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Enhanced Thermal Bondlines: Nanocomposite Thermal Interface Material and the Minimization of Bondline Thermal Resistance

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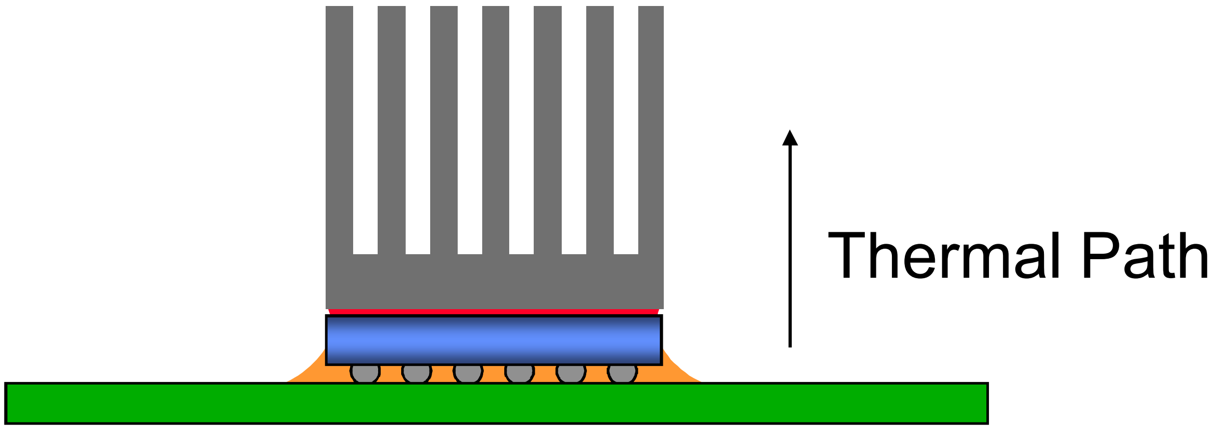
Outline

Introduction
Experimental
Results
- Bulk Samples
- Multilayer Samples
- Comparison of Materials

Summary and Conclusions
Acknowledgments

Introduction



- Transistors generate heat from lossey switching
- Heat sink transfers heat to ambient
- Thermal interface material (TIM) connects the components
    - Mechanically
    - Thermally

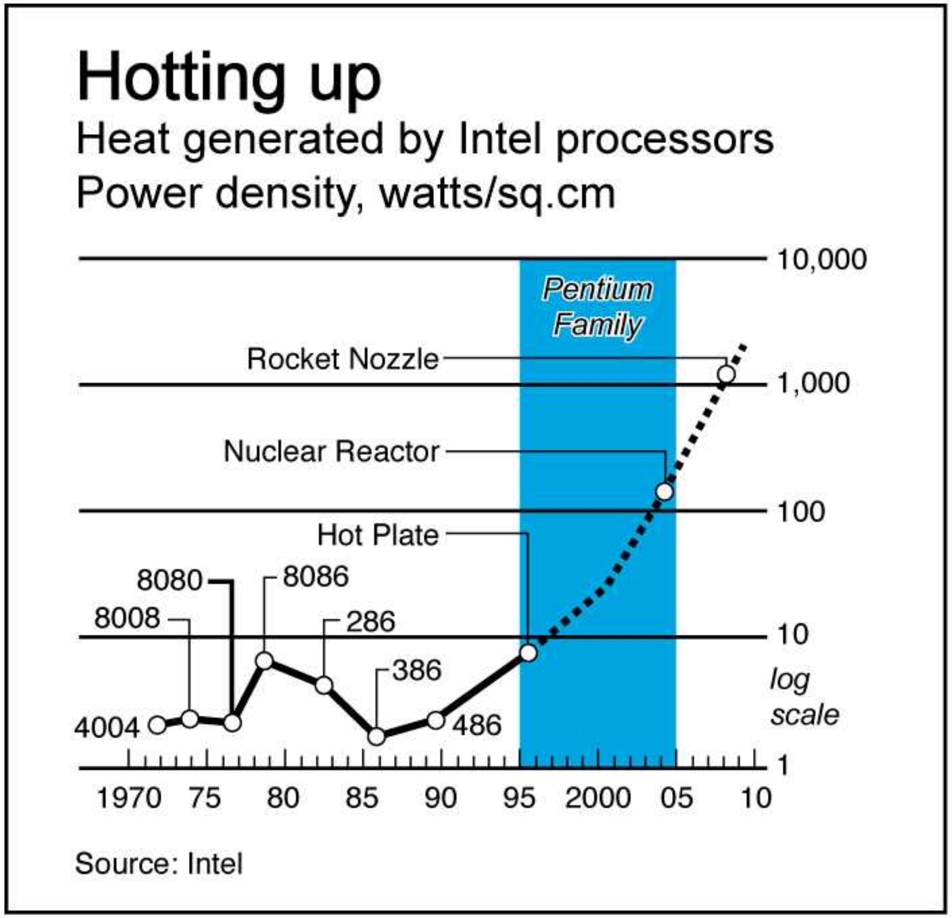
Introduction

Electronic assemblies continue to shrink

Heat flux is increasing

Pentium Processors:
- P1: ~10 W/cm^2
- P4: ~100 W/cm^2

The thermal path must become more efficient



[Economist, 2003]

