Extending the Limits of Air Cooling for Microelectronic Systems

CMAP Year 1 Project Review

J. Richard Culham, Pete Teertstra

Rakib Hossain, Ashim Banik

Microelectronics Heat Transfer Laboratory

Department of Mechanical Engineering

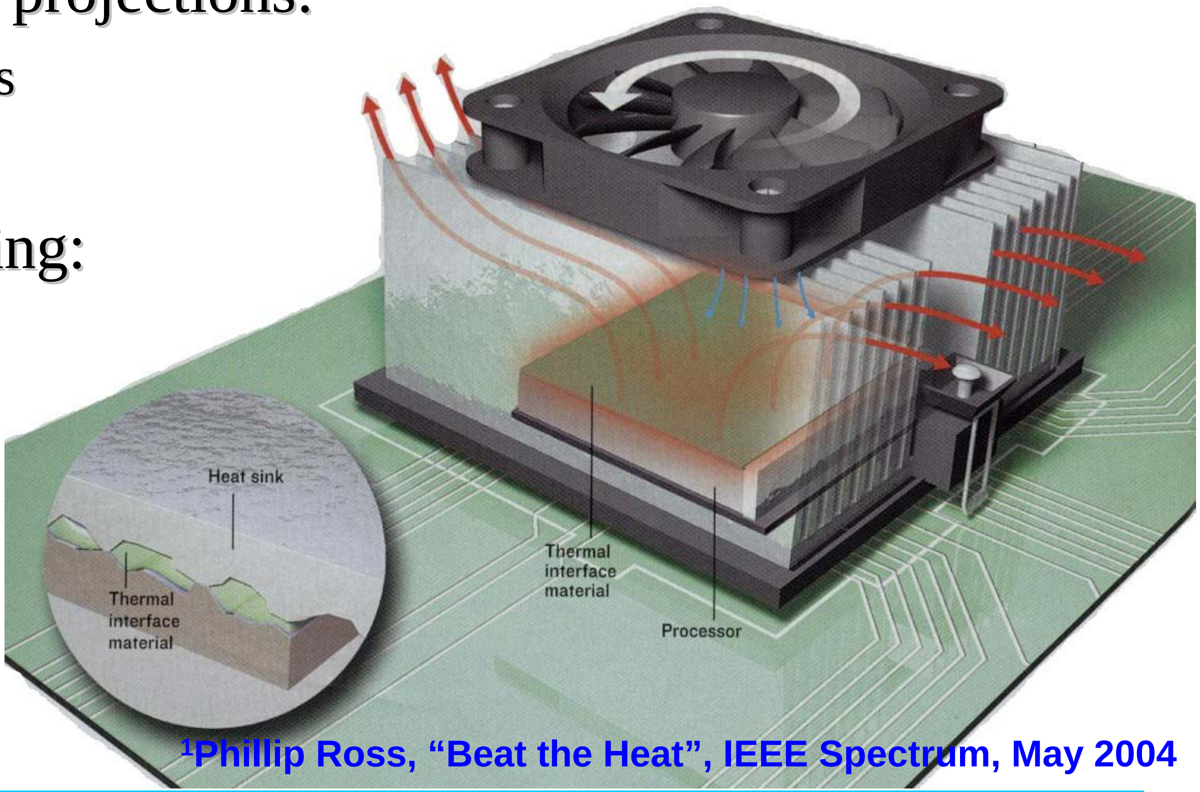
University of Waterloo

Presentation Outline

- Review of project goals and deliverables
- Progress reports:
  - Optimization models for air cooled heat sinks
  - Impact of surface conditions on thermal joint resistance with TIMs
- Plan for project completion

Motivation

- Current trend in industry of applying air cooling as long as possible – rapidly approaching the limits of air cooling
- 2005 power dissipation projections:
  - 100 *W* for office systems
  - 250 *W* for large systems
- Alternatives to air cooling:
  - Liquid cooling
  - Refrigeration
  - Thermoelectric coolers
  - Significant cost, time required to implement



[1]Phillip Ross, "Beat the Heat", IEEE Spectrum, May 2004

Air Cooling Limits

- Air cooling limit = when fan-driven convection is insufficient to maintain temperature levels necessary for reliable operation
- Previous air cooling limits often based on system-wide air temperature rise, i.e. Telcordia specs
- Air cooling limit for particular component / location / application function of:
  - Available space and airflow
  - Heat sink geometry and materials
  - Quality of thermal contact between heat sink and package

Project Descriptions

- Extend knowledge base for air cooling limits through two part research study
- Predict air cooling limits
  - Develop and validate tools to predict air cooling limits for specific component / location / application
- Extend air cooling limits
  - Optimize surface roughness of contacting surfaces with thermal interface materials (TIMs) to minimize thermal contact resistance

Optimization Models for Air Cooled Heat Sinks in Variable By-pass Conditions

Objective

- Use entropy generation minimization (EGM) technique to develop analysis tools for predicting air cooling limits as function of:
  - Conduction heat transfer
    - Spreading resistance
    - Thermal joint resistance
  - Forced convection heat transfer
    - Plate fin, folded fin, pin fin heat sinks
  - Hydrodynamic behaviour
    - Pressure drop, side and top by-pass

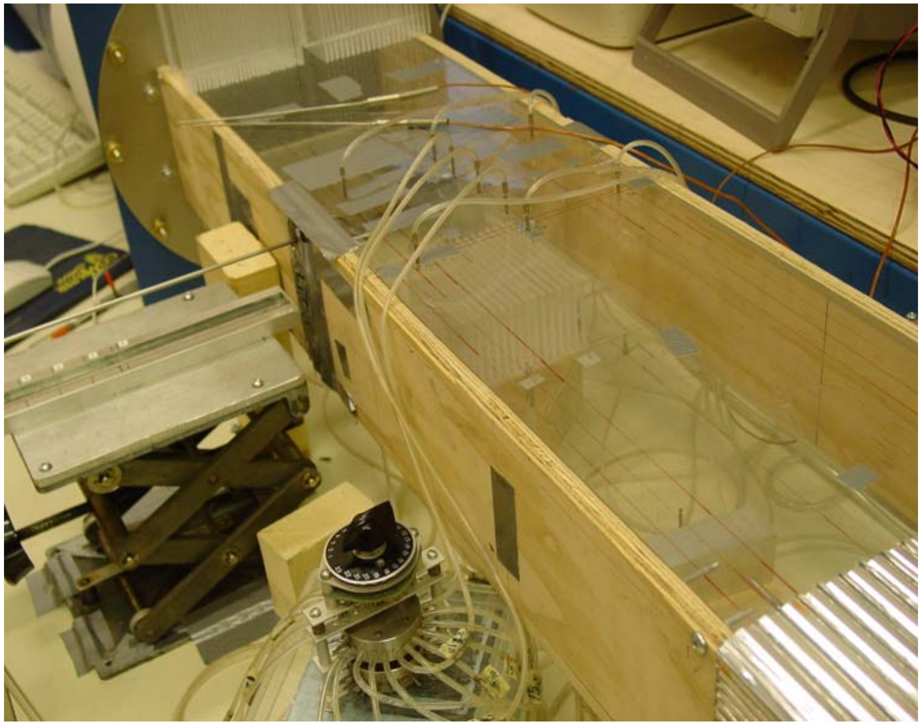
Model Development

- EGM model developed based on available sub-models:
  - Spreading resistance
  - Thermal joint resistance
    - TIMs (Savija, 2002; Smith, 2004; Banik, 2005)
  - Forced convection heat transfer for shrouded heat sinks
    - Plate fins (Teertstra et al, 2000)
    - Pin fins (Khan, 2004)
  - Flow bypass models
    - Plate fins, top by-pass only (Leonard, 2002)
- No analytical models available to predict top and side by-pass for plate fin, pin fin heat sinks

