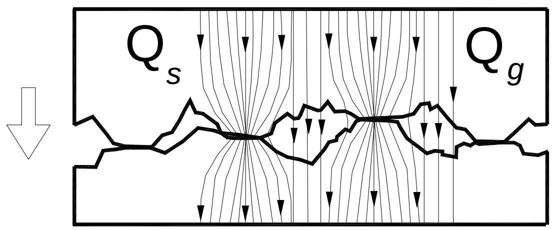
Thermal Resistances of Gaseous Gap for Non-Conforming Rough Contacts

M. Bahrami
J. R. Culham
M. M. Yovanovich

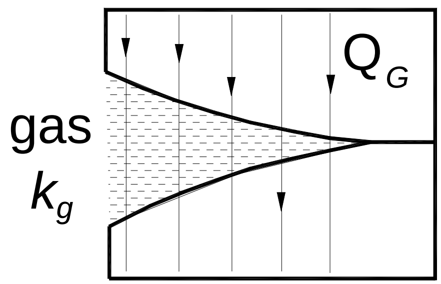
Department of Mechanical Engineering
Microelectronics Heat Transfer Laboratory
University of Waterloo
Waterloo, ON, Canada

CONTENTS

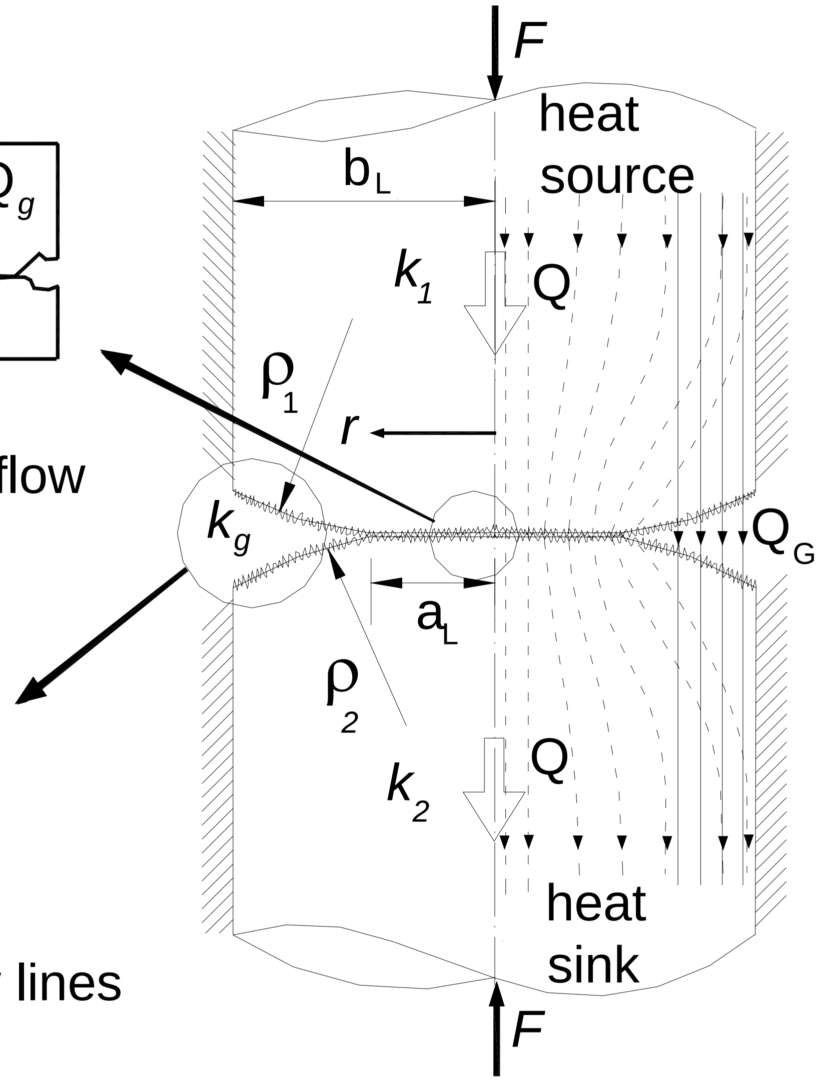
INTRODUCTION



microgaps and microcontacts heat flow lines

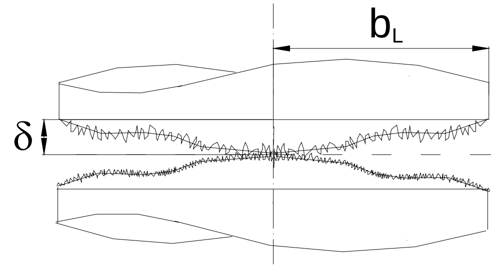


macrogap heat flow lines

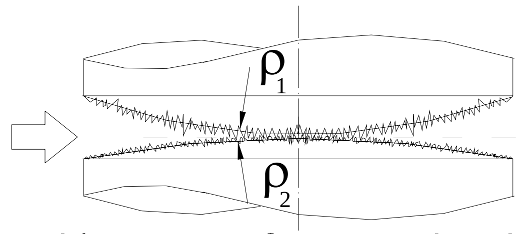


GEOMETRICAL MODELING

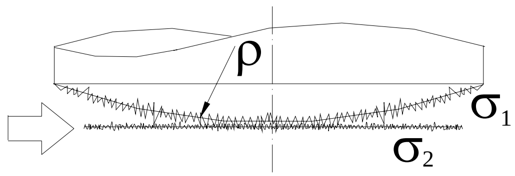
$$\rho = \frac{b_L^2}{2\delta}$$



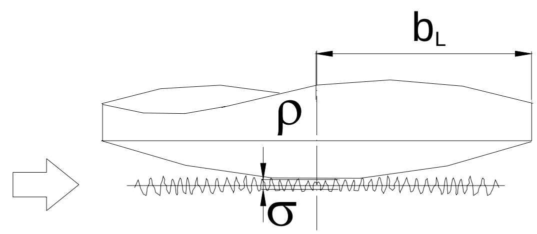
a) contact of non-conforming rough surfaces



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

$$\sigma = \sqrt{\sigma_1 + \sigma_2} \text{ and } m = \sqrt{m_1 + m_2}$$

$$\frac{1}{E'} = \frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_2^2}{E_2} \qquad \frac{1}{\rho} = \frac{1}{\rho_1} + \frac{1}{\rho_2}$$

