

# From Material Behavior to Reliability: Characterizing Epoxy Molding Compounds for Power Electronics and Heterogenous Integration in Harsh Environments

Przemyslaw Gromala

Robert Bosch Kft

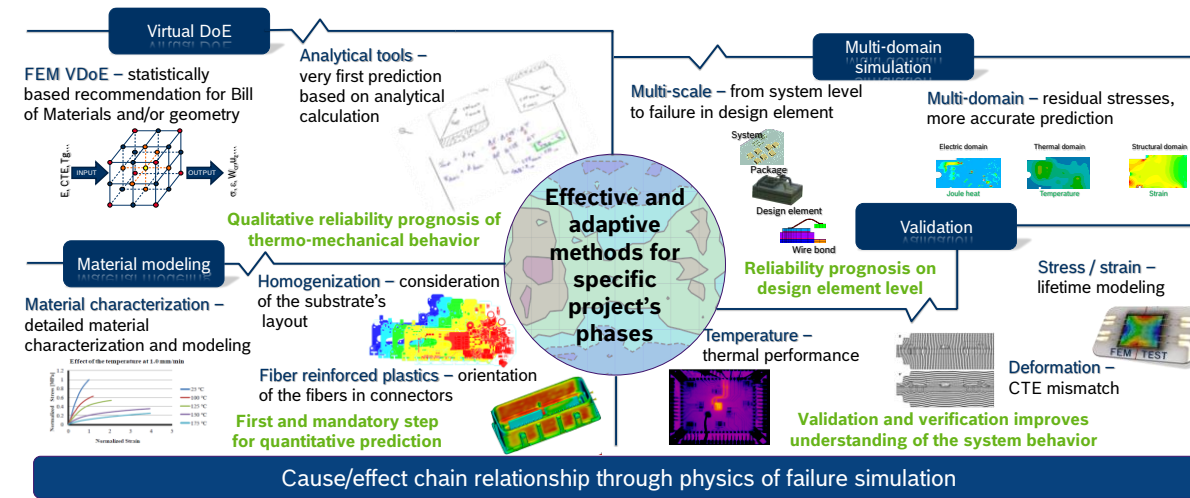
IEEE EPS Senior Member

## Przemyslaw Gromala

- Robert Bosch Kft, Mobility Electronics, Budapest
- Simulation Senior Expert and R&D Project leader
- General Chair of the 77<sup>th</sup> ECTC 2027 Conference
- IEEE EPS BoG member and IEEE EPS Germany chapter chair
- Chair of the EPoSS TWG: Advanced Packaging

## Expertise:

- Simulation driven co-design
  - Virtual Design of experiment
  - Material characterization and modeling
  - Coupled multi-domain simulation
  - Validation lab (warpage, stress and strain measurements)
- Publicly funded projects



# Before we start...



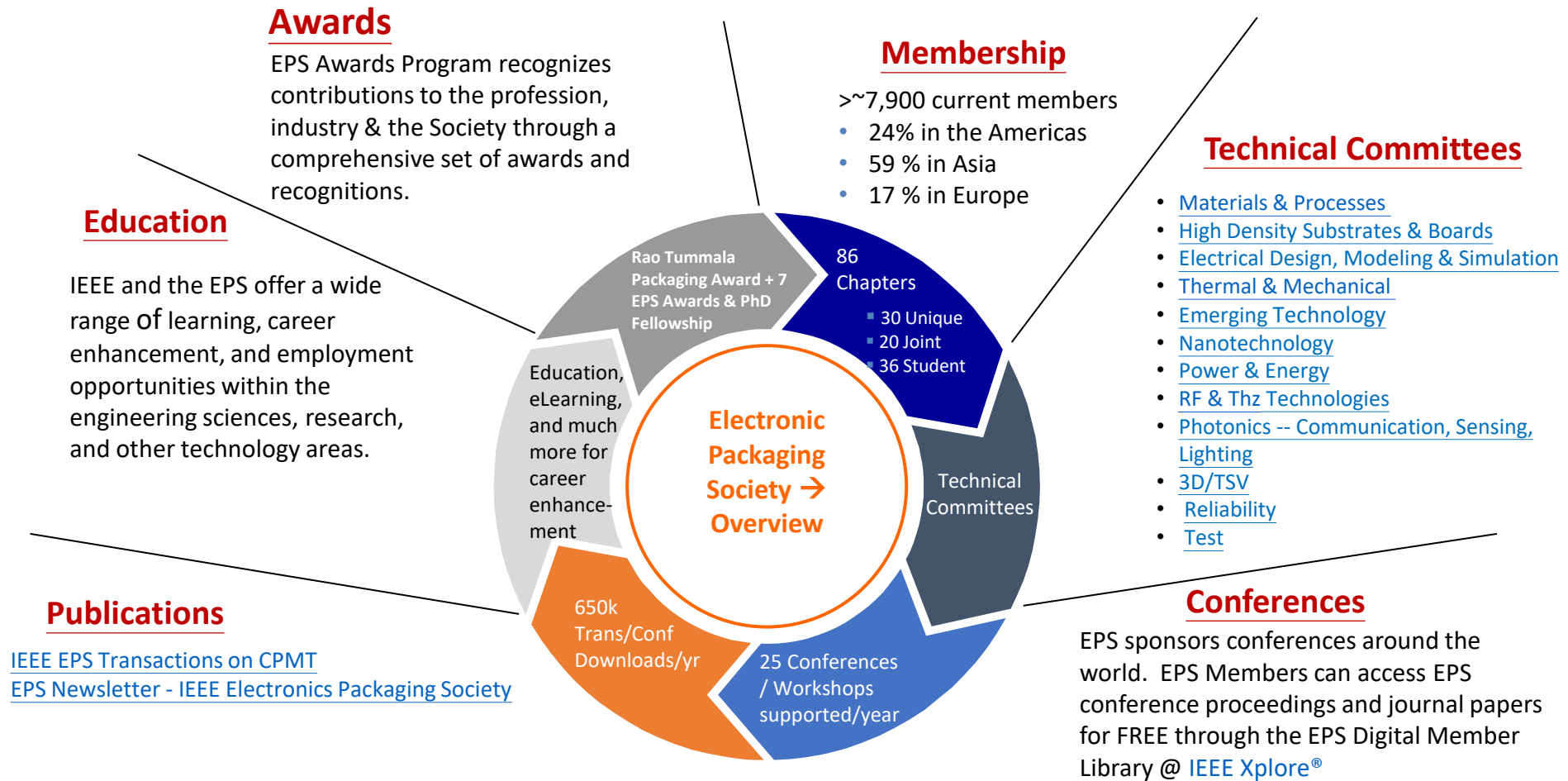
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Electronics  
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- What is your name?
- Where do you work?
- What is your responsibility?
- What are your expectations from this training?
- How can I help you in your work?





“Emerging technologies—such as AI, 5G, edge, cloud, and data center, autonomous vehicles and wearable technology hold great promise for improving the lives of individuals across the globe,” (HIR)

1. Introduction
2. Material Selection and Key Influencing Mechanisms
3. EMC Material Characterization Essentials
4. From Material Data to Simulation Models
5. Summary and Key Takeaway

- 1. Introduction**
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# Motivation

CONECTIVITY



AUTOMATION



SHARING



ELECTRIFICATION



# Challenges in front of us

| Traditional Vehicle |        |       |
|---------------------|--------|-------|
| Service Life        | 15     | Years |
| Service time        | 131400 | Hours |
| Driving             | 10000  | Hours |
| Parked-off          | 121400 | Hours |

| Electric Vehicle     |        |       |
|----------------------|--------|-------|
| Service Life         | 15     | Years |
| Service time         | 131400 | Hours |
| Driving              | 10000  | Hours |
| Charging - Stand by  | 30000  | Hours |
| Inhabited - Stand by | 67000  | Hours |
| Parked-off           | 24400  | Hours |

| Autonomous Vehicle  |        |       |
|---------------------|--------|-------|
| Service Life        | 15     | Years |
| Service time        | 131400 | Hours |
| Driving - operating | 100000 | Hours |
| Charging - Stand by | 20000  | Hours |
| Parked-off          | 11400  | Hours |