Methodology

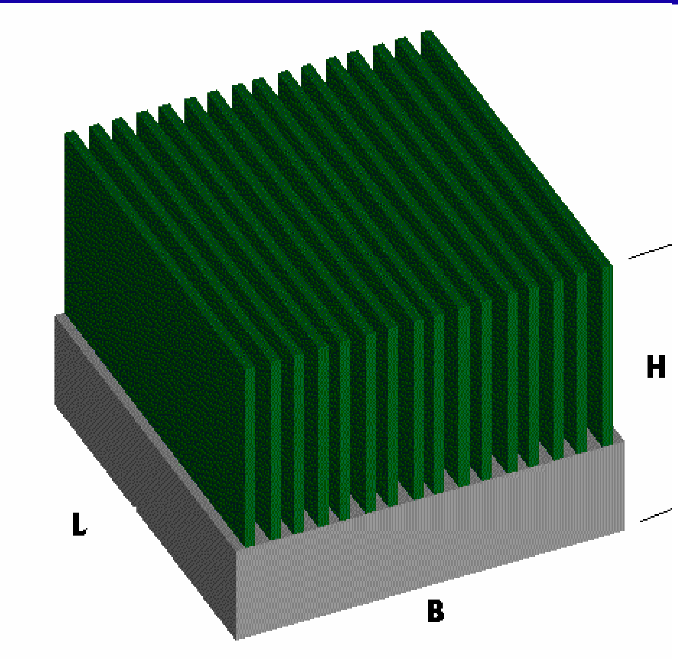
- Analytical modelling of by-pass is complex problem
  - Behaves as both flow between parallel plates (internal) and flow over a plate (external)
  - Many independent variables required to describe geometry
- Preliminary experimental measurements
  - Aid in understanding the physics of the problem
  - Identify key parameters, simplifying assumptions, physical relationships
  - Leads to development of more effective analytical model
  - Validation
- Experimental measurements performed in two parts:
  - By-pass measurements - pressure drop and local velocity for heat sinks with variable top and side bypass.
  - Thermal measurements – validation data for EGM model

By-pass Measurements

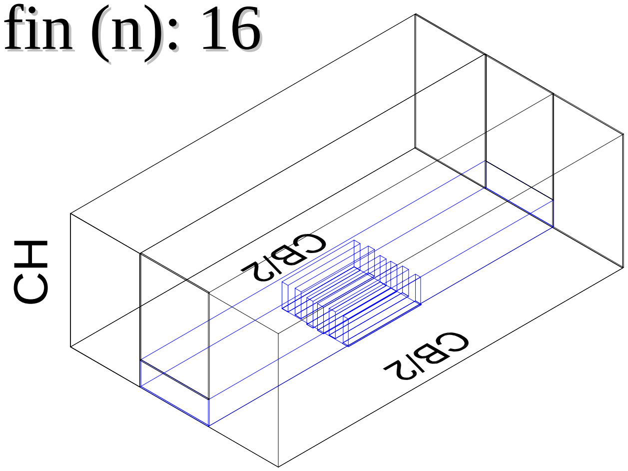


- 150 cfm airflow test chamber
- Test section with movable top and side walls
- Pitot tubes, differential pressure transducer for velocity measurement
- Labview / Keithley DAQ system for data management

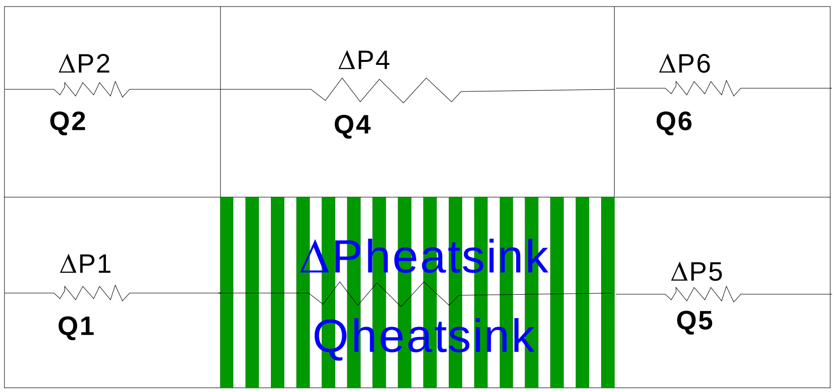
By-pass Measurements



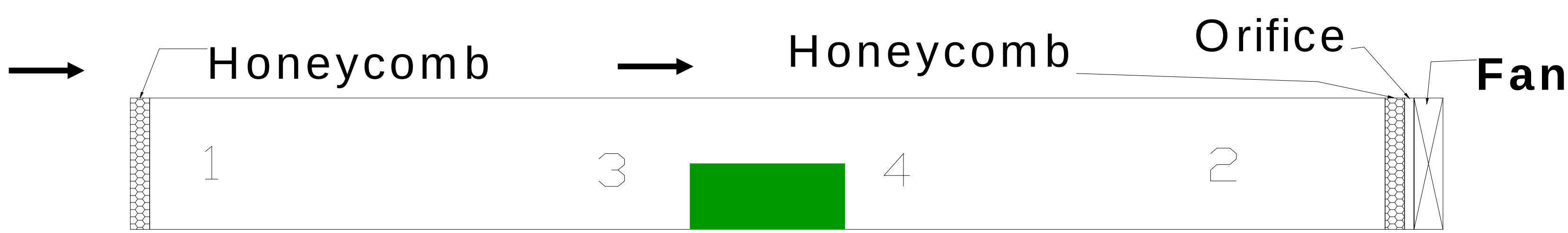
- Heat sink geometry
  - Width (B): 4”
  - Length (L): 4”
  - Height (H): 2”
  - Fin spacing (s): 1/8”
  - Fin thickness (t): 1/8”
  - No of fin (n): 16
- Duct Bypass
  - Side bypass (CB): 4” (2+2”)
  - Top bypass (CH): 2”
  - Ratio of Bypass CB:B=1; CH:H=1



