Measurement of Three Critical Parameters As A Basis for A Simple Thermal Barrier Coating Life Prediction Methodology

University of Connecticut

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SCIES Project 02- 01- SR 097

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

Tom J. George, Program Manager, DOE/NETL

Richard Wenglarz, Manager of Research, SCIES

Project Awarded (05/01/02, 36 Month Duration)

$ 478,495 Total Contract Value ($ 478,495 DOE)

Gas Turbine Need

- **Industrial Gas Turbine Performance & Durability Depend Strongly On Use Of Thermal Barrier Coatings**

- **Aggressive Application of TBCs Limited By Lack of NDI And Lifing Methods**

Gas Turbine Need

Non-Destructive Assessment of Remaining Life Strongly Impacts Operating Cost

- **Reduce occurrence of unplanned shut down**
- **Reduce wasteful precautionary part replacement for parts that don't need it, increasing part utilization**
- **Increase understanding of failure mechanisms leading to coating with improved durability and provide a physical basis for NDI**

Project Objectives

To develop and experimentally validate a method for the nondestructive prediction of remaining life of by measurement of :

- **Initial Surface Geometry**
- **Thermally Grown Oxide (TGO) Stress**
- **TGO Thickness**

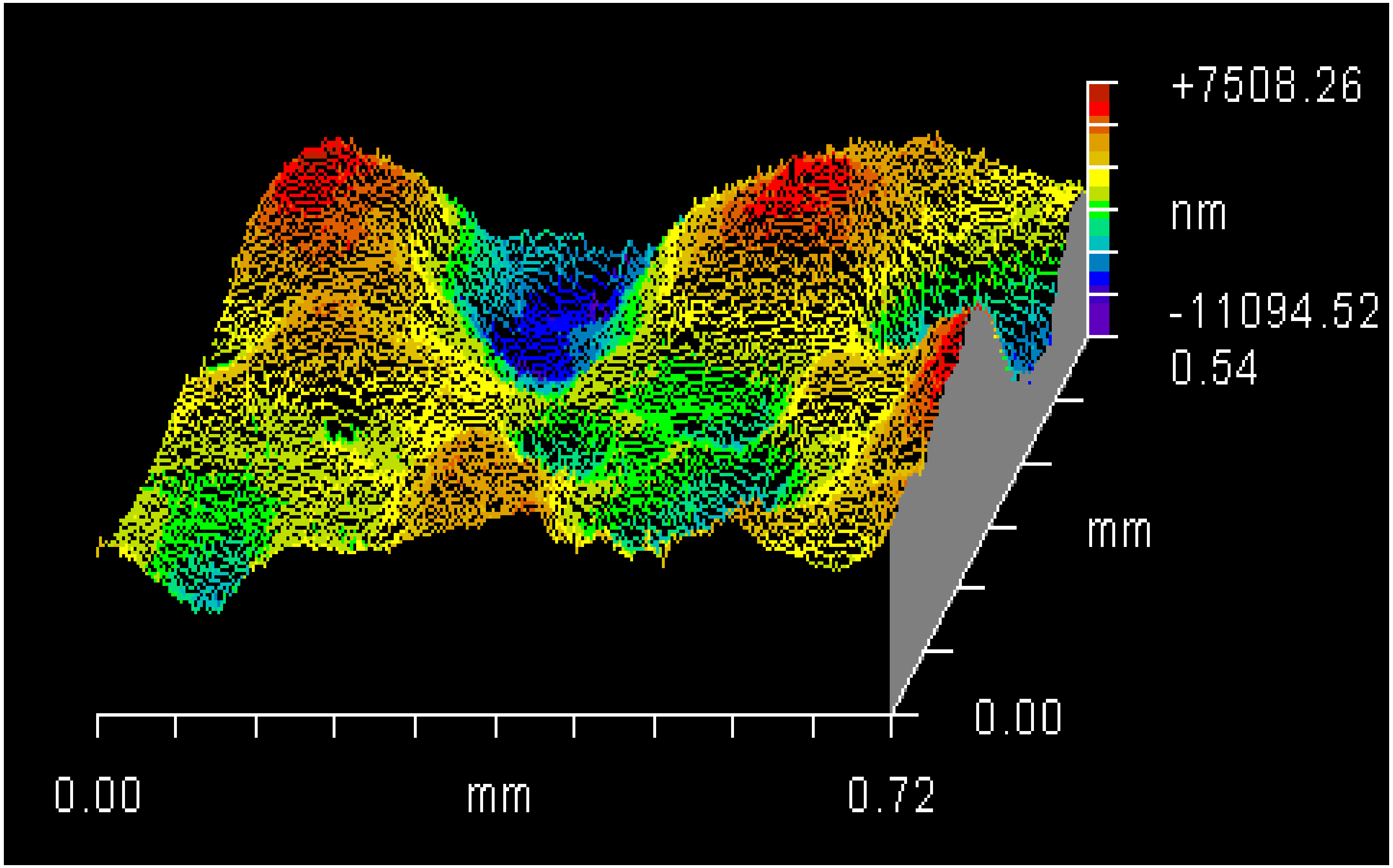
ACOMPLISHMENTS

- An accurate remain life NDI based on TGO Stress measurement
  - Showed a direct relation to damage and failure
- A new surface metric more related to damage than RMS etc.
- Transferred Technology to Industry

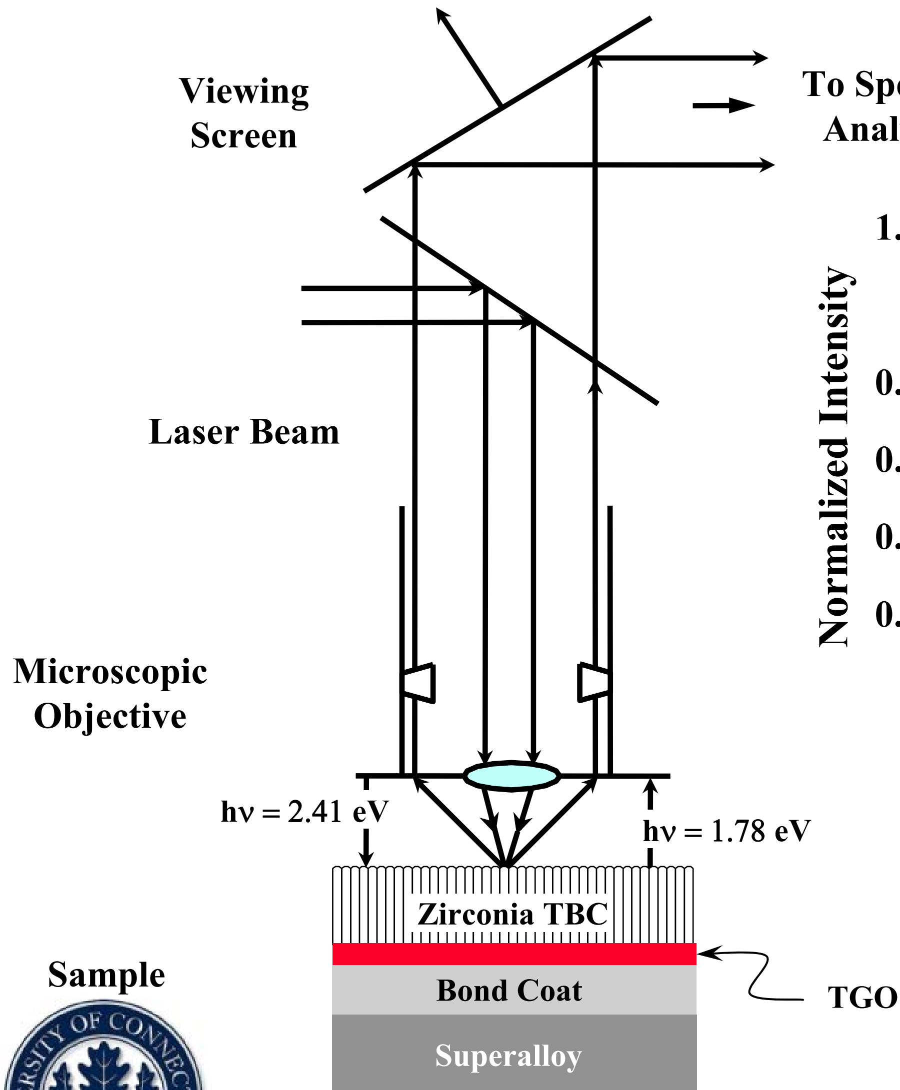
ACOMPLISHMENTS

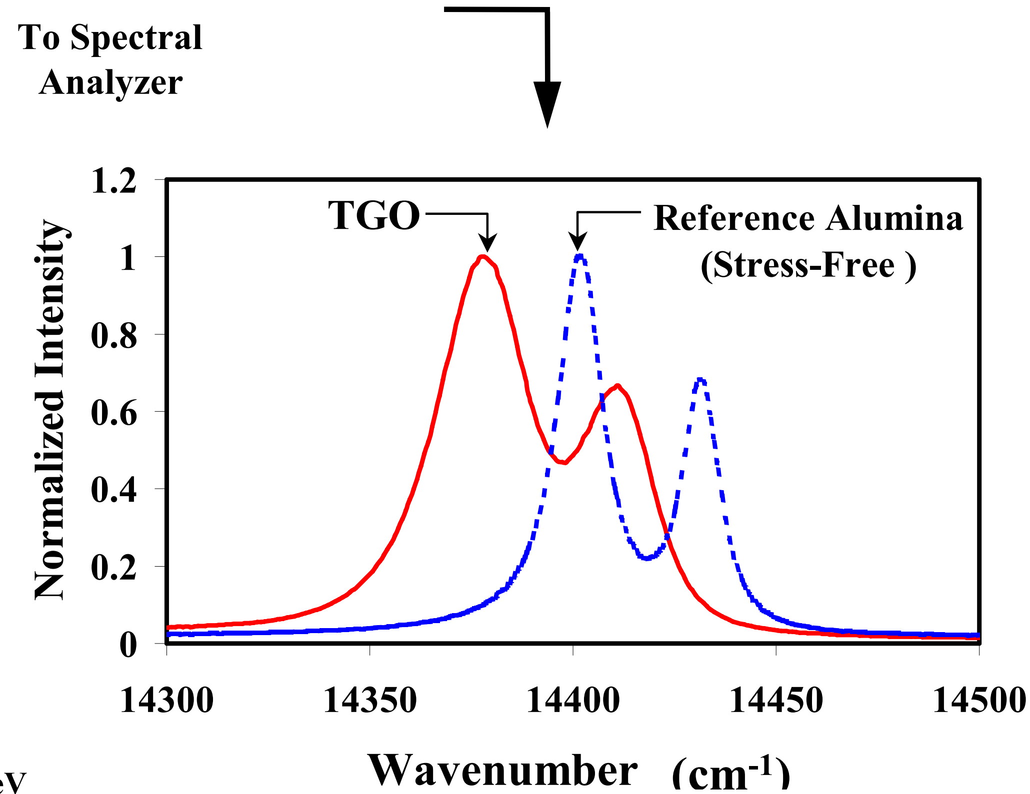
- Two Ph D and two masters ¾ female
  - Swetha Sridharan
  - Mei Wen
  - Jessica Shen
  - Manish Madhwal

Surface Geometry Determined by Interferometer Surface Profiler



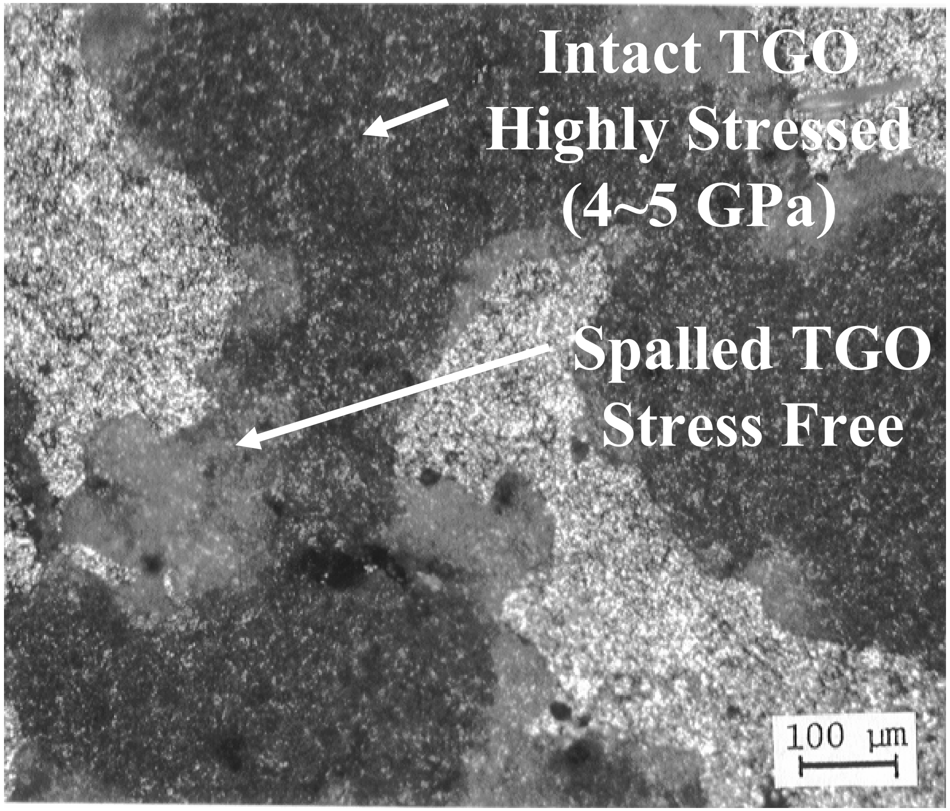
Photoluminescence Piezospectroscopy (PLPS) for Measuring TGO Stress

