Thermoelectric Mechanical Reliability

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Overview

Timeline

- Project start: October 2006
- Project end date: March 2012
- Percent complete: 45%

Budget

- Total project funding
  - DOE: 100% pre Mar 2009
  - DOE: 67% post Mar 2009
  - Marlow (CRADA): 33% post Mar09
- FY08: $300k
- FY09: $300k

Barriers

- Barriers addressed
  - TE materials are inherently brittle and susceptible to thermal-induced fracture
  - Thermomechanical stresses must be managed and TE material strength improved to fully exploit TE devices
- Targets*
  - 5000h life or 10 yr or 150k mile lifetime
  - Brittle bulk materials must survive thermal and mechanical stresses for life

Partners

- Marlow Industries
- General Motors
- Michigan State University

* "A Science-Based Approach to Development of Thermoelectric Materials for Transportation Applications, Office of FreedomCAR and Vehicle Technologies, August 8, 2007.

Objectives

- **Measure needed thermomechanical and thermophysical properties of candidate TE materials considered for waste heat recovery and cooling applications in vehicular applications.**

- **Combine measured data with established probabilistic reliability and design models to optimally design automotive and heavy vehicle TE devices for heat recovery and cooling.**

Milestones

- **FY08: Generate thermomechanical property database on a candidate p- and n-type thermoelectric materials that will be used to model and predict probabilistic reliability of a TE device.**

- **FY09: Generate thermoelastic and mechanical property database as a function of temperature on at least one candidate high-temperature-capable p- and n-type material.**

Technical Approach

- Measure elastic modulus, Poisson's ratio, strength, coefficient of thermal expansion, heat capacity, thermal conductivity as a function of temperature in candidate TE materials. Compare properties against those of mature TE materials.

- Execute finite element analysis (FEA) to model thermomechanical stresses in TE materials and TE devices.

- Enable confident design of high-temperature-capable TE devices.

Technical Accomplishments – 1 of 13

Overview of FY08 results

- Established a strength database for a reference TE material usable for future comparisons to new, higher-temperature-capable TEs
- Studied fracture in a reference TE material (Bi_2Te_3)
- Examined the roles of several independent parameters on strength
  - N- versus P-type
  - Orientation (transverse isotropy)
  - Temperature
  - What is the potential (i.e., the volume or bulk) strength?
- Measured thermal conductivity, CTE, E, and Poisson's ratio of a reference TE material (Bi_2Te_3)

Technical Accomplishments – 2 of 13

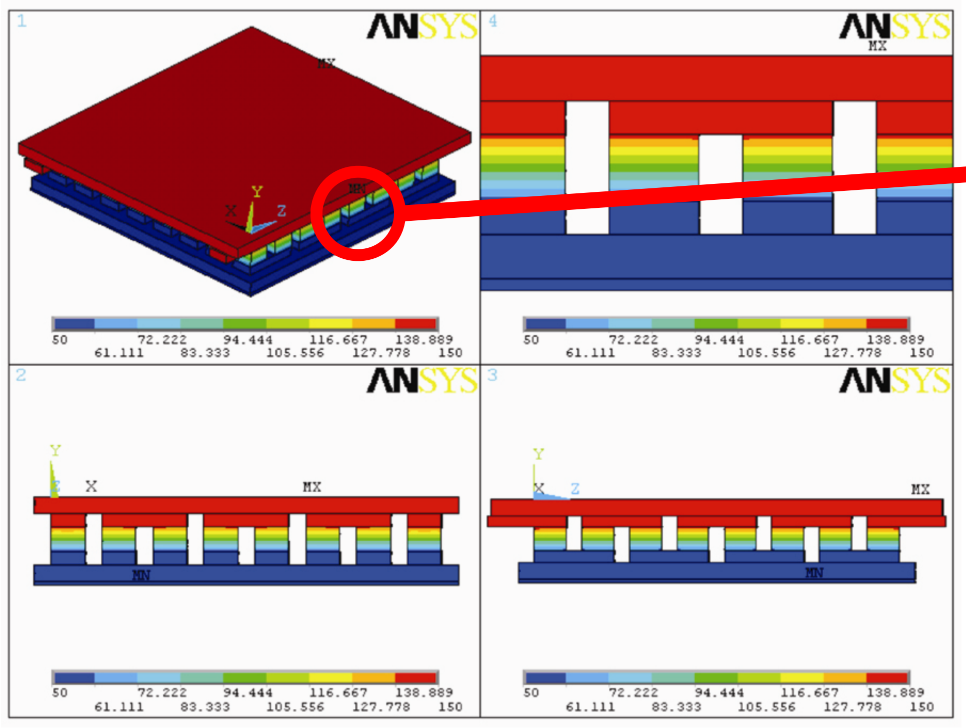
Why is mechanical strength important to TE materials?