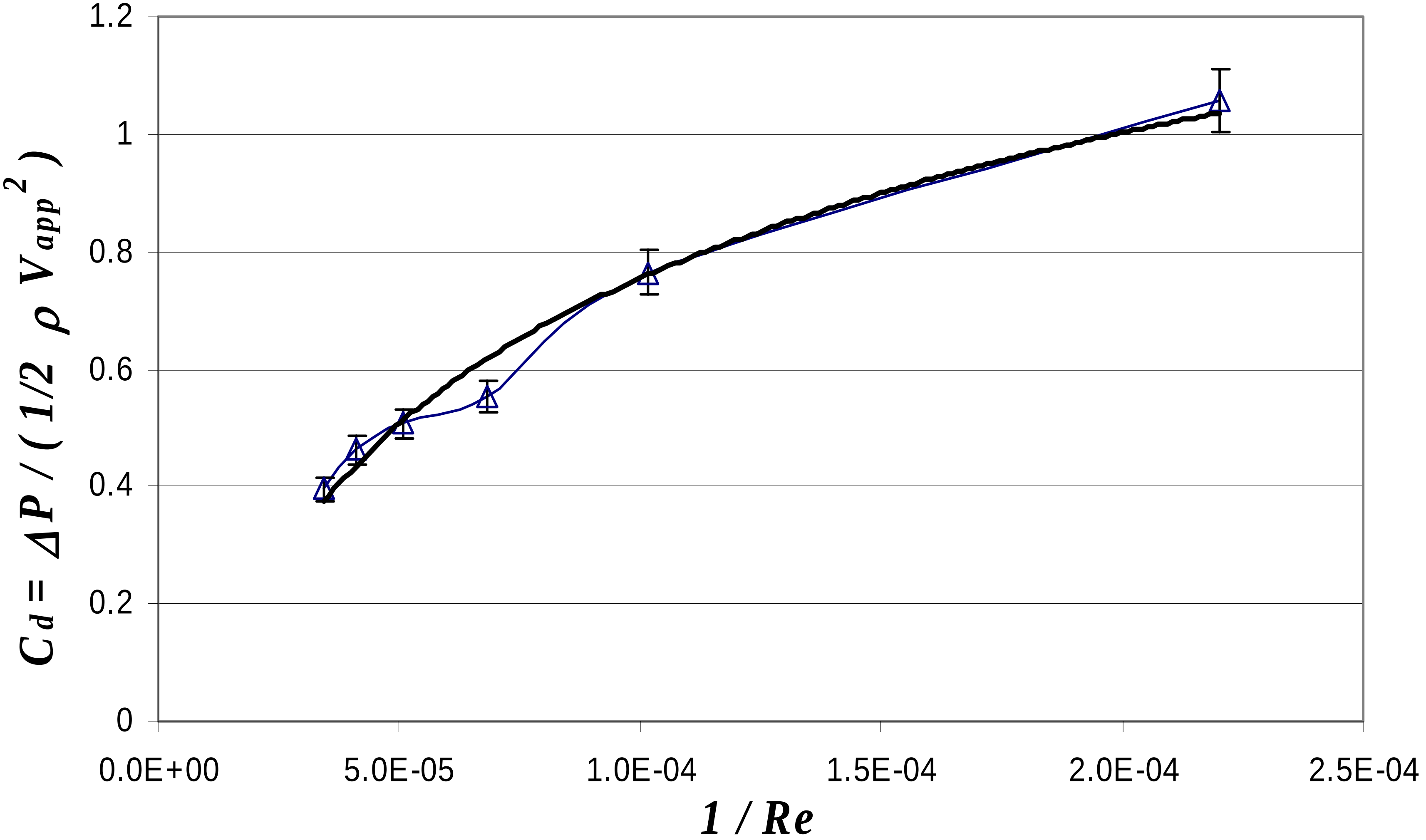
Flow Network Model



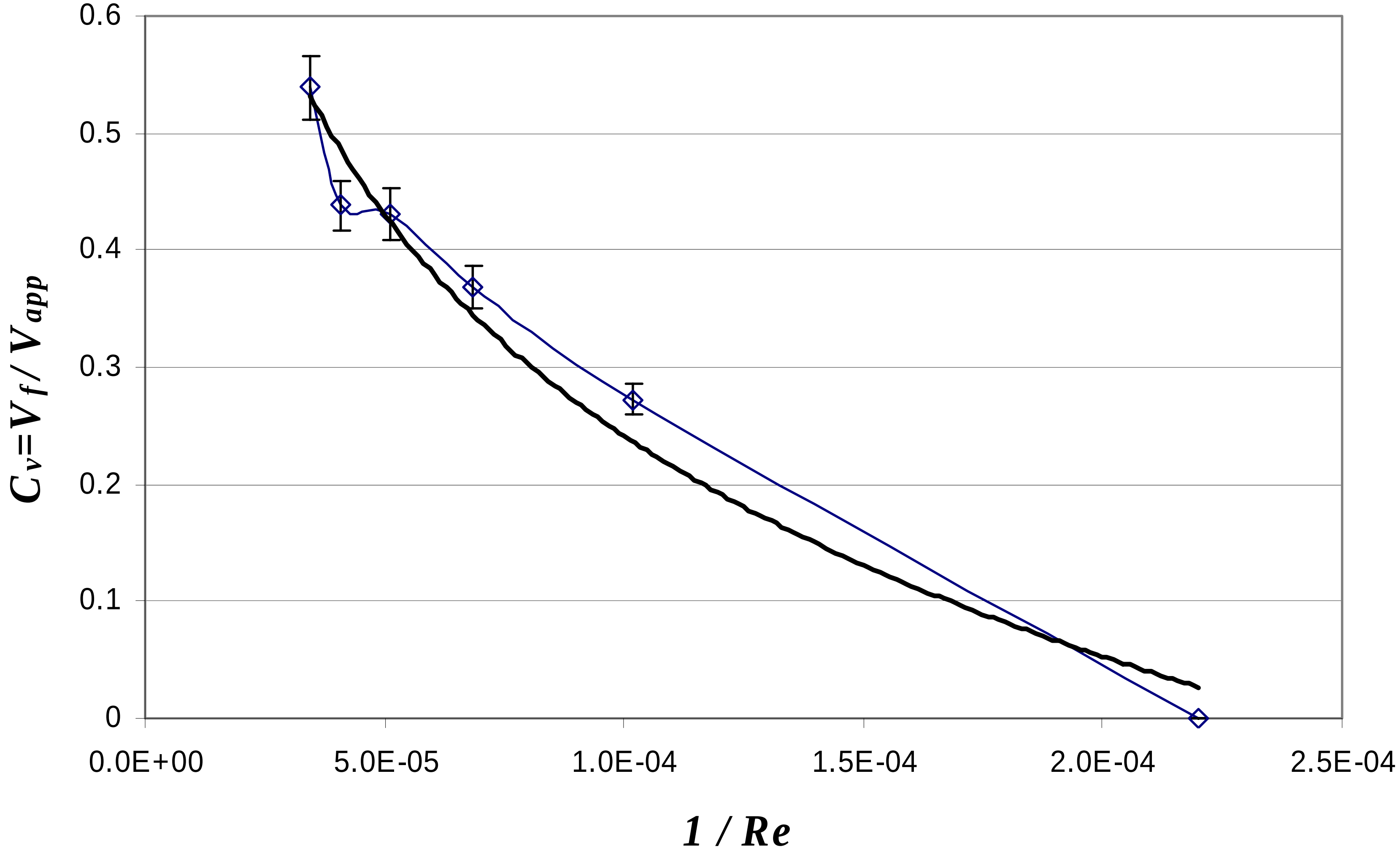
- Static pressure measured for $4000 < Re_{Dh} < 30000$.
- Total flow rate Q from integration of pitot tube measurements
- Flowrate through heat sink $Q_{heatsink} = Q_{total} - (Q_1+Q_2+Q_4+Q_5+Q_6)$ where Q_{total} from orifice plate