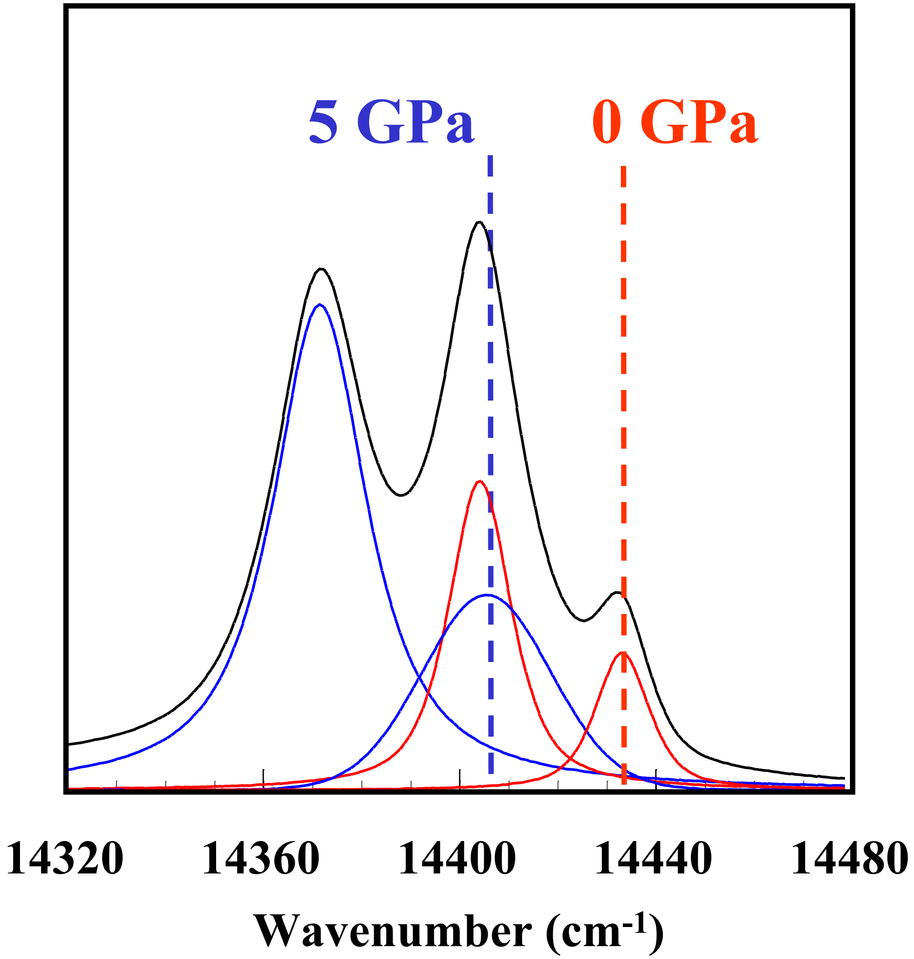




$$\overline{\Delta\nu}_{stress} = \frac{2}{3}\Pi_{ij}\sigma_o$$

Bimodal Spectra





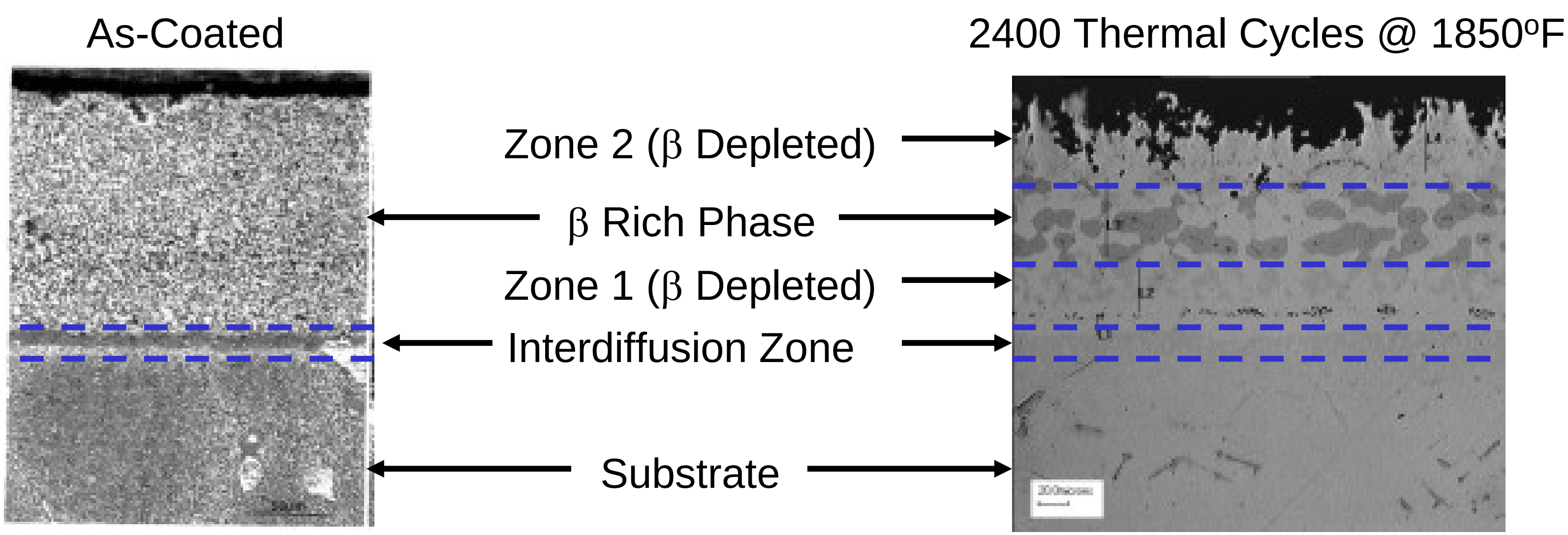
Top of MCrAlY Bond Coat Surface After Spallation of 7YSZ

Automated Deconvolution of PLPS Spectra

- **Solution- Optimized fit to R1-R2 peak pairs with enforced spacing**
- **Benefit- 100X reduced user effort and reduced user training level**

TGO Thickness Measured by Advanced AC Potential Drop

- **Beta depletion zone thickness determined from electrical resistivity vs. depth inferred from AC Potential Drop.**
- **JENTEK measurement system deemed best in Round-Robin Test**



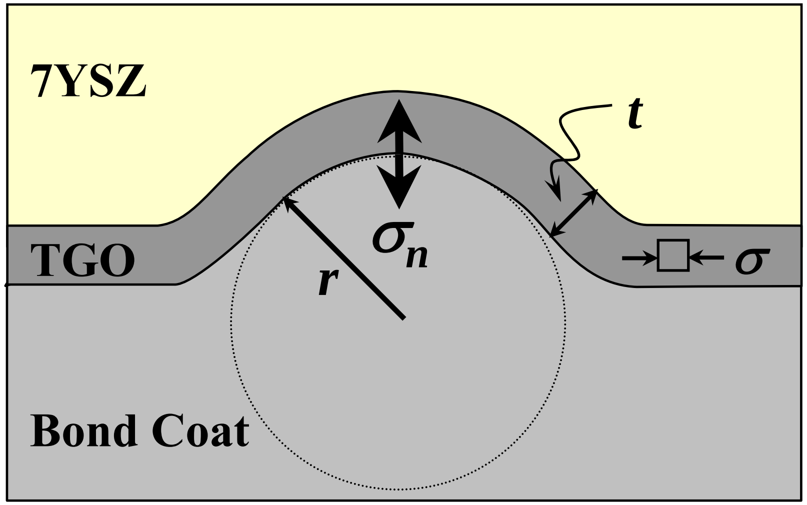
Different Type of Specimens Used In The Program

Type	Superalloy Substrate	Bond Coat		Ceramic (7YSZ)	
		Type	Thickness (μm)	Type	Thickness (μm)
I	Single Crystal CMSX-4	Ni-20Co-18Cr-12.5Al-0.6 Y-0.4 Si-0.25 Hf wt.%	100	EB-PVD	145
II	Single Crystal CMSX-4	Grit Blasted-[(Ni,Pt) Al]-Ni-21 Al-20 Pt wt.%	50	EB-PVD	140
III a,b	Single Crystal CMSX-4	Grit Blasted-[(Ni,Pt) Al]-Ni-21 Al-20 Pt wt.%	75	EB-PVD	150

Type I. Specimen Life Prediction
Use all 3 Parameters

Failure Occurs at Constant Value of Out of Plane Interface Stress

$$\sigma_n = \sigma t(1/r_x + 1/r_y) = \sigma t(1/r_{mean})$$



t= *TGO thickness*

r_y, r_x = *Principal radii of curvature*

σ_n = *Normal tensile stress at asperity*

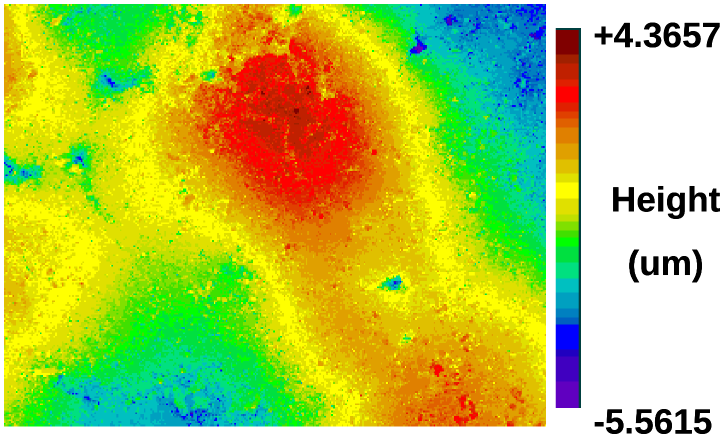
σ_y, σ_x = *in-plane compressive stress*

If $\sigma_y = \sigma_x = \sigma$

Development of Geometry Feature Extraction Software

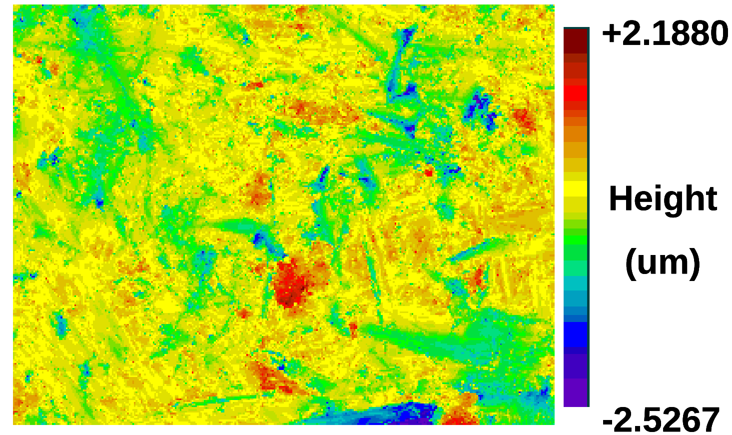
- Smooth the Raw Data by Filtering
- Cubic Splines Are Used to Fit the Data
- Compute Mean Curvature from Derivatives