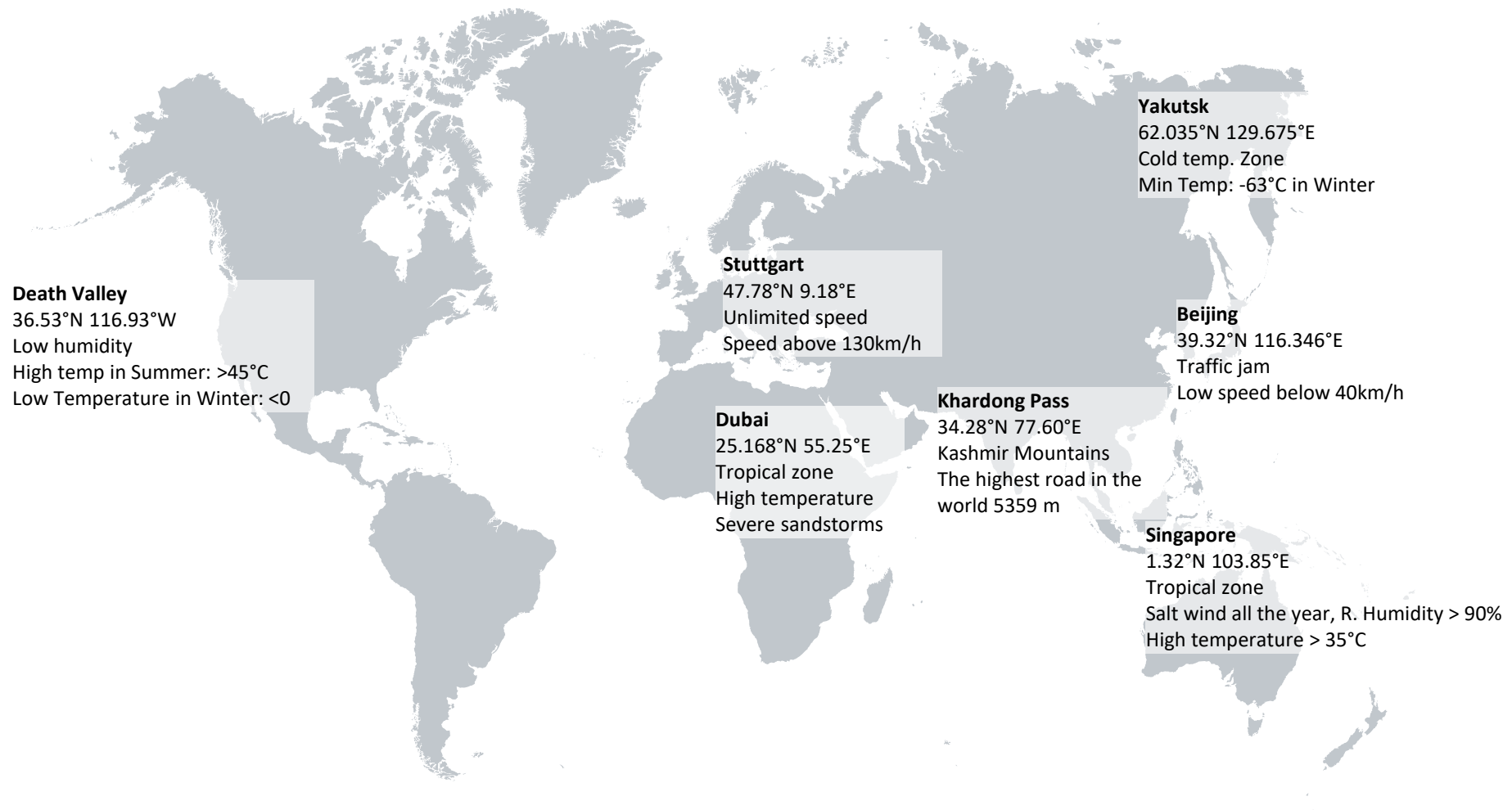
## Source:

Fen Chen, Principal HW Reliability Engineer  
Cruise LLC

PDC: Reliability Engineering Testing Methodology and Statistical Knowledge for Qualifications of  
Consumer Electronic Products and Automotive Electronic Components  
ECTC 2022

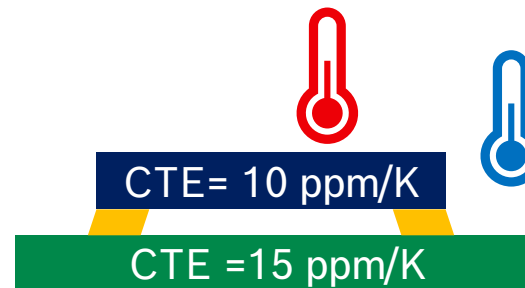
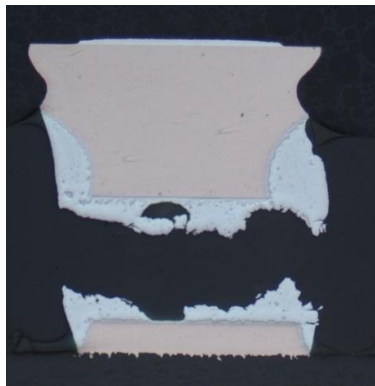
Electrification and autonomous driving – new use case scenarios

# What is harsh environment



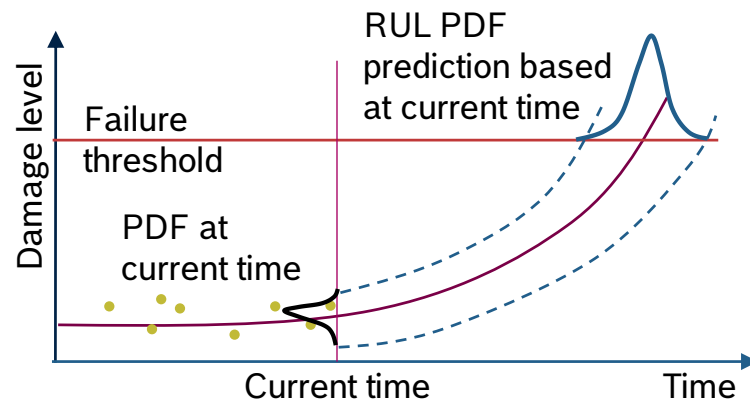
# What is failure mode and mechanism

- **Failure mode:** an event that causes functional failure
- **Solder joint crack**
  - During temperature cycling – low cycle fatigue (low strain rates, relatively large strains)
  - During vibration test – high cycle fatigue (high frequency, high strain rates, low strains)
- **Failure mechanism:** is a physical process of materials' degradation that leads to failure
- **Solder joint crack**
  - During temperature cycling – CTE mismatch of materials
  - During vibration test – mechanical fatigue due to bending



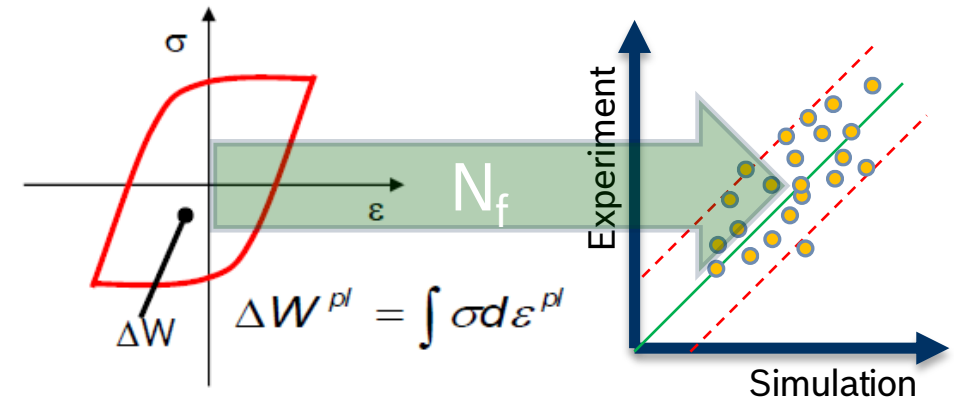
Although failure mode is the same mechanism of failure is different

- **Data driven lifetime models:** In-situ measurements and learn trends, derive decision based on historical data



Transfer to another product is not possible

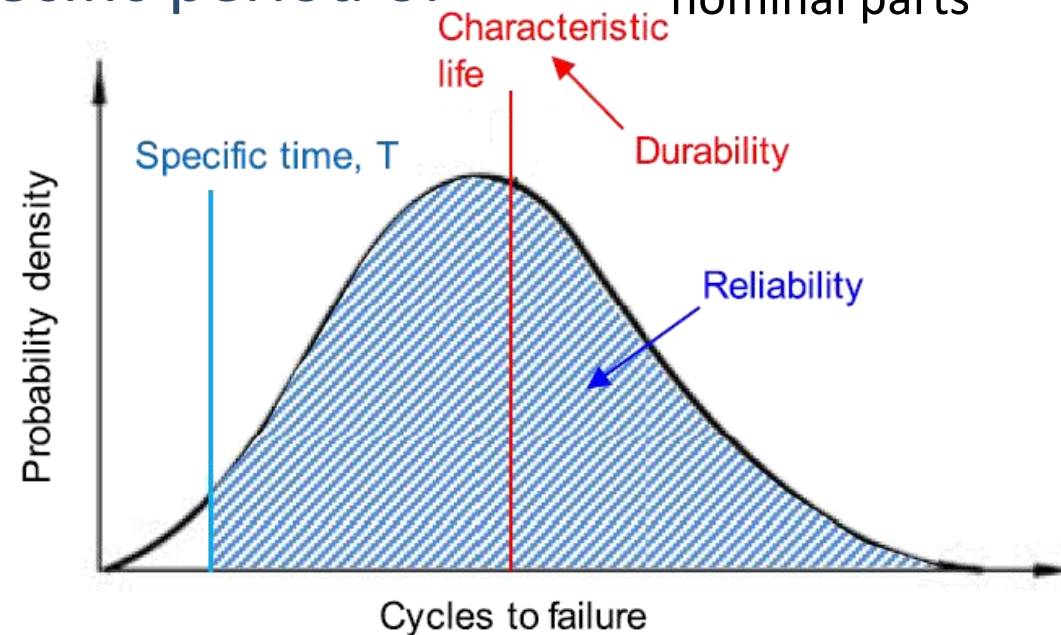
- **Physics based lifetime models:** Lifetime is based on known geometries, materials, loads, damage mechanism and failure criteria