Drag Coefficient (C_d)



Velocity Coefficient (C_v)



Future Work

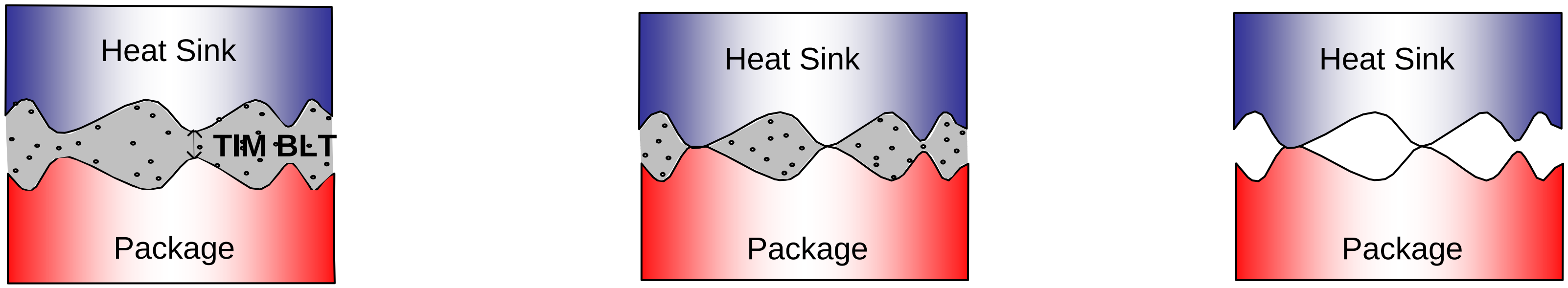
- Experimental
  - By-pass measurements
    - Bypass: CB/B= .75, .5, 0 CH/H= .75, .5, 0
    - Heat sink geometry: s = 1/16”- 1/8”; t = 1/16”
  - Heat transfer measurements
    - Wind tunnel testing of forced convection for different heat sink geometries with variety of bypass conditions
    - Validation data for analytical models
- Analytical modelling
  - By-pass modelling for heat sinks
  - Incorporate by-pass, spreading and contact resistance models into EGM analysis

Study of Contact Resistance for Flycut Aluminum 2024 Surfaces

Objectives

- Experimental study of thermal contact resistance for face-milled (flycut) aluminum 2024 joints
  - Microscopic study of surface parameters
    - Surface roughness
    - Mean asperity slope
    - Asperity height distribution
    - Micro hardness
  - Experimental measurements of thermal contact resistance for a wide range of loads
- Comparison with existing conforming rough surface contact models

Motivation



- Typical contact between heat sink and component with TIM compound
  - TIM fills voids, air gaps
  - Bondline thickness (BLT) supports load, prevents direct surface contact
- Maximize contact conductance by minimizing BLT, leading to direct surface contact
- Analytical models of contact resistance problem for conforming rough surfaces with TIM compounds

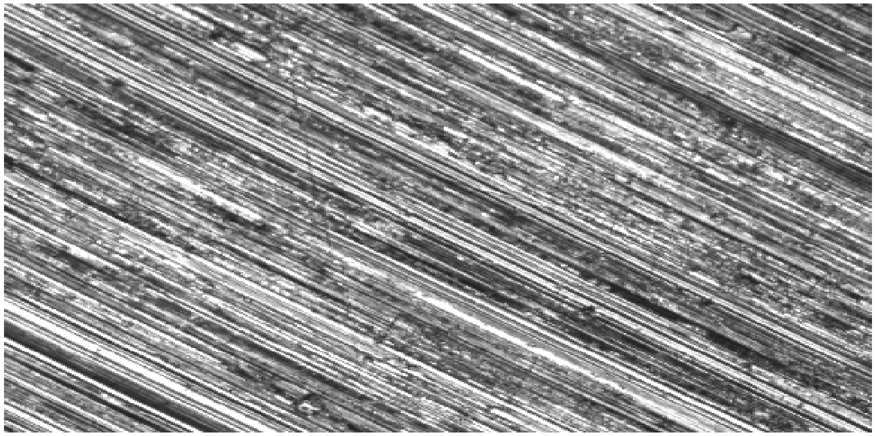
Motivation

- Experimental measurements for conforming rough surfaces with TIM compounds:
  - Total joint resistance R_j
  - In-situ BLT thickness
- If surfaces are in contact the bulk resistance of the TIM determined by reducing contact resistance from total joint resistance

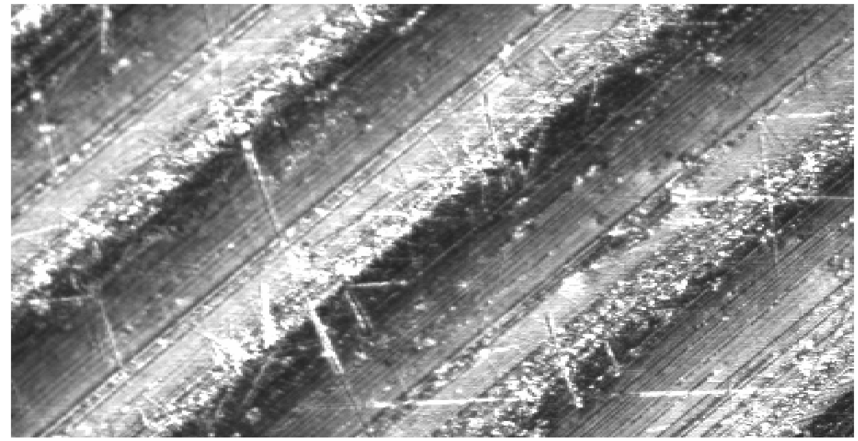
$$\frac{1}{R_b} = \frac{1}{R_j} - \frac{1}{R_c} \qquad\qquad R_b = \frac{BLT}{k_{TIM}\, A_a}$$