Curvature Map Superior to RMS in Characterizing Surface Geometry



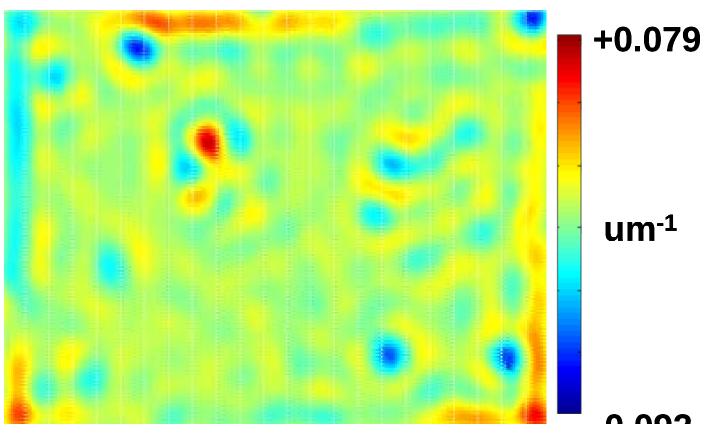
Surface of As-received

RMS=1.456 um

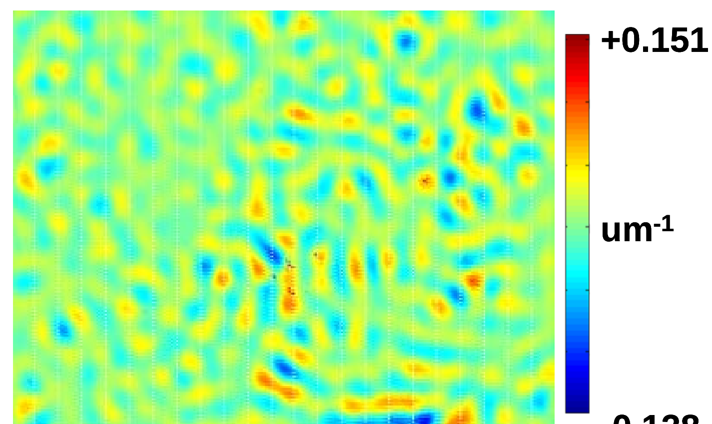


Surface of Barrel Finish

RMS=0.452 um

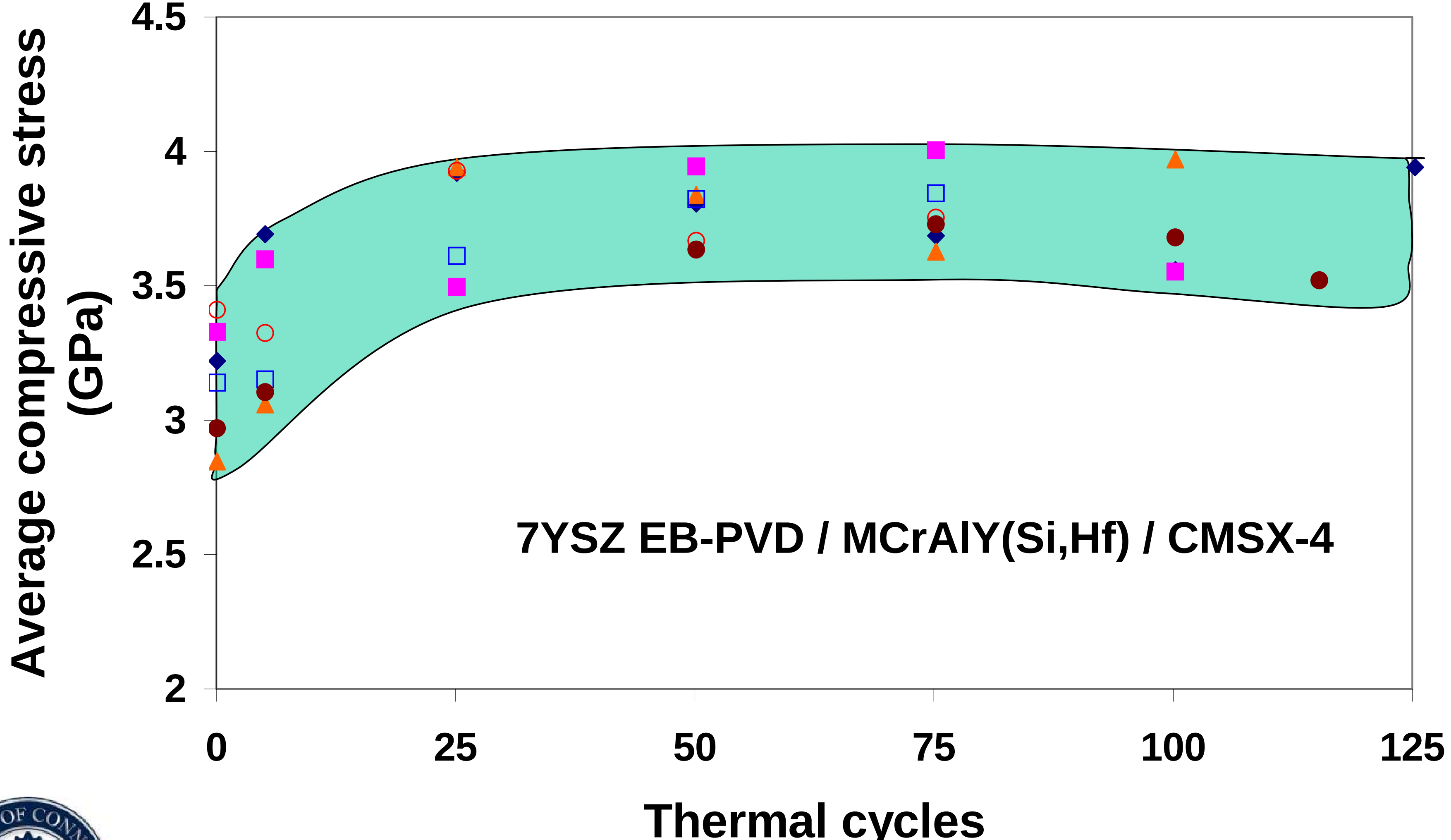


Curvature of As-received Surface

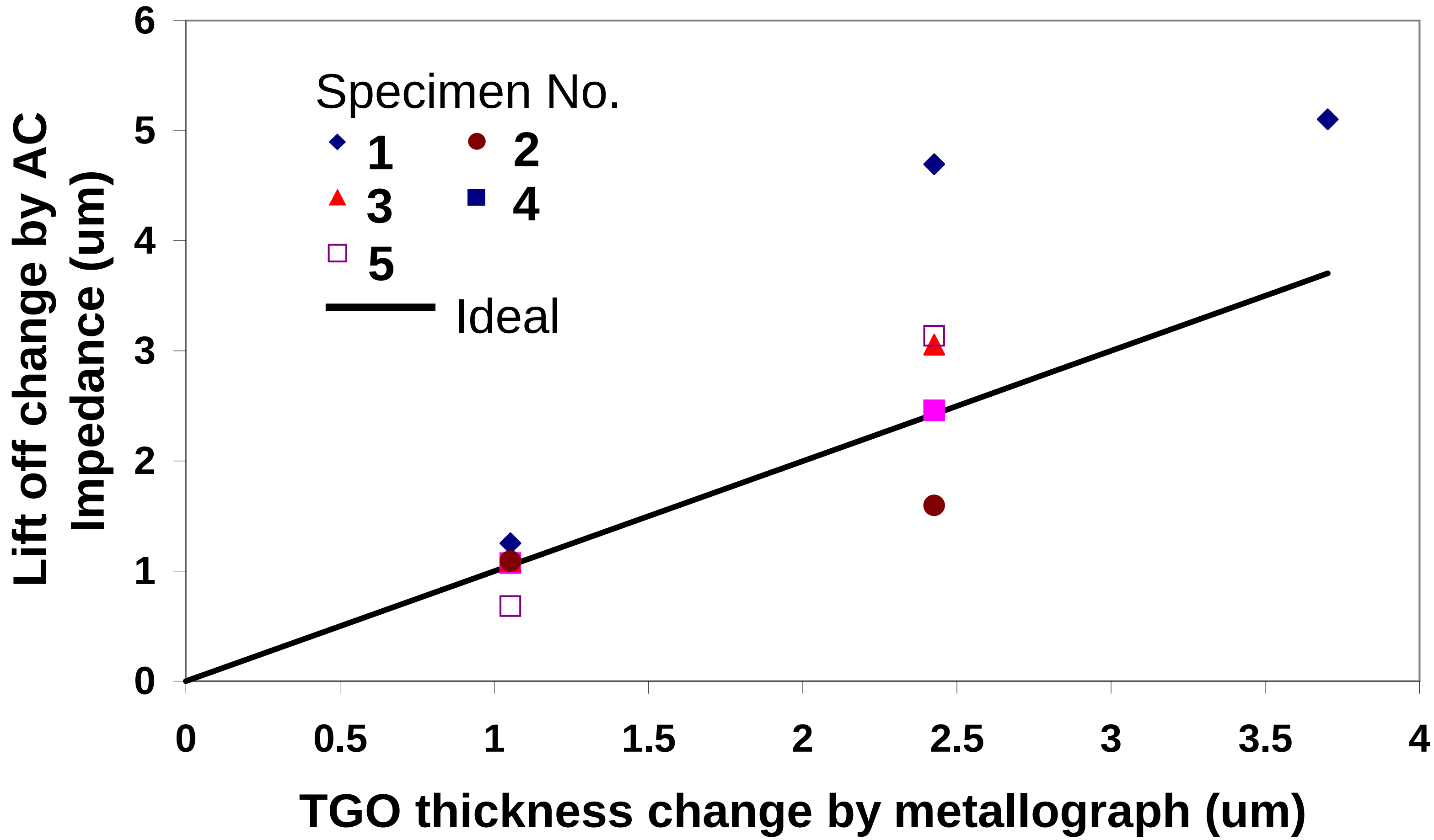


Curvature of Barrel Finish Surface

Evolution of TGO Stress throughout Thermal Cycling

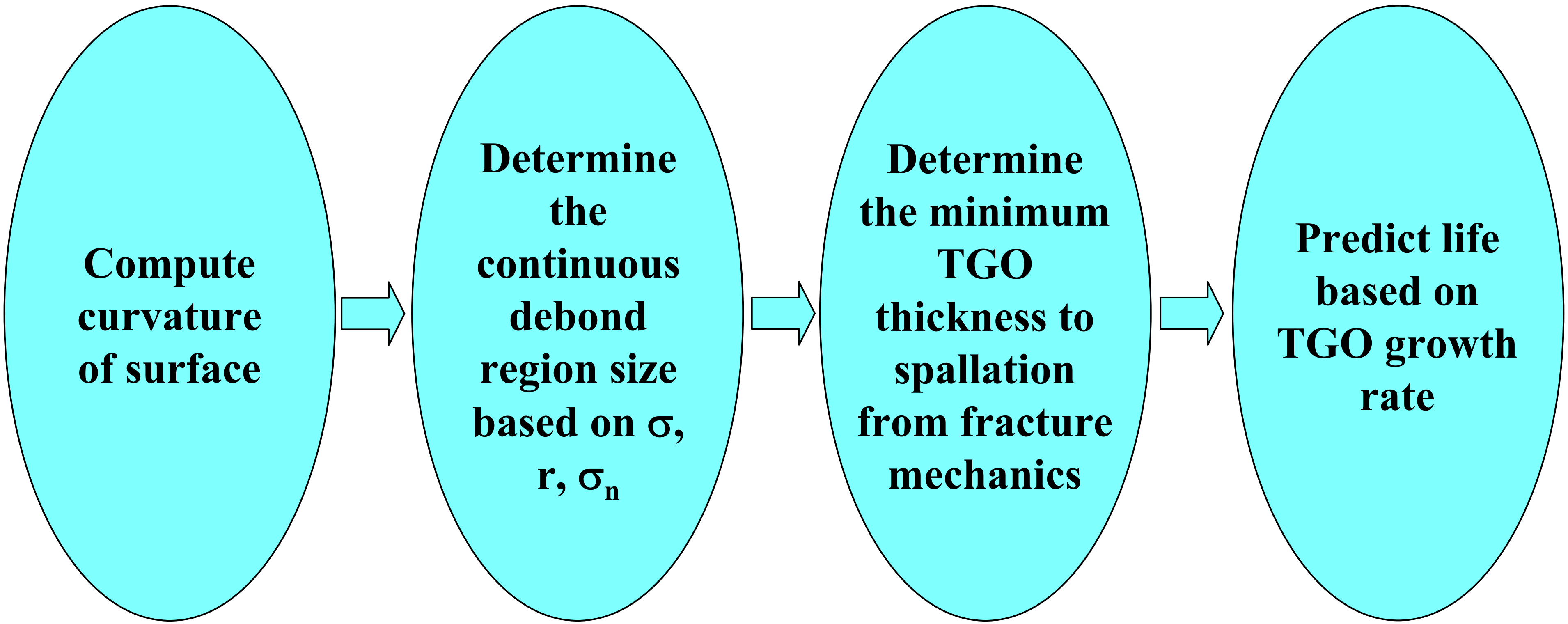


TGO Thickness Measured by AC Impedance Method

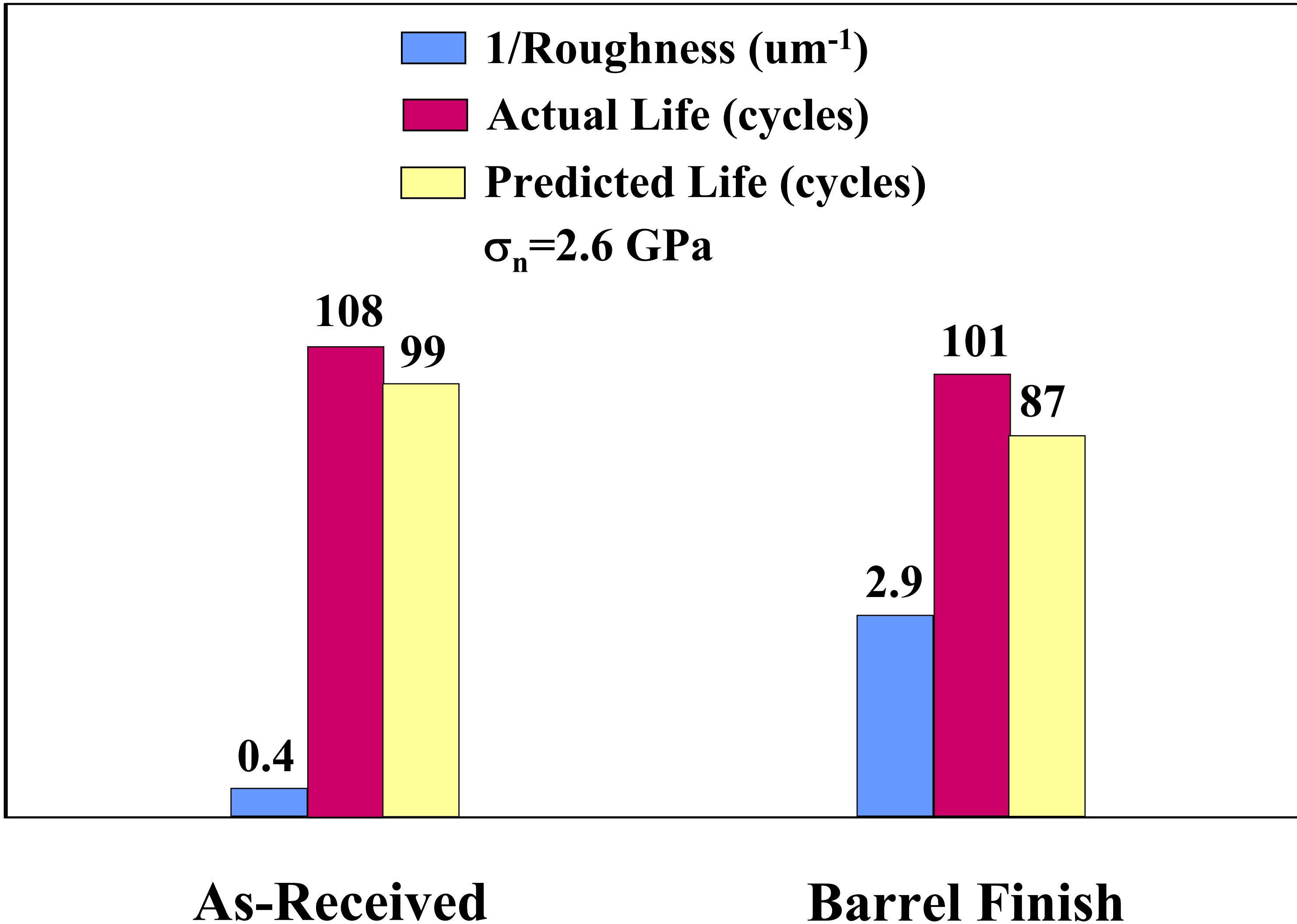


Oxide growth rate $h = 0.3859\ t^{1/2} + 0.742$

Life Prediction Methodology



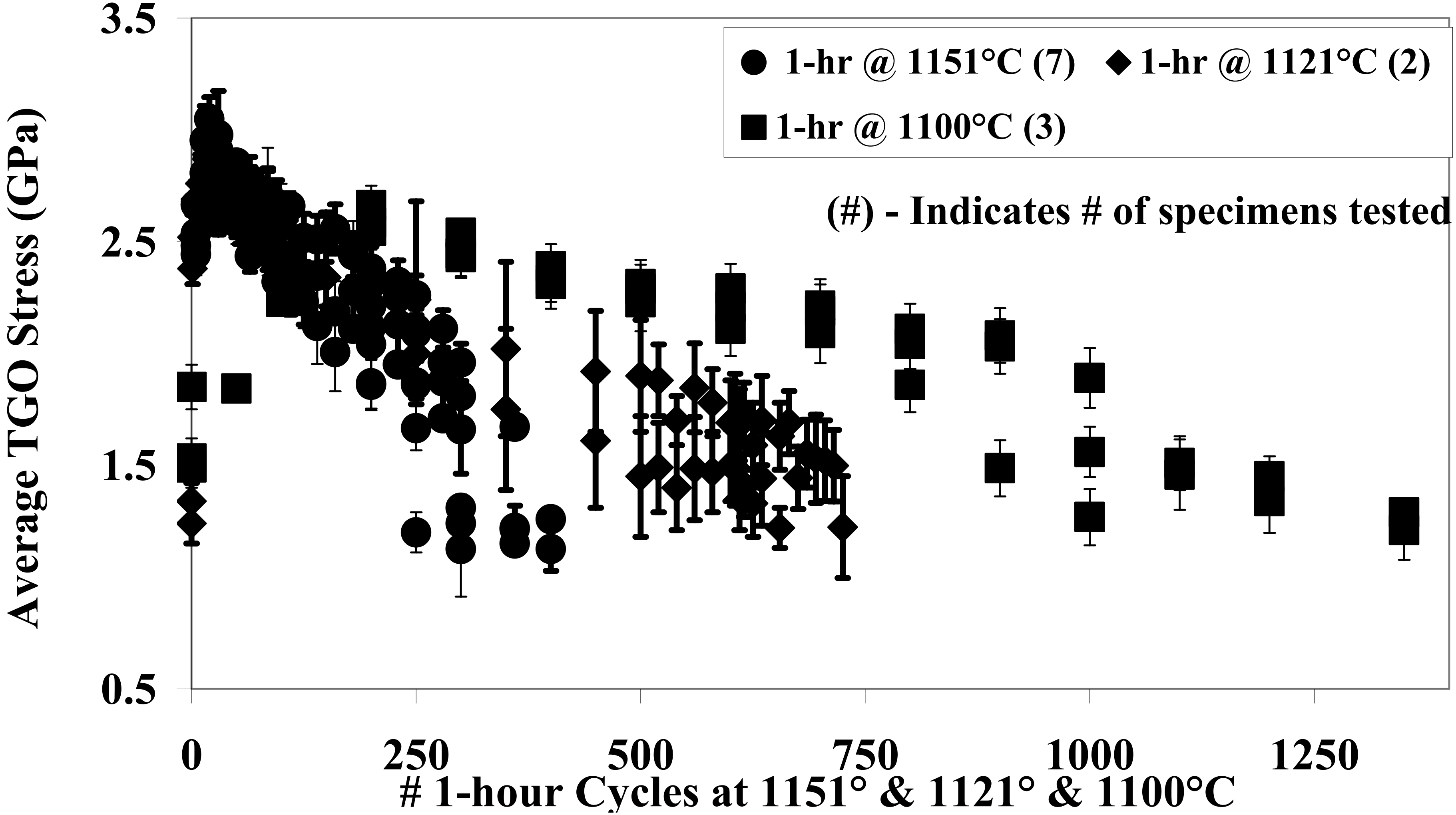
Summary of Surface Roughness, Real Life and Predicted Life