Transfer to another product is possible

- **Reliability:** the probability that a product will perform its intended function under operating conditions, for a specific period of time

- **Durability:** the length of the time that product will provide its intended function under operating conditions, such as the mean time to failure (MTTF) or its equivalent, which represents the reliability of nominal parts



Most of the physics-based lifetime models are durability models

# Simulation driven design



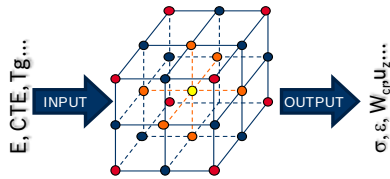
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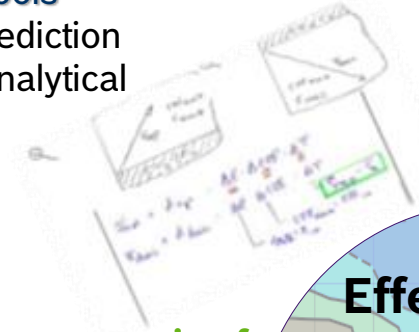
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## Virtual DoE

**FEM VDoE** – statistically based recommendation for Bill of Materials and/or geometry

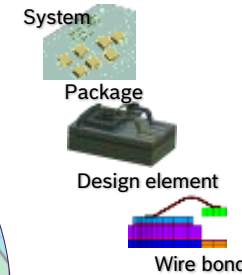


Analytical tools – very first prediction based on analytical calculation

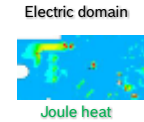


## Multi-domain simulation

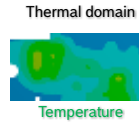
**Multi-scale** – from system level to failure in design element



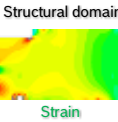
**Multi-domain** – residual stresses, more accurate prediction



Joule heat



Temperature



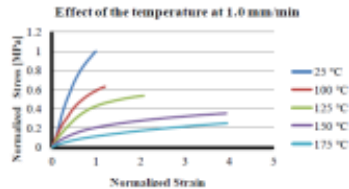
Strain

**Effective and adaptive methods for specific project's phases**

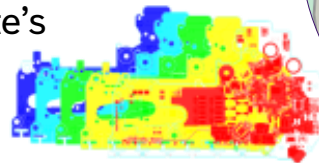
**Qualitative reliability prognosis of thermo-mechanical behavior**

## Material modeling

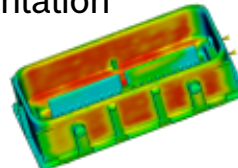
**Material characterization** – detailed material characterization and modeling



**Homogenization** – consideration of the substrate's layout



**Fiber reinforced plastics** – orientation of the fibers in connectors



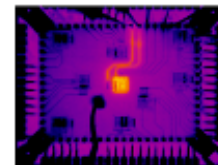
**First and mandatory step for quantitative prediction**

## Validation

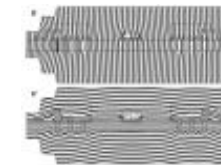
**Reliability prognosis on design element level**

**Stress / strain – lifetime modeling**

**Temperature – thermal performance**



**Deformation – CTE mismatch**

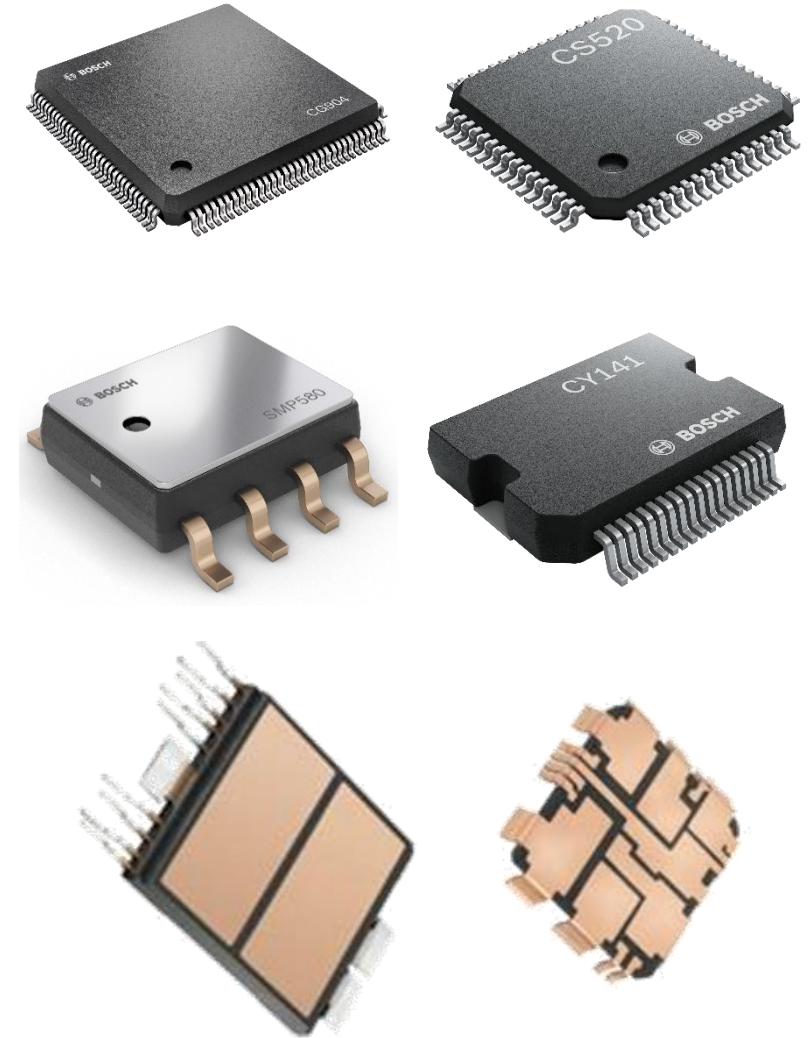


**Validation and verification improves understanding of the system behavior**

**Cause/effect chain relationship through physics of failure simulation**

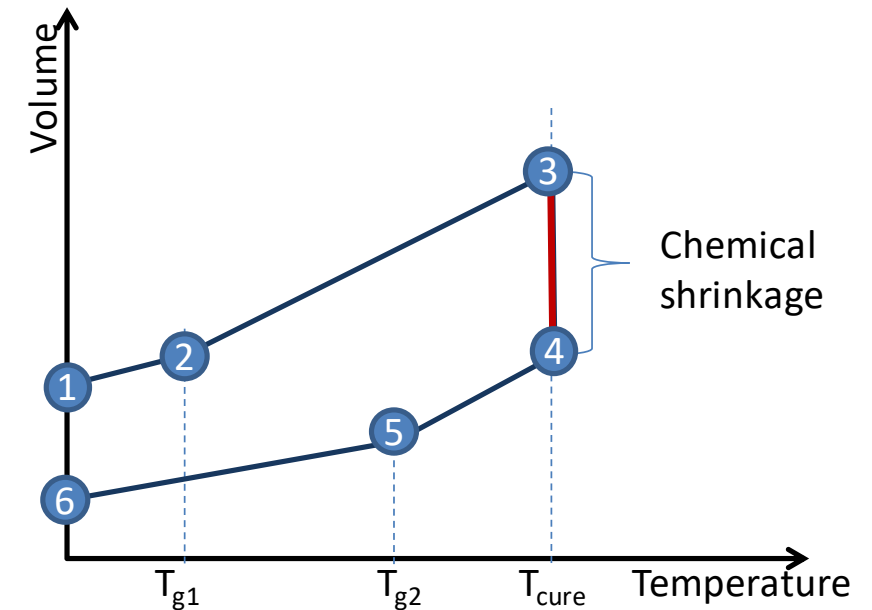
- Numerical simulation plays an important role in development process of electronic components and systems.
- Accuracy of the numerical simulation strongly depends on input provided in the FEM model.
- A material data sheet typically contains very limited amount of the information.
- Material characterization is critical → this is the first but important step towards accurate FEM simulation results.