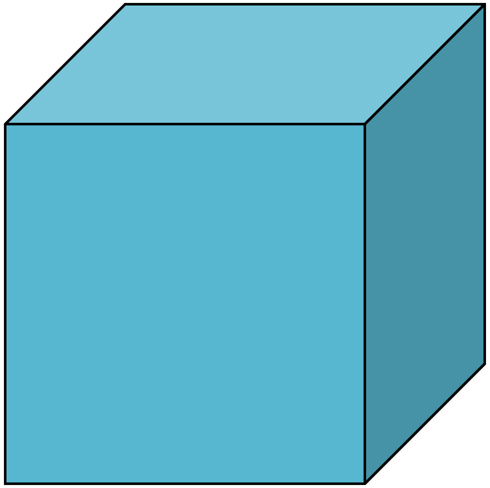
$$R_{Therm} = \frac{S_{Tens}(1-\nu)\kappa}{\alpha E}$$

R_{Therm}	=	Thermal resistance parameter (the larger the better)
S_{Tens}	=	Strength (tensile)
ν	=	Poisson's ratio
κ	=	Thermal conductivity
α	=	Coefficient of thermal expansion
E	=	Elastic modulus

Kingery, J. Am. Cer. Soc., 38:3-15 (1955).

TE legs and potentially active flaws:





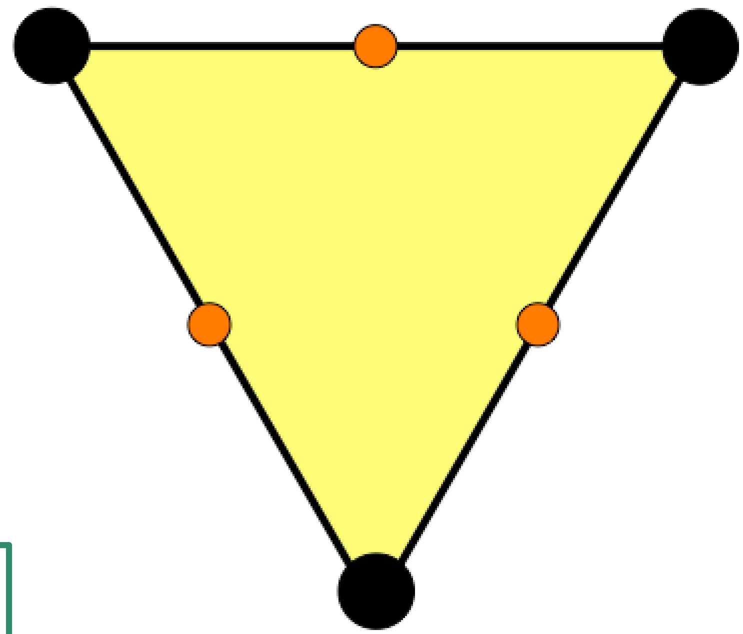
- **Legs ➔ prisms**
- **Volume-, surface-, and edge-located strength-limiting flaws all possibly active**
- **e.g., 3 x 3 x 3 mm**

Technical Accomplishments – 4 of 13

Strength-limiting flaw classification for brittle materials

Volume Type
(3-Dimensional)

Pores
Porous Regions
Large Grains
Agglomerates
Inclusions



Surface Type
(2-Dimensional)

Machining Damage
Pitting
Handling Damage
Chemical RXN Product
Oxidation

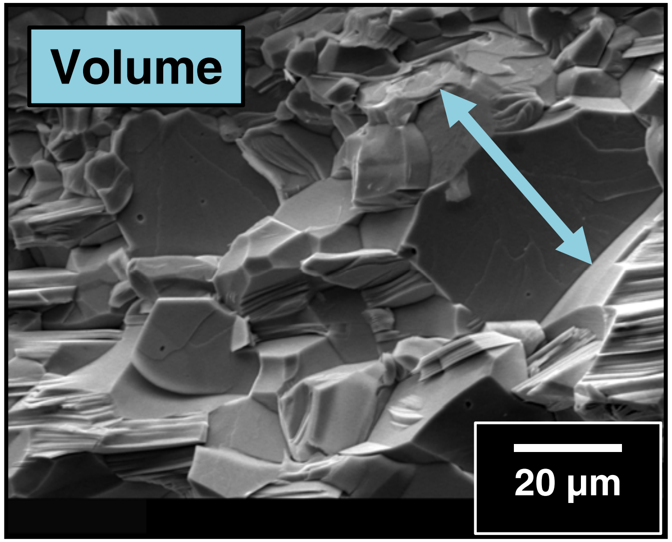
Edge Type
(1-Dimensional)