Type II & III a,b Specimen Use
TGO Stress Only

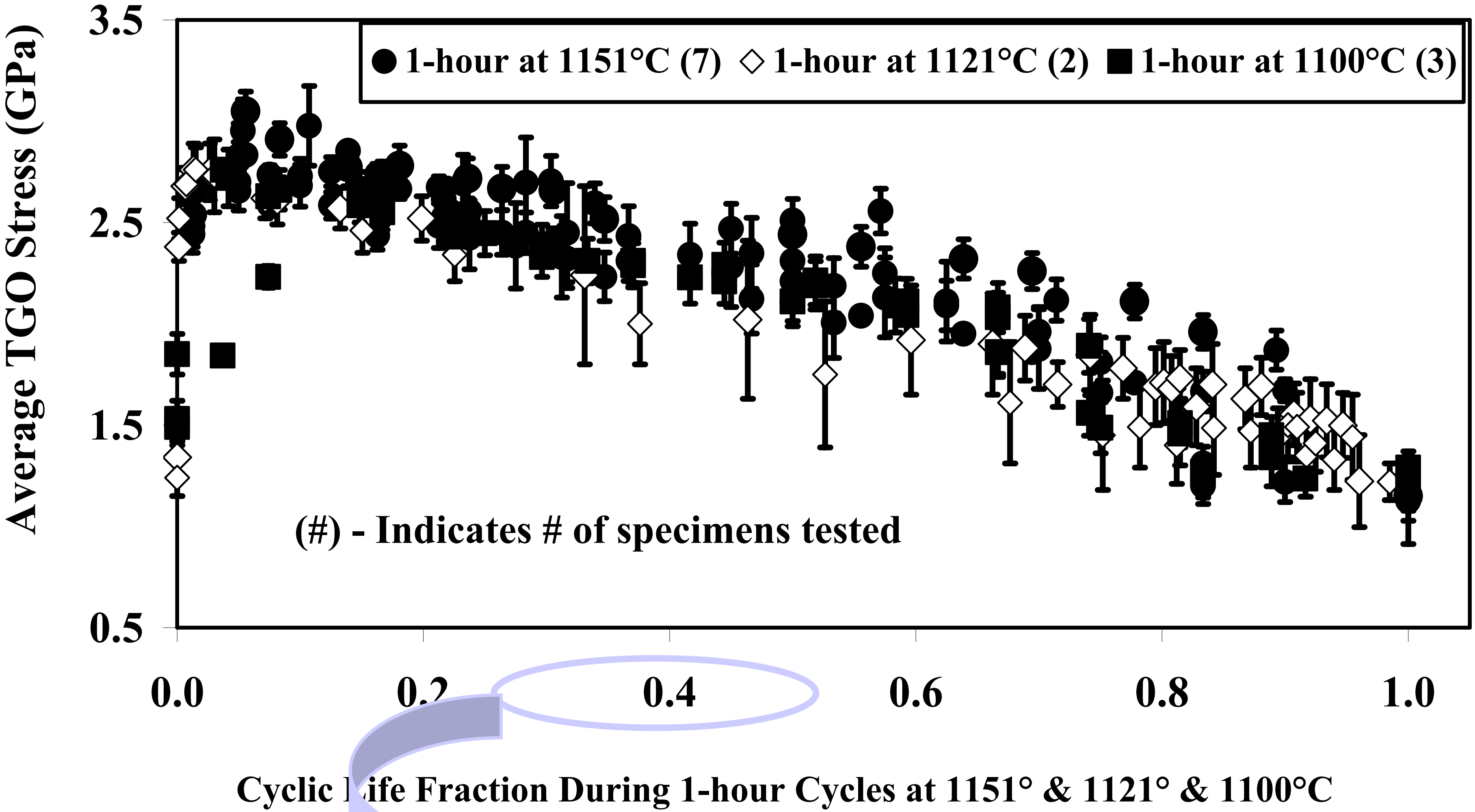
Type I TBC – TGO Stress Versus Cycles

1-hour Tests



Type I TBC – TGO Stress Versus Cyclic Life Fraction

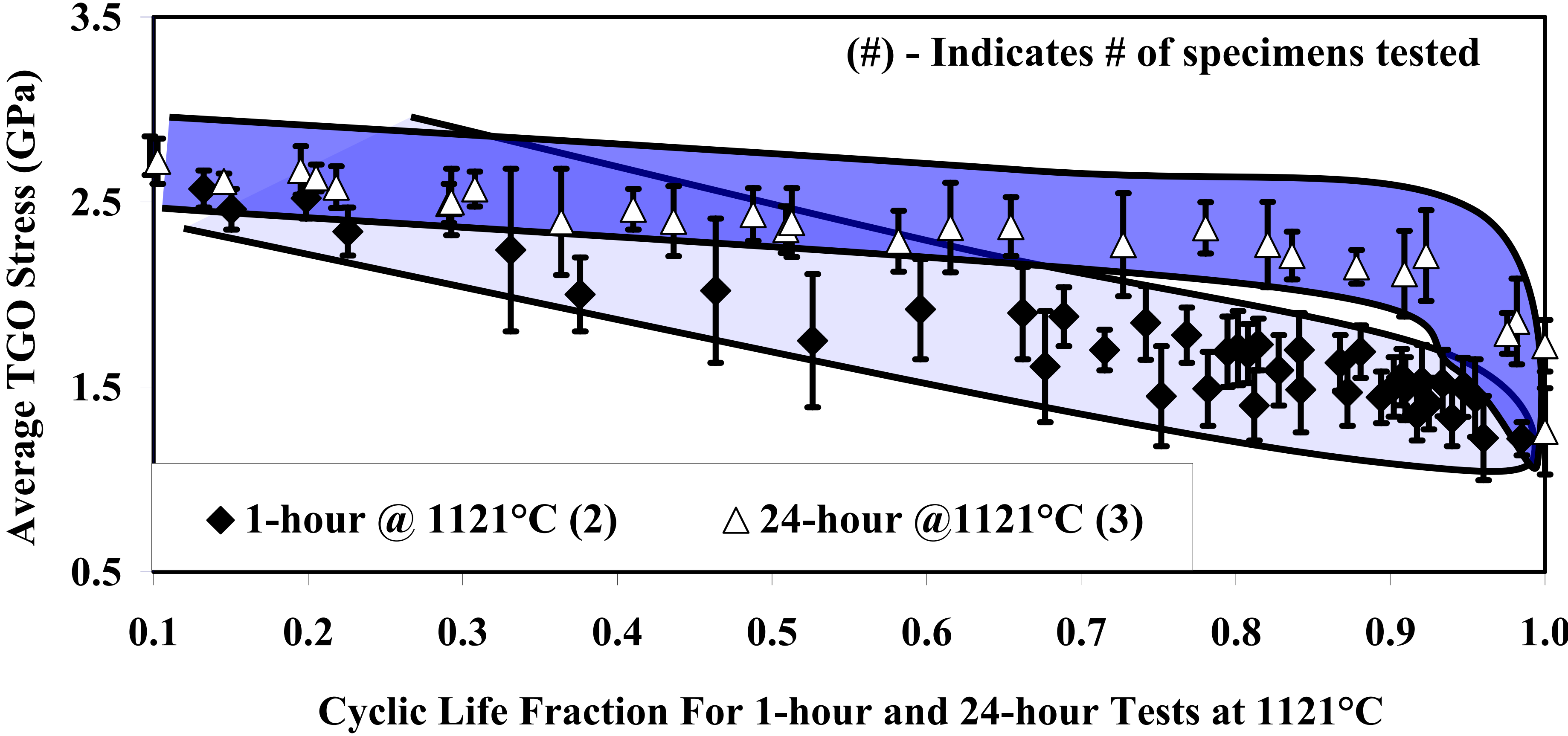
1-hour Tests



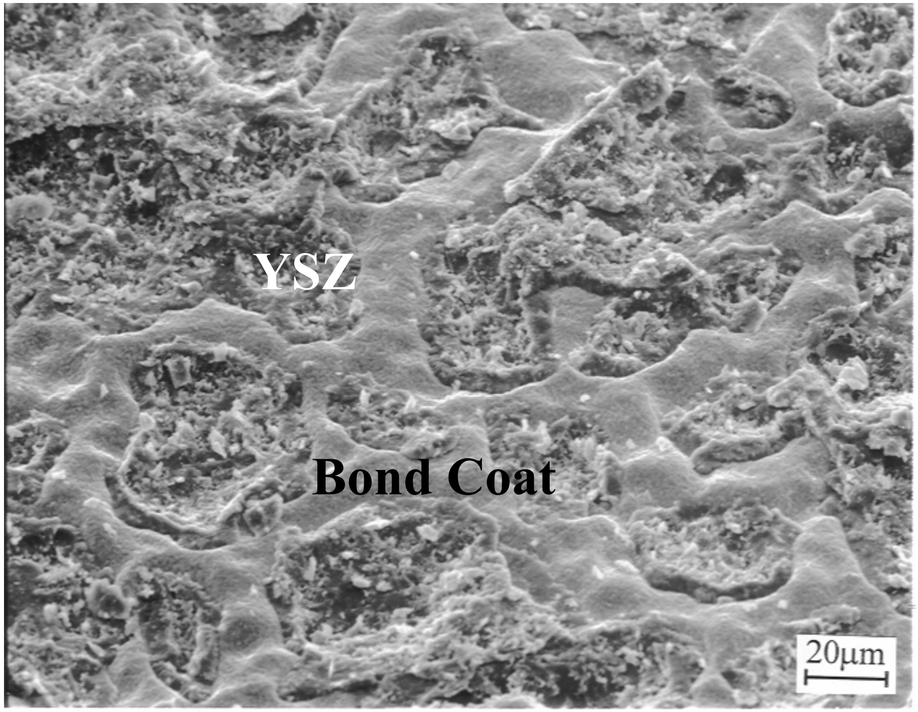
# of Cycles / # of Cycles To Failure

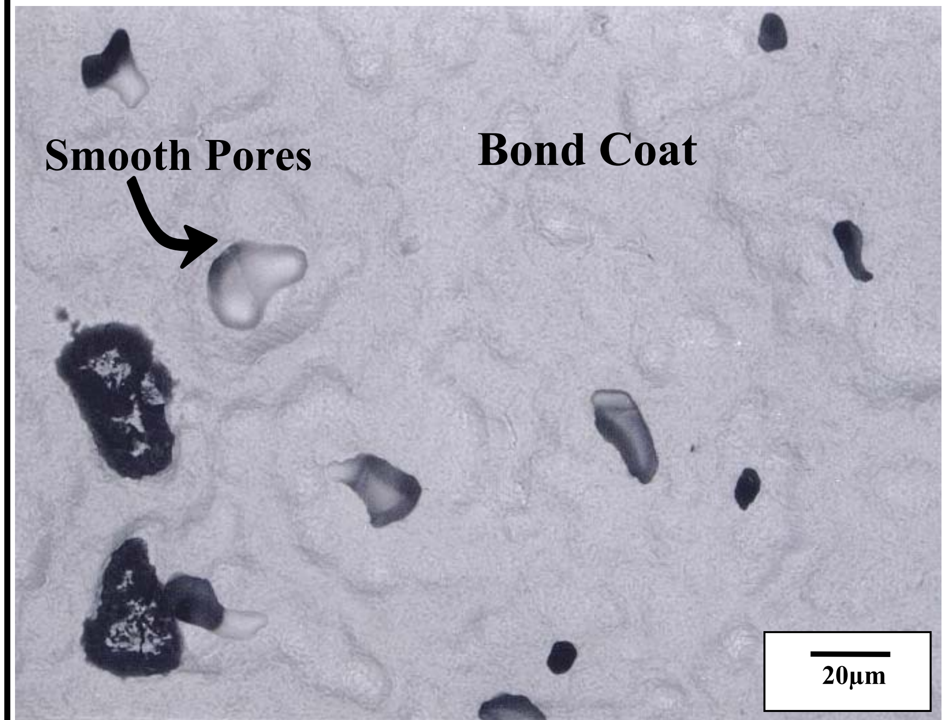
Type I TBC – TGO Stress Versus Cyclic Life Fraction

24-hour Tests



RESULTS – 1-hour Versus 24-hour Tests





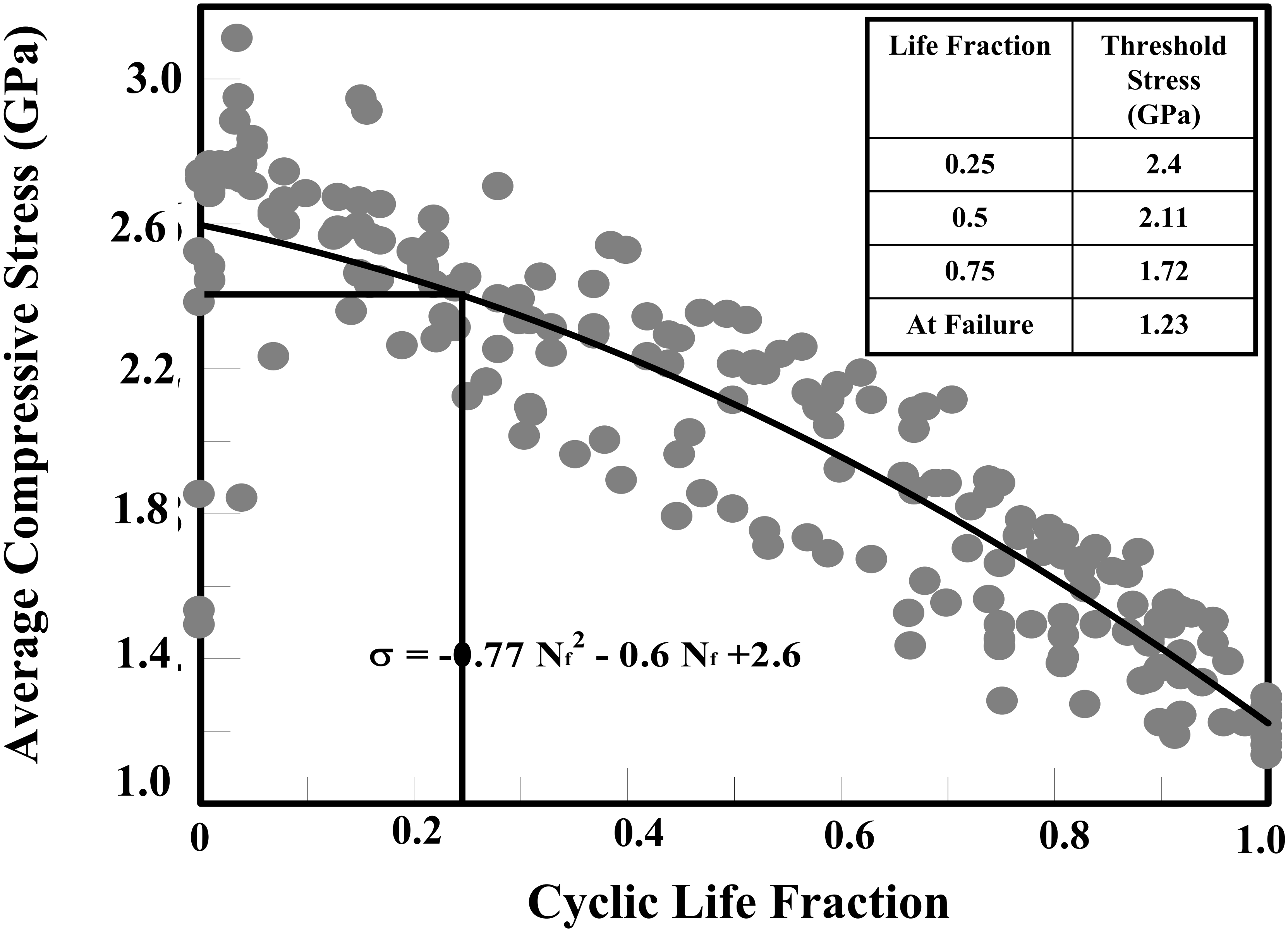
Failed after 33 24-hour Cycles @ 1121°C

<u>1-hour Tests:</u> Failure Predominantly In The YSZ At or Near the <u>TBC/TGO</u> Interface

<u>24-hour Tests:</u> Failure Predominantly At <u>TGO/Bond Coat</u> Interface

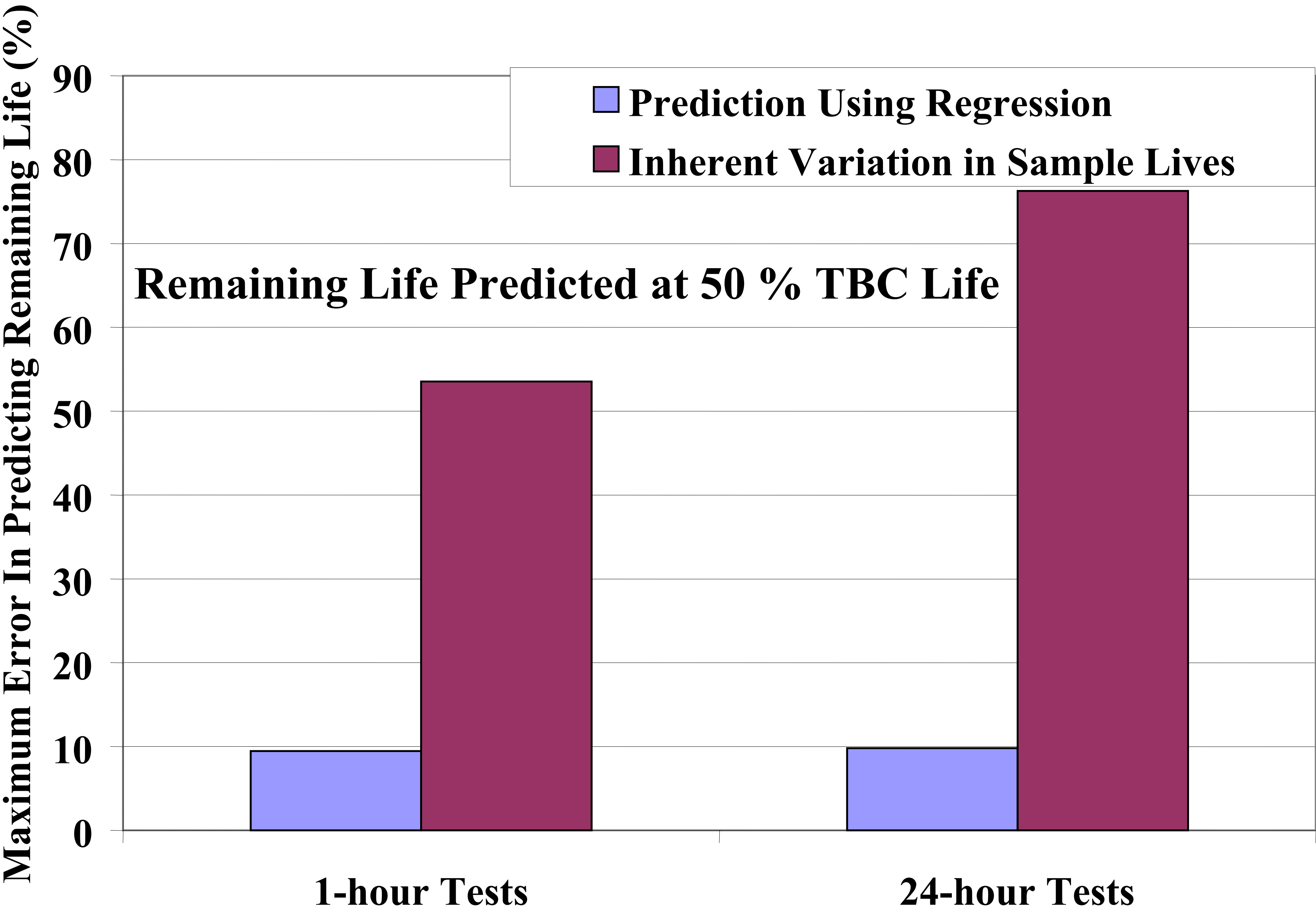
Remaining Life Prediction Based on PLPS Data without knowledge of temperature
I. Regression Method
For Type III