The goal of this training is to give an overview of material characterization and modelling of the epoxy based thermosets used in semiconductor industry.



Typical applications for epoxy-based thermosets

- Most materials are non-linear, all are temperature dependent, some in addition time dependent
- Polymer materials require detailed characterization
- Properties depends on process conditions
- Shifting of  $T_g$  and rubbery modulus to higher temperature regime
- Curing shrinkage occurs during crosslinking.

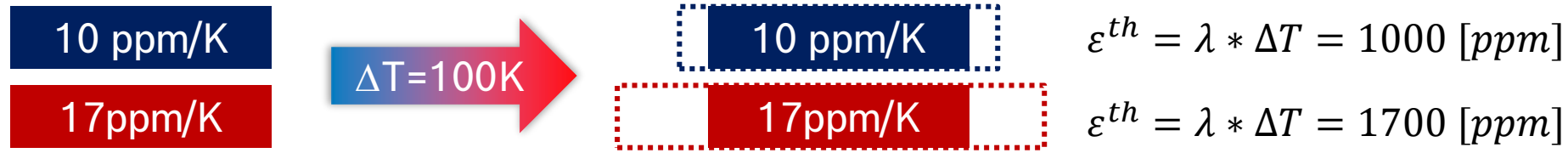


1. Introduction
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How to properly select materials for semiconductor packaging and modules?

# Why do we need to know the stress state

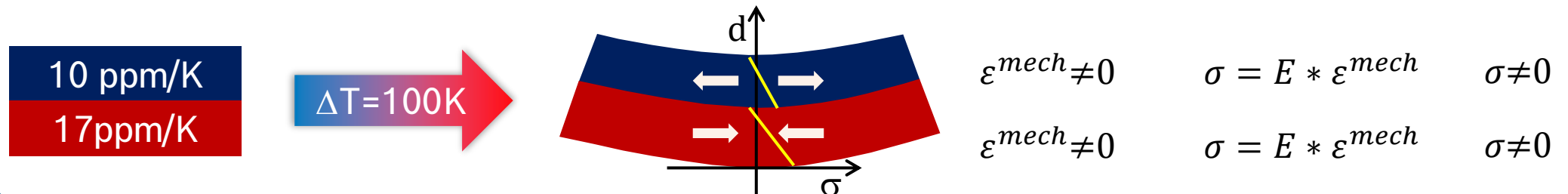
- Materials have different thermal expansion, after applying temperature they expand by different length

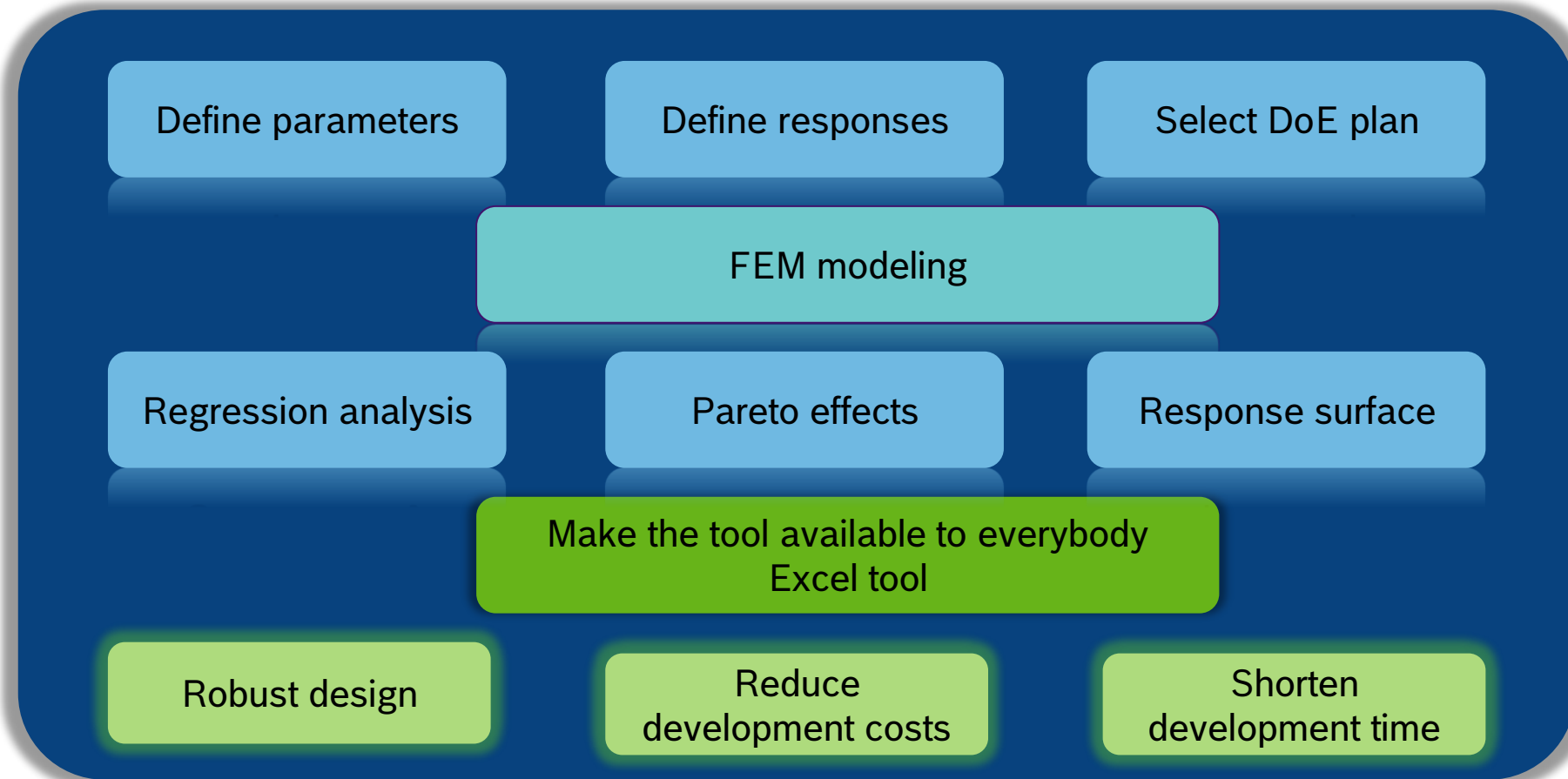


- If materials are separated  $\rightarrow$  there is no mechanical strain  $\rightarrow$  no stress in materials



- If materials are joined  $\rightarrow$  leads to warpage  $\rightarrow$  mechanical strain exist  $\rightarrow$  stress





Qualitative reliability prognosis at early design stage

## Qualitative approach: Selection of the molding compound

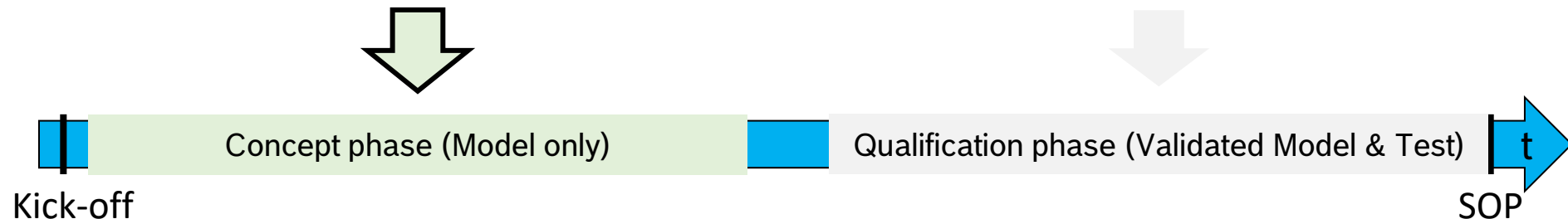
- Parameters:
  - CTE1;
  - CTE2;
  - T<sub>g</sub>;
  - E;
  - Curing shrinkage.
- E.g. Central composite faced plan.
- Total 52 simulations:
  - Linear elastic model;
  - Passive temperature cycling.