SOLID-SOLID THERMAL RESISTANCE

- contact of rough spheres, Bahrami et al. (2003) a

$$P(\xi) = P_0\left(1-\xi^2\right)^{\gamma} \quad \text{where } \xi = r / a_L$$

$$\gamma = 1.5\left(P_0 / P_{0,H}\right)\left(a_L / a_H\right)^2 - 1$$

$$P_0 = \frac{P_{0,H}}{1+1.37\,\alpha\,\tau^{-0.075}} \;\&\; a_L = 1.8\,a_H \frac{\sqrt{\alpha + 0.31\tau^{0.056}}}{\tau^{0.028}} \;\&\; \alpha = \frac{\sigma\rho}{a_H^2} \;\&\; \tau = \frac{\rho}{a_H}$$

- micro and macro thermal resistances, Bahrami et al. (2003) b

$$R_s = \frac{0.565 c_1 (\sigma / m)}{k_s F}\left(\frac{\sigma}{m}\right)^{c_2}$$

$$R_L = \frac{\left(1 - a_L / b_L\right)^{1.5}}{2 k_s a_L}$$

$$k_s = \frac{2 k_1 k_2}{k_1 + k_2}$$

PRESENT MODEL

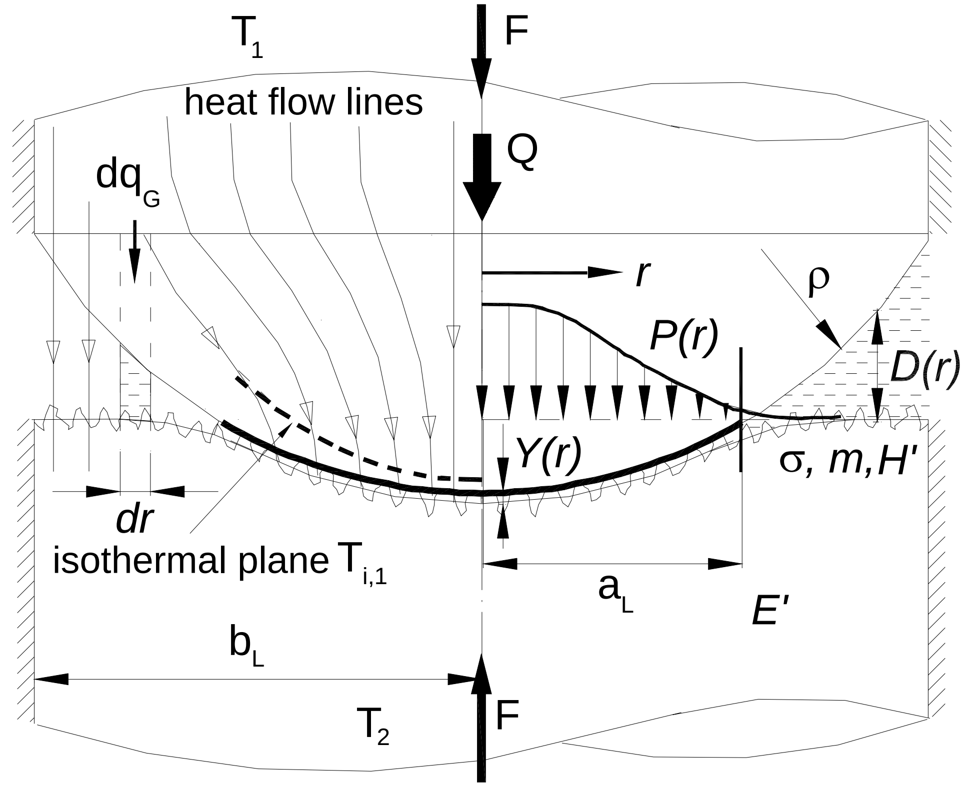
University of Waterloo

<u>assumptions</u>

- Gaussian roughness
- plastically deformed asperities
- bulk deforms elastically
- microcontacts are isothermal