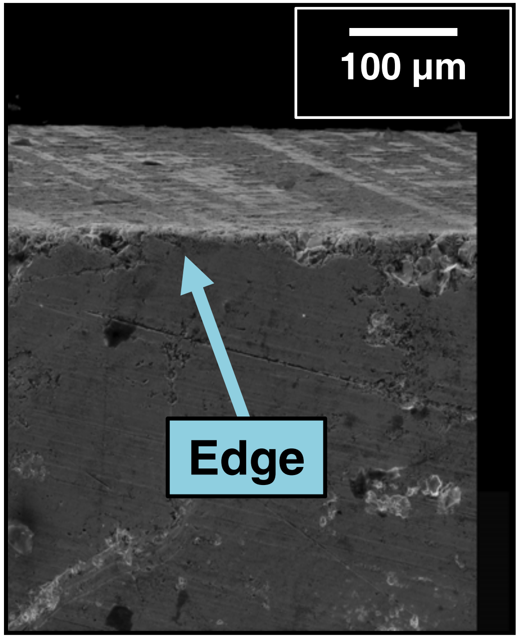
Edge chipping

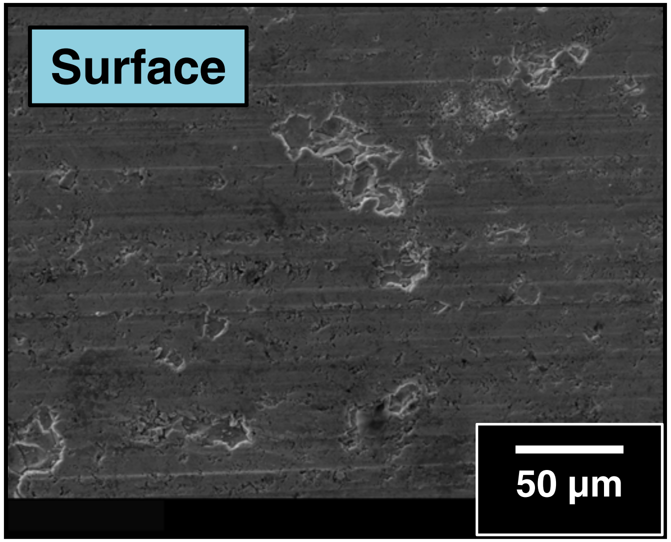
Bi-Dimensional
Hybrid Flaw

Technical Accomplishments – 5 of 13

Possible failure initiation locations in TE legs

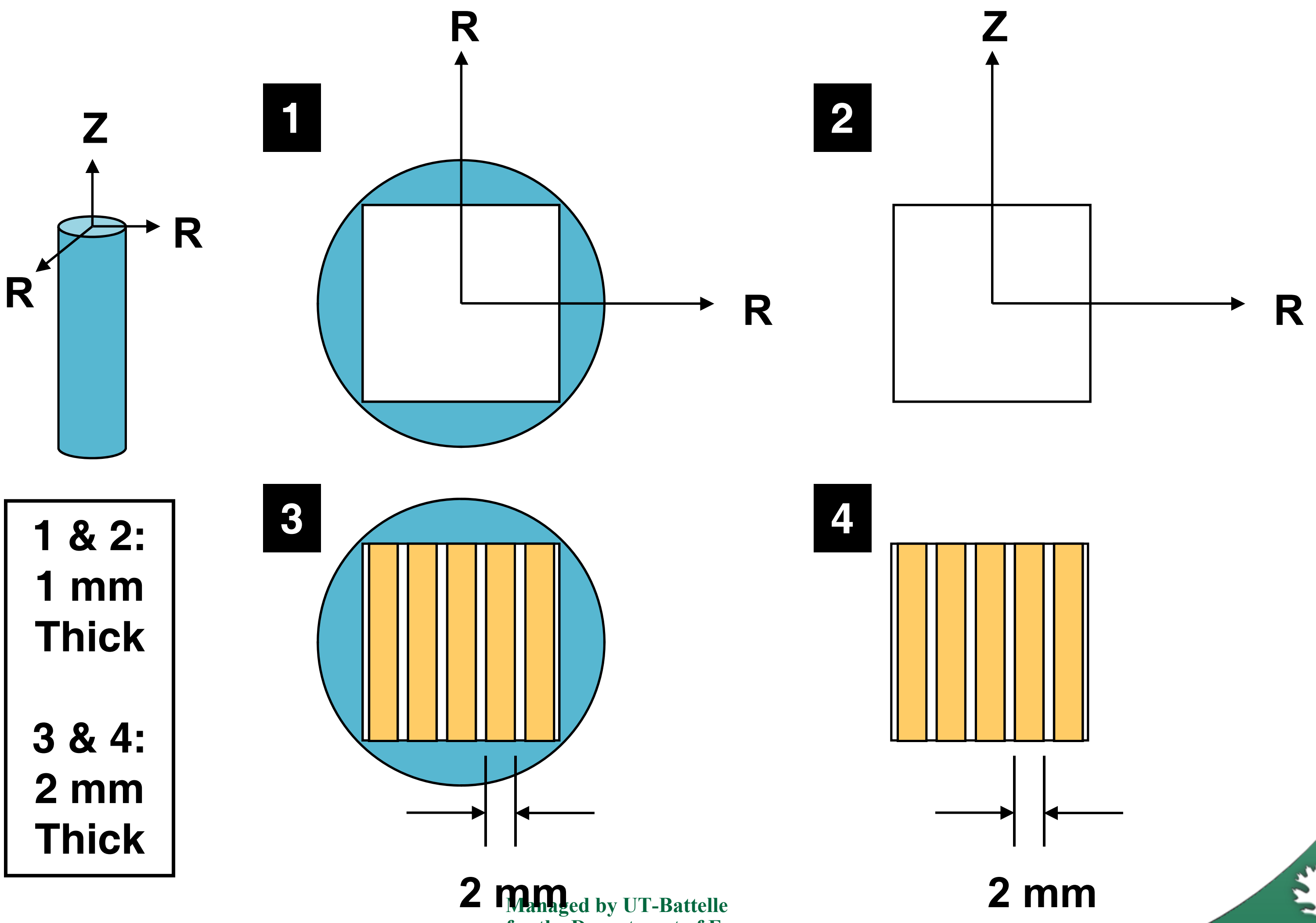






