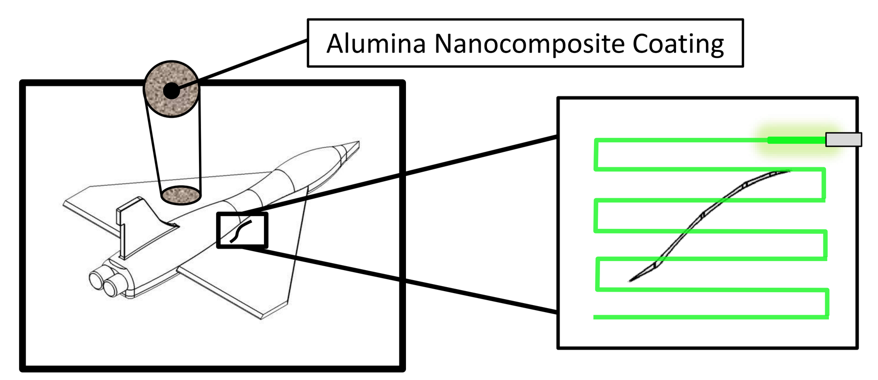
Alumina Particulate-Epoxy Composite Mechanics via Piezospectroscopy

Imad Hanhan, Joseangel Rosas, Any Lai, Erik Durnberg, Ashley Jones, Gregory Freihofer, Seetha Raghavan

Mechanical and Aerospace Engineering, College of Engineering and Computer Science, University of Central Florida, Orlando, FL 32816, USA

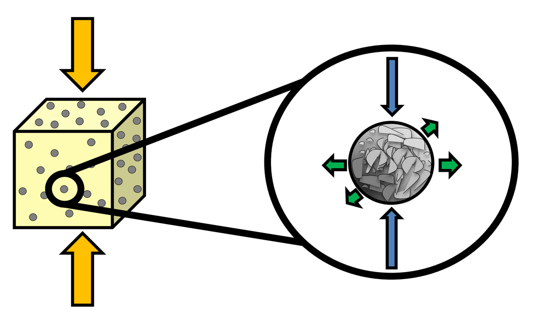
INTRODUCTION & MOTIVATION

Nanoparticles embedded within a matrix have the capability of improving a wide variety of mechanical properties. Alumina-based nanocomposites have the ability to provide intrinsic characteristics of this enhancement through the stress-sensitivity of photo-luminescent emissions.



Damaged zone on an Aerospace structure coated with an alumina nanocomposite

Scan pattern to identify stress concentrations using Piezospectroscopy



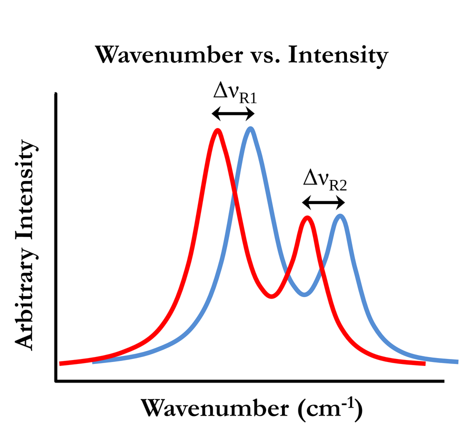
There are a number of theoretical models that have steered both the understanding of load transfer between a matrix and a particle, and the effect of strain rate.

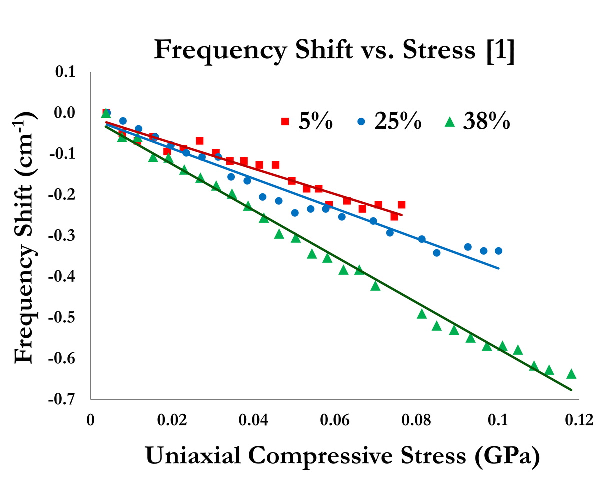
OBJECTIVES

- Study Al_2O_3 particulate mechanics with piezospectroscopy.
- Establish particle-matrix load transfer characteristics under varying parameters including volume fraction and strain rate.