Type I TBC - Quadratic Curve Fit For Multiple History Data



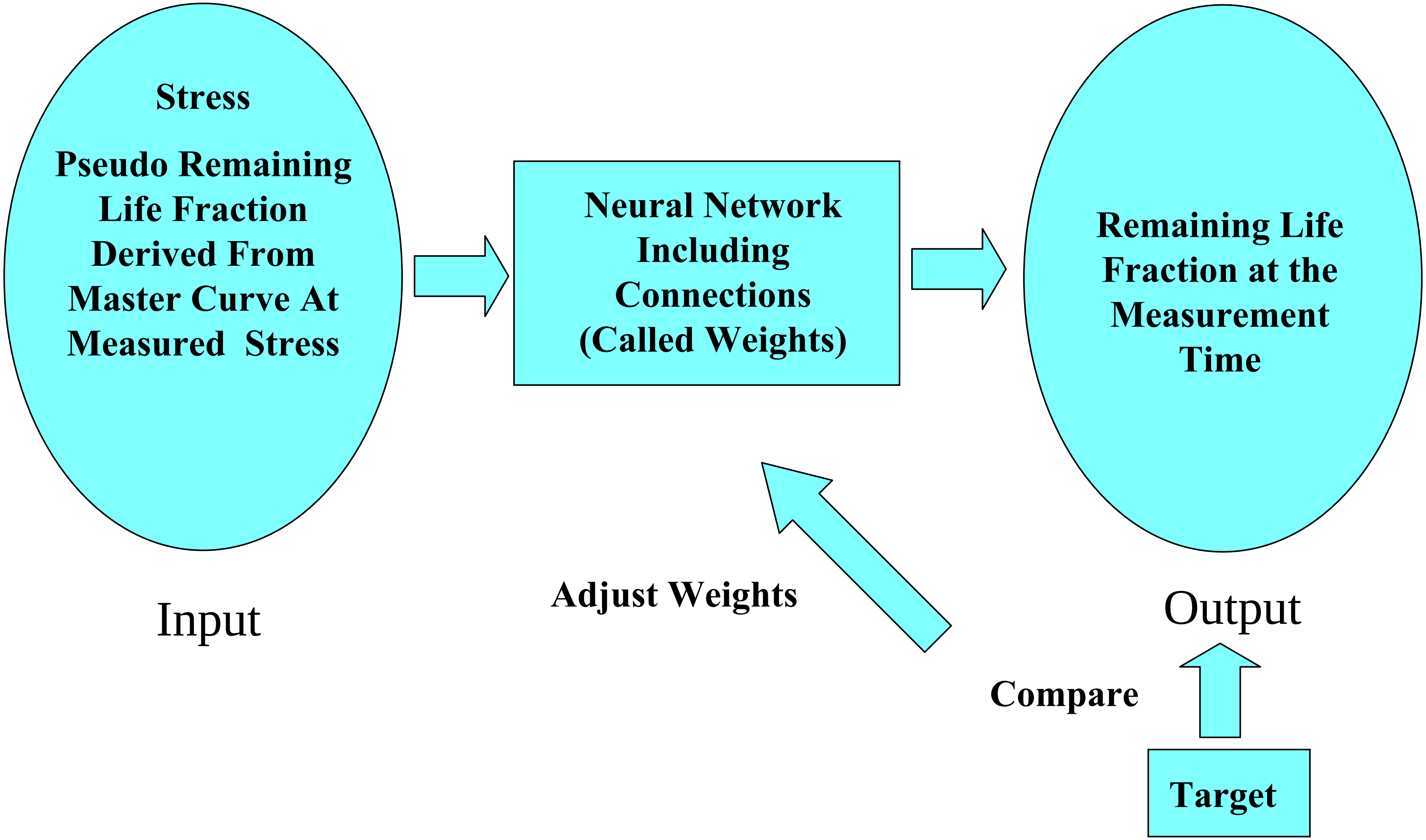
Life Fraction	Threshold Stress (GPa)
0.25	2.4
0.5	2.11
0.75	1.72
At Failure	1.23

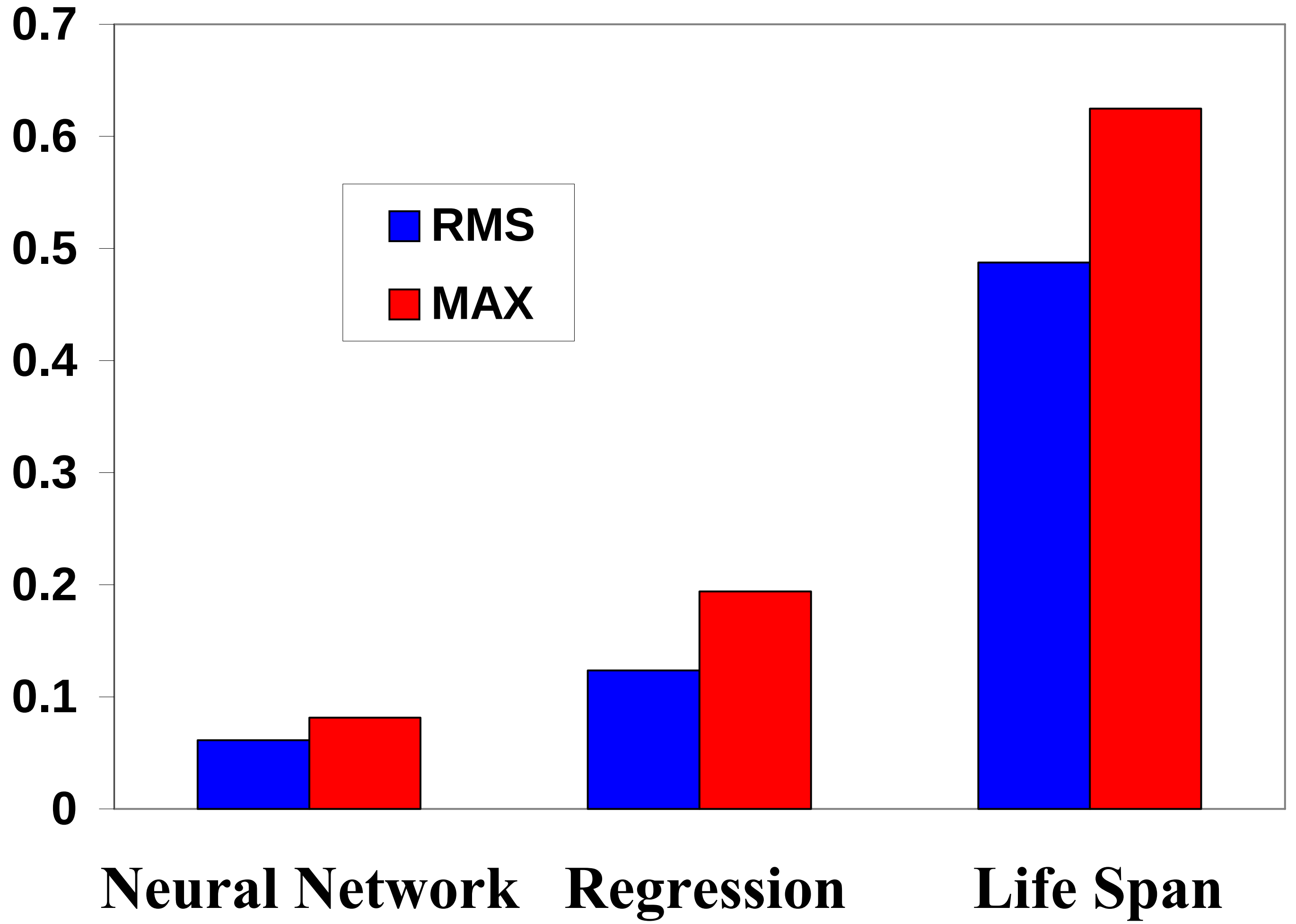
Remaining Life Predictions Versus TBC Life Scatter



Remaining Life Prediction Based on PLPS Data without knowledge of temperature
II. Neural Network Method For Type II

Method II. Stress with Master Curve





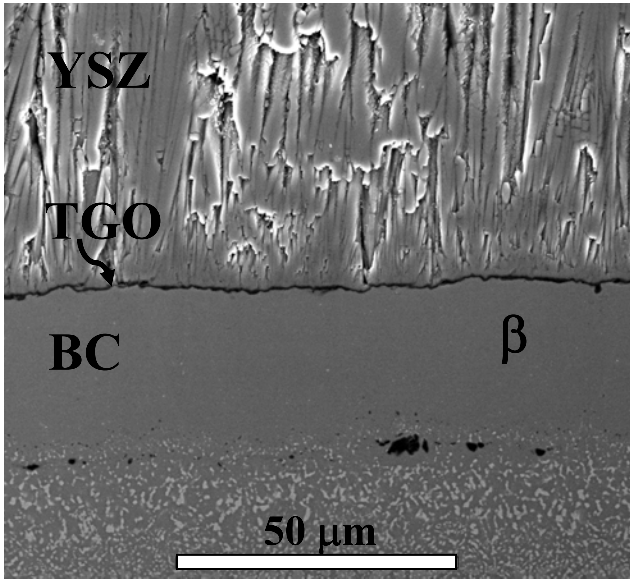
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
RMS
MAX
Neural Network
Regression
Life Span

Type III Had Bimodal

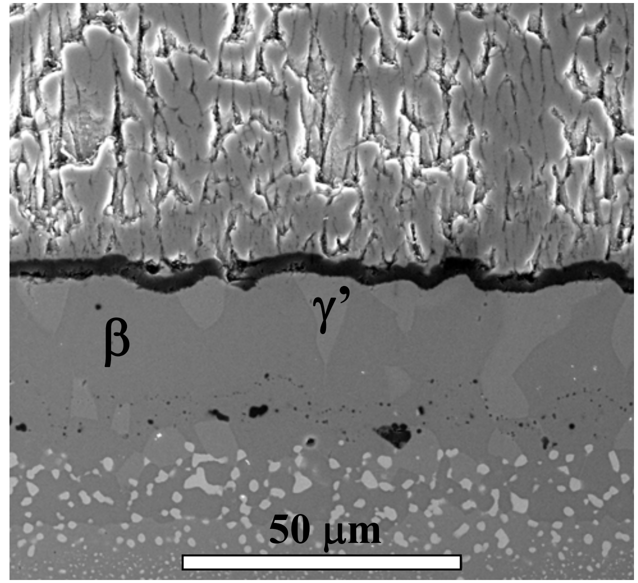
- Bimodal can be mapped and used as a indication that failure is near