4 specimen combinations considered

(2 Orientations x 2 Geometries)

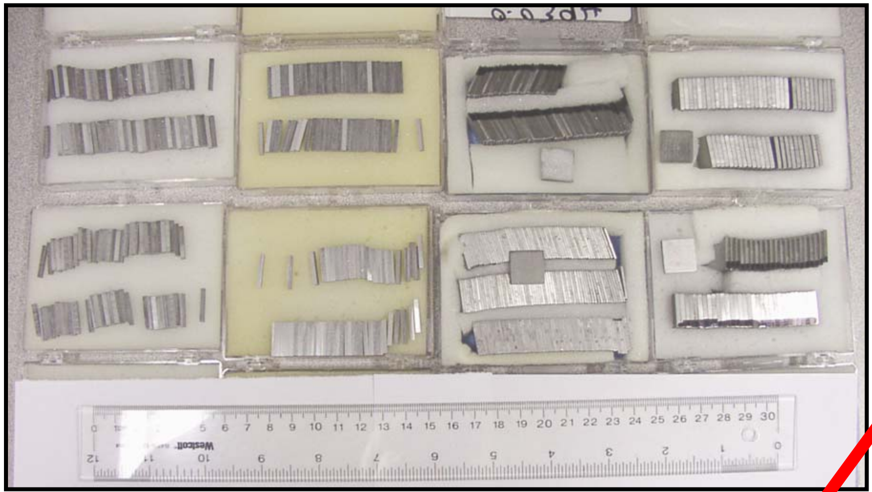


1 & 2:
1 mm
Thick

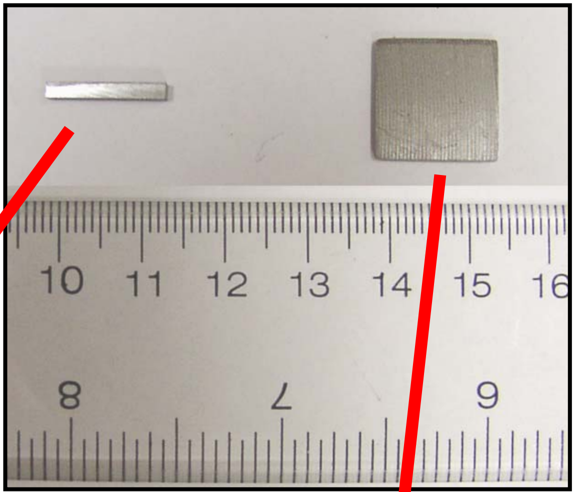
3 & 4:
2 mm
Thick

Technical Accomplishments – 8 of 13

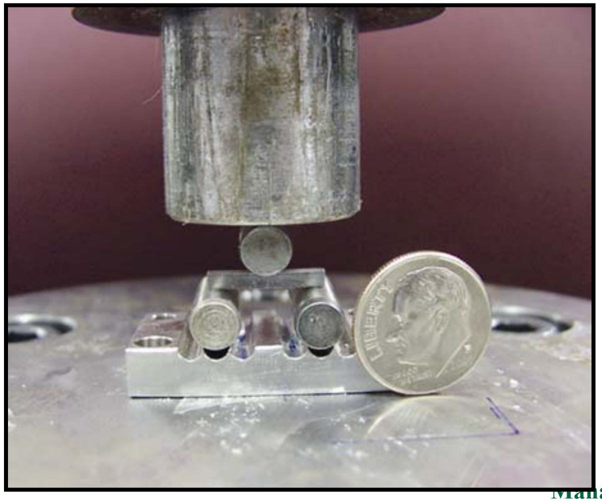
Specimens (Hundreds)