PIEZOSPECTROSCOPY

Piezospectroscopy is the method of monitoring the optical spectrum of a photo-luminescent material and correlating spectral peak shifts to stress through the PS coefficient. Once excited with a laser source, alumina emits an optical spectra consisting of distinct stress-sensitive peaks, R1 and R2, due to its naturally occurring Chromium ion (Cr^{3+}) impurity. By monitoring the resulting spectral peak shifts of R1 and R2, particle stress can be determined.

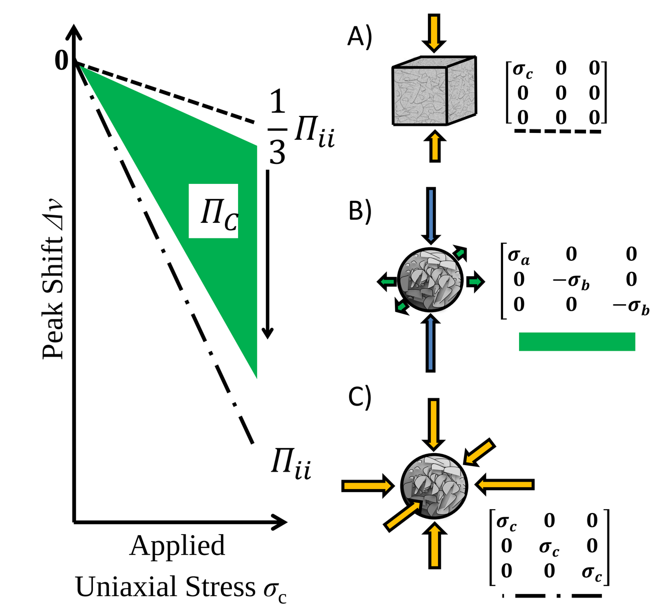




Our previous work showed that by embedding alumina nanoparticles within an epoxy matrix, the piezospectroscopic sensitivity to applied stress on the nanocomposite could be tuned with respect to particle volume fraction [1].

LOAD TRANSFER THEORY

Theoretical-Experimental Relationship



Stress Ratio in terms of PS coefficient

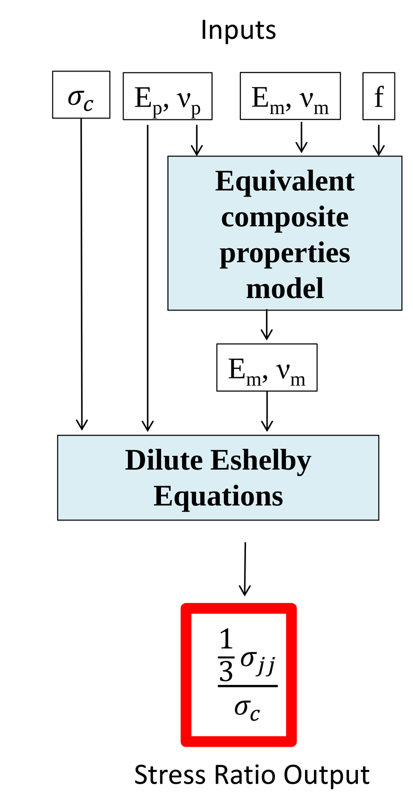
$$\Delta\nu_P = \Delta\nu_{NC}$$
$$\Delta\nu_{NC} = \Pi_{NC}\Delta\sigma_A$$
$$\Delta\nu_P = \Pi_P\Delta\sigma_H$$
$$\Pi_P\Delta\sigma_H = \Pi_{NC}\Delta\sigma_A$$
$$\frac{\Delta\sigma_H}{\Delta\sigma_A} = \frac{\Pi_{NC}}{\Pi_P}$$