Claim: Rumpling Primary Causes of Stress Drop

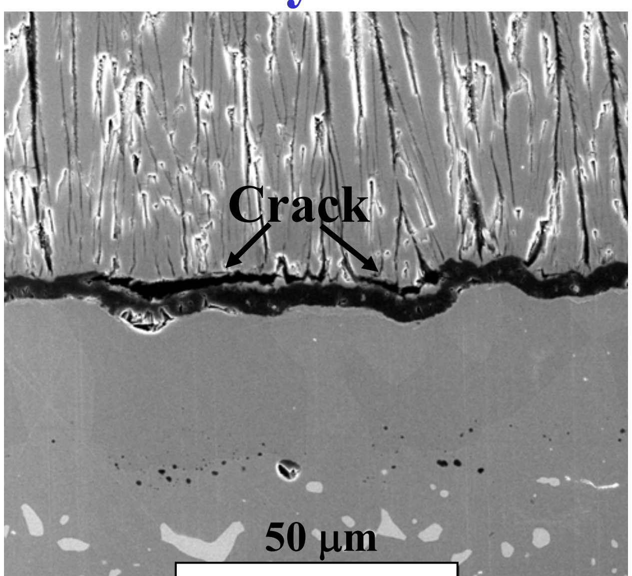
Microstructural Evolution



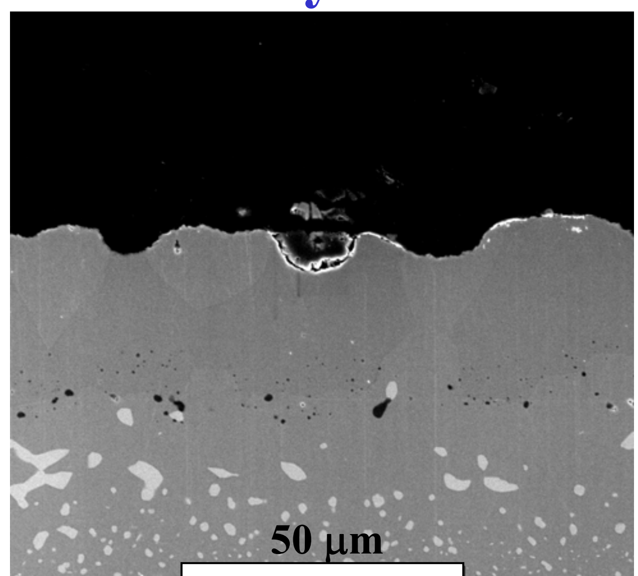
0 cycles



60 cycles



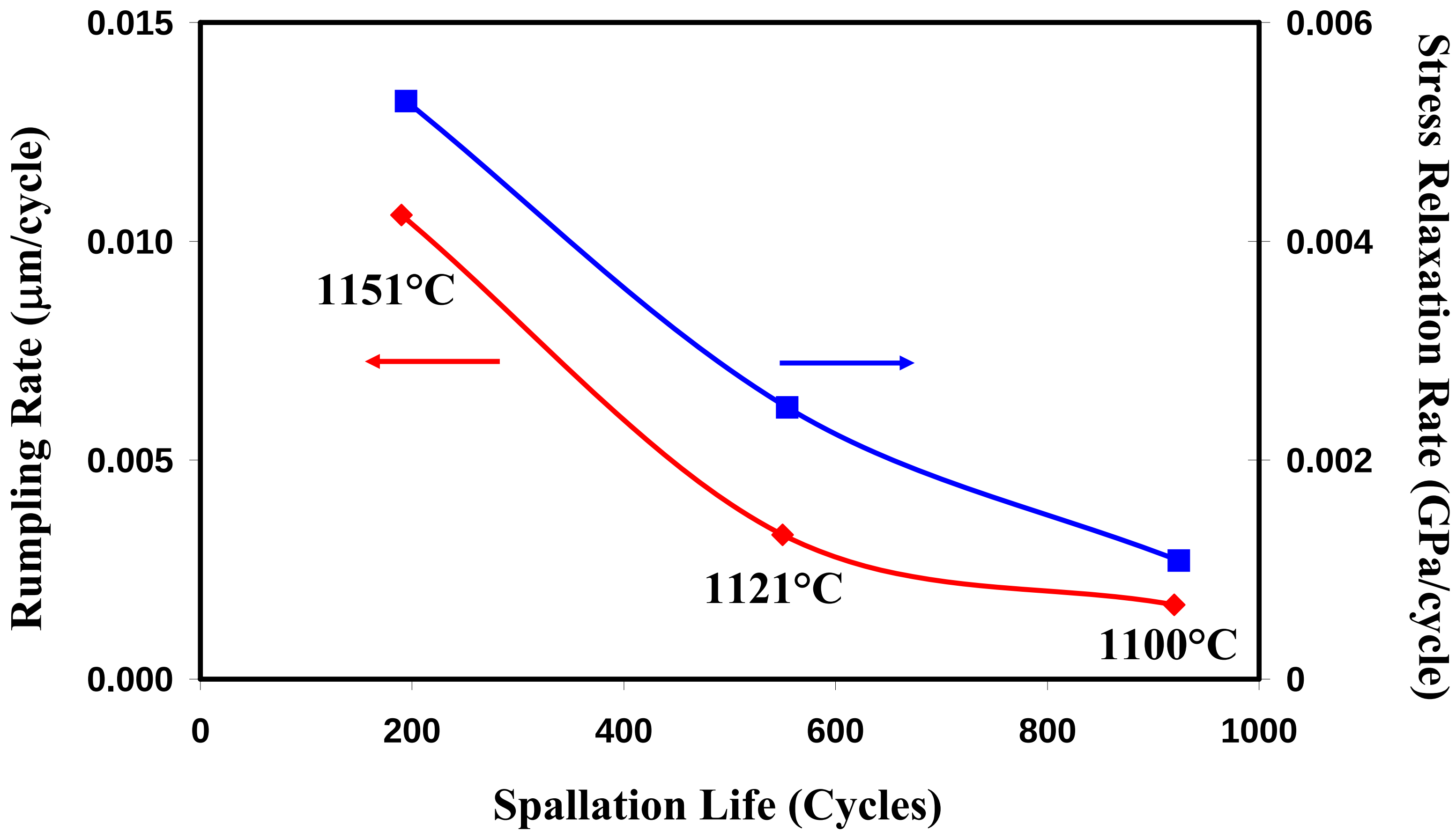
125 cycles



190 cycles

- Interface Rumpling
- TGO Thickening
- β-(Ni,Pt)Al →γ’-Ni_3Al
- Cracking

Relationships Among Life, Rumpling And TGO Stress

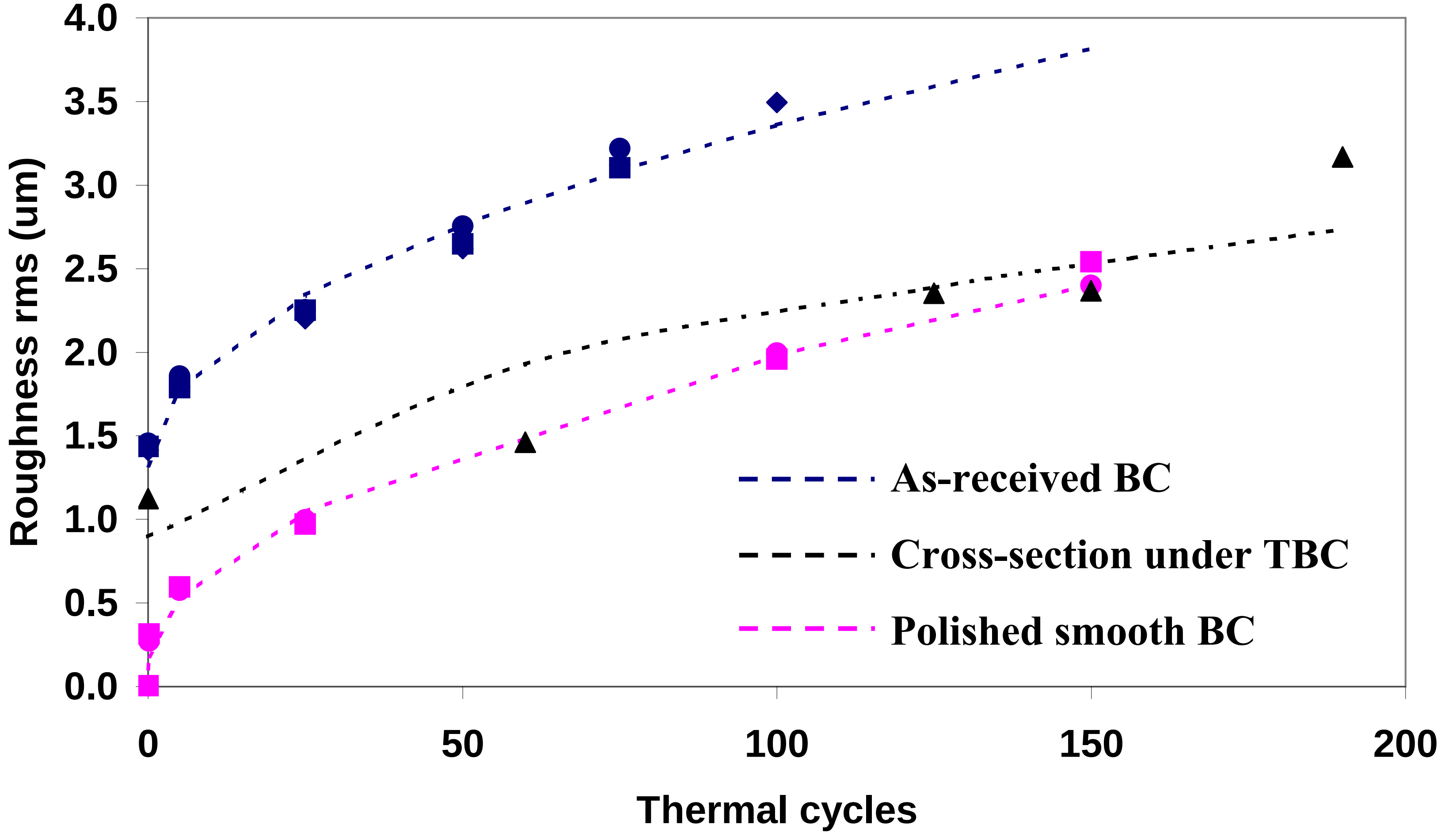


- Life Prediction Is Possible Based on TGO Stress

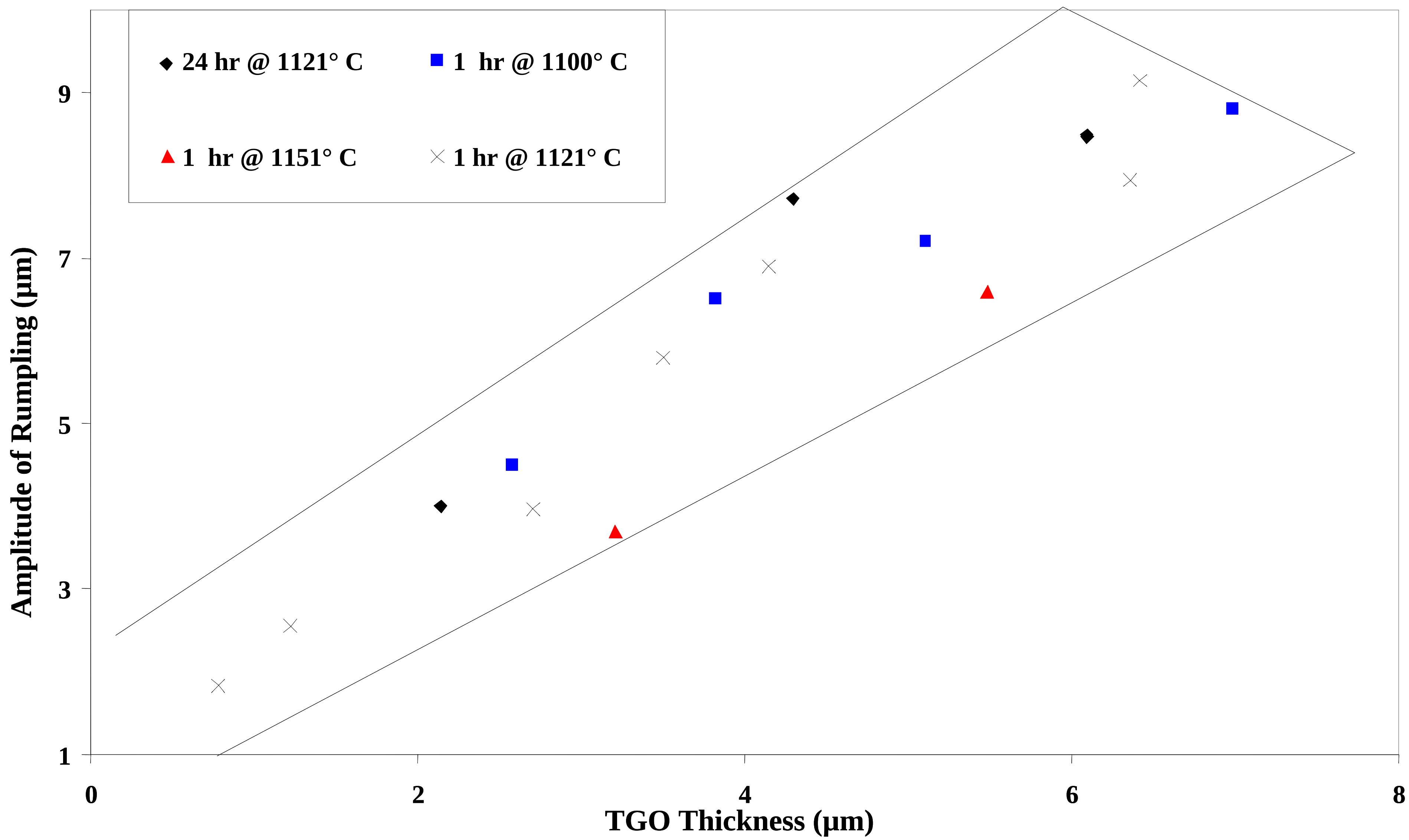
Stress Based NDI has Physical Basis

- Rumpling Causes Stress Drop
- Rumpling causes failure
- Rumpling is important

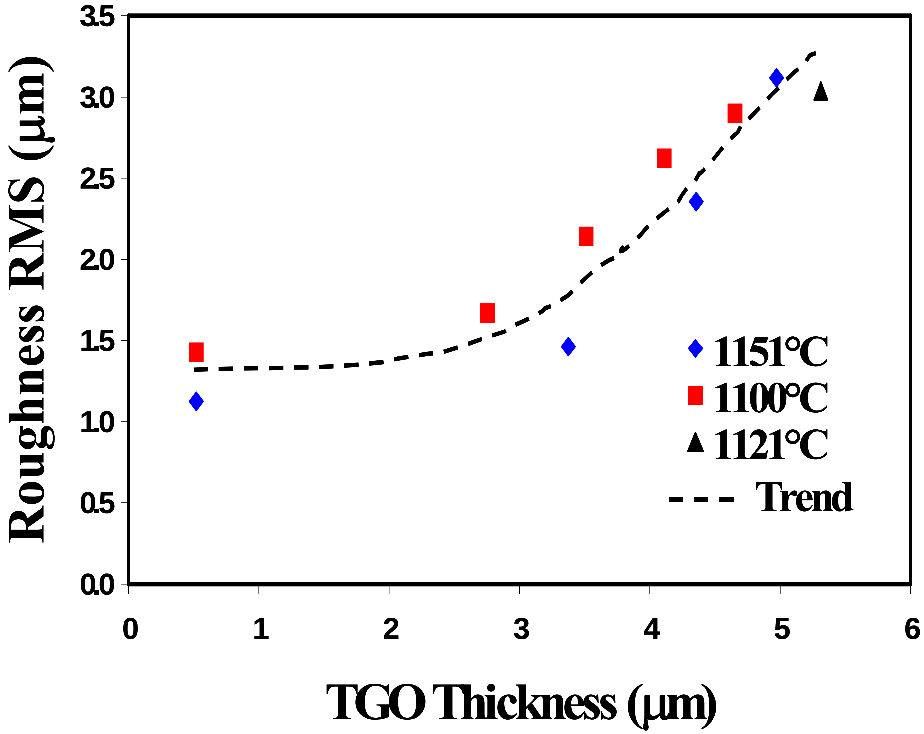
Roughness vs. thermal cycling: Type II

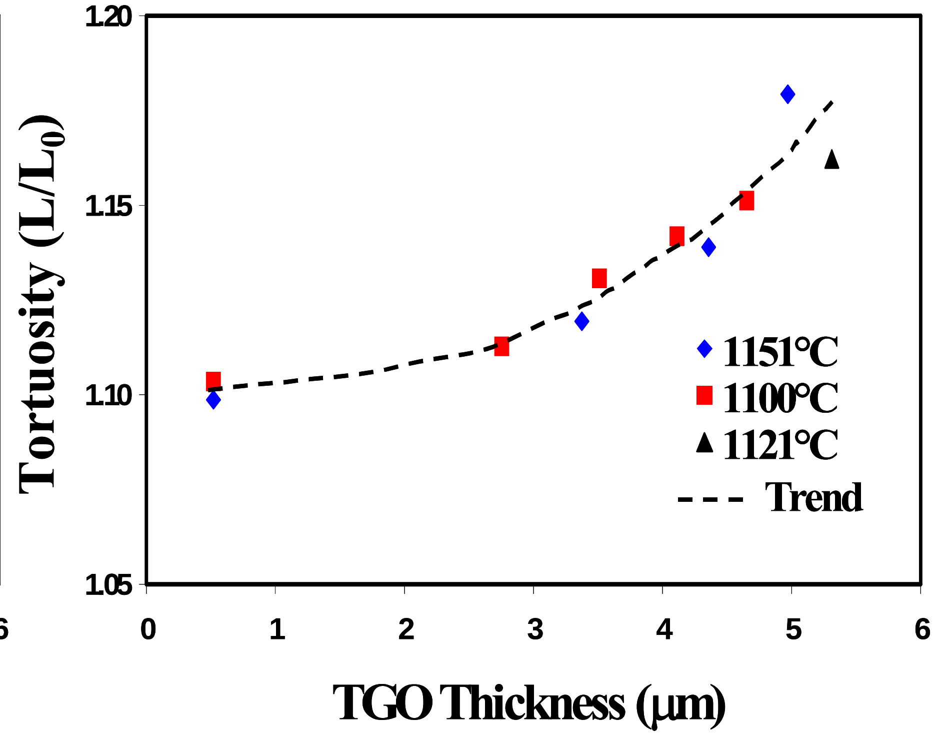


Single Valued Relation Between Rumpling Amplitudes And TGO Thickness Type II



Rumpling Dependence On TGO Growth
Type III

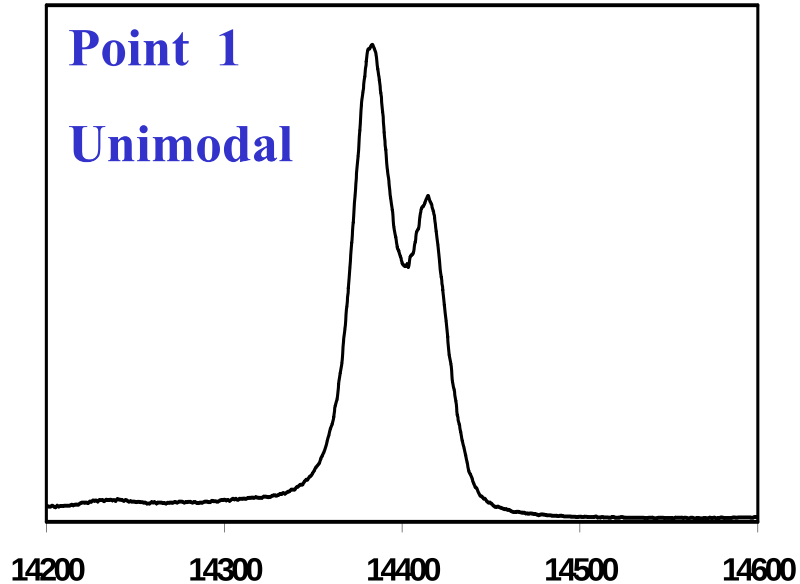


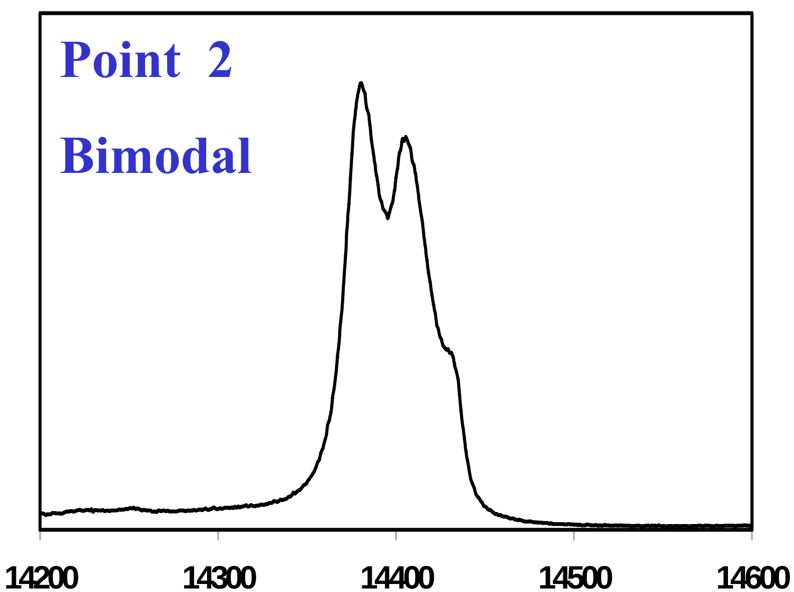