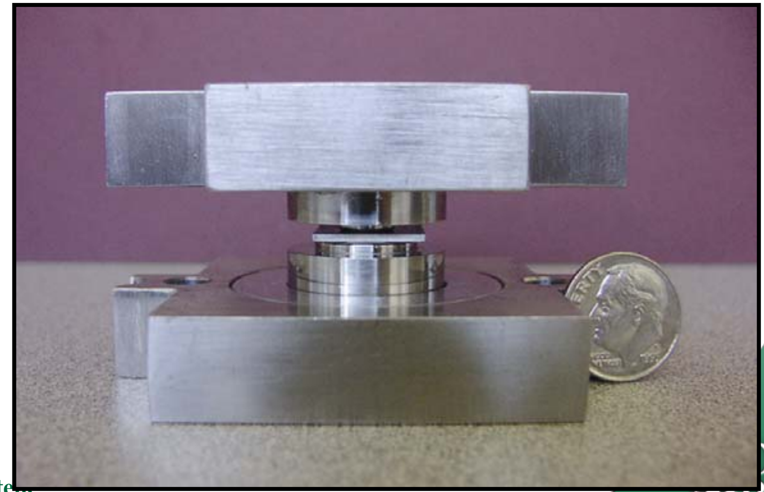
Specimen Geometries



3-Pt-Bend (Uniaxial Flexure)

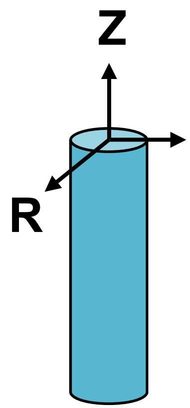


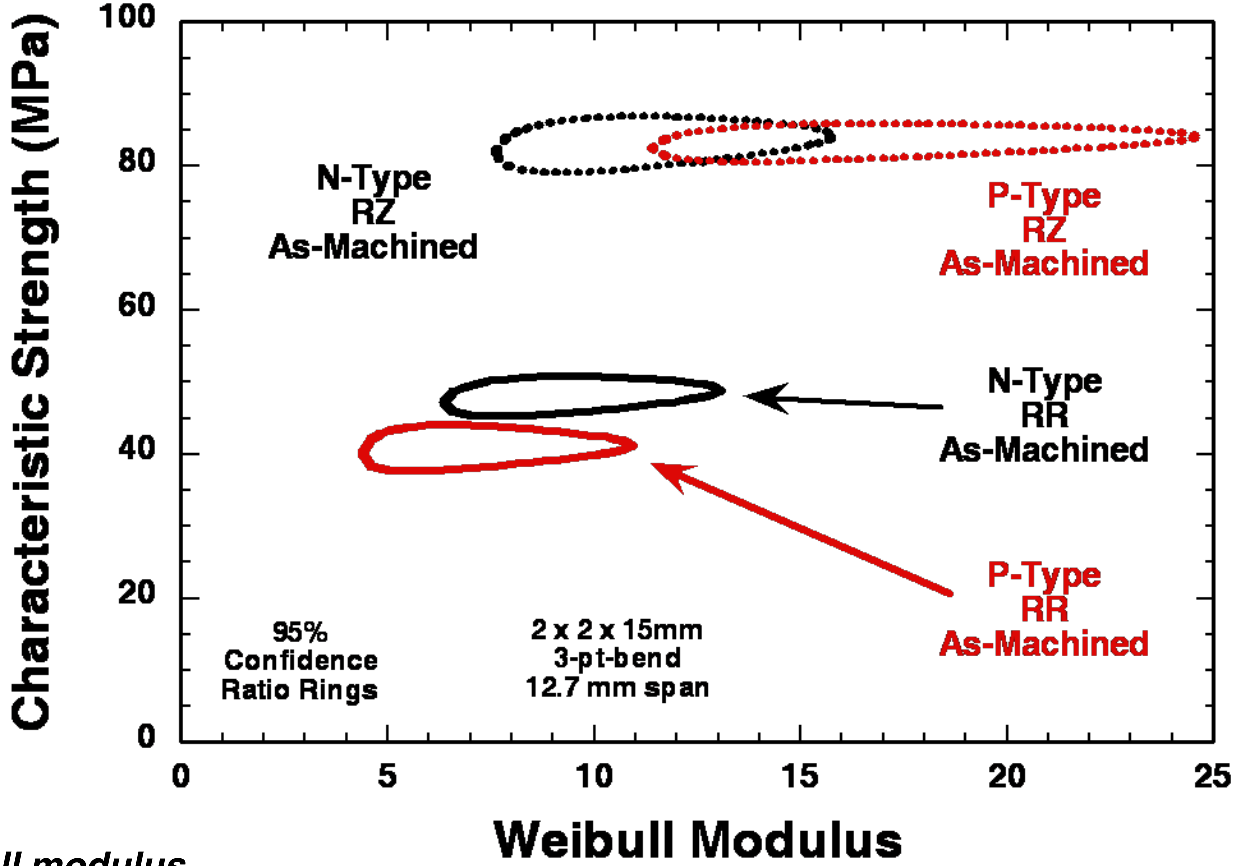
Ring-on-Ring (Biaxial Flexure)



Technical Accomplishments – 9 of 13

- **RZ orientation stronger in both types**
- **N-type slightly stronger in the RR**