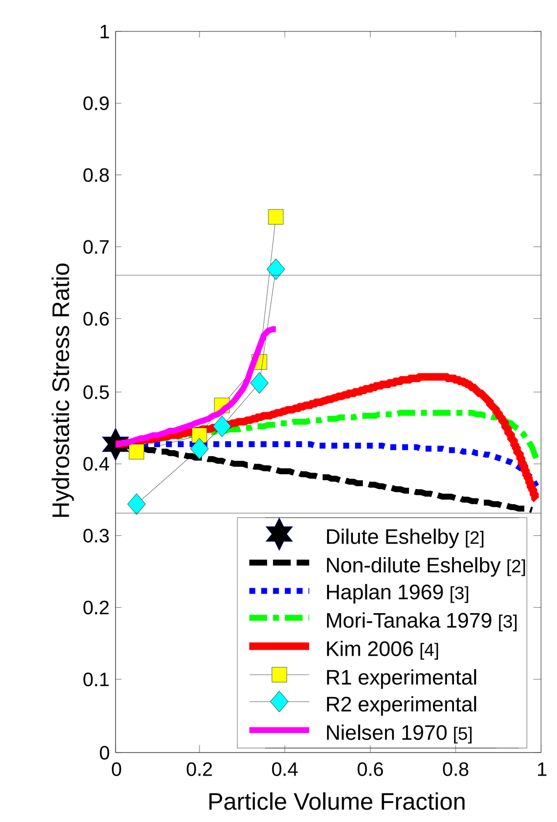
It is known that

$$\Pi_P(R1) = -7.59\,\frac{cm^{-1}}{GPa}\ [2]$$

Compared to pure alumina in perfect axial loading (A) and alumina in perfect hydrostatic loading (C), alumina nanoparticles in composites experience mixed loading conditions (B) characterized by their PS coefficients.