- Need to determine R_c experimentally, analytically

Surface Analysis: SEM



Feed rate 12mm/min, Magnification 20X



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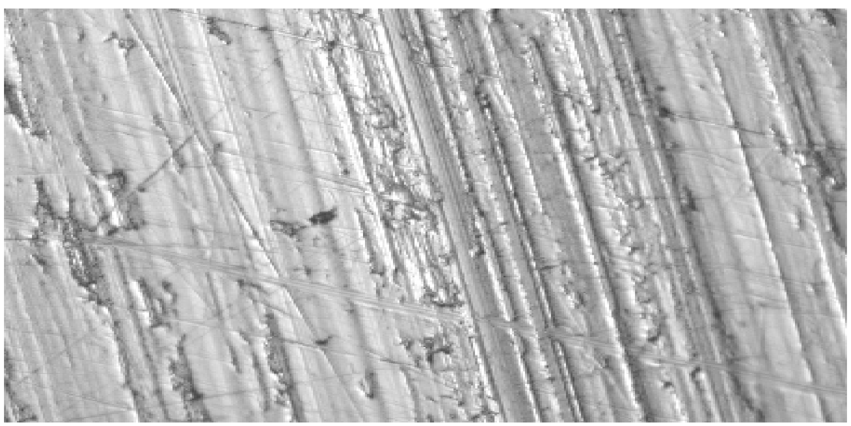

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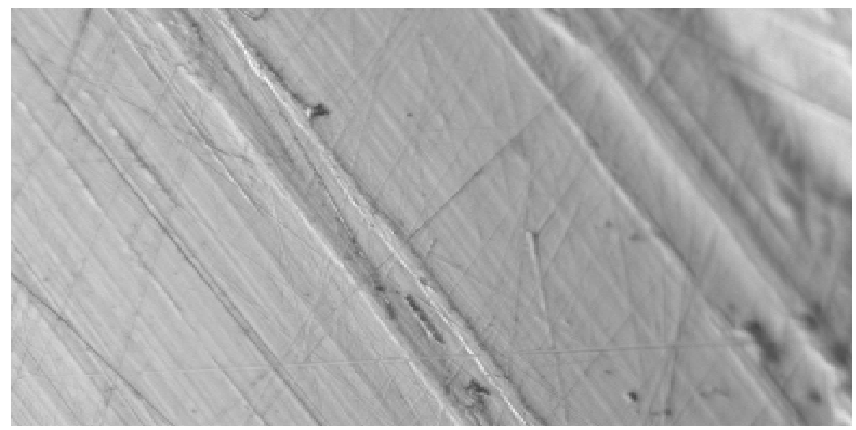

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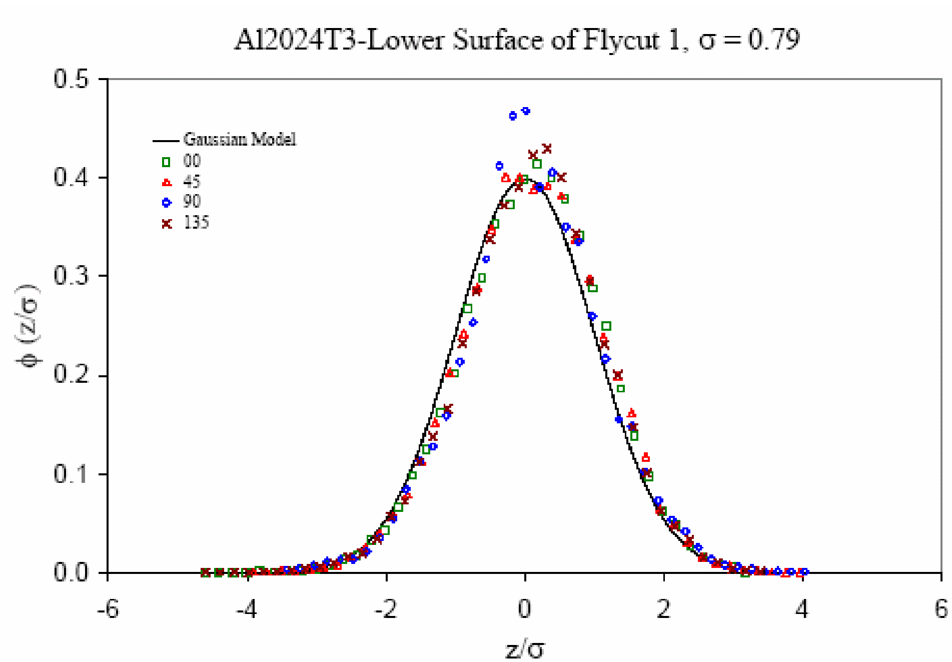
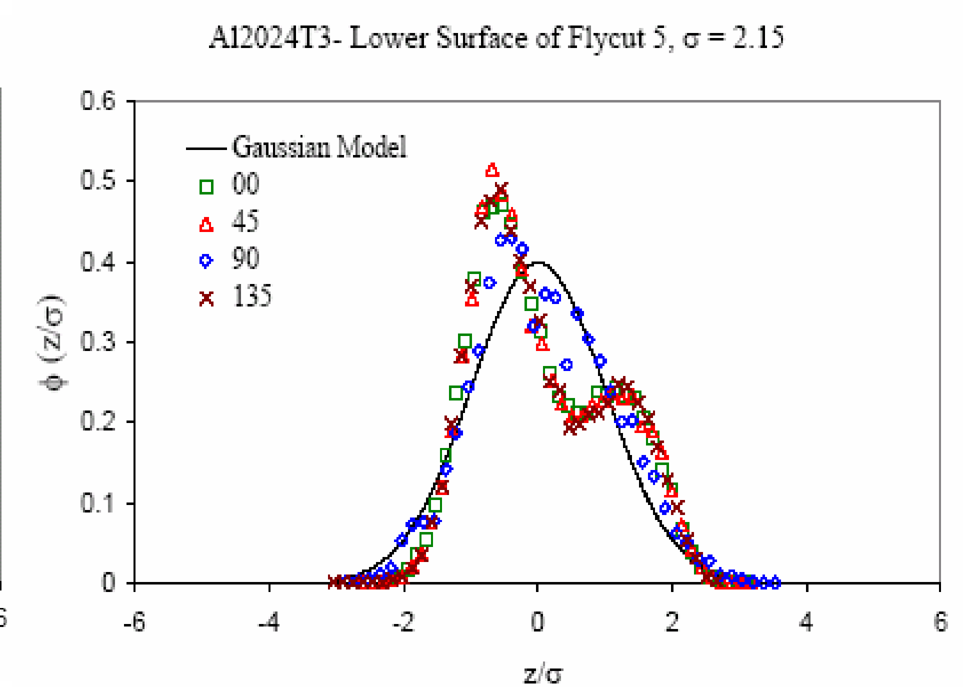
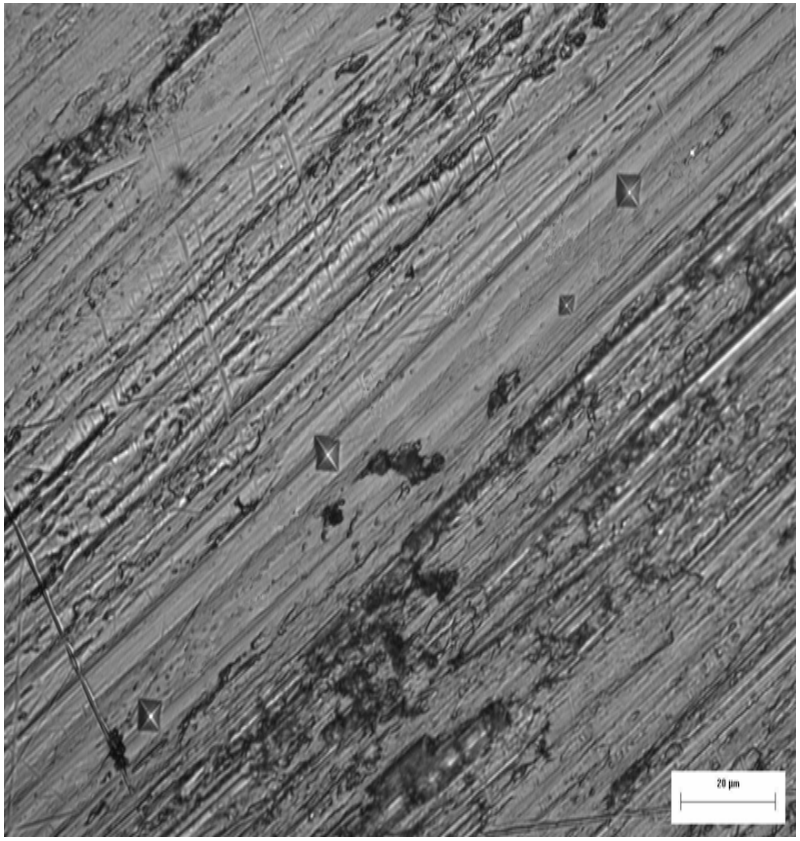
Asperity Heights Distribution