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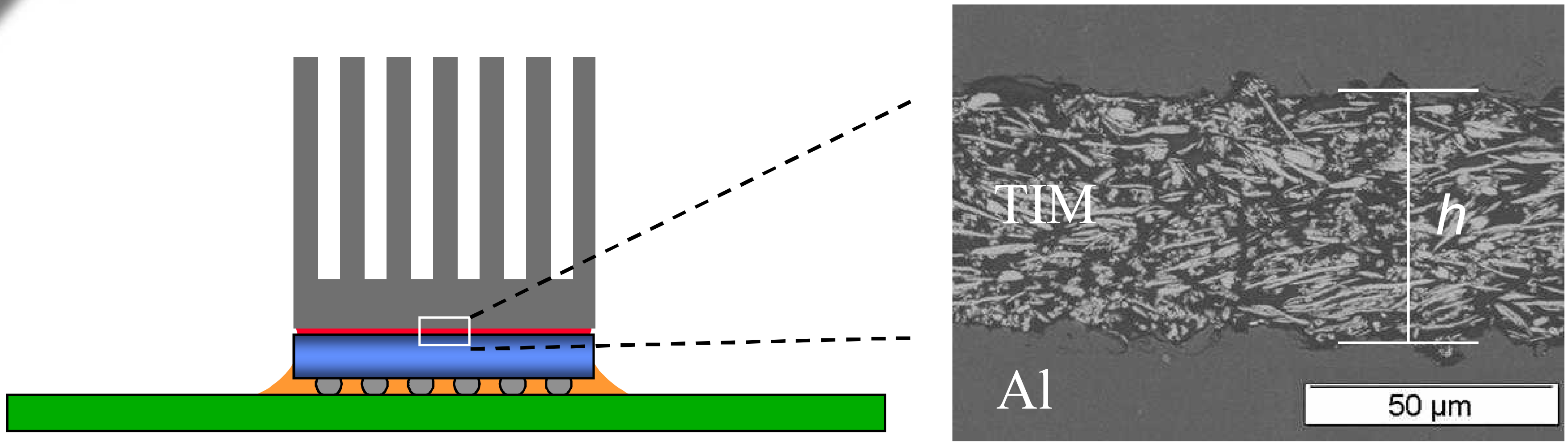
Thermal Bondline

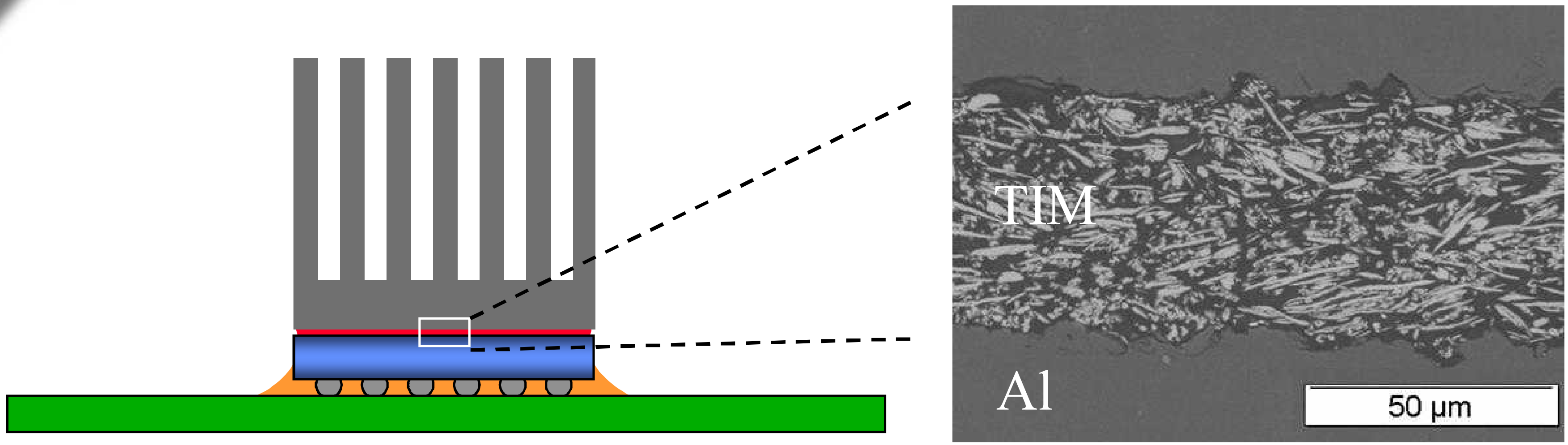


$$R_{bondline} = \frac{\Delta T_{bondline}}{q}$$

Factors to optimize:

- *h* bondline thickness
- λ_{TIM}
- $R_{contact}$

Thermal Bondline



Deviation from theoretical $R_{bondline}$ may be due to:

- Phonon scattering at the interfaces
- Incomplete wetting
- Voiding or delamination
- Processing induced heterogeneity

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Research Overview

Research goal:

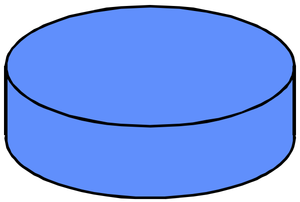
- Minimize $R_{bondline}$

Approach:

- Study the bondline formation process
- Assess bondline thermal performance
- Characterize bondline microstructure
- Determine sources of $R_{bondline}$
- Develop enhanced TIM materials

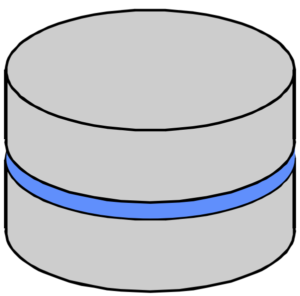
TIM Samples

Bulk Samples:



- 12.7 mm diameter
- 1 mm thick
- Used for ρ, C_p, λ_{bulk} measurements

Multilayer Samples:



- Aluminum 6061 T6 alloy substrates
- 12.7 mm diameter
- Substrates 1 mm thick
- *h* determined with thickness gauge
- Used for $R_{bondline}$ measurements