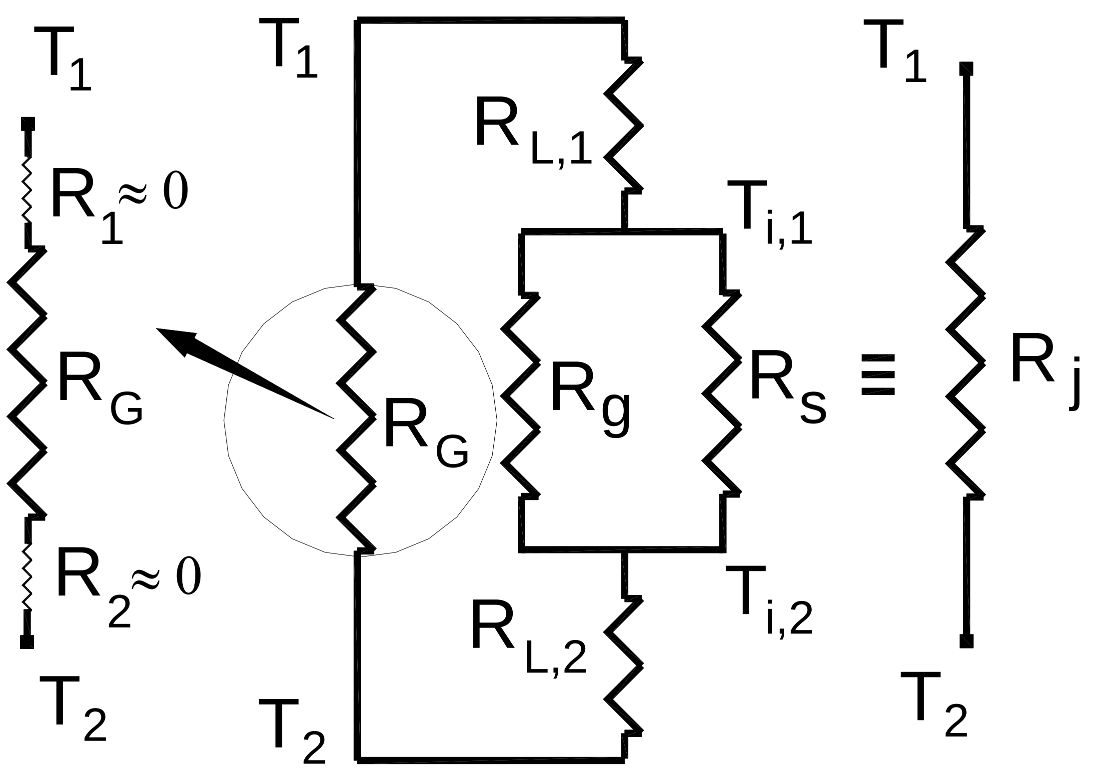
<u>heat flow paths</u>

- solids or microcontacts, Q_s
- microgap, Q_g
- macrogap, Q_G



$$R_s\,,\,R_L\,,\,R_g\,,\,R_G$$

THERMAL RESISTANCE NETWORK



$$R_j = \left(\frac{1}{\left(1/R_s + 1/R_g\right)^{-1} + R_L} + \frac{1}{R_G} \right)^{-1}$$

