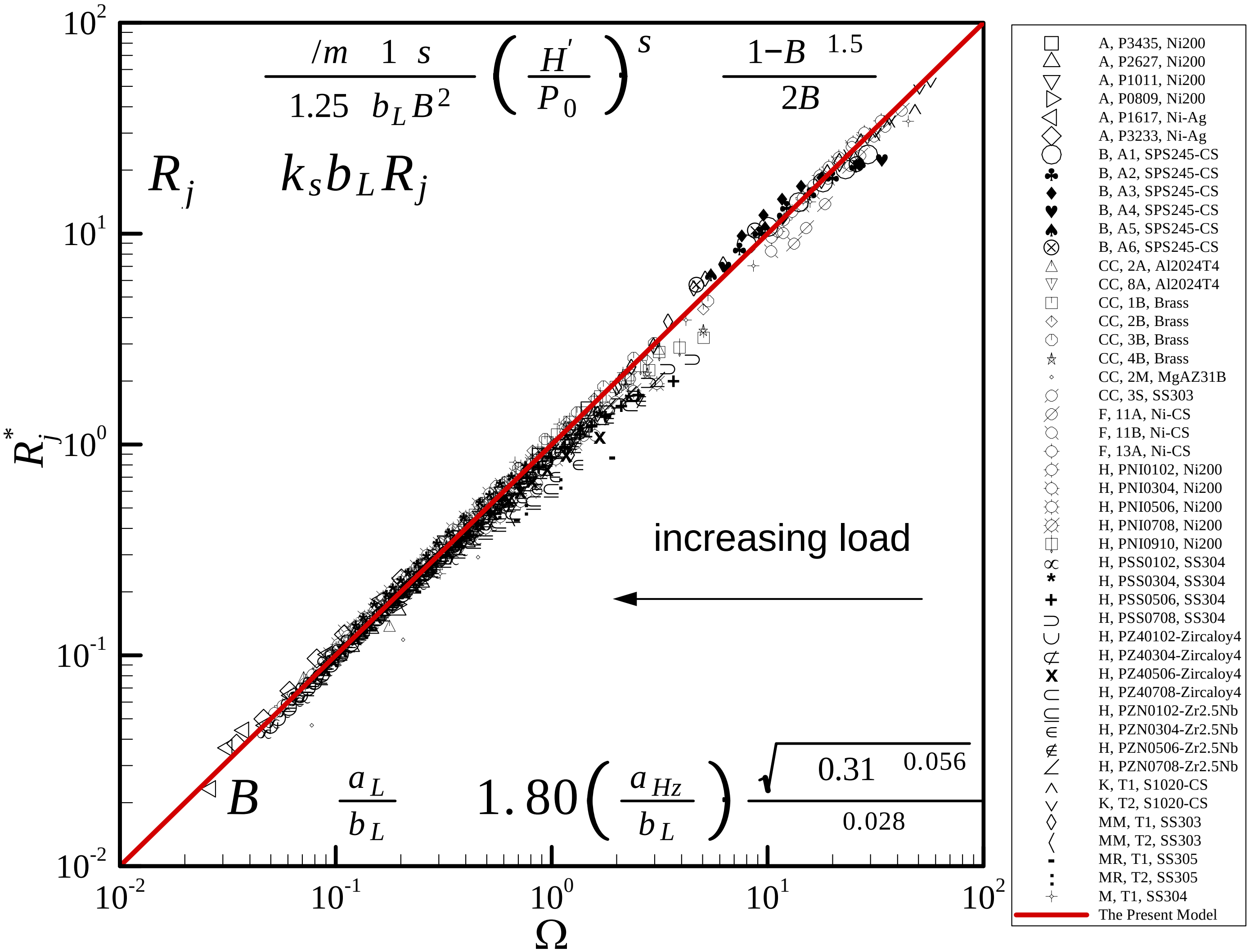
$$\gamma = 1.5P_0'(a_L')^2 - 1$$

EXPERIMENTAL DATA

Parameter
$7.15 \le b_L \le 14.28 \; mm$
$25.64 \le E' \le 114.0 \; GPa$
$7.72 \le F \le 16763.9 \; N$
$16.6 \le k_s \le 227.2 \; W/mK$
$0.04 \le m \le 0.34 \; -$
$0.12 \le \quad \le 13.94 \; m$
$0.013 \le \quad 120 \; m$

Ref.	Researcher	Material(s)
A	Antonetti	Ni200 Ni200-Ag
B	Burde	SPS 245, CS
CC	Clausing-Chao	Al2024 T4 Brass Anaconda Mg AZ 31B SS303
F	Fisher	Ni 200-Carbon Steel
H	Hegazy	Ni200 SS304 Zircaloy4 Zr-2.5%wt Nb
K	Kitscha	Steel 1020-CS
MM	McMillan-Mikic	SS303
MR	Mikic-Rohsenow	SS305
M	Milanez et al.	SS304

COMPARISON WITH DATA



SUMMARY AND CONCLUSIONS

- superposition of macro and micro thermal resistance
- effects of major parameters, i.e., roughness, load, and radius of curvature on TCR were investigated
- for non-conforming rough contact, there is a value of surface roughness that minimizes TCR
- at relatively large loads effect of roughness on TCR becomes negligible
- simple correlations were derived that cover entire range of TCR

SUMMARY AND CONCLUSIONS 2

- model was compared with more than 700 experimental data points, collected by many researchers
- comparison includes all three regions of TCR and wide range of mechanical, thermal, and surfaces characteristics
- data include contact between dissimilar metals such as Ni200-Ag and SS-CS
- RMS relative difference between the model and the data was estimated to be approximately 11.4%