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Bondline Assembly

TA Instruments ARES rheometer used

Squeeze rate and target bondline thickness controlled:

- 0.4 to 40 μm/s possible
- 40 to 200 μm bondlines

Normal force vs. gap width monitored

Laser Flash Diffusivity Measurements

Equipment:
Anter FlashLine 5000

Analysis:
Anter Advanced Diffusivity software (bulk samples)

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Laser Flash Diffusivity Analysis

Multilayer Sample Analysis:

- New numerical model from Anter
    - Considers heat losses from front and back faces
    - Considers the middle layer as a contact resistance
    - No need to provide ρ, Cp, or *h*
    - Used for TIM 1 and TIM 3 nanocomposite

- Multilayer method developed by Lee [1976]
    - Requires middle layer ρ, Cp, and *h*
    - Does not consider heat losses from front and rear faces
    - Used for TIM 2 samples

Bulk TIM Sample - Results

ID	Material	ρ (g/cm^3)	Cp (J/gK)	α (cm^2/s)	λ (W/mK)	λ_{vendor} (W/mK)
Epoxy 1	Unfilled epoxy	1.13	1.3	0.0013	0.2	-
TIM 1	Ag-flake filled epoxy	3.13	0.51	0.0113	1.8	29
TIM 2	Ag-flake filled TIM	2.84	0.45	0.0830	10.6	17
TIM 3	5% Nanocomposite of TIM 1	2.76	0.61	0.0051	0.6	-

Preparation:

- 3 samples of each tested, average is shown
- Au/Pd and graphite overcoat layers
- λ deviation 10-16%

Results:

- All filled materials provide improvement over unfilled epoxy
- Both commercial epoxies λ_{exp} lower than on data sheet λ_{vendor}
- No discernable benefit to addition of 5% nanoparticles for bulk λ

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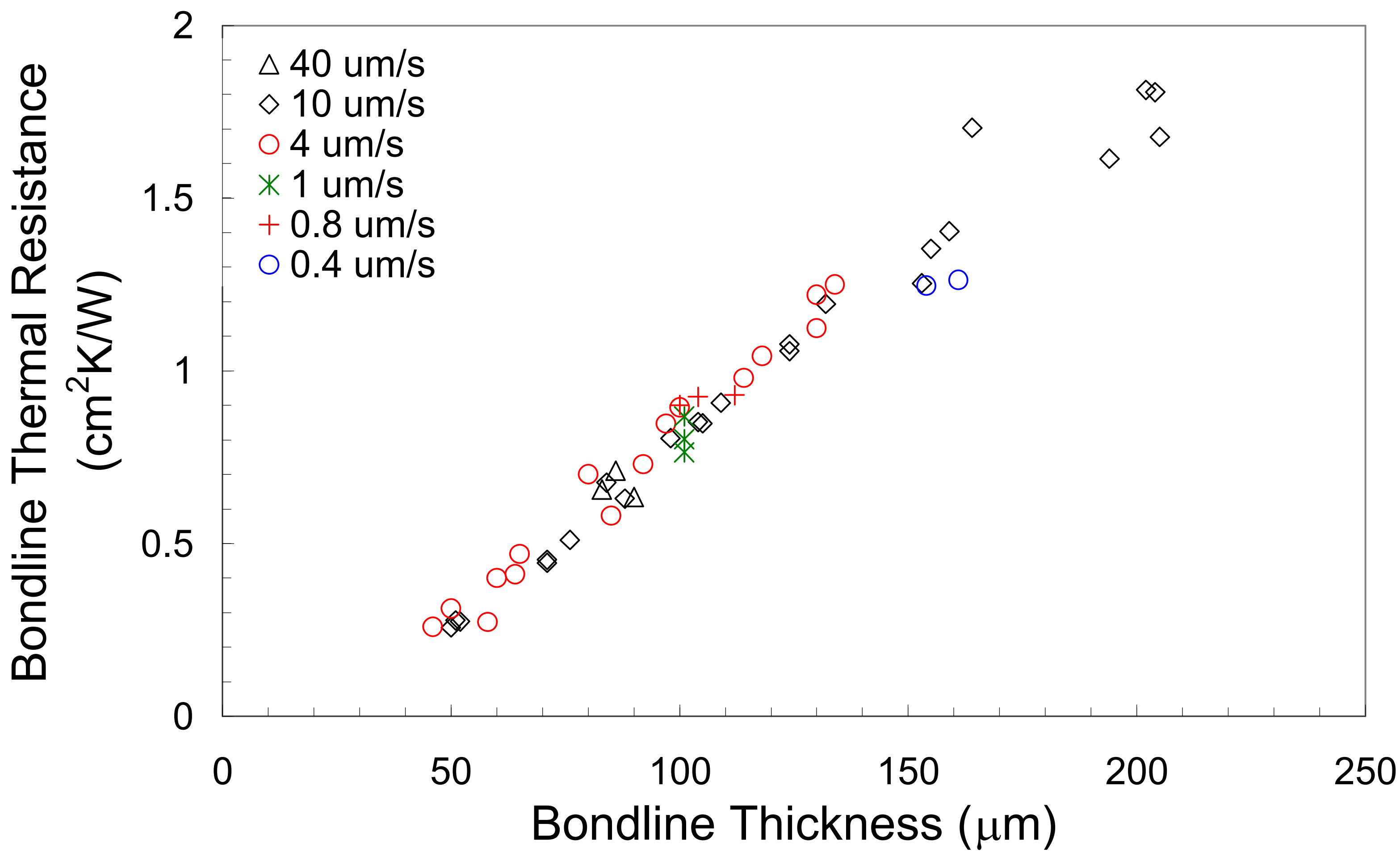
Multilayer – TIM 1