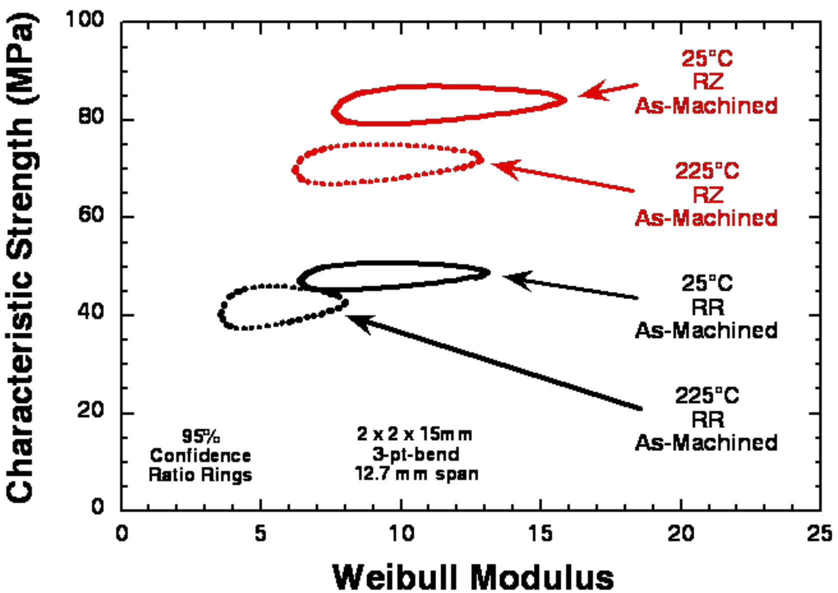


The larger the Weibull modulus the lesser the scatter in strength

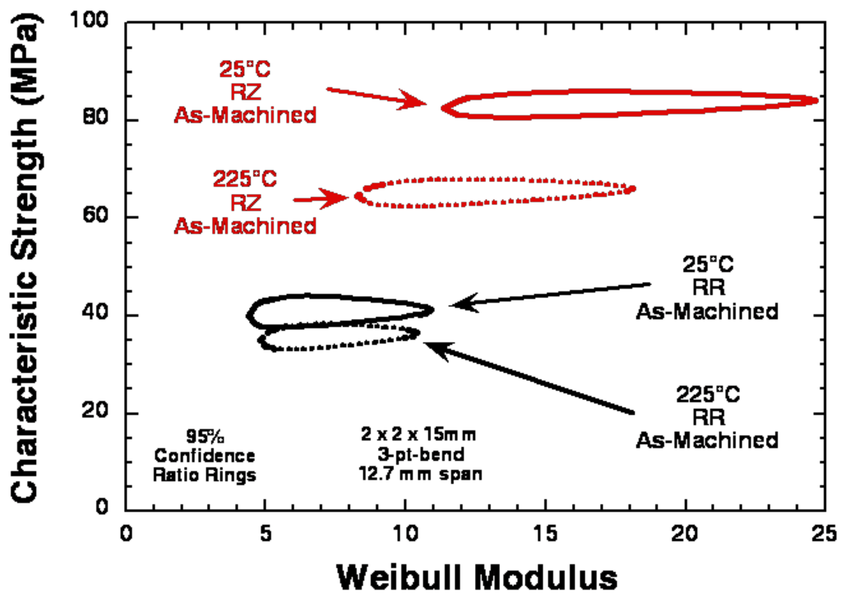
Technical Accomplishments – 10 of 13

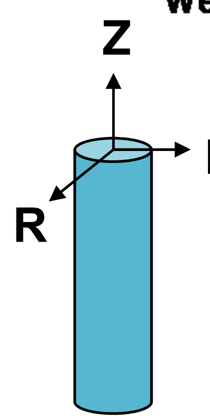
Strength decreased with increased temperature