**Recommendation: at the concept phase**

## Quantitative approach: Investigation of the stress state during active power cycling to estimate risk of crack in molding compound

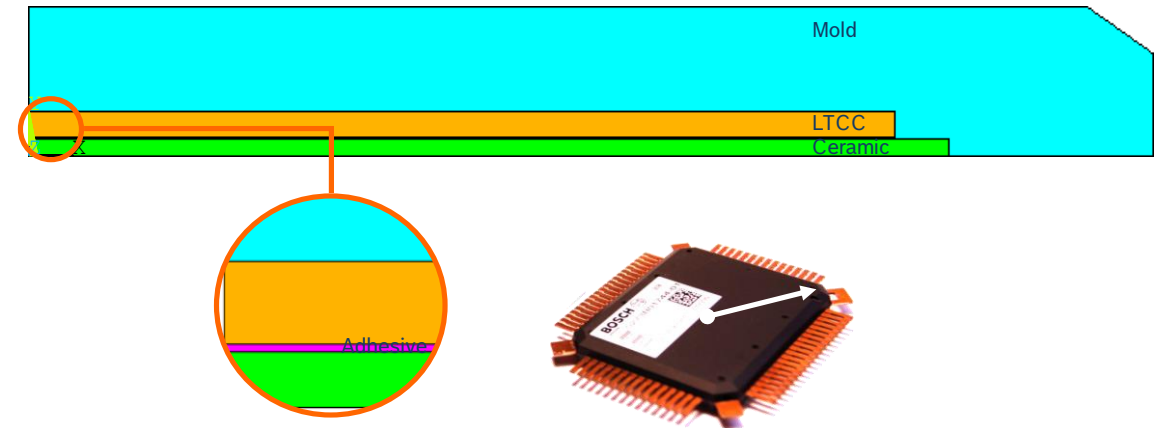
- Parameters:
  - Ambient temperature;
  - Time of load;
  - Applied power;
  - Cooling condition.
- D-optimal plan.
- Total 15 simulations:
  - Non-linear viscoelasticity;
  - Multi-domain.

**Recommendation: at the later stage**



## Understand the effect of the molding compound on the stress and deformation in molded control unit.

- Design of experiment.
- Sensitivity analysis.
- Parameter identification.
- Failure criteria for different failure modes.
- Recommendation at the early design stage.



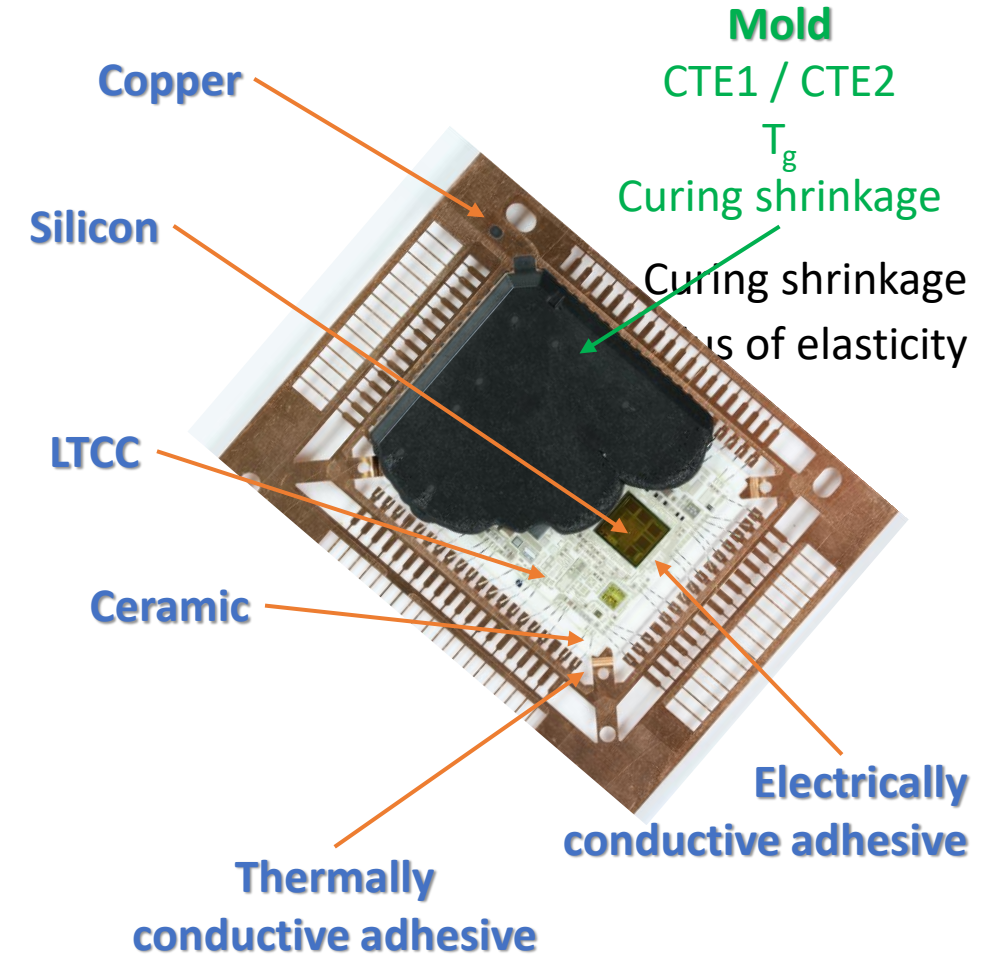
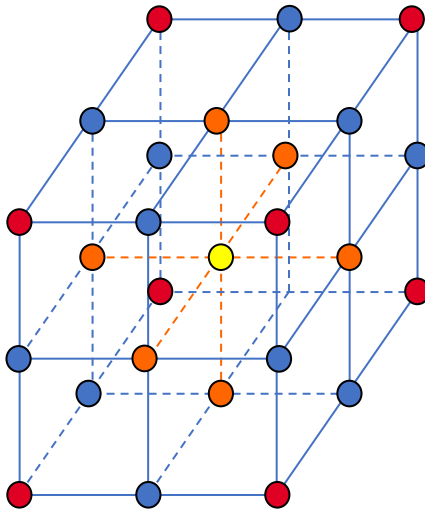
What influence the stress

Main parameter is  $T_g$ .

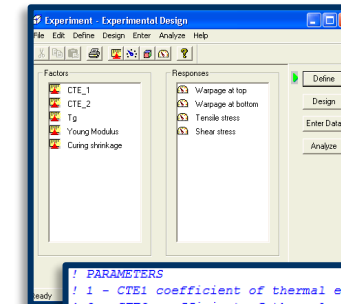
CTE and E are the second most important factor.

Minimize the stress and deformation state in the construction

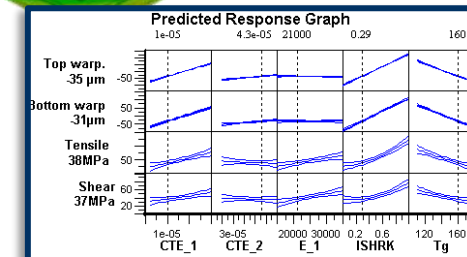
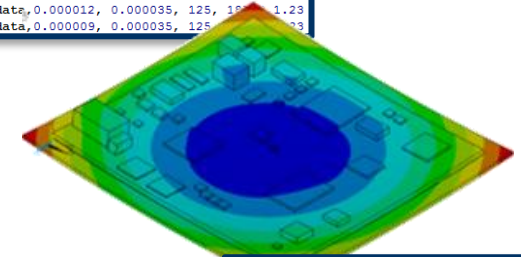
- Parameters of molding compound (DoE parameters):
  - Coefficient of thermal expansion below glass transition
  - Coefficient of thermal expansion above glass transition
  - Glass transition temperature