- Effect of squeeze rate was not discernable from that of *h*
- Negative intercept [Campbell et al., 2000]

Thermal Bondline Resistance

$$R_{bondline} = \frac{h}{k_{TIM}} + R_{contact}$$

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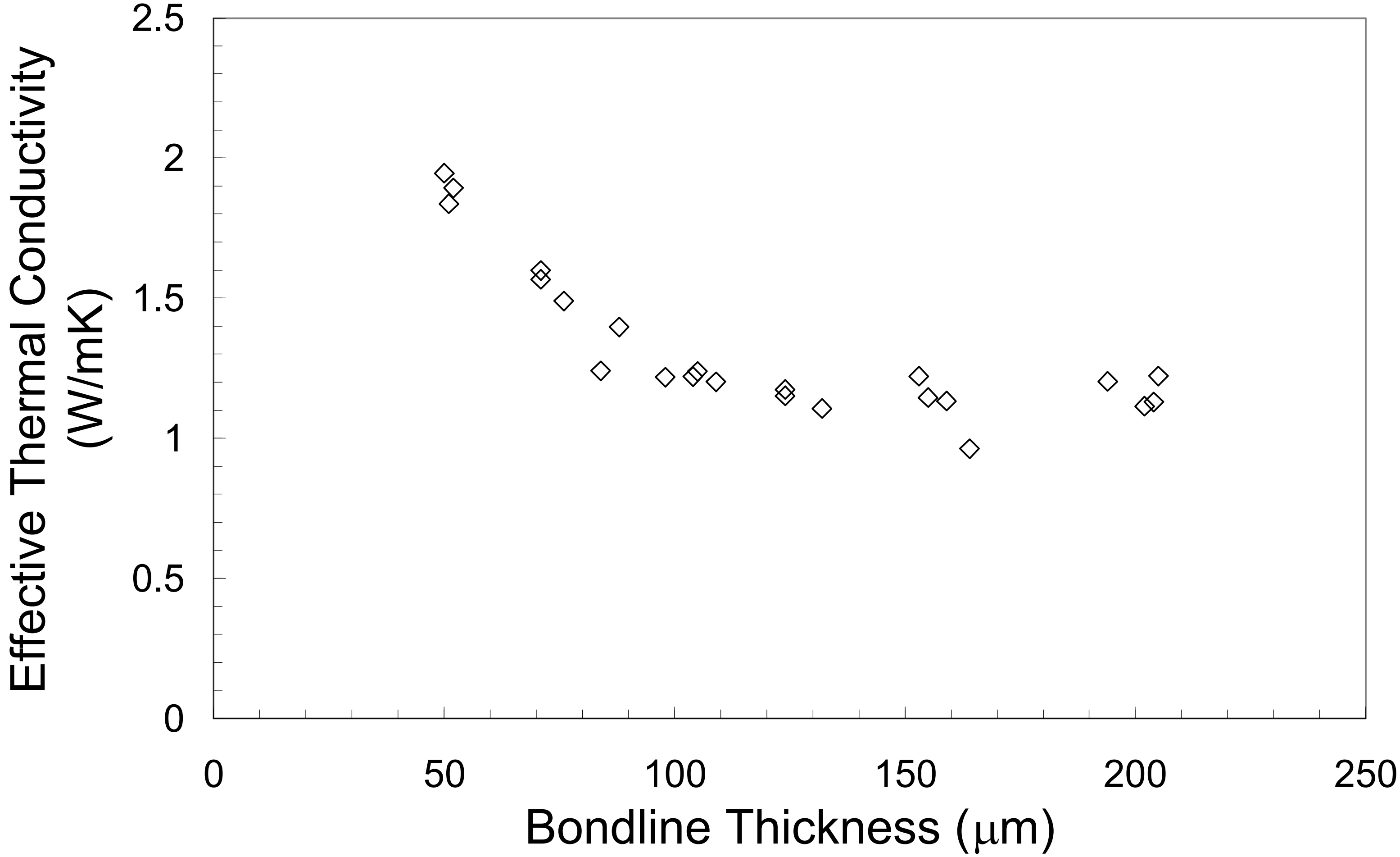
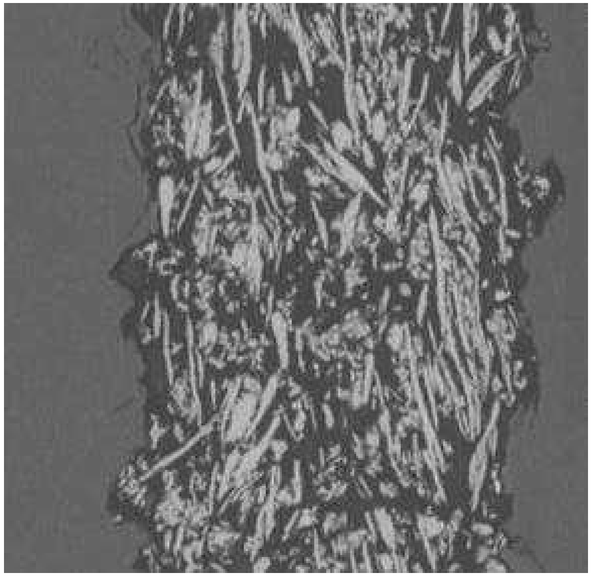
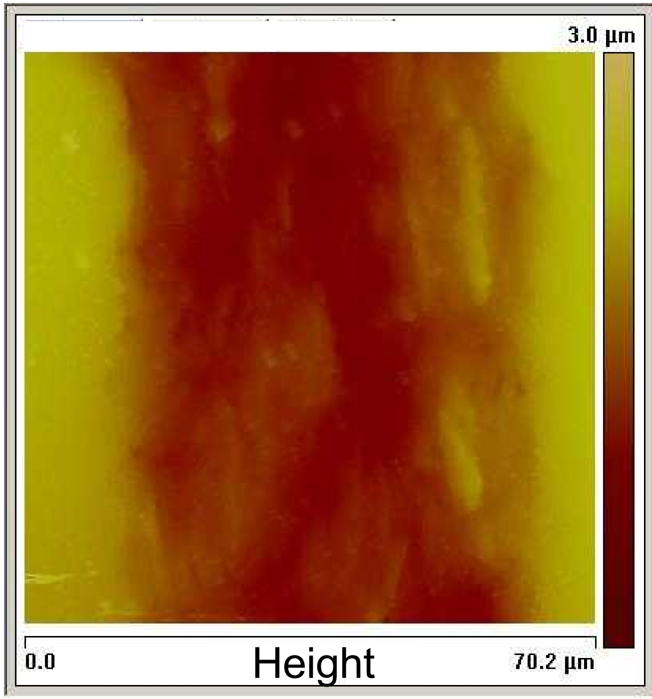
Multilayer – TIM 1