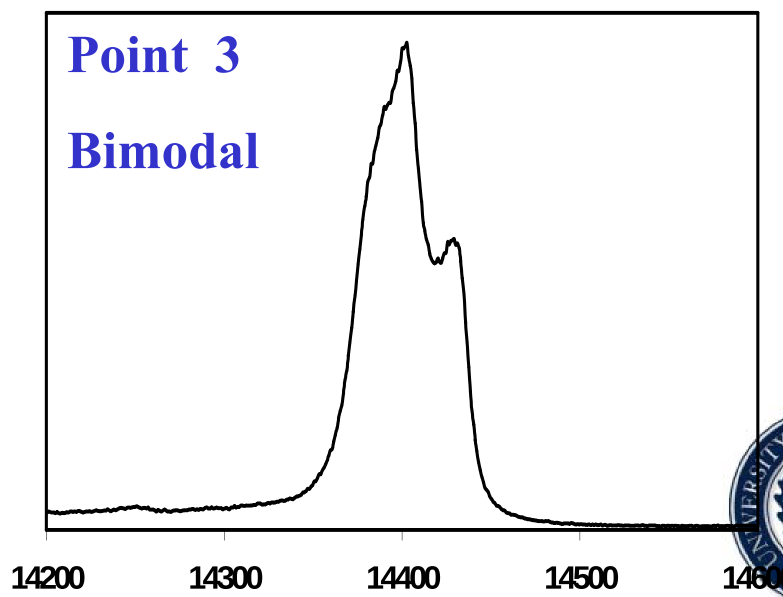
- TGO Growth Controls Rumpling

We have Proved Bimodal Spectra Come from Cracking

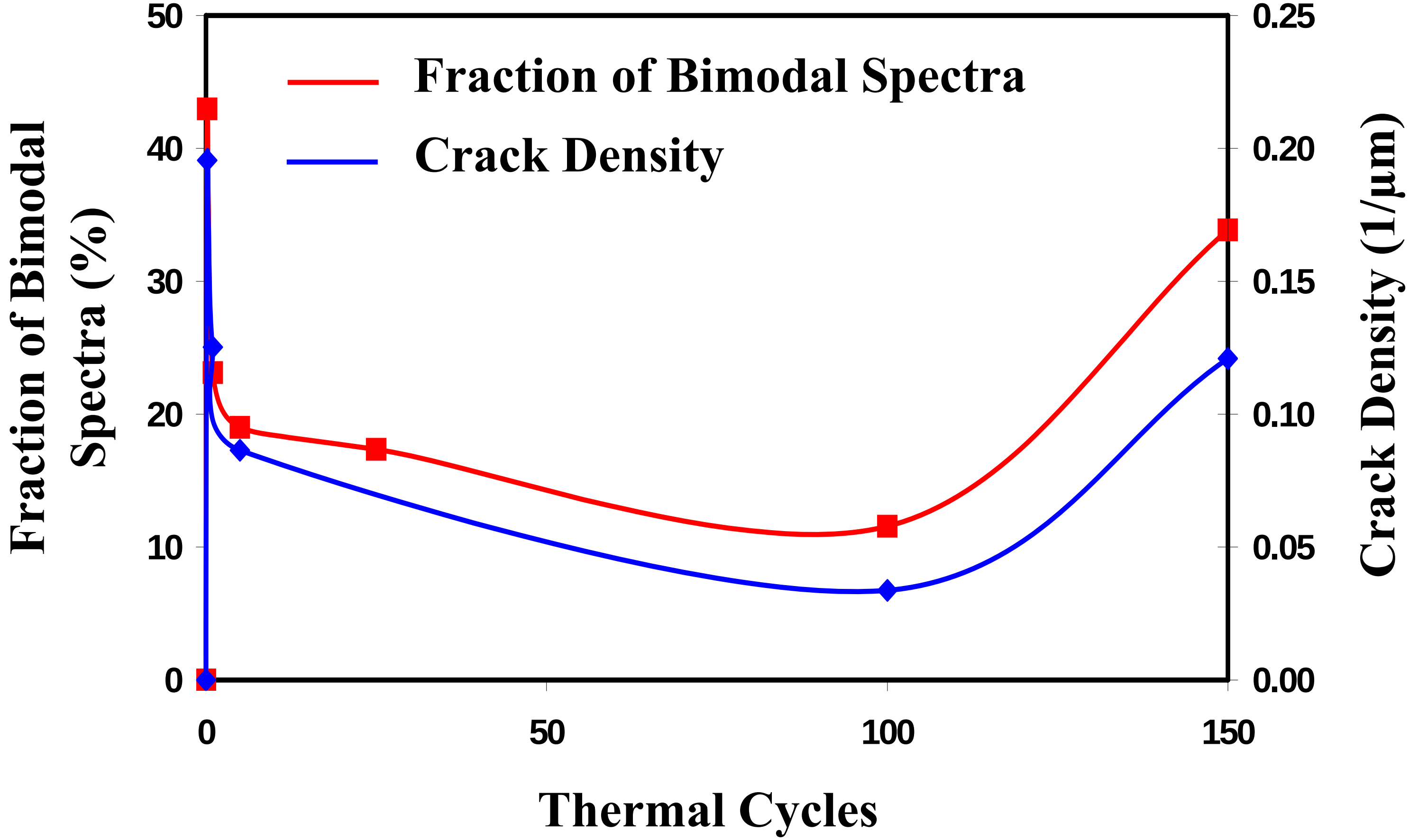
Bimodal Luminescence Related To TGO Cracking





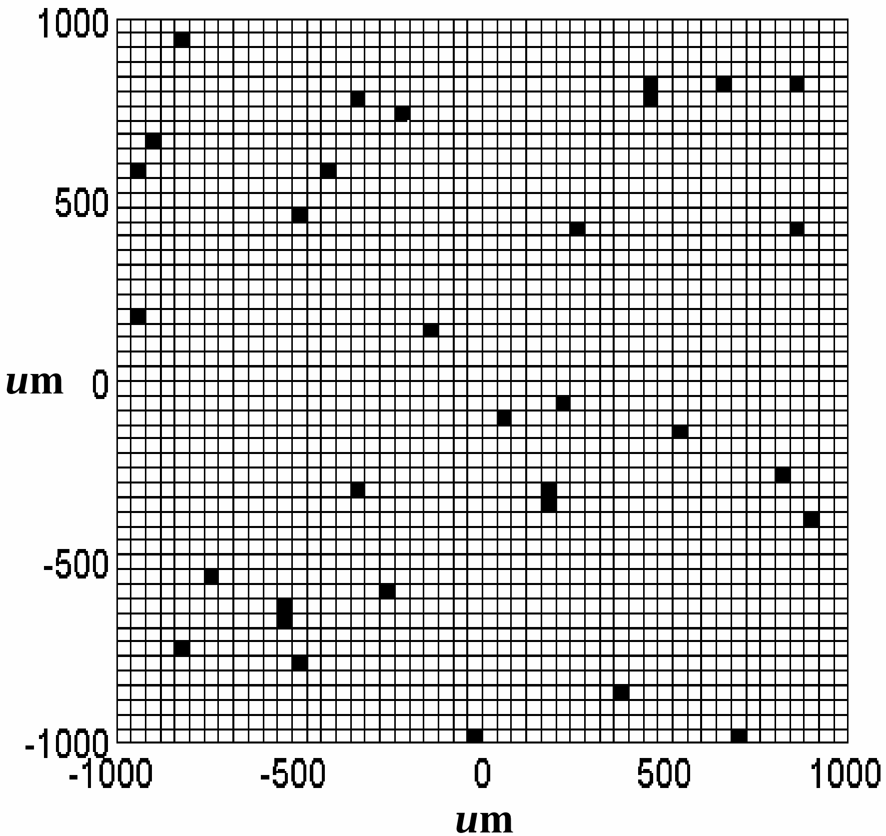


Fraction of Bimodal Spectra and Crack Density

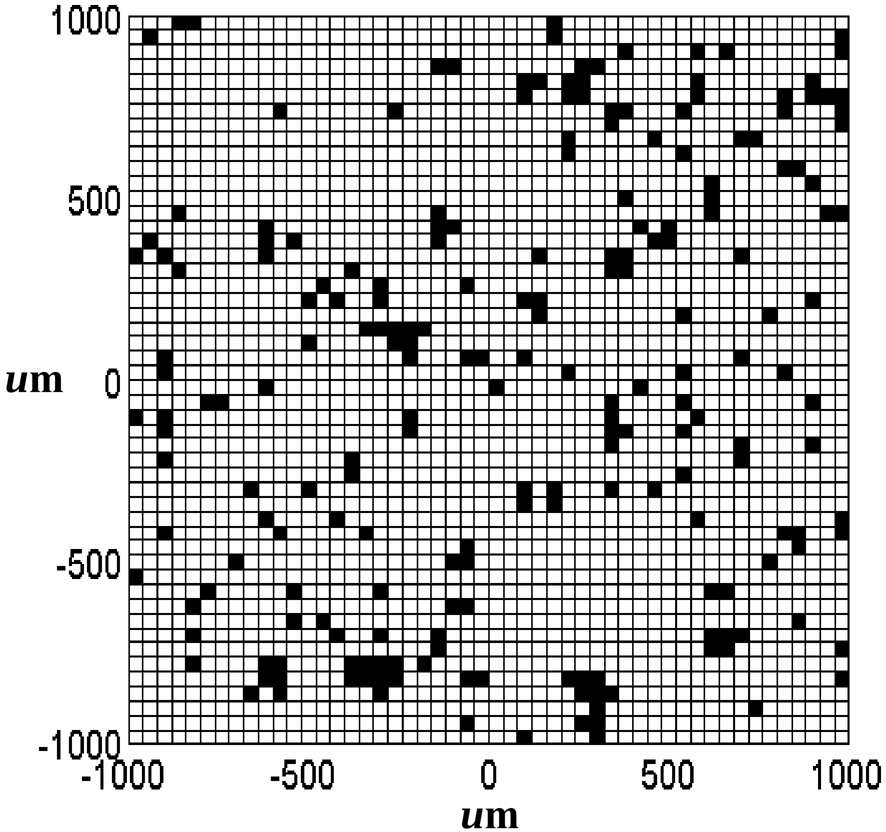


- Fraction of Bimodal Spectra and Crack Density Change in a Similar Manner with Thermal Cycles

Area Mapping – Damage Accumulation



27 cycle



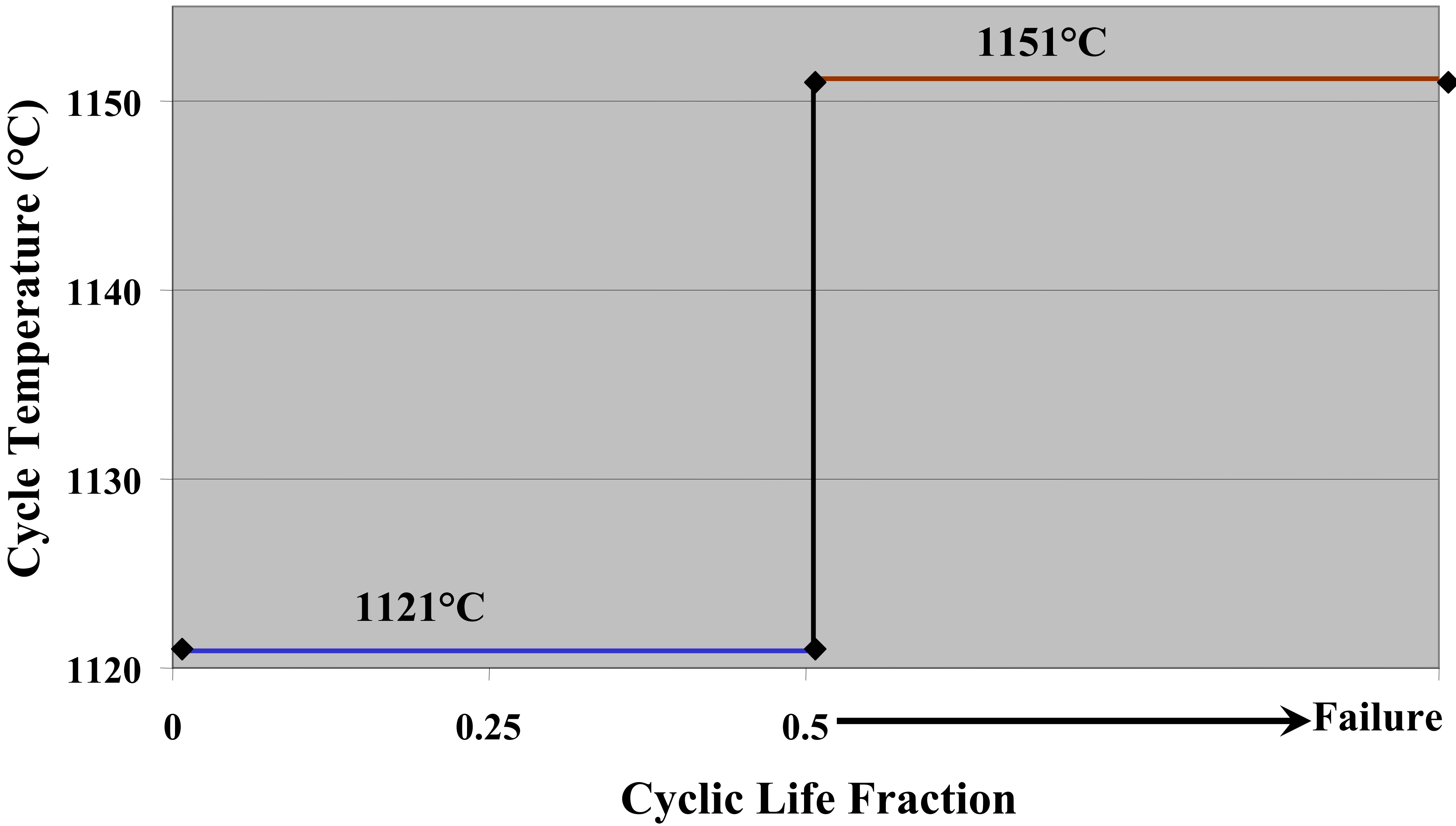
470 cycle

■ Damage (Bi-modal)

□ Intact

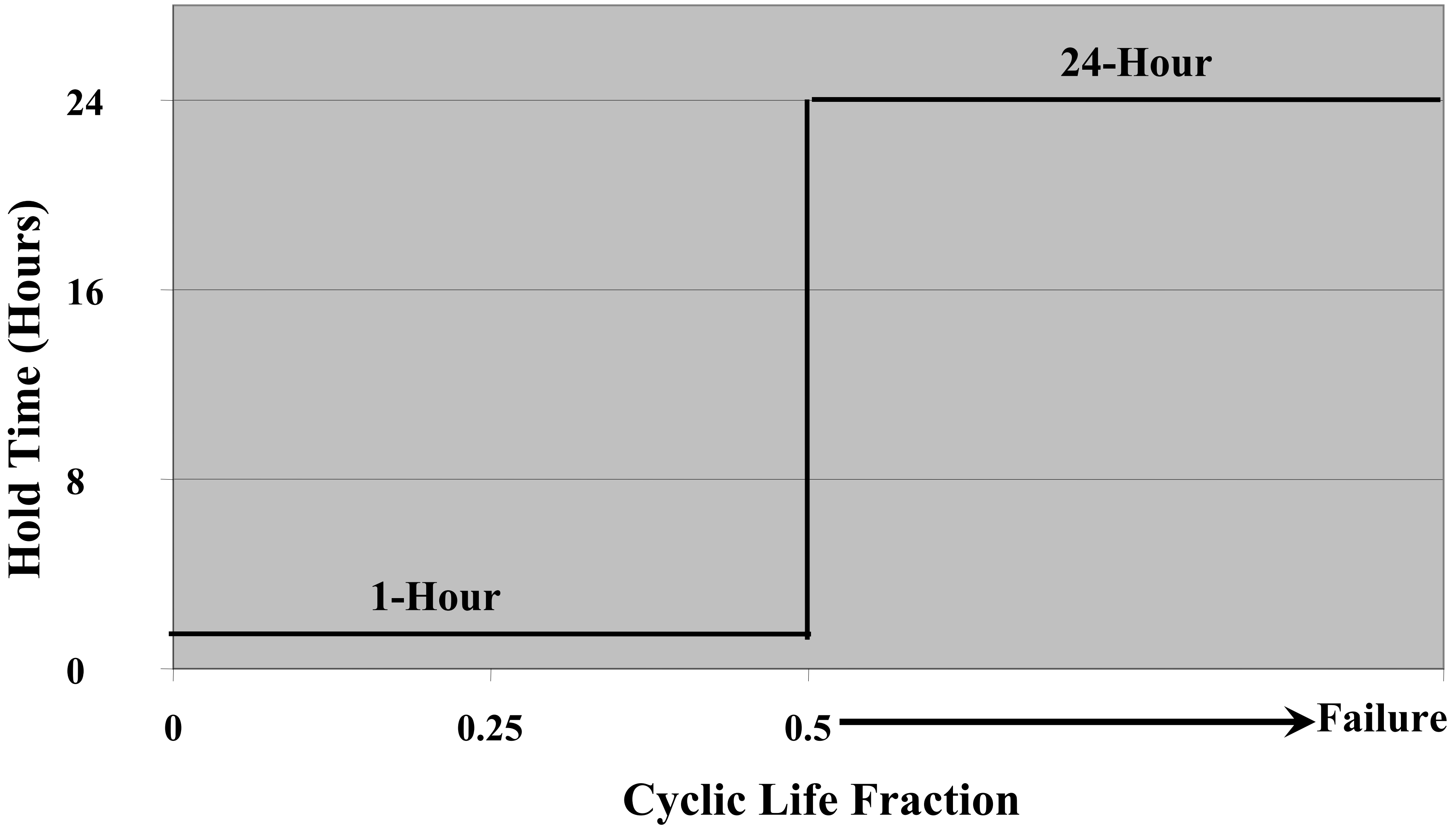
Non-Constant Amplitude Tests

Two Temperature Cyclic Tests



Non-Constant Amplitude Tests

Two Hold Time Cyclic Tests



Linear Damage Example 1121° C followed by 1151° C

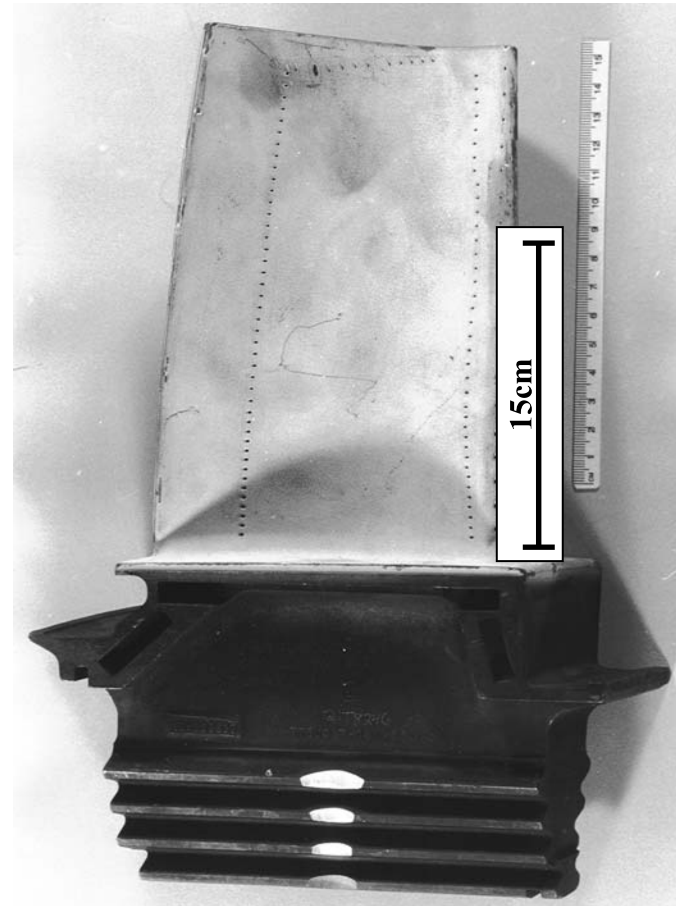
- Failure life at 1121°C N_{f1}=677
- Cycles run n_1= 335
- Life fraction =335/677=0.49
- $N_1/N_{f1}+n_2/N_{f2}=1$
- At 1151°C N_{f2}=358
- Predicted life=0.51*358=