- FEM simulation:
  - Deformation
  - Stress & strain
  - Energy
  - Temperature
- Regression analysis
- Response surface:
  - $y = b_0 + b_1 * A + b_2 * B + b_3 * A * B + b_4 * A^2 + b_5 * B^2 + b_6 * A * B$
- Simulation results are used for the determination of the coefficients  $b_0, b_1, \dots, b_n$
- Response surface is used to calculate stress state for available EMCs



```
! PARAMETERS
! 1 - CTE1 coefficient of thermal expansion below Tg
! 2 - CTE2 coefficient of thermal expansion above Tg
! 3 - Tg glass transition temperature
! 4 - E1 Modulus of elasticity below Tg
! 5 - Shrink Curing shrinkage
*Vfill,sim(1, 1),data,0.000012, 0.000035, 150, 18750,1.23
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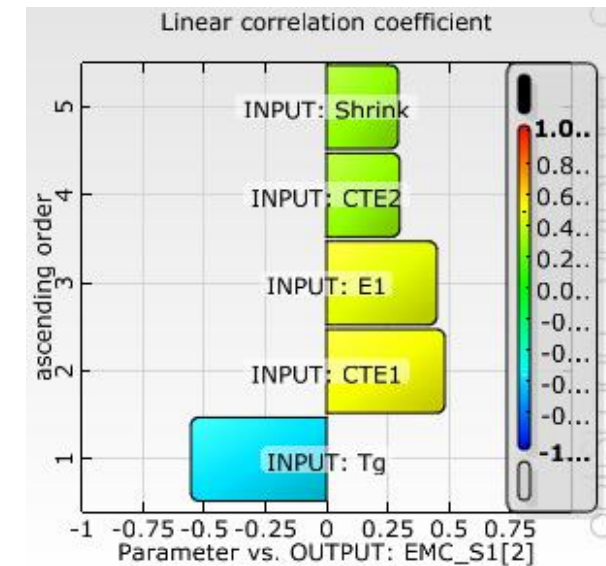
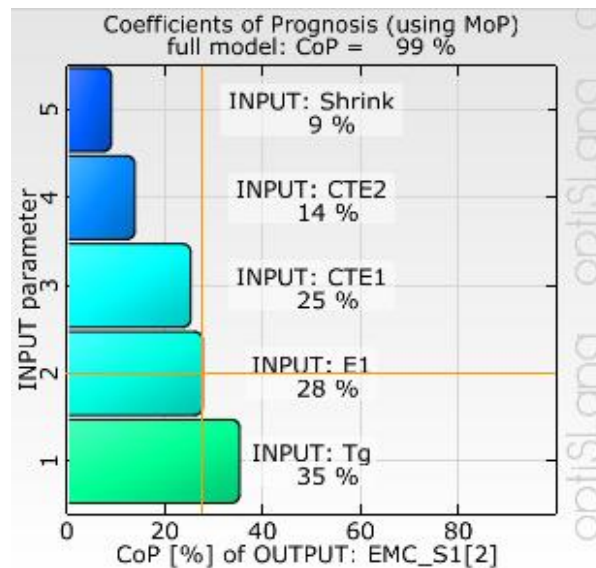
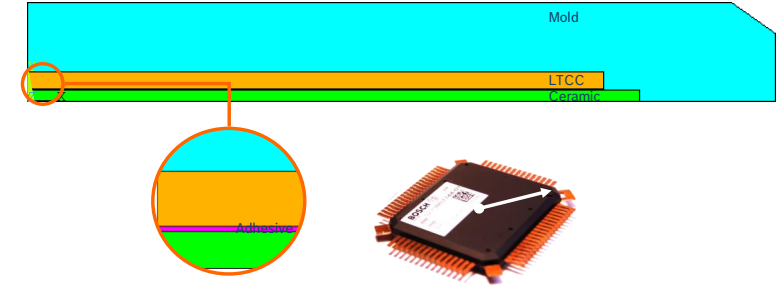


A. Sasi, A. Yadur, P. Gromala, "Simulation driven design of novel integrated circuits - Part 1: Selection of the materials based on the Virtual DoE," EuroSimE, 2015.

# How to use response surface – stress in molding compound

## Reduce the stress in molding compound

- What influence the stress in EMC:
  - Main parameter is  $T_g$
  - CTE and E are the second most important factor

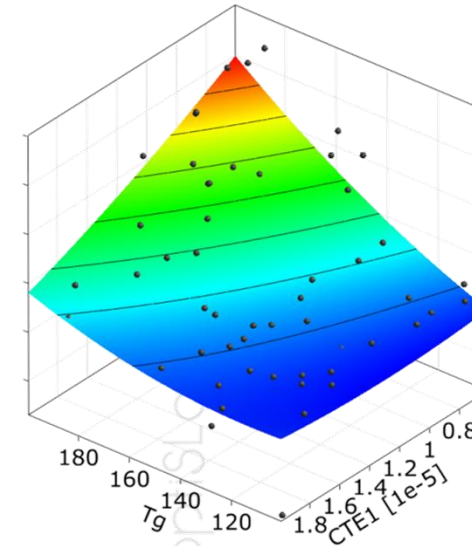
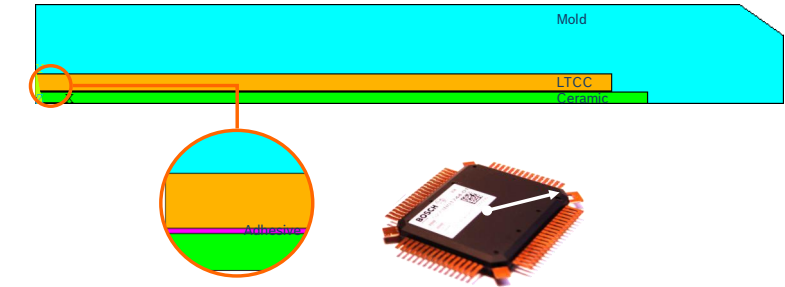
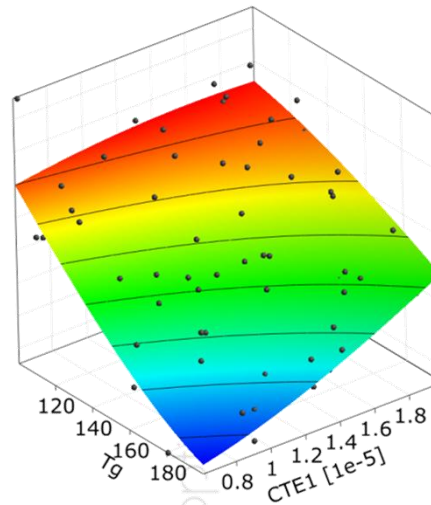
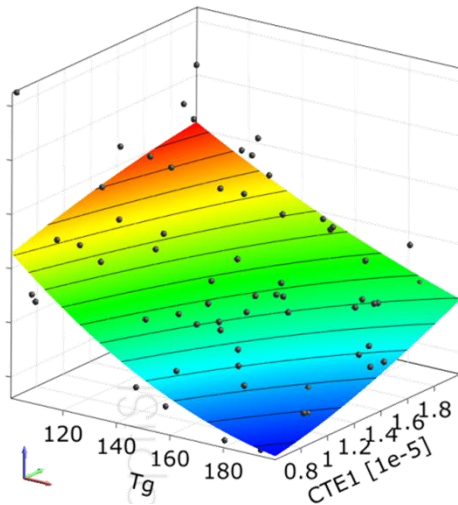


For particular construction EMC should have high  $T_g$ , low CTE and low modulus of elasticity

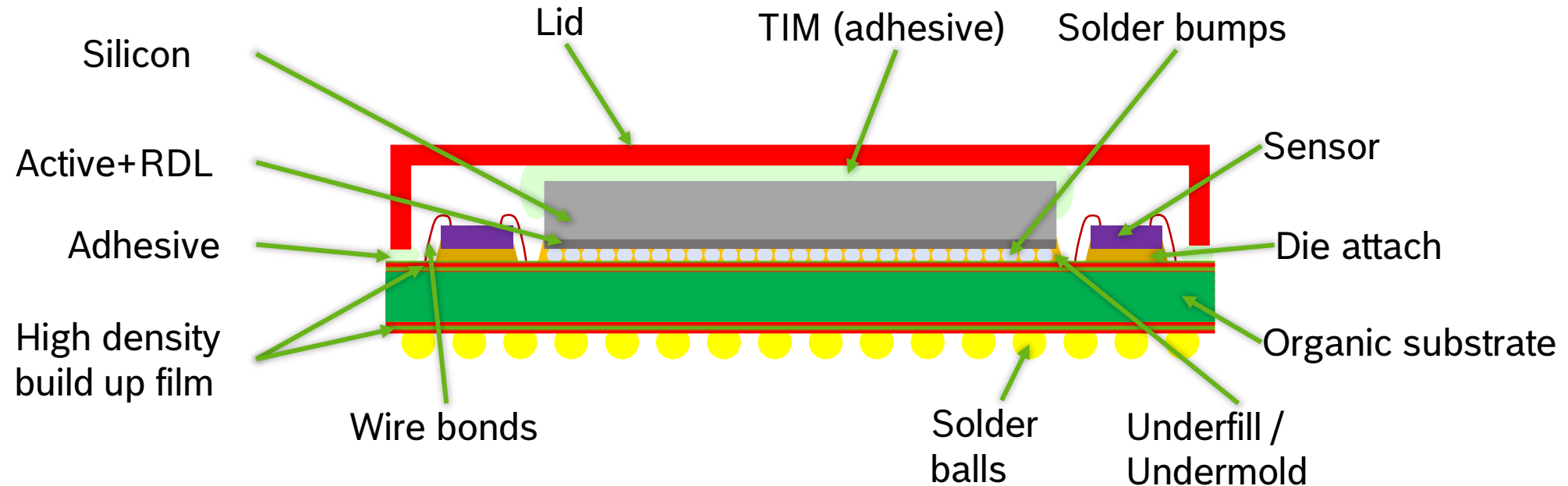
# How to use response surface – stress in other parts

## Reduce the stress in the all other materials

- What influence the stress:
  - T<sub>g</sub> is the most important parameter
  - CTE plays second most important role.
  - Modules of elasticity of molding compound doesn't play significant role.



For particular design EMC should have high T<sub>g</sub>, low CTE

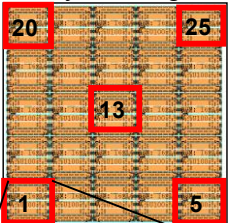


## Understanding thermo-mechanical behavior of advanced GPU during active operation

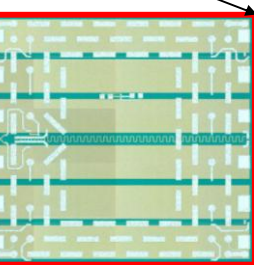
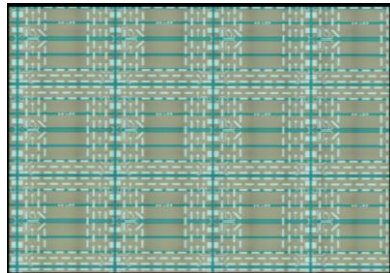