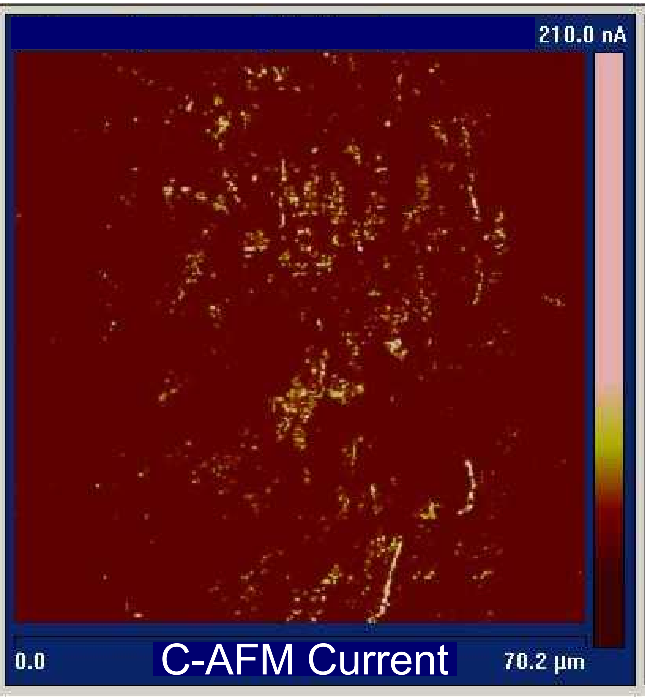
- Effective conductivity increases at small *h*
- Alignment of silver plates at smaller gaps may increase probability of contact and percolation path