- Gaussian distribution of asperity heights is a common assumption made in contact resistance models
- As feed rate increases, surface roughness increases and height distribution no longer Gaussian

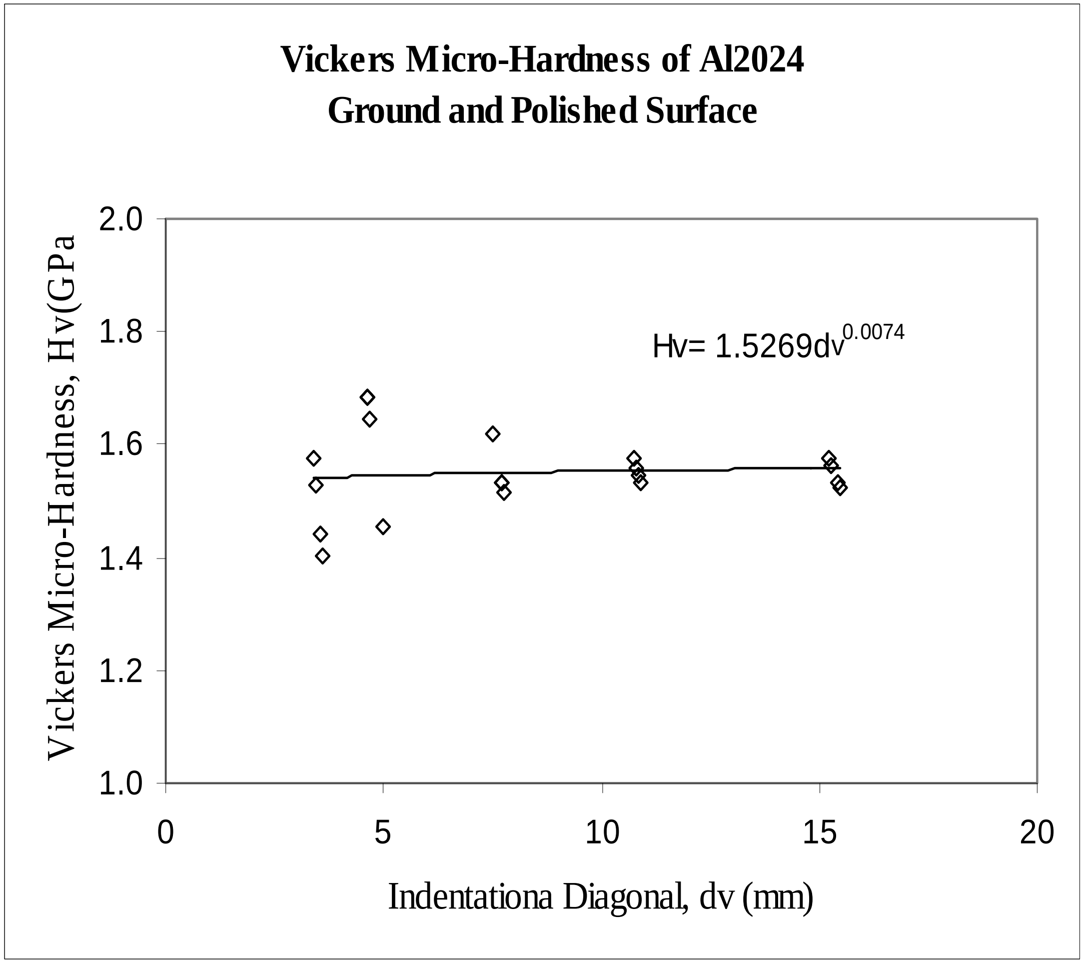




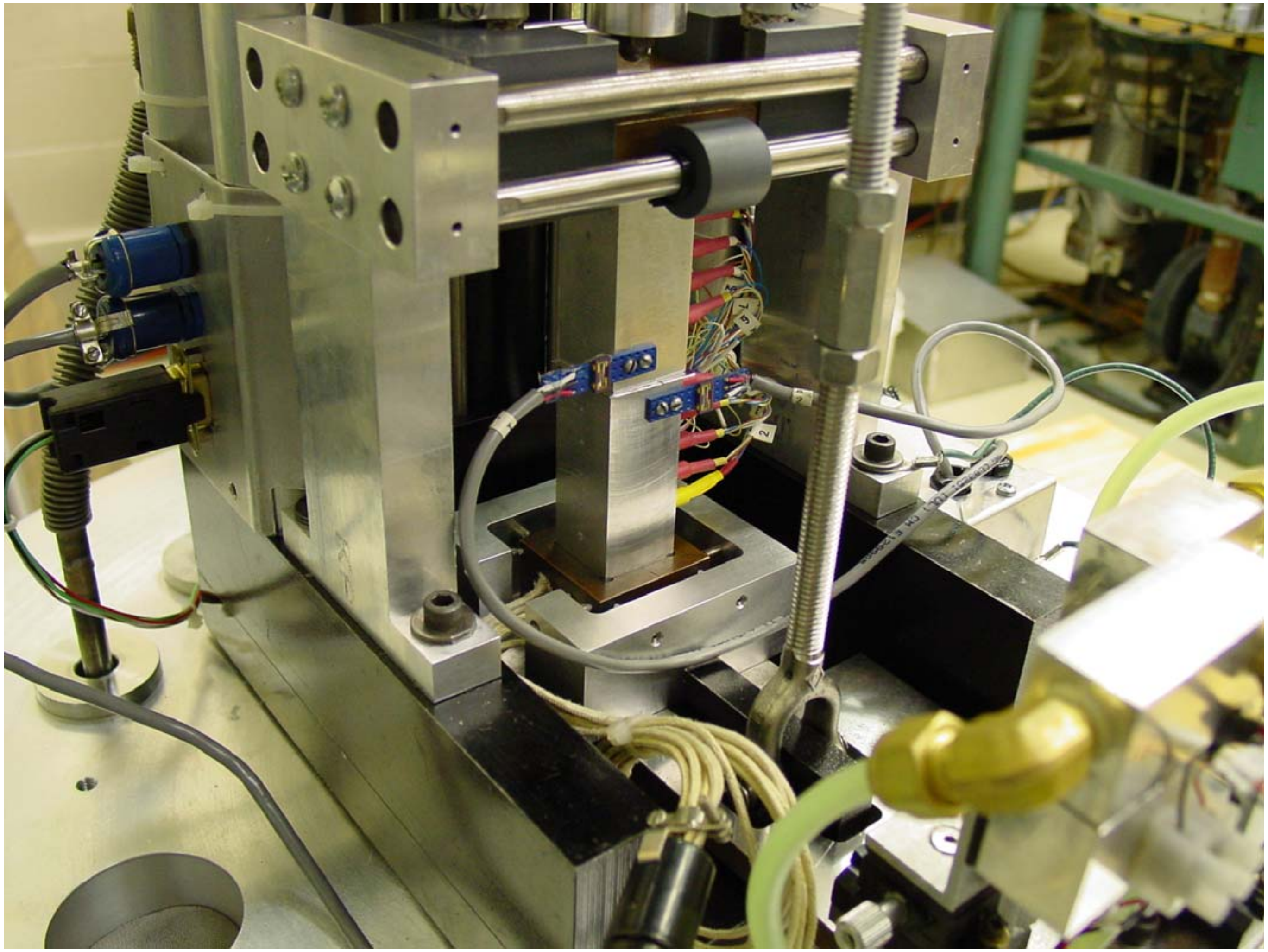
Micro Hardness of Surfaces