M. Hager, P. Gromala, B. Wunderle and S. Rzepka, "Affordable and Safe High Performance Vehicle Computers with Ultra-Fast On-Board Ethernet for Automated Driving" in Advanced Microsystems for Automotive Applications 2018. AMAA 2018. Lecture Notes in Mobility, Cham:Springer, 2019.

## Thermal chip

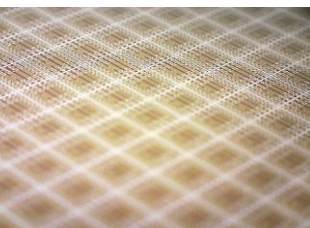
Layout image



Fabricated chip image

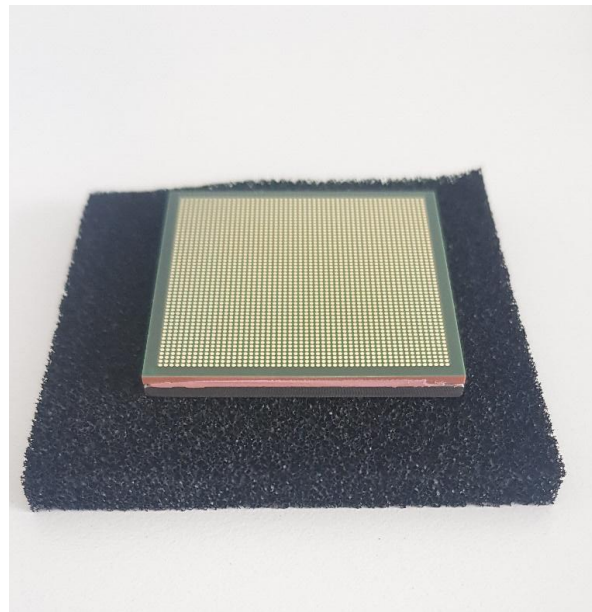


Fabricated cell image

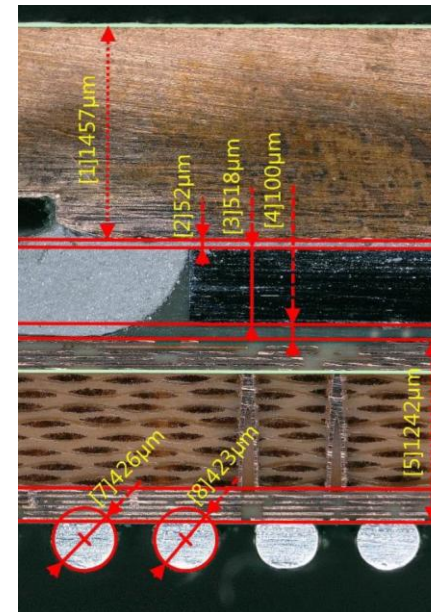


Processed Silicon Wafer

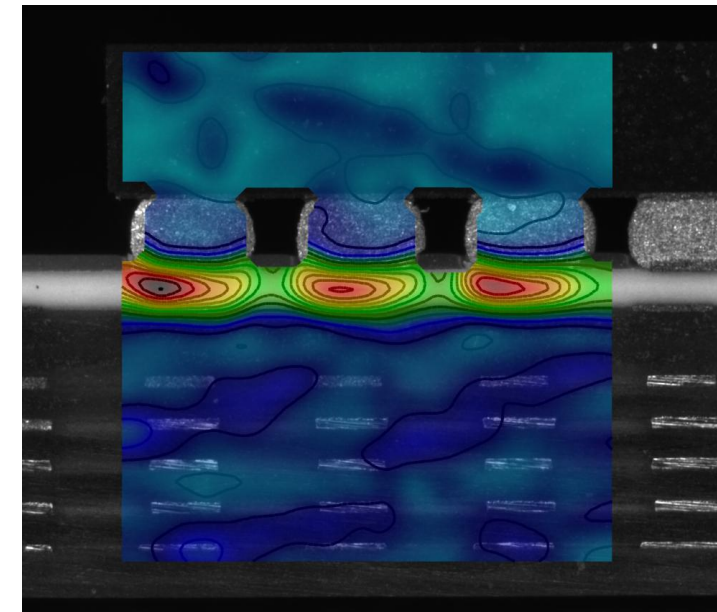
## Power SiP



## Characterization

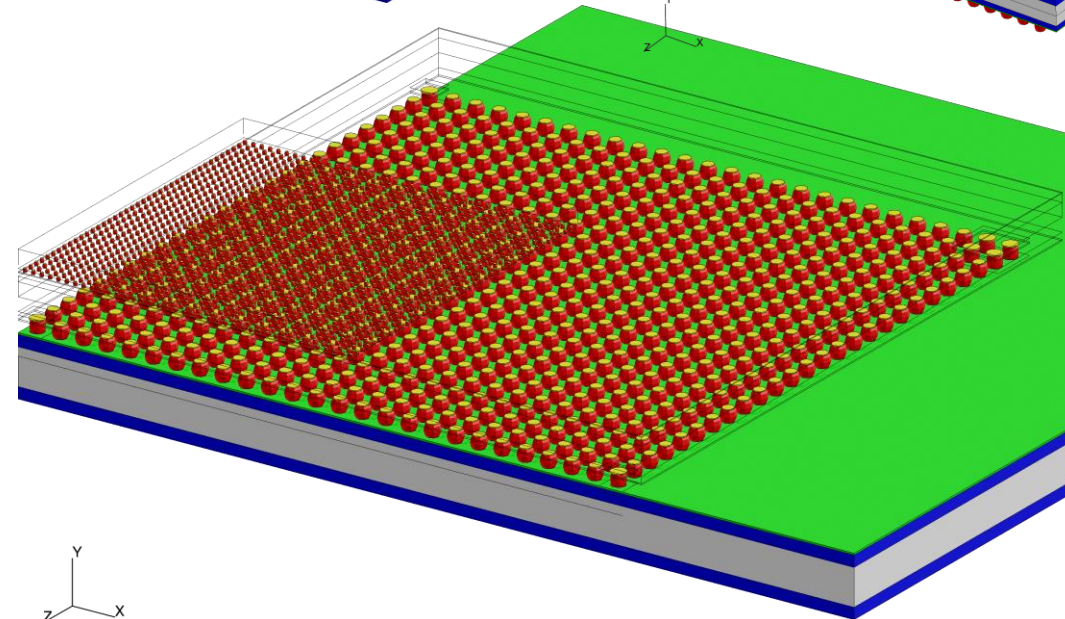
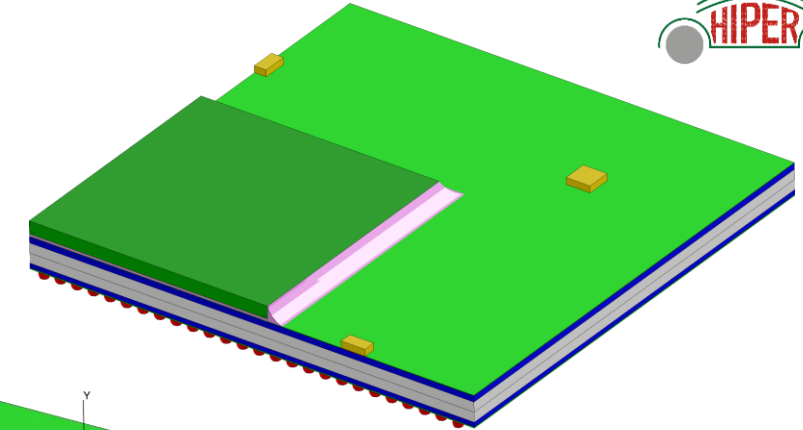
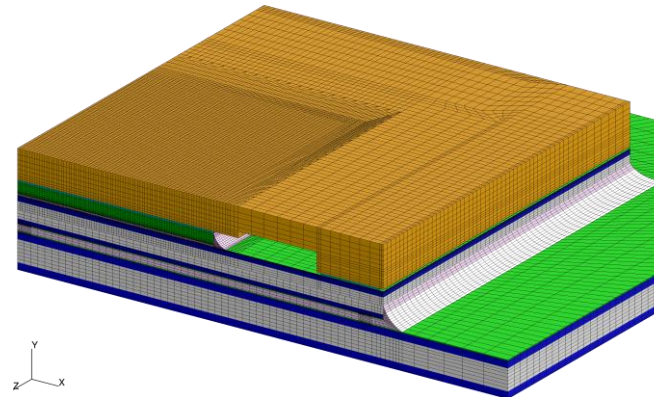


## Validation

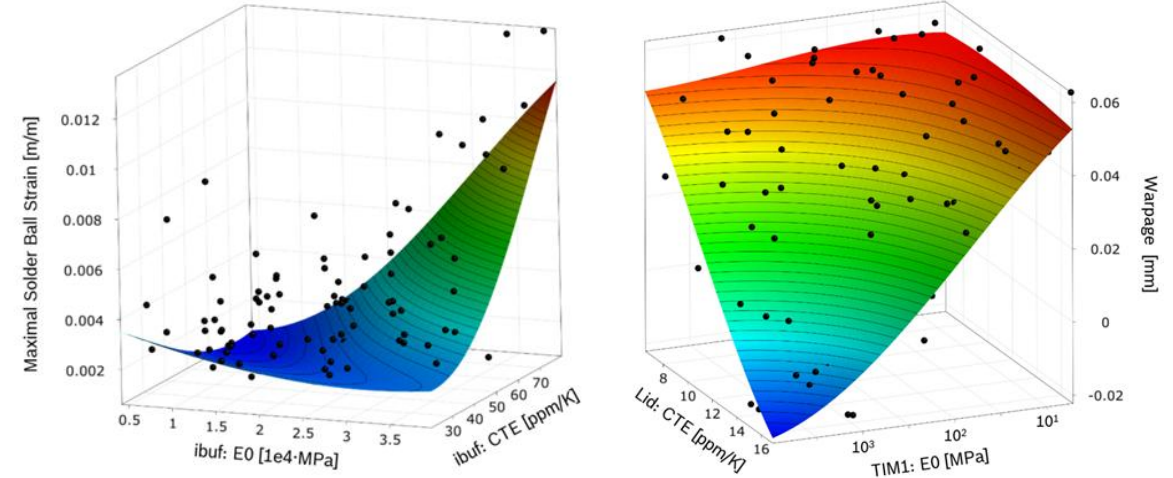
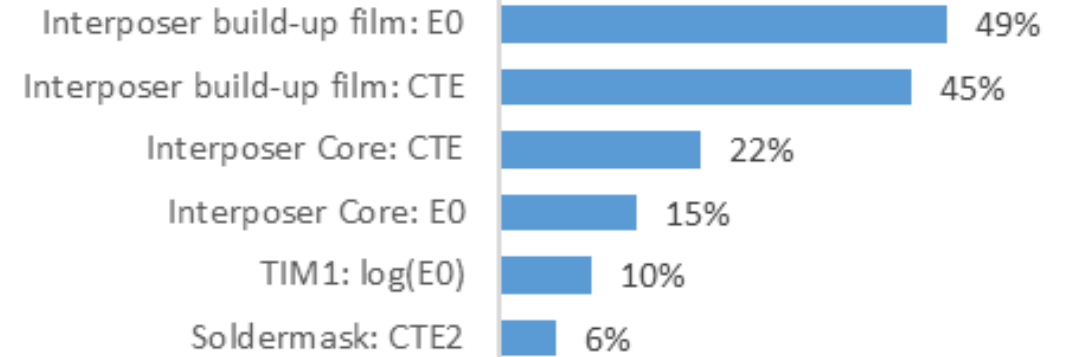
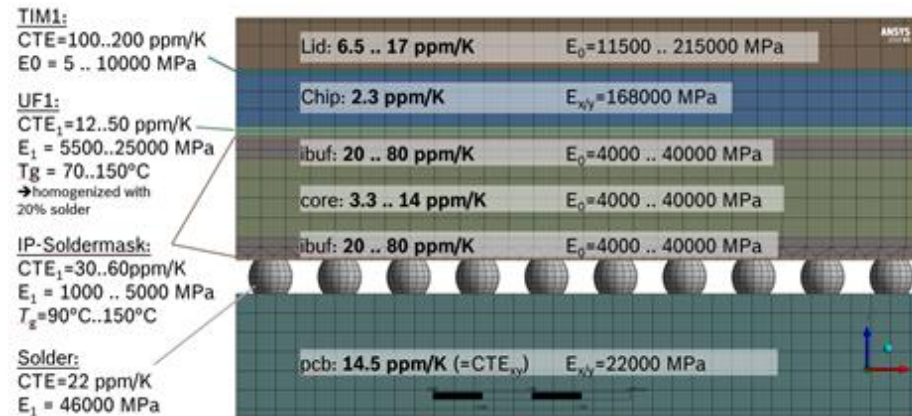


# How simulation helps?

- Building FEM parametric model
  - Virtual DoE – select materials
  - Material characterization and modeling
  - Validation of FEM model
  - Physics of failure simulations
- 
- In future:
    - Digital twin
    - Prognostics and health managements

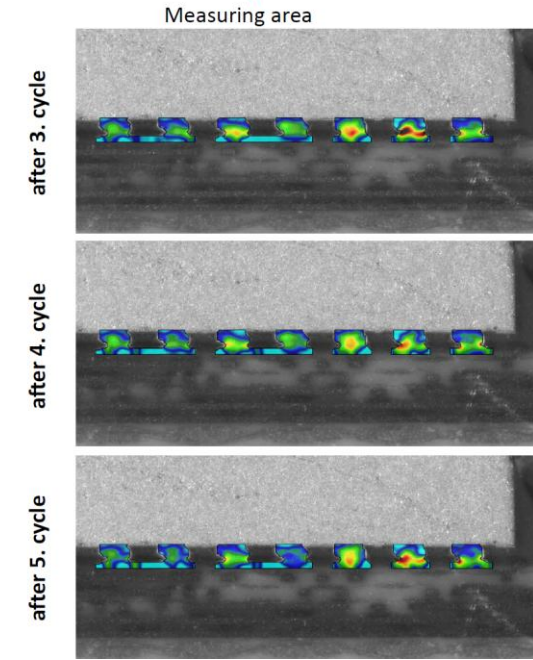
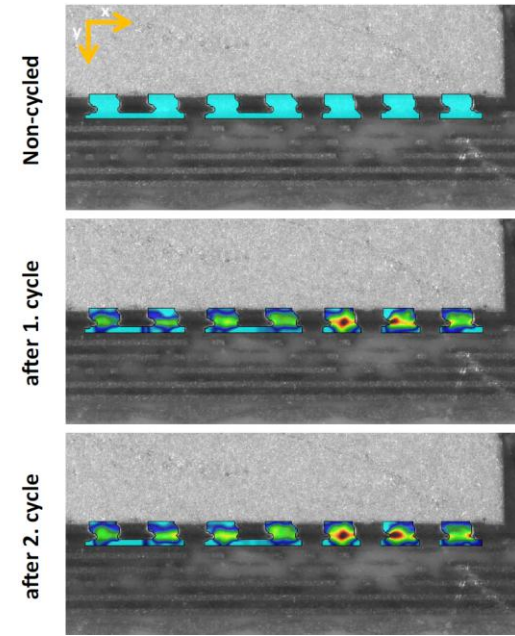
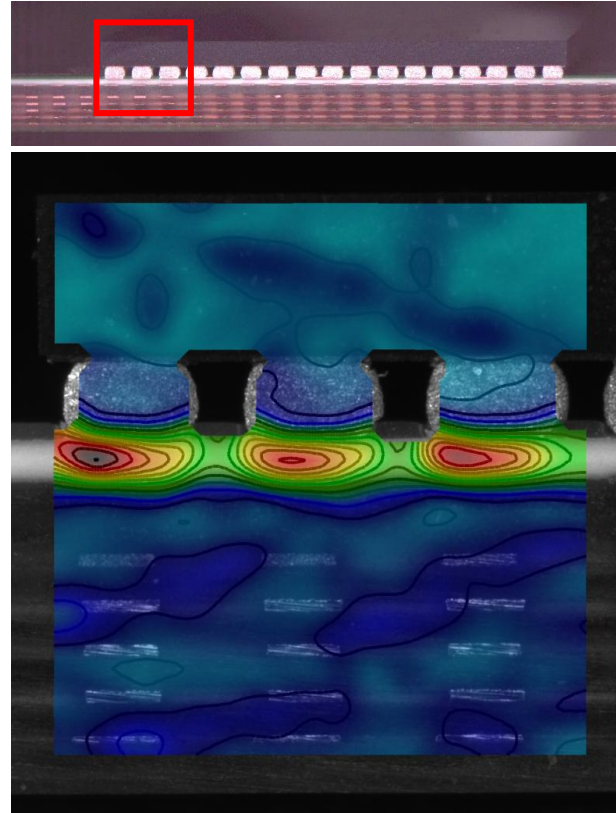