MICROGAP THERMAL RESISTANCE

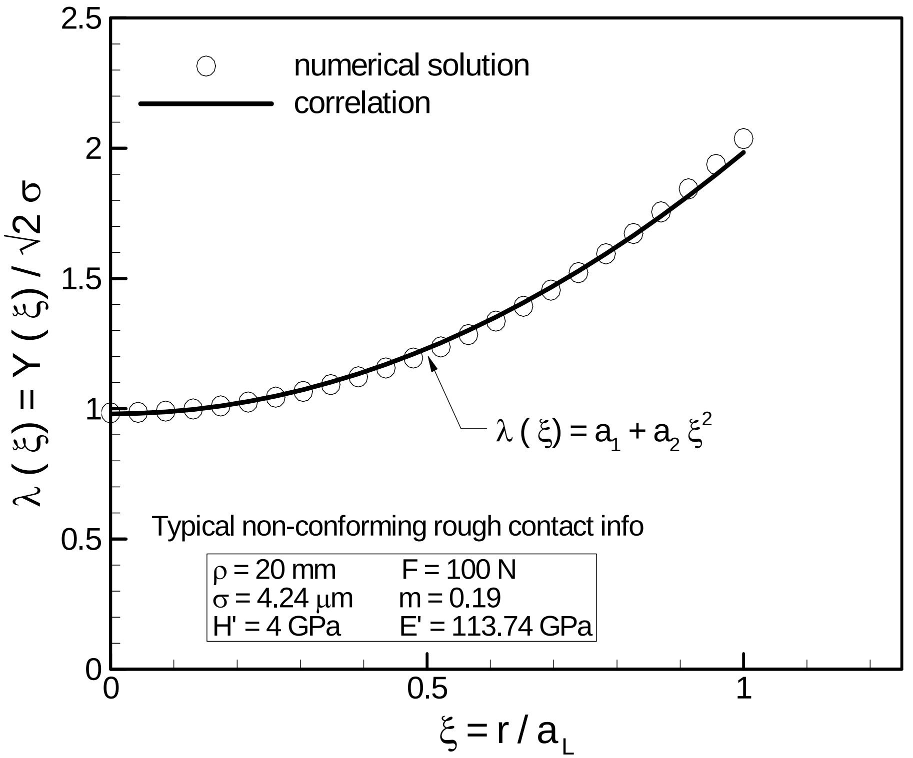
- applying energy balance

$$R_g = \frac{1}{2\pi k_g}\left[\int_0^{a_L}\frac{rdr}{Y(r)+M}\right]^{-1}$$

- non-dimensional separation

$$\lambda(\xi) = a_1 + a_2\xi^2$$

$$a_1 = \text{erfc}^{-1}\left(\frac{2P_0}{H'}\right) \& \, a_2 = \text{erfc}^{-1}\left(\frac{0.03P_0}{H'}\right) - a_1$$



- effective microgap resistance

$$R_g = \frac{\sqrt{2}\,\sigma\, a_2}{\pi k_g a_L^2 \ln\left(1+\dfrac{a_2}{a_1 + M/\sqrt{2}\,\sigma}\right)}$$

MACROGAP THERMAL RESISTANCE

- applying energy balance

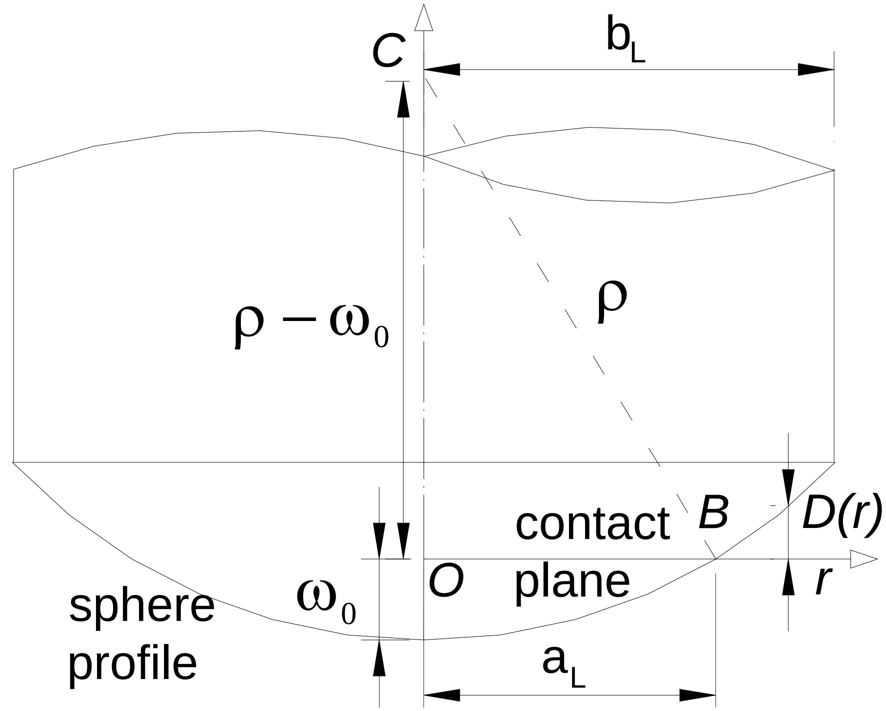
$$R_G = \frac{1}{2\pi k_g}\left(\int_{a_L}^{b_L} \frac{r dr}{D(r)+M}\right)^{-1}$$