50 μm Bondline – TIM 1


SEM

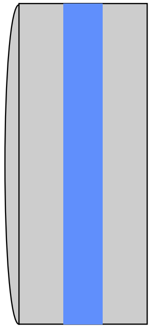


Height



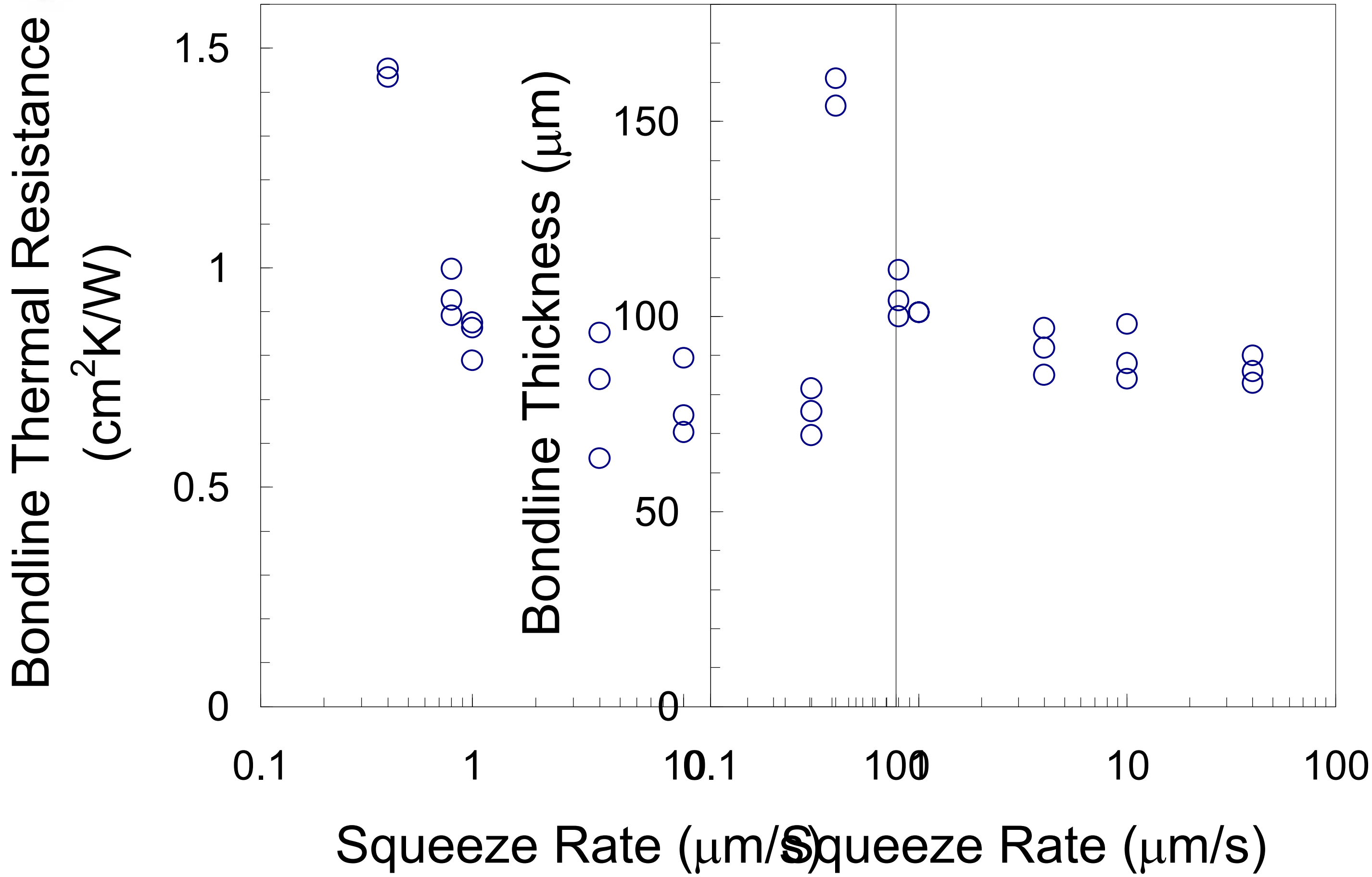
C-AFM Current

- Electrical connectivity shown
- Sample grounded at rear


Sample orientation

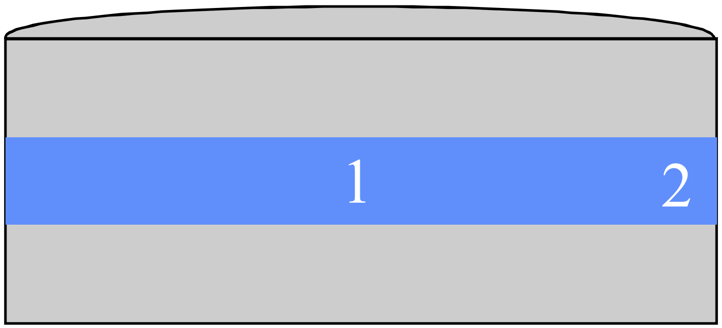
*SEM image from different region on same sample

Effect of Squeeze Rate – TIM 1



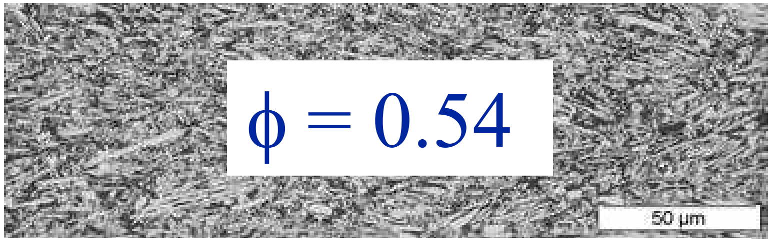
- Resistance at the 0.4 μm/s is ~double that of 4 μm/s and greater