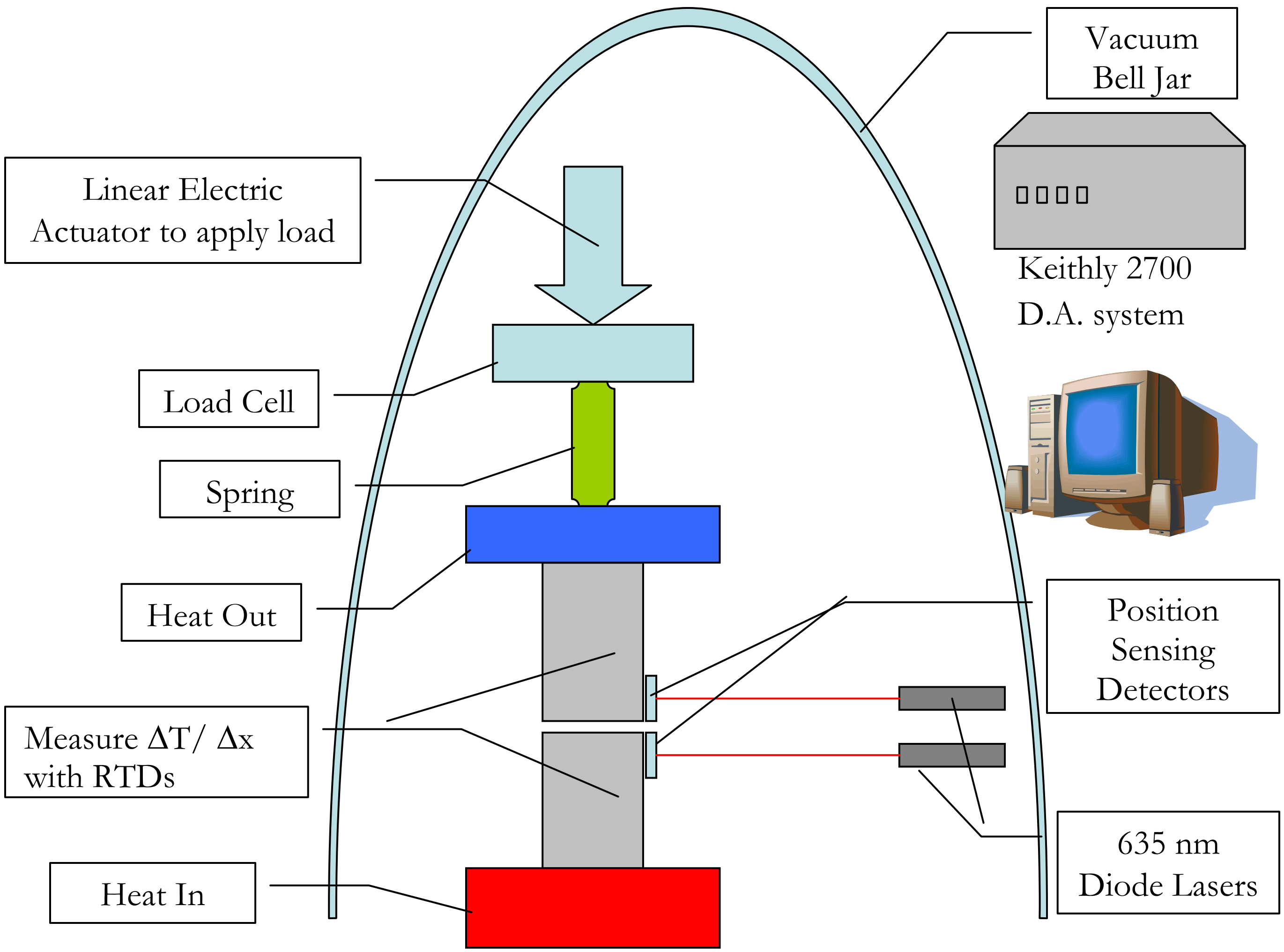
Vicker's Microhardness Testing



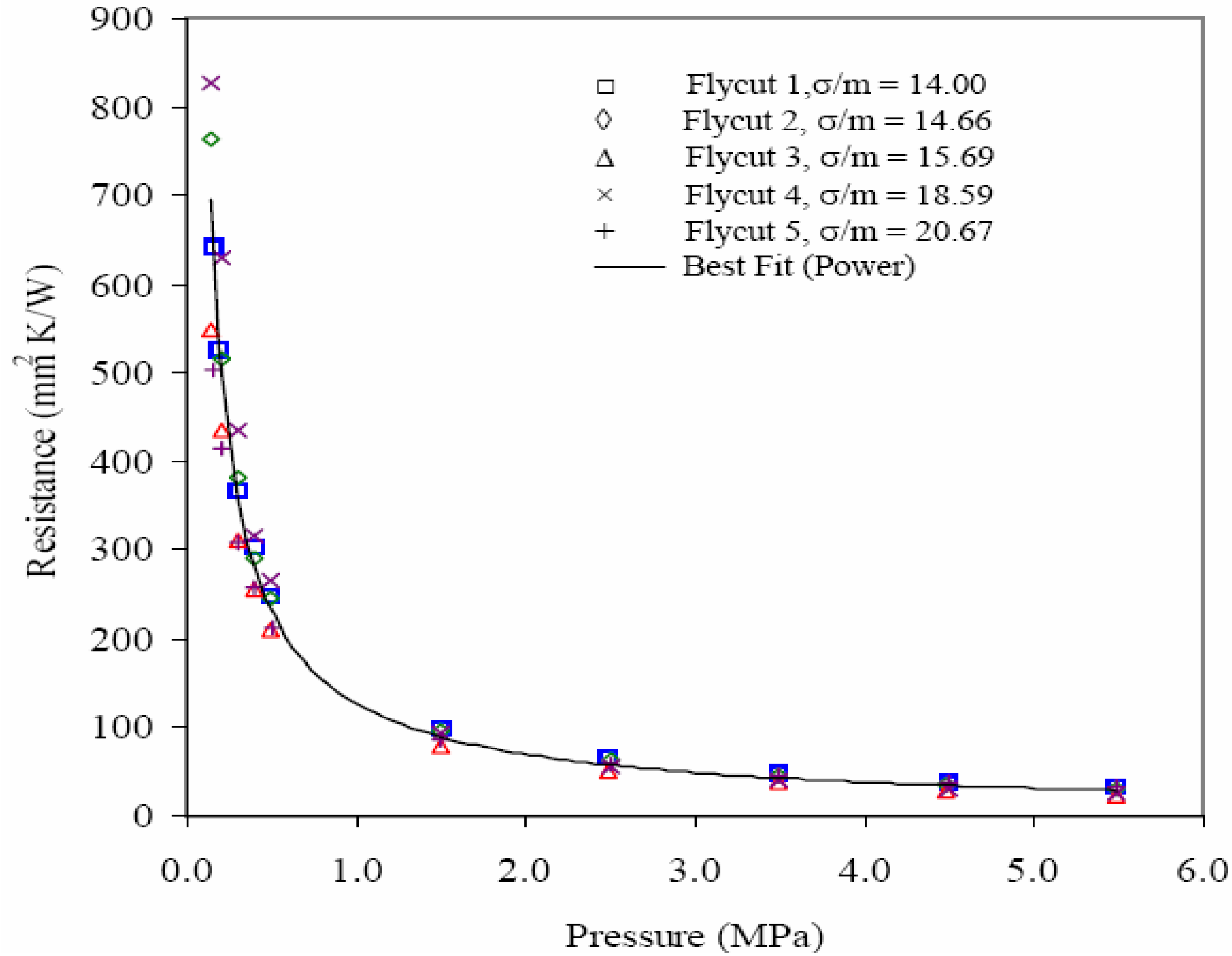
TIM Test Apparatus



TIM Test Apparatus Schematic



Contact Resistance Test Results

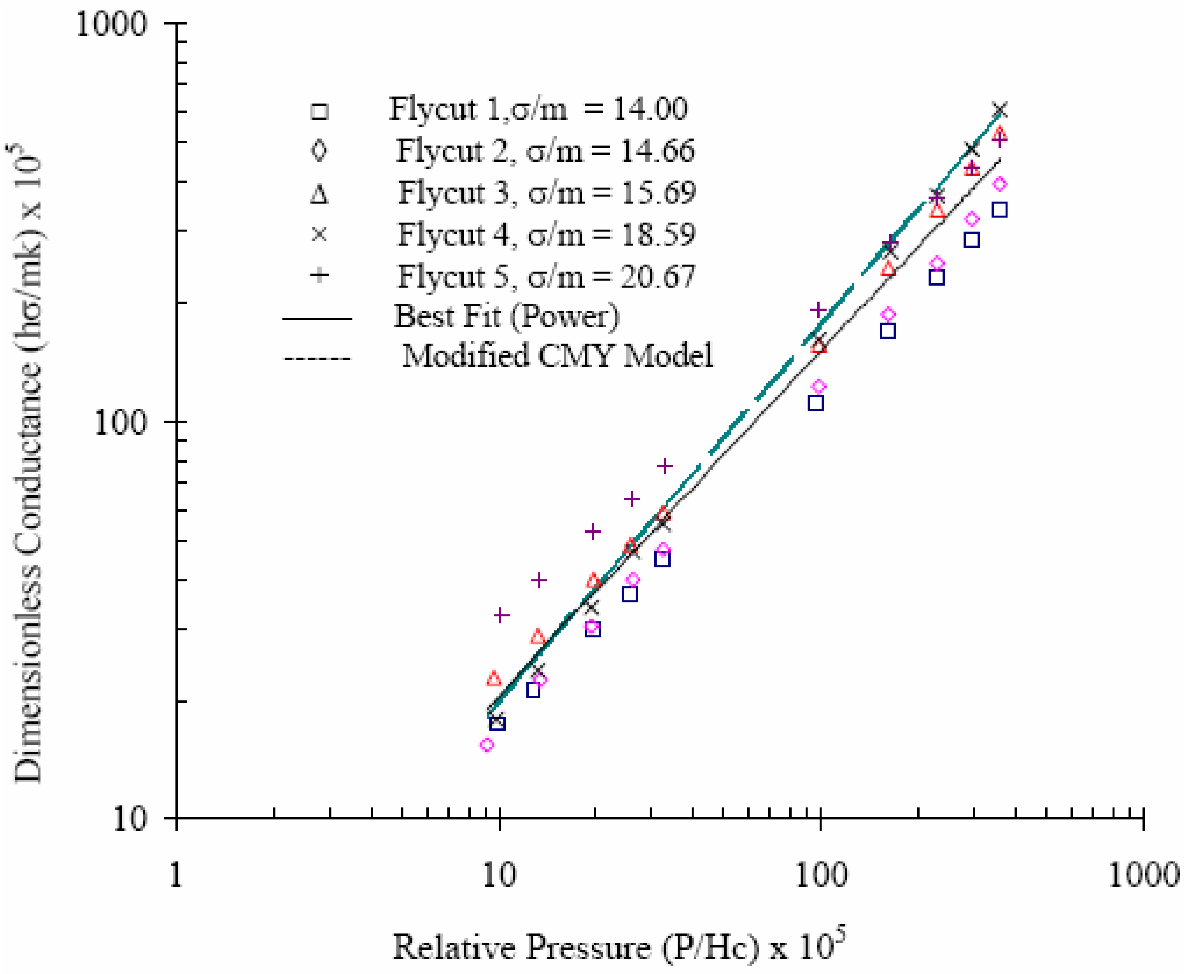


Comparison with Existing Model

- Modified CMY model: (Cooper, Mikic, Yovanovich, 1969)

$$h_c = 1.25 \frac{m}{\sigma} k_s \left(\frac{P}{Hc} \right)^{.95}$$

- 22% RMS difference



Future Work

- Laser-scan micrometer to measure BLT

- Thermal joint resistance, bulk resistance and thermal conductivity measurements for variety of TIM compounds
- Analysis of optimum surface roughness as function of BLT, TIM properties, load, etc.