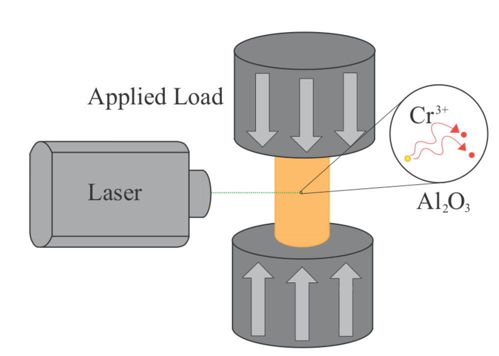
Theoretical Models





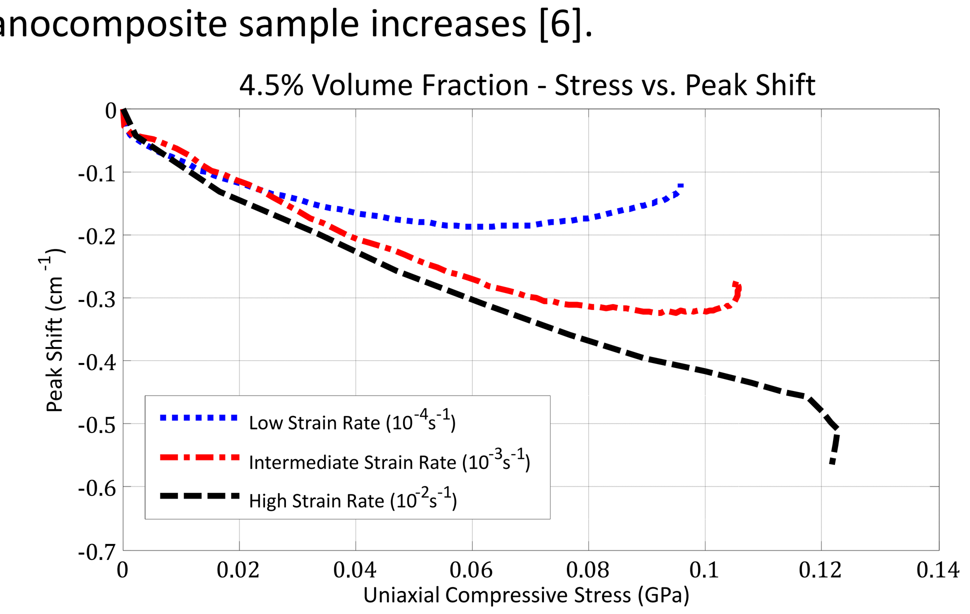
RESULTS OF PIEZOSPECTROSCOPIC RESPONSE

NANOCOMPOSITE STRAIN RATE EFFECT



The experimental set up contains a load frame which places the sample in compression, while PL data is collected by utilizing a laser excitation source.

Varying strain rates resulted in varying load transfer from the matrix into the nanoparticles. As the strain rate (10^{-2} s^{-1}, 10^{-3} s^{-1}, and 10^{-4} s^{-1}) increases, the ultimate strength of a nanocomposite sample increases [6].



- All 3 sensitivities look to be similar at low stress and start to differ during the failure regime.
- Increase in stress transferred to the nanoparticle with increase in strain rate in the failure regime.
- Normal load transfer mechanics can be seen in the failure regime of the lower strain rates as the material shows a softening effect, where there can be de-bonding and micro cracking taking away stress concentrations on the nanoparticles.
- The higher strain rate shows a hardening effect in the failure regime.

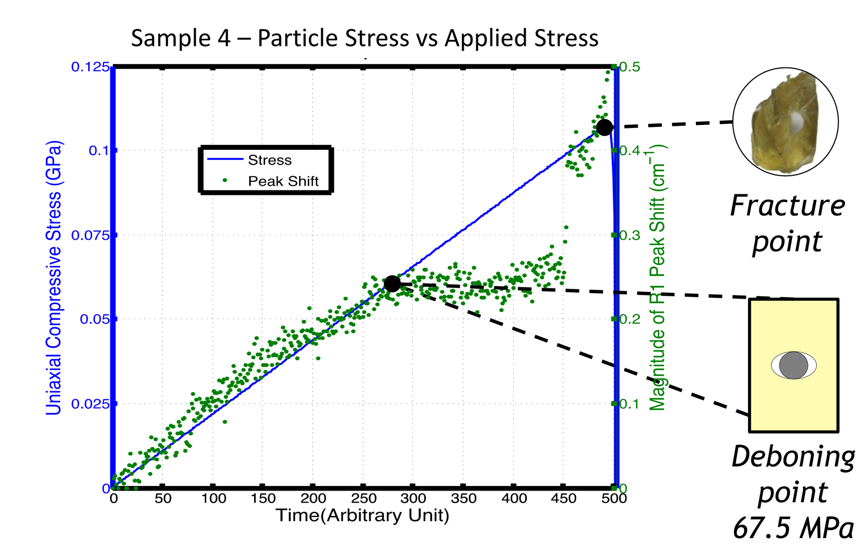
ISOLATED PARTICLE LOAD TRANSFER RESULTS

To better understand particulate load transfer, a macro-scale analysis of single particle composites, on the millimeter scale, was conducted.