Cross Sectioned Multilayers

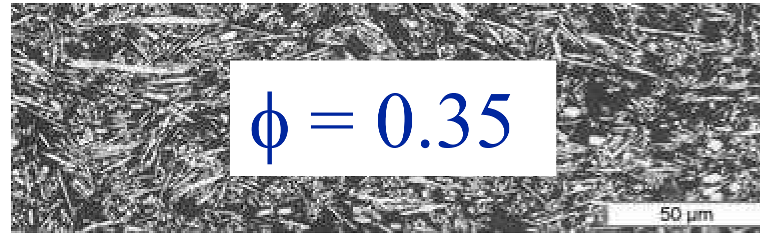


1 – center
2 – near edge

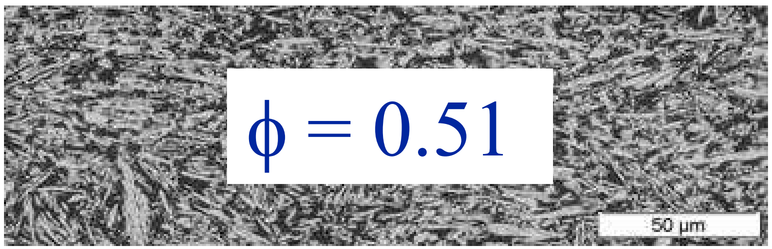
Effect of Squeeze Rate – TIM 1



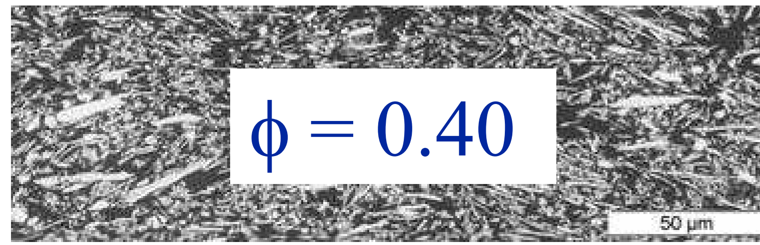
0.4 μm/s - Center



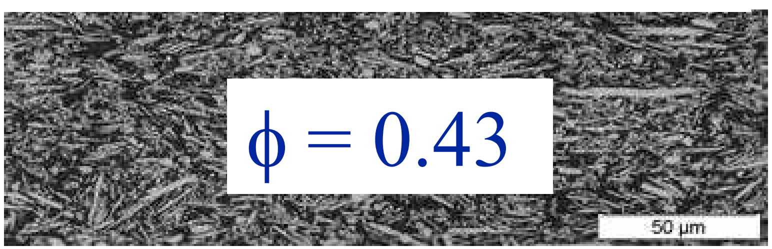
0.4 μm/s – Near edge



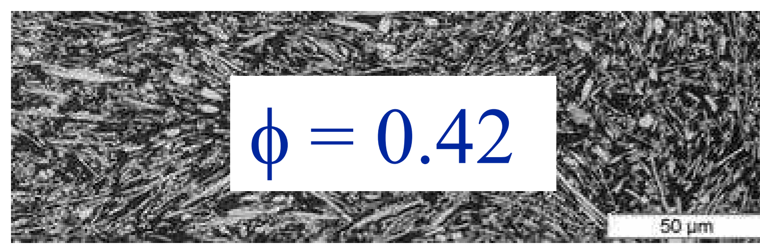
1 μm/s - Center



1 μm/s – Near edge



4 μm/s - Center



4 μm/s – Near edge

- Heterogeneity due to assembly conditions

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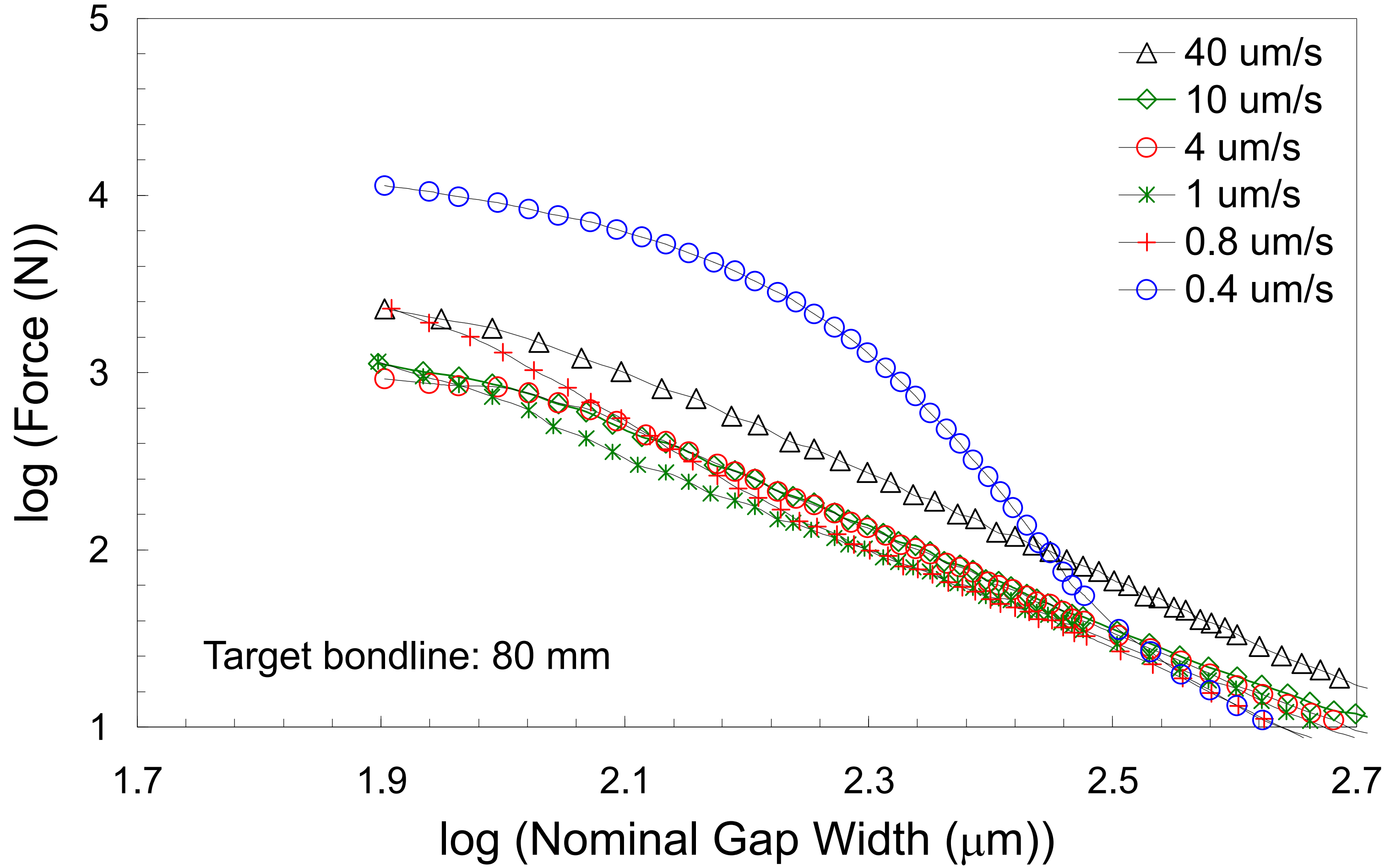
Force vs. Gap – Multilayer Assembly



- Filtration observed to correspond with Peclet Number *Pe* < 1

Peclet Number

Peclet number:

$$Pe = \frac{\tau_w}{\tau_s}$$

where:

- τ_w is the characteristic time for fluid filtration
- τ_s is the characteristic time for deformation of the suspension

$$Pe = \frac{\mu_w U^{1-m} h^{m+1}}{Ak}$$

$$U_c = \left(\frac{Ak}{\mu_w h^{m+1}} \right)^{1/1-m}$$

[Chaari et al., 2003; Collomb et al., 2003]