First Ever Sequence Effect Tests

Linear Damage Fractions – Type I TBC

First exposure	→	Second exposure	Linear Damage Sum $= N_1/N_{1f} + N_2/N_{2f}$
1-hour, 1121°C	→	1-hour, 1151°C	1.08
1-hour, 1151°C	→	1-hour, 1121°C	1.10
1-hour, 1121°C	→	24-hour, 1121°C	0.75
24-hour, 1121°C	→	1-hour, 1121°C	0.93

Portable PLPS NDI Instrument Available



ACOMPLISHMENTS

- **An accurate remain life NDI based on TGO Stress measurement**
  - **Showed a direct relation to damage and failure**
- **A new surface metric more related to damage than RMS etc.**
- **Tested the linear damage rule for TBC life prediction for the fist time**
- **Revealed failure mechanisms**

ACOMPLISHMENTS

- **Transferred technology to industry**

- **Two Ph D and two masters ¾ female**
  - **Swetha Sridharan**
  - **Mei Wen**
  - **Jessica Shen**
  - **Manish Madhwal**

Goal Was to Develop Practical Tool

- **We are one year into an industrial contract to apply Stress Measurement Method developed under HEET/AGTSR funding to blade retirement for cause.**

Thank You

Approach

Task I : Specimen Procurement

Task II : (a) Bond Coat Surface Geometry

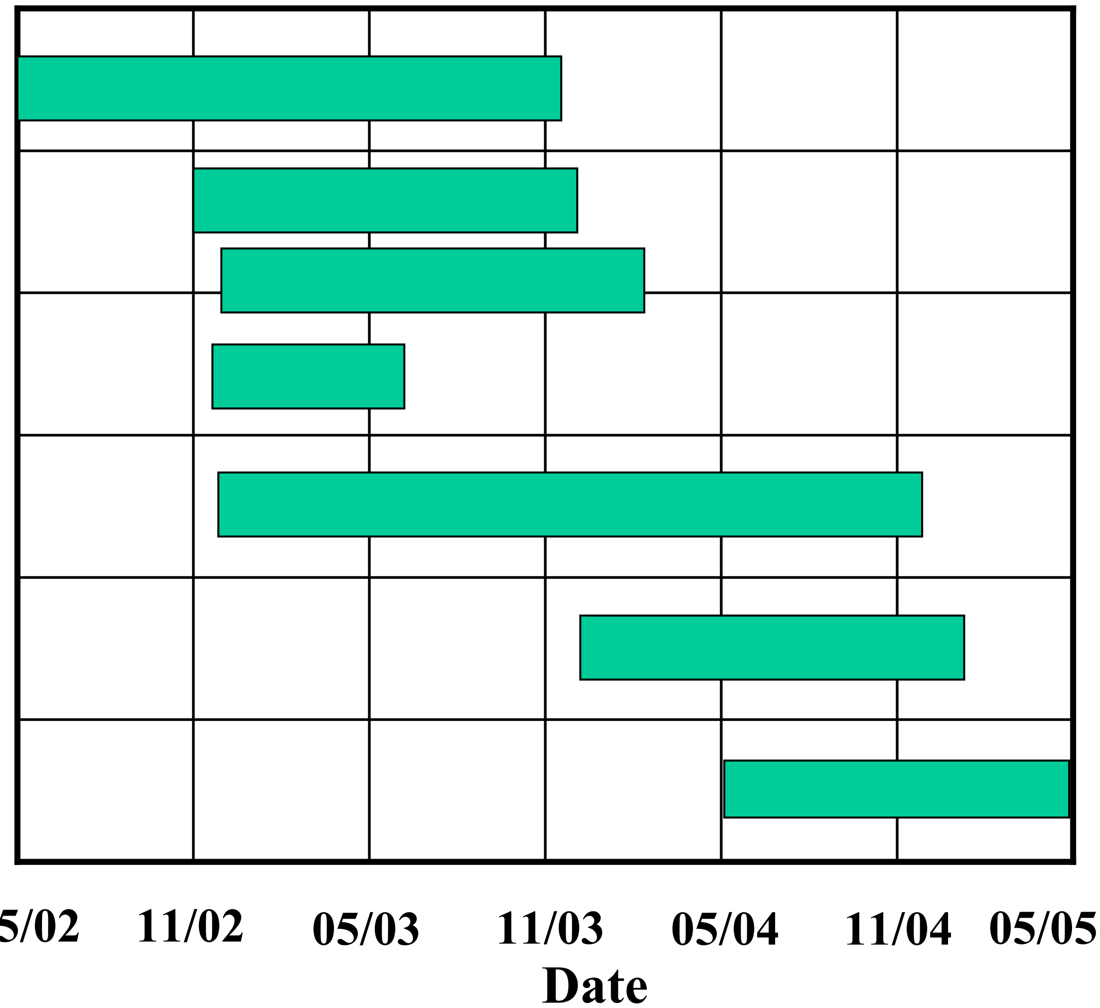
(b) TBC Coating

Task III : Geometric Feature Software Development

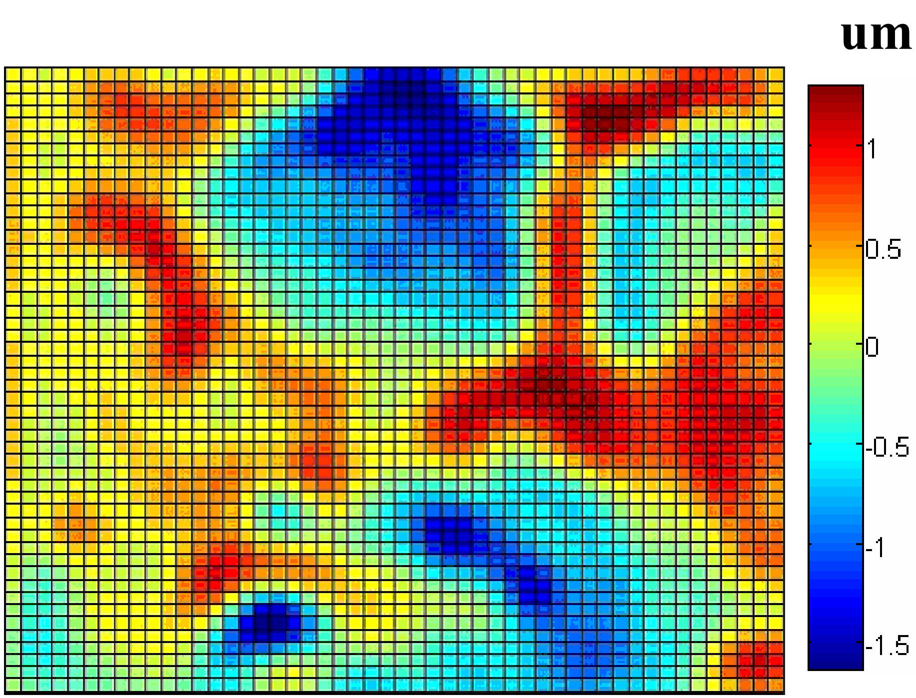
Task IV : Cyclic Furnace Tests

Task V : Measurements of Engine Blades

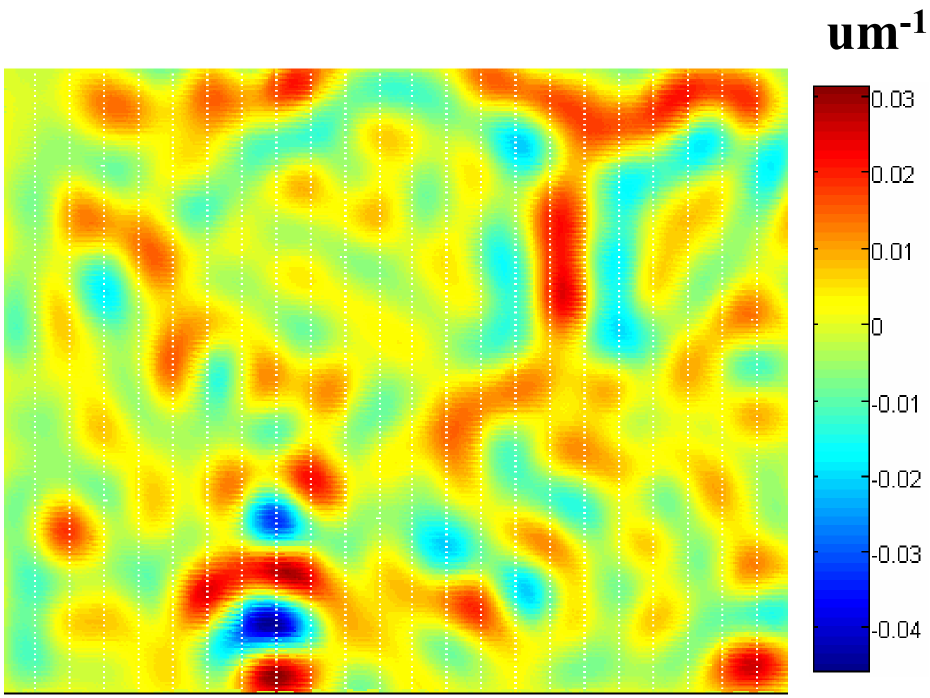
Task VI : Development of Lifetime Prediction Methodology



Mapping of Curvature by MATLAB



Original Surface



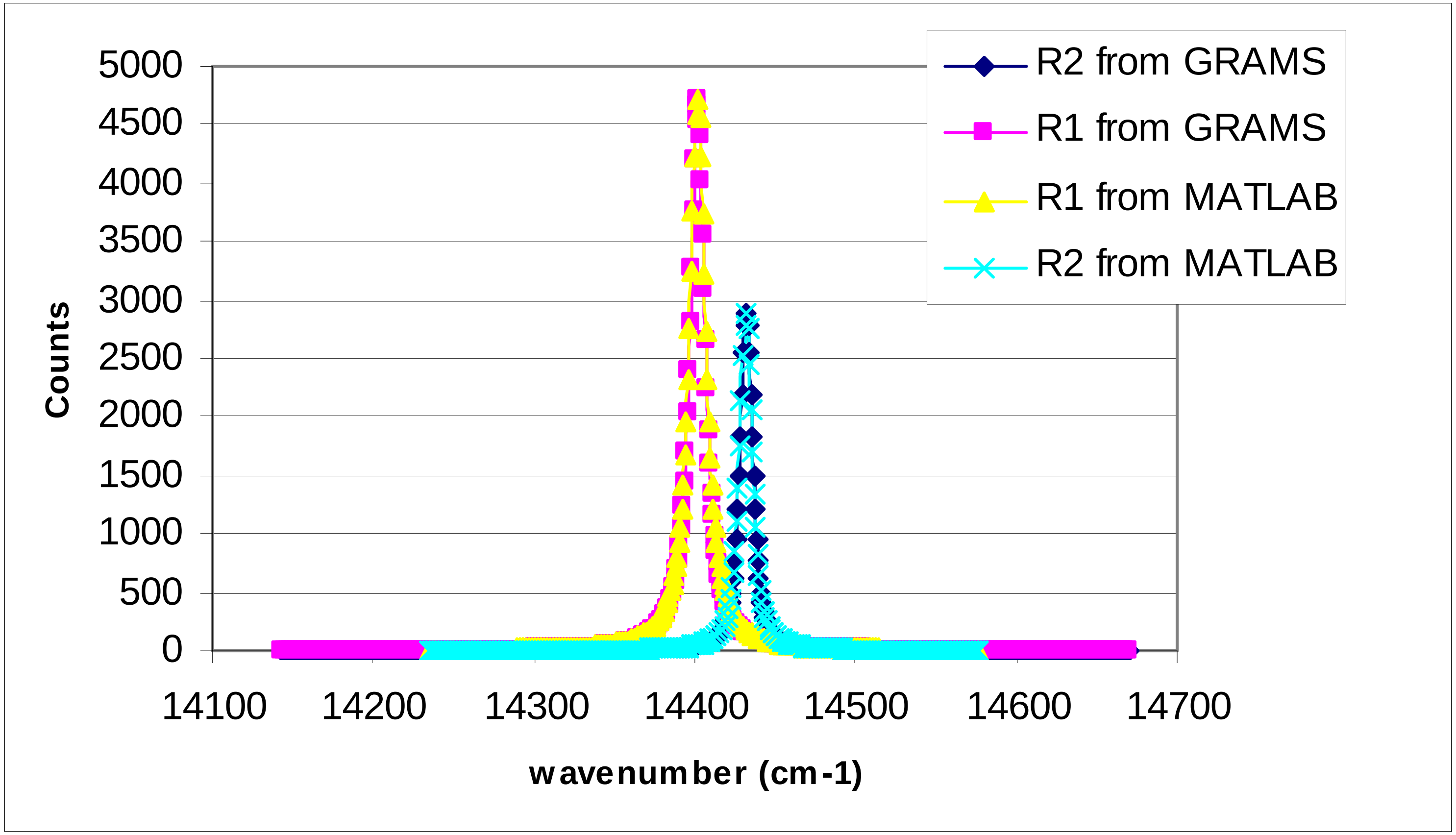
Curvature

Project Objectives

To develop and experimentally validate a method for the nondestructive prediction of remaining life of by measurement of :

- **Initial Surface Geometry**
- **Thermally Grown Oxide (TGO) Stress**
- **TGO Thickness**

Results of Automated Analyzing PLPS Spectra



	L_{R2}	V_{R2}	W_{R2}	H_{R2}	L_{R1}	H_{R1}
Grams	0.7581	14432	9.6300	1.4690e5	0.9898	2.3452e5
Matlab	0.7290	14432	9.7534	1.4617e5	0.9990	2.3492e5

Results of Multi-Temperature Cyclic Tests – 1-hour @ 1121°C Followed By 1-hour @ 1151°C

Exposure Condition	Cycled To		Average Failure Life		Linear Damage Fraction	
	# Cycles	Hot Time (Hours)	# Cycles	Hot Time (Hours)	Based on Cycles	Based On Hot Time (Hours)
1-hour @ 1121°C	335	251	**677** ± 55	**508**	**0.49**	**0.49**
	335	251			**0.49**	**0.49**
1-hour @ 1151°C	205 (Failed)	154	**358** ± 65	**269**	**0.57**	**0.57**
	225 (Failed)	169			**0.63**	**0.63**
	Total = 356 Cycles	**Total = 520 Hours**			**Total = 1.06**	**Total = 1.12**