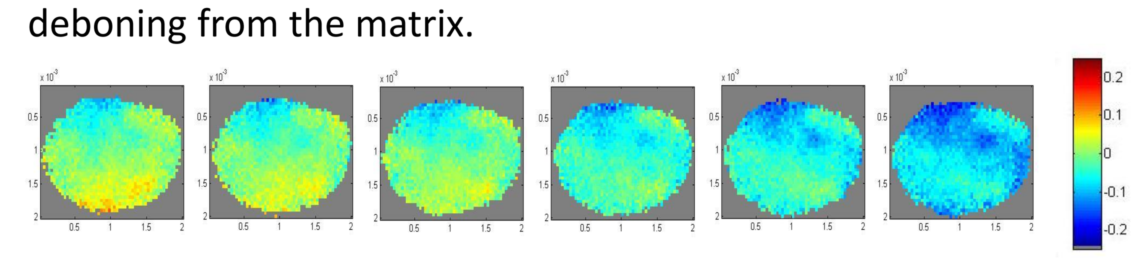
Sample Number	R1 PS Coefficient (cm^{-1}/GPa)	R2 PS Coefficient (cm^{-1}/GPa)
1	-4.279	-3.966
2	-4.541	-4.208
3*	-3.463	-2.975
4	-4.622	-4.349
5*	-1.973	-3.187
6	-4.807	-4.456

* Outlying samples not used in calculations.

Experimental values lead to an R1 PS coefficient of **-4.56 ± 0.21 cm^{-1}/Gpa.** This indicates that the particle is sustaining a stress ratio of **0.60** [7].



All isolated particle results follow the trend above in which the particle sustains load up to a certain point, and then maintains a constant peak position. This could be due to the particle debonding from the matrix.

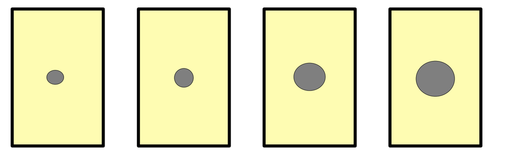


By conducting a photo-luminescent map of the single particle as the force is increased on the matrix, it was found that the stress distribution on the particle is non-uniform, which is not accounted for by the theoretical models.

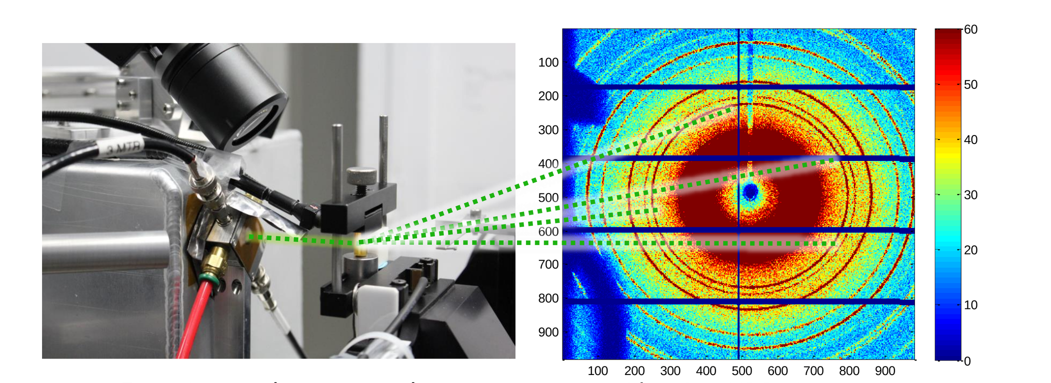
FUTURE WORK

Future work includes the analysis of X-Ray diffraction results from experiments conducted at the Canadian Light Source X-Ray Synchrotron Facility. X-Ray diffraction was chosen due to its ability to measure stress *through* the particle, as opposed to photo-luminescence which is a surface measurement.

These experiments included samples with varying Al_2O_3 particle sizes to analyze particle size effect and compare to volume fraction effect.



A manually-actuated load frame was used to apply force to the epoxy matrix, and a load cell was used to collect force data. As a force is held on the matrix, the x-ray synchrotron beam produces XRD rings which are strain sensitive. The ring distortion can be measured and related to strain.



Experimental set-up at the Canadian Light Source

Alumina XRD rings

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[7] Erik Durnberg, Imad Hanhan, Gregory Freihofer, and Seetha Raghavan, “Experimental Piezospectroscopic Measurements To Study Load Transfer in a Single Alumina Particle Embedded Within an Epoxy Matrix,” Proceeding of the Society for the Advancement of Material and Process Engineering 2014 conference, 2-5 June 2014, Seattle, WA.

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