N-Type



P-Type

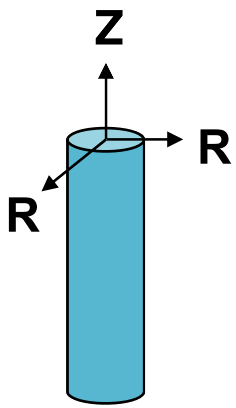


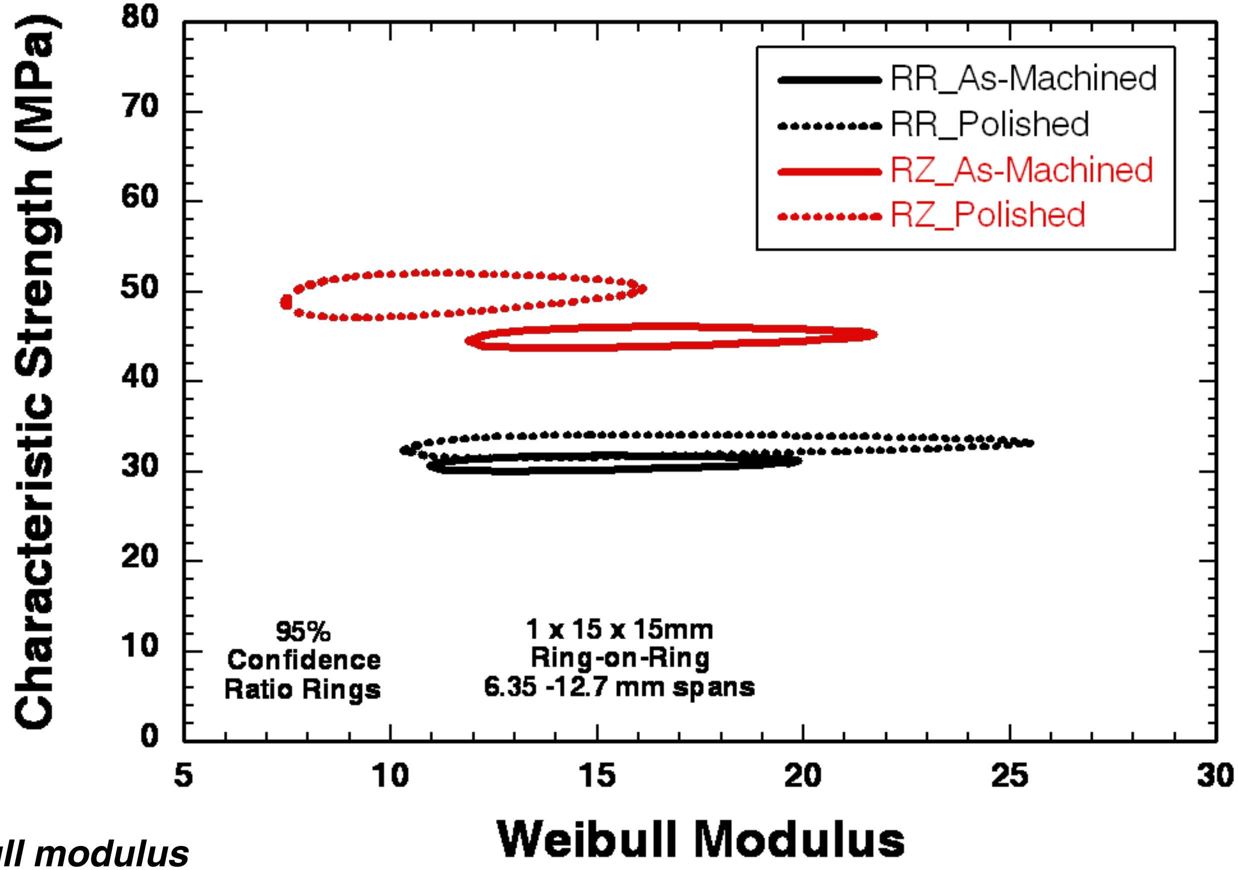


The larger the Weibull modulus the lesser the scatter in strength

Technical Accomplishments – 11 of 13

Polishing slightly increases strength



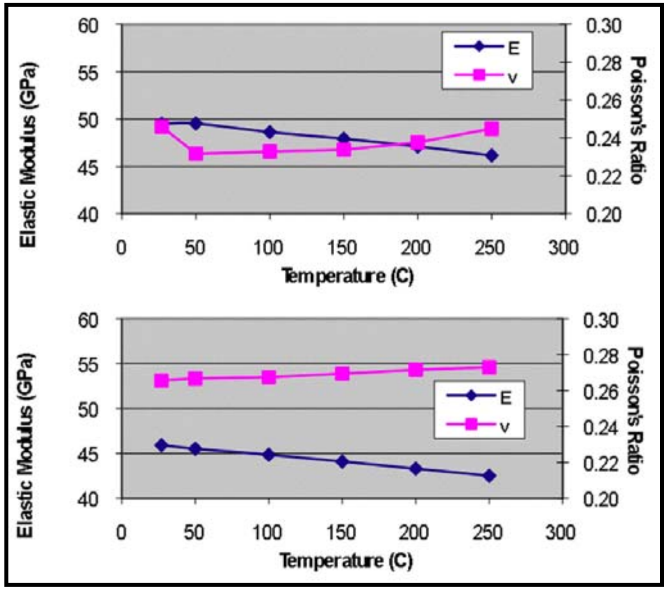


The larger the Weibull modulus the lesser the scatter in strength

Technical Accomplishments – 12 of 13

Additional measured properties needed for analysis

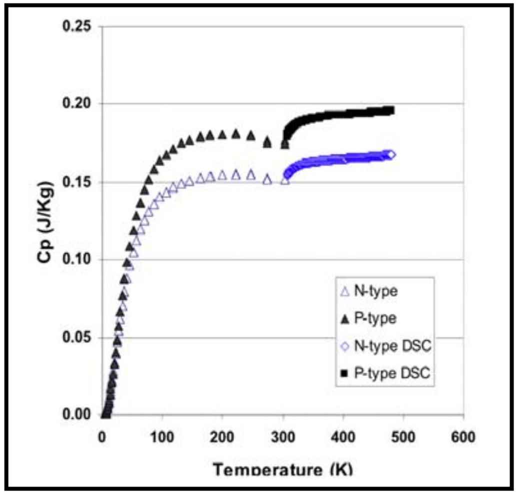
E



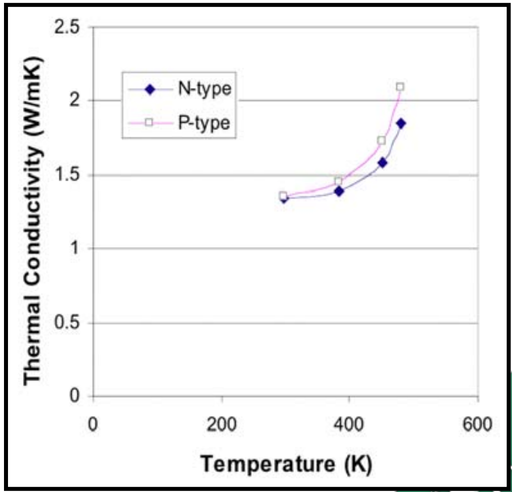
CTE

Type	Orientation	Specimen Number	Average CTE up to 240°C (ppm/°C)
P	R - R	1	18.9
P	R - R	2	18.7
P	R - R	3	18.8
P	R - Z	1	14.3
P	R - Z	2	13.9
P	R - Z	3	13.8
N	R - R	1	17.1
N	R - R	2	17.3
N	R - R	3	17.3
N	R - Z	1	14.7
N	R - Z	2	14.4
N	R - Z	3	14.3

Cp



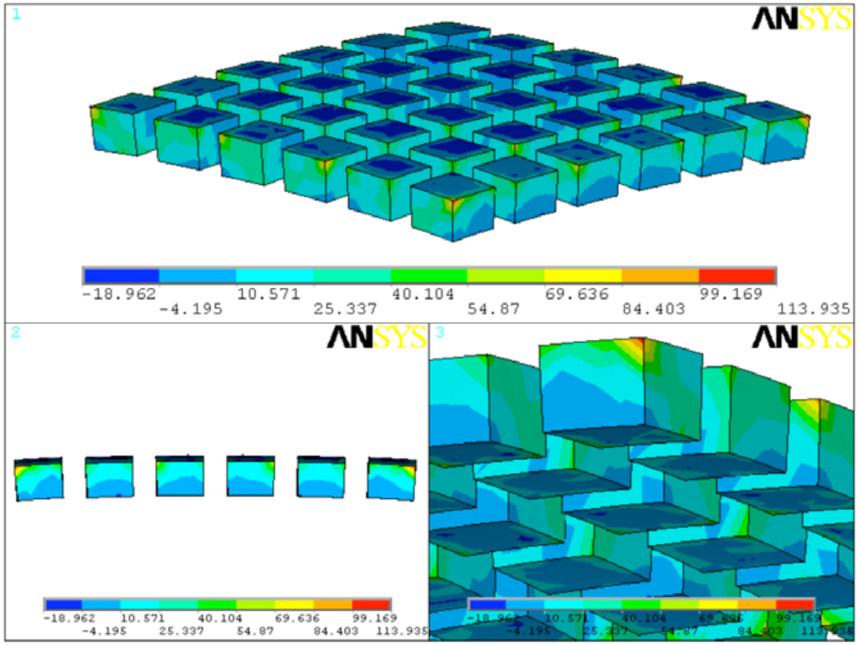
κ



Technical Accomplishments – 13 of 13

How will this information be used?

- **High 1st principal tensile stresses exist in the bulk and on surfaces and edges**
- **Apply (censored) strength data to estimate and reduce risk of fracture**
- **Improve reliability by:**
  - **Improving strength of TE material**
  - **Lessening tensile stresses in the legs (via geometrical changes)**
  - **Both**



Must manage the competition and concurrent activities of Edge- vs. Surface- vs. Volume-based strength limitation

Future Work

- **Collaborate with a manufacturer of high-temperature-capable TEMs and TEDs and contribute to the reliability improvement of their candidate TEMs (FY09 & FY10).**

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- **Develop a thermomechanical test system that will enable strength measurement of TEM specimens while a thermal gradient is concurrently imposed through the specimen thickness (FY09-10).**

- **Develop method to quantify strength-limiting flaw populations (FY10).**

Summary

- **Generated thermomechanical property database on a baseline p- and n-type thermoelectric material (Bi_2Te_3)**
  - **N- and P-types had equivalent strengths in the RZ-orientation but N-type was slightly stronger in the RR**
  - **The RZ-orientation is ~ 2x stronger than the RR-orientation**
  - **Strength decreases ~ 15% between 25 and 225°C**
  - **Polishing slightly increases strength**
- **Developed finite element analysis model to predict probabilistic reliability of a TE device.**