$$D(r) = \rho - \omega_0 - \sqrt{\rho^2 - r^2}$$

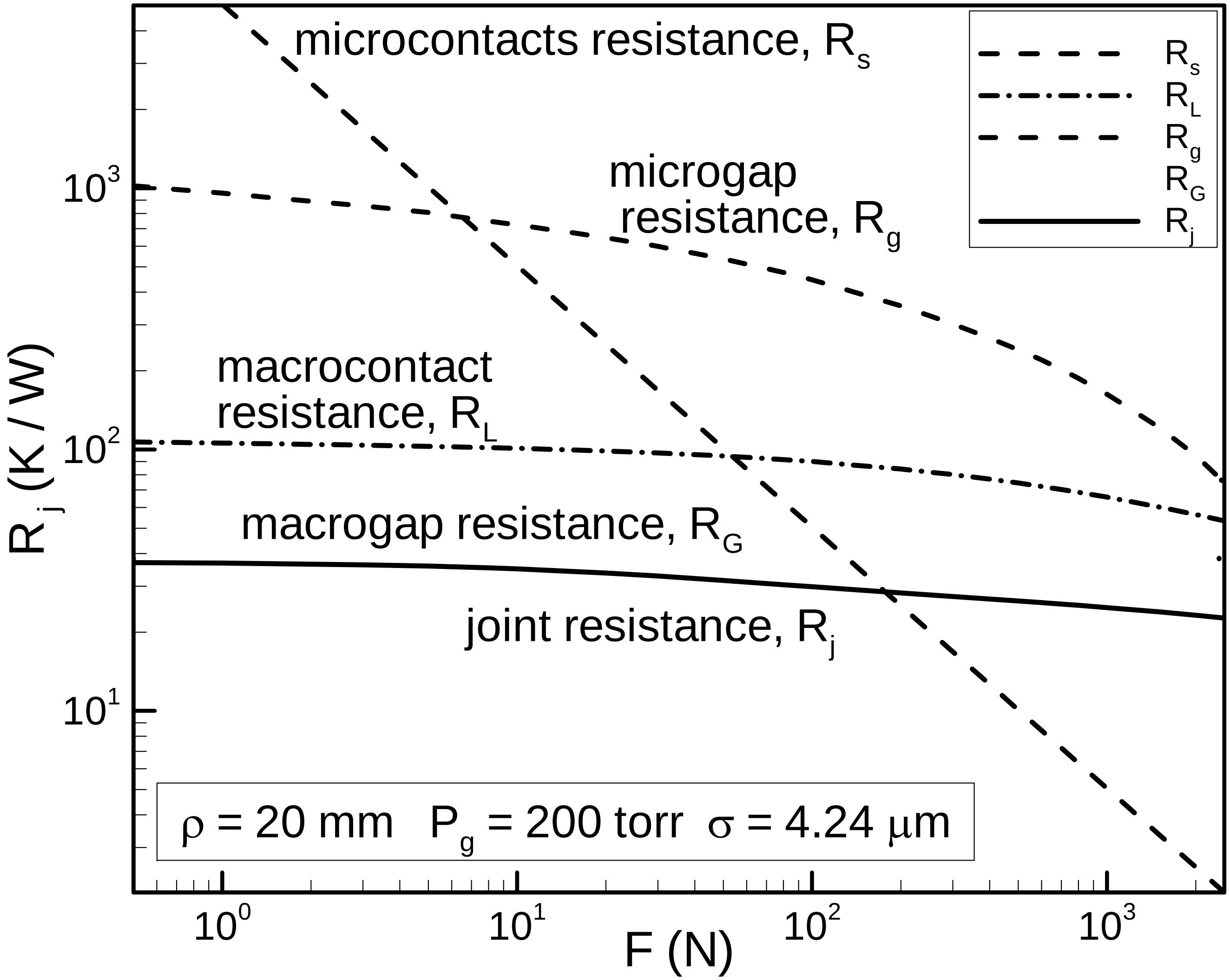
- macrogap thermal resistance

$$2\pi k_g R_G = \frac{1}{S \ln\left(\frac{S-B}{S-A}\right) + B - A}$$

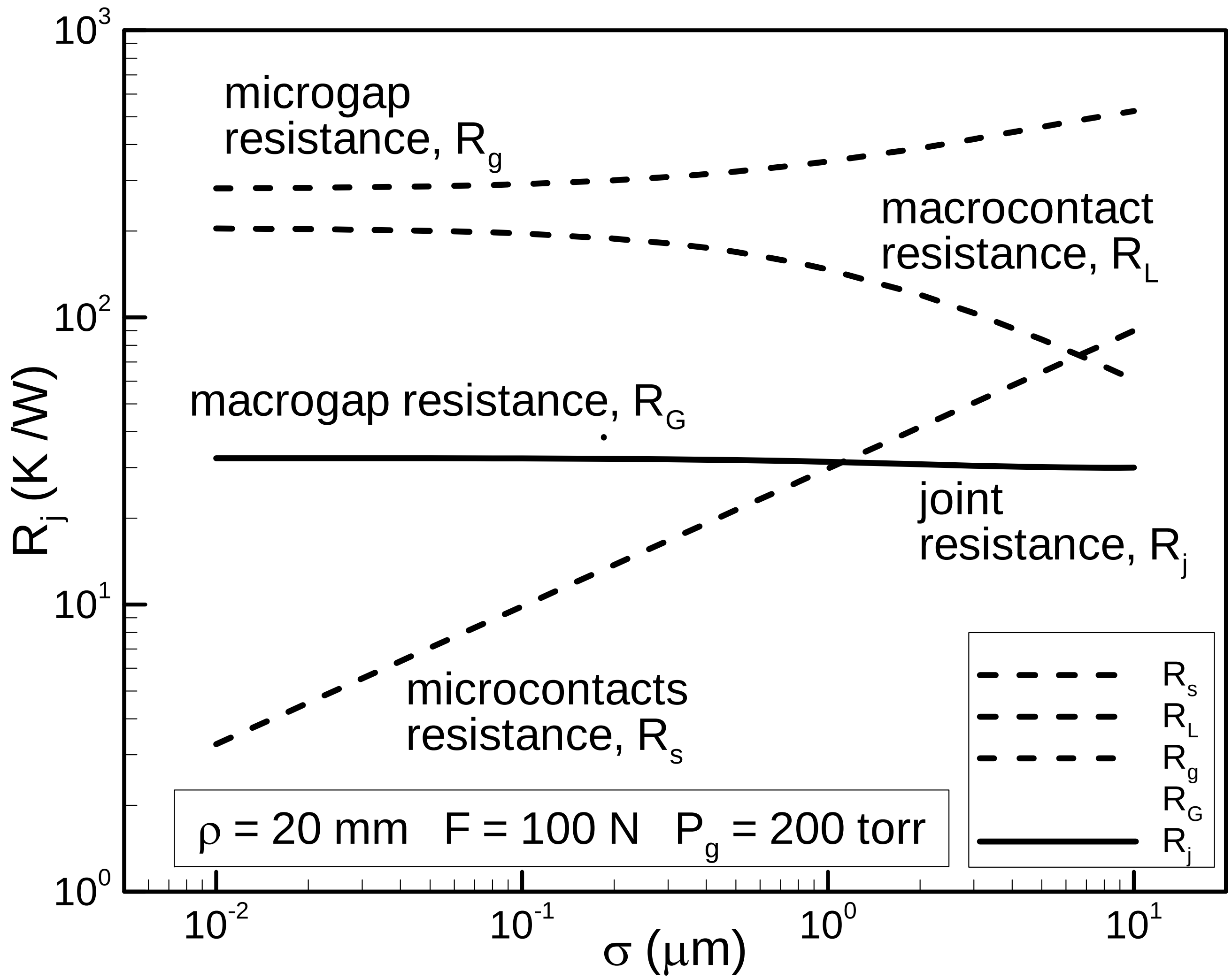
$$A = \sqrt{\rho^2 - a_L^2} \ \& \ B = \sqrt{\rho^2 - b_L^2} \ \& \ S = \rho - \omega_0 + M$$