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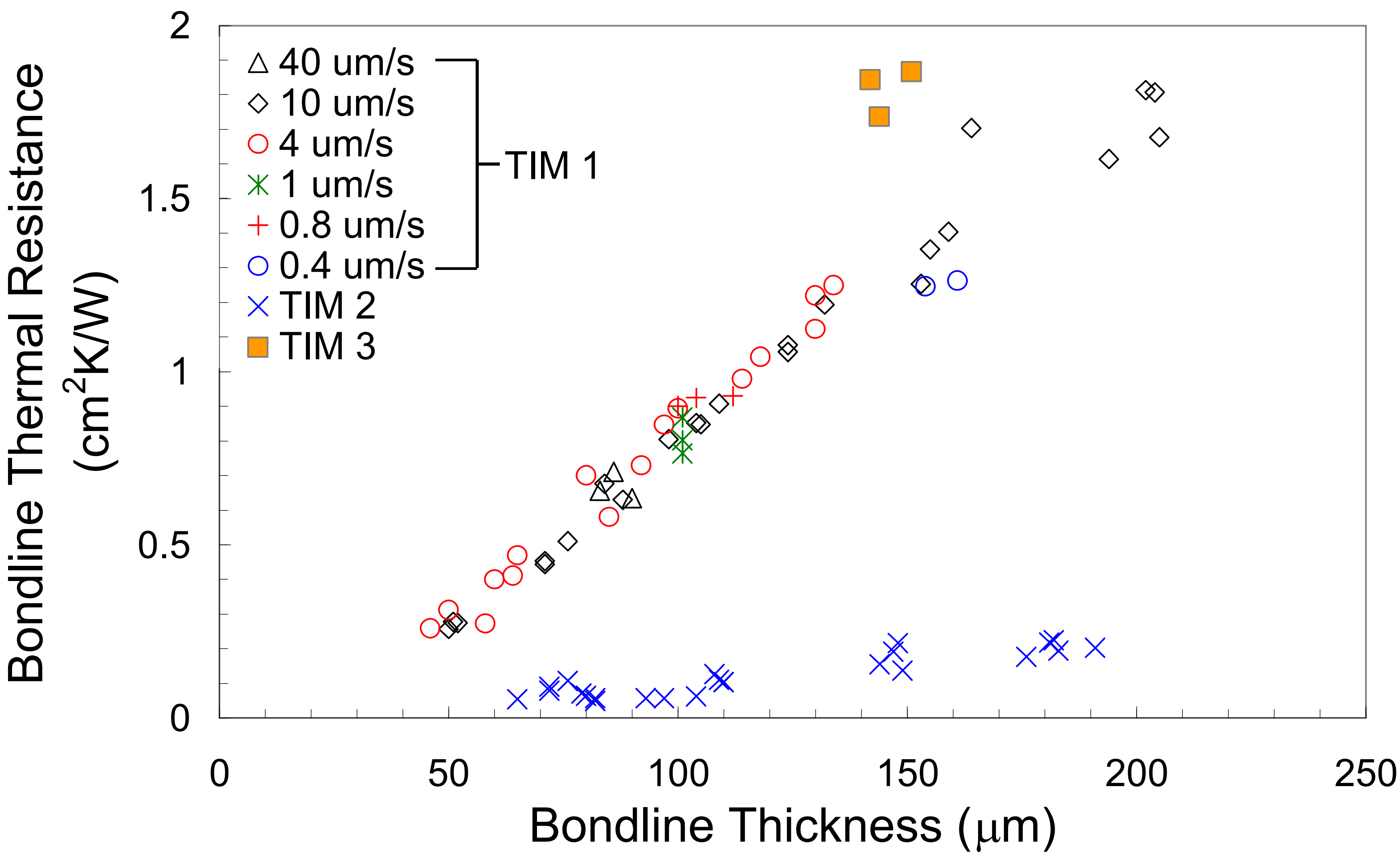
Multilayer – Comparison of Materials



- TIM 2 showed a significant improvement in $R_{bondline}$ over TIM 1
- TIM 3 (nanocomposite) showed a decreased performance

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Summary and Conclusions

TIM materials may not attain λ_{vendor}

$R_{bondline}$ is primarily shown to be a factor of h

For Pe < 1, nonuniform lateral filler distribution observed

- Can affect the ability of the assembly equipment to reach final bondline thickness, increase in $R_{bondline}$
- Did not significantly increase $R_{bondline}$ beyond that of homogeneous bondlines of equivalent thickness

Nanocomposite improved neither bulk or multilayer properties

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Acknowledgments

Tony Thermitus – Laser flash analysis and discussion

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John Macha and Tom Westrich – Sample preparation and thermal analysis

Michael Saavedra and Tim Mitchell – Machining

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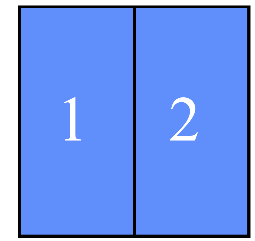
Numerical Model (Anter)

$$\frac{\partial^2 T_1}{\partial x^2} = \frac{1}{\alpha_1}\frac{\partial^2 T_1}{\partial t}$$

heat diffusion within first layer



$$\frac{\partial^2 T_2}{\partial x^2} = \frac{1}{\alpha_2}\frac{\partial^2 T_2}{\partial t}$$

heat diffusion within second layer

$$-\lambda_1 \frac{\partial T_1}{\partial x} = -h(T_1 - T_0) + Q(t)$$

boundary condition at first layer

$$\lambda_1 \frac{\partial T_1}{\partial x} = -\frac{1}{R}(T_2 - T_1)$$

$$\lambda_1 \frac{\partial T_1}{\partial x} = \lambda_2 \frac{\partial T_2}{\partial x}$$

thermal interface condition

$$\lambda_2 \frac{\partial T_2}{\partial x} = -h(T_2 - T_0)$$

boundary condition at second layer

$$T_1(x,0) = T_2(x,0) = T_0$$

initial condition

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