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CONFORMING ROUGH DATA

Ref.	E'		m	c_1	$-c_2$	k_s	b_L
A,P3435	112.1	8.48	.34	6.3	.26	67.1	14.3
A,P2627	112.1	1.23	.14	6.3	.26	64.5	14.3
A,P1011	112.1	4.27	.24	6.3	.26	67.7	14.3
A,P0809	112.1	4.29	.24	6.3	.26	67.2	14.3
A,P1617	63.9	4.46	.25	.39	0	100	14.3
A,P3233	63.9	8.03	.35	.39	0	100	14.3
H,NI12	112.1	3.43	.11	6.3	.26	75.3	12.5
H,NI34	112.1	4.24	.19	6.3	.26	76.0	12.5
H,NI56	112.1	9.53	.19	6.3	.26	75.9	12.5
H,NI78	112.1	13.9	.23	6.3	.26	75.7	12.5
H,NI910	112.1	0.48	.23	6.3	.26	75.8	12.5
H,SS12	112.1	2.71	.07	6.3	.23	19.2	12.5
H,SS34	112.1	5.88	.12	6.3	.23	19.1	12.5
H,SS56	112.1	10.9	.15	6.3	.23	18.9	12.5
H,SS78	112.1	0.61	.19	6.3	.23	18.9	12.5
H,Z412	57.3	2.75	.05	3.3	.15	16.6	12.5
H,Z434	57.3	3.14	.15	3.3	.15	17.5	12.5
H,Z456	57.3	7.92	.13	3.3	.15	18.6	12.5
H,Z478	57.3	0.92	.21	3.3	.15	18.6	12.5
H,ZN12	57.3	2.50	.08	5.9	.27	21.3	12.5
H,ZN34	57.3	5.99	.16	5.9	.27	21.2	12.5
H,ZN56	57.3	5.99	.18	5.9	.27	21.2	12.5
H,ZN78	57.3	8.81	.20	5.9	.27	21.2	12.5
M,SS1	113.8	0.72	.04	6.3	.23	18.8	12.5

ROUGH SPHERE-FLAT DATA

Ref.	E'	$/m$		$c_1/-c_2$	k_s	b_L
B,A-1	114.0	0.63/.04	.013	3.9/0	40.7	7.2
B,A-2	114.0	1.31/.07	.014	3.9/0	40.7	7.2
B,A-3	114.0	2.44/.22	.014	3.9/0	40.7	7.2
B,A-4	114.0	2.56/.08	.019	4.4/0	40.7	7.2
B,A-5	114.0	2.59/.10	.025	4.4/0	40.7	7.2
B,A-6	114.0	2.58/.10	.038	4.4/0	40.7	7.2
CC,2A	38.66	0.42/-	14.0	1.6/.04	141	12.7
CC,8A	38.66	2.26/-	14.7	1.6/.04	141	12.7
CC,1B	49.62	0.47/-	3.87	3.0/.17	125	12.7
CC,2B	49.62	0.51/-	4.07	3.0/.17	125	12.7
CC,3B	49.62	0.51/-	3.34	3.0/.17	102	12.7
CC,4B	49.62	0.51/-	4.07	3.0/.17	125	12.7
CC,3S	113.7	0.11/-	21.2	4.6/.13	17.8	12.7
CC,2M	25.64	0.11/-	30.3	.41/0	96	12.7
F,11A	113.1	0.12/-	.019	4.0/0	57.9	12.5
F,11B	113.1	0.12/-	.038	4.0/0	57.9	12.5
F,13A	113.1	0.06/-	.038	4.0/0	58.1	12.5
K,T1	113.8	0.76/-	.014	4.0/0	51.4	12.7
K,T2	113.8	0.13/-	.014	4.0/0	51.4	12.7
MM,T1	113.7	2.7/.06	.128	4.0/0	17.3	12.7
MM,T2	113.7	1.75/.07	2.44	4.0/0	22	12.7
MR,T1	107.1	4.83/-	21.2	4.2/0	19.9	12.7
MR,T2	107.1	3.87/-	39.7	4.2/0	19.9	12.7

CORRELATIONS

$$F_c \quad \frac{4E'}{3} \max \ 0,\ b_L^2 - 2.25 \quad ^{3/2}$$

$$R_s^* = \begin{cases} \left(\dfrac{\pi H' b_L^2}{F}\right)^s & F_c = 0 \\ \left(\dfrac{b_L}{a_L}\right)^2 \left(\dfrac{H'}{P_0}\right)^s (1 + s\gamma) & F \leq F_c \\ \left(\dfrac{H'}{P_{0,c}}\right)^s (1 + s\gamma_c) + \left(\dfrac{\pi H' b_L^2}{F - F_c}\right)^s & F \geq F_c \end{cases}$$

$$R_s \quad 1.25 \ b_L^2 k_s \ m/ \quad R_s$$

$$s \quad 0.95/\ 1 \quad 0.071 c_2$$

$$H' \quad c_1 \ 1.62 \ ' /m \ ^{c_2}$$

$$P_0' \quad \frac{P_0}{P_{0,Hz}} \quad \frac{1}{1 \ 1.37 \quad ^{-0.075}}$$

$$a_L' \quad \frac{a_L}{a_{Hz}} \quad 1.80 \frac{\sqrt{\quad 0.31 \quad ^{0.056}}}{0.028}$$