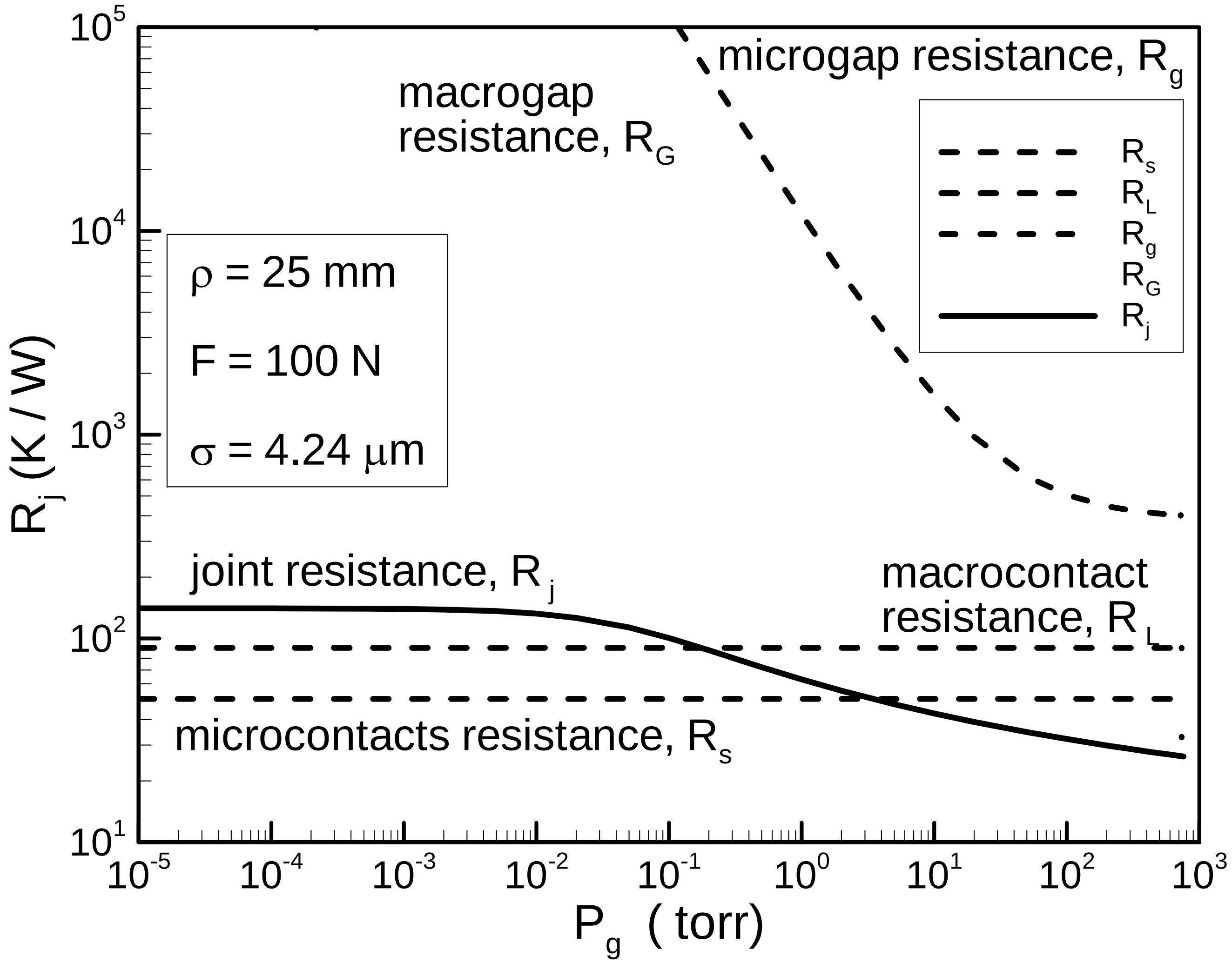
EFFECT OF LOAD ON JOINT RESISTANCE



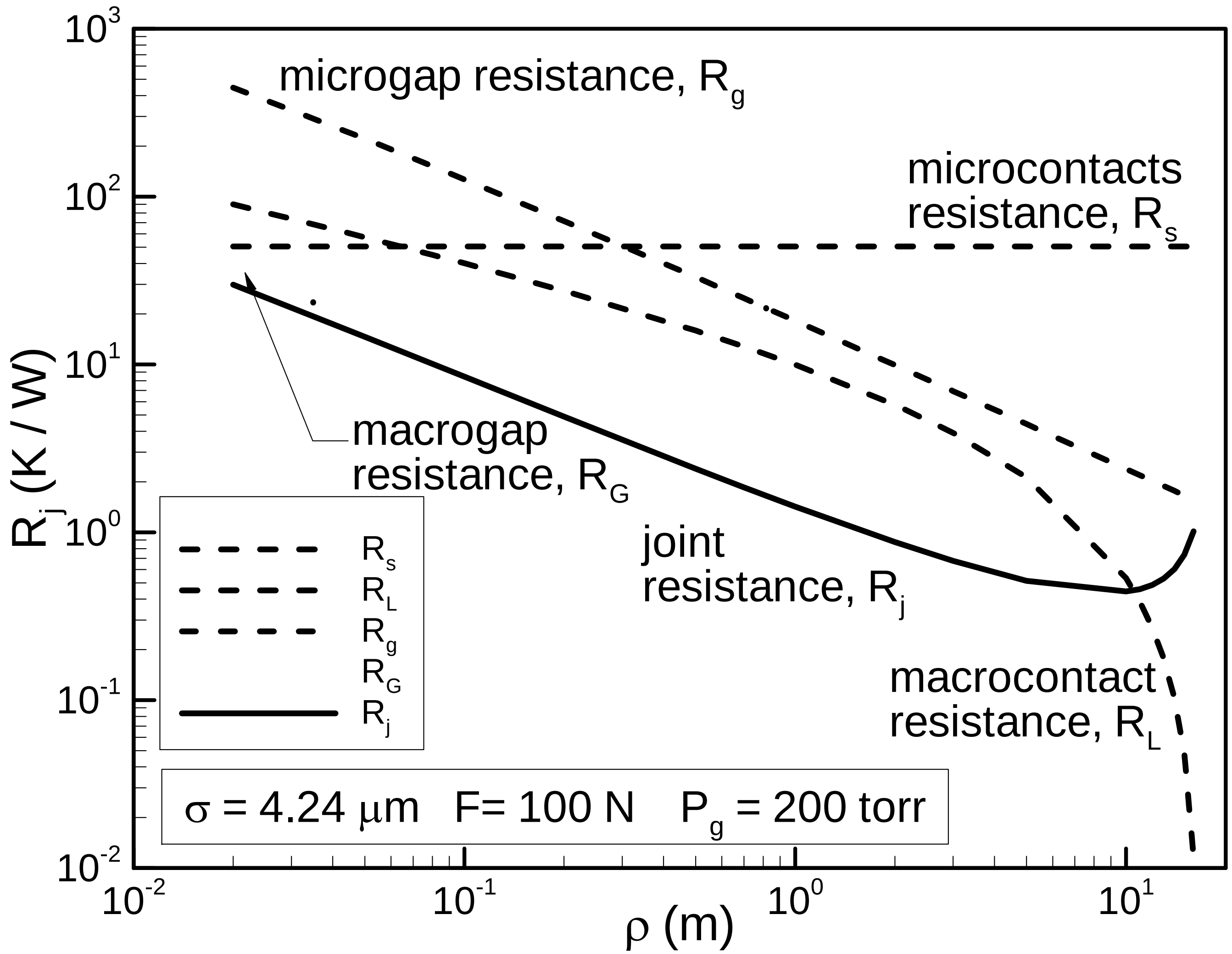
EFFECT OF ROUGHNESS ON JOINT RESISTANCE



EFFECT OF GAS PRESSURE ON JOINT RESISTANCE



EFFECT OF RADIUS OF CURVATURE ON JOINT RESISTANCE



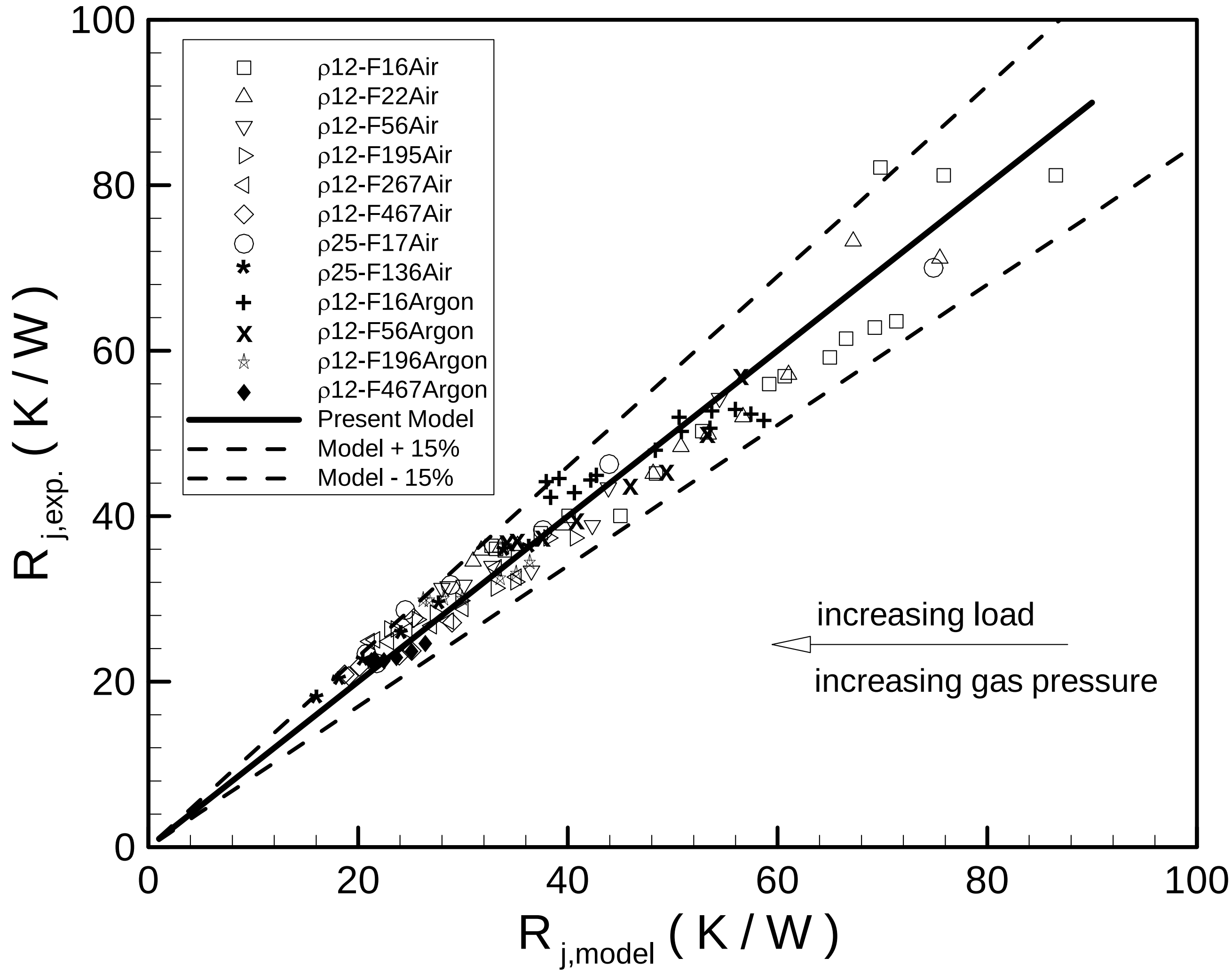
EXPERIMENTAL DATA

- Kitscha (1982)
  - 110 data points
  - three sets of carbon steel ball with steel 1020 flats in air and argon

gas	k_g	Pr	TAC	$_g$	$_0$
	W/mK	–	–	–	nm
air	.0021 8E-5T	0.70	0.87	1.39	64.01
Ar	.0159 4E-6T	0.67	0.9	1.67	66.55

test		gas	F
	mm		N
T1	12.7	air	16.7 - 467
T2	25.4	air	16.9 - 135
T3	12.7	argon	17.8 - 467

COMPARISON WITH KITSCHA DATA



SUMMARY AND CONCLUSIONS

- a compact model was developed for TCR of non-conforming rough joints in gaseous environment
- model covers four regimes of gas heat conduction, continuum, temperature-jump or slip, transition, and free molecular
- model accounts for gas and solid mechanical and thermal properties, gas pressure and temperature, surface roughness, radii of curvature, and applied load
- a correlation for local separation between non-conforming rough surfaces was derived

SUMMARY AND CONCLUSIONS

- parametric studies showed
  - at light loads, most of heat transfer take place through macrogap
  - a surface curvature exists that minimizes joint resistance
- model was compared with 110 experimental data points of Kitscha (1982)
  - carbon steel and steel 1020, with two gases: air and argon
  - model showed good agreement, RMS difference 7.2%

ACKNOWLEDGEMENTS

• Natural Sciences and Engineering Research Council of Canada (NSERC)

• The Center for Microelectronics Assembly and Packaging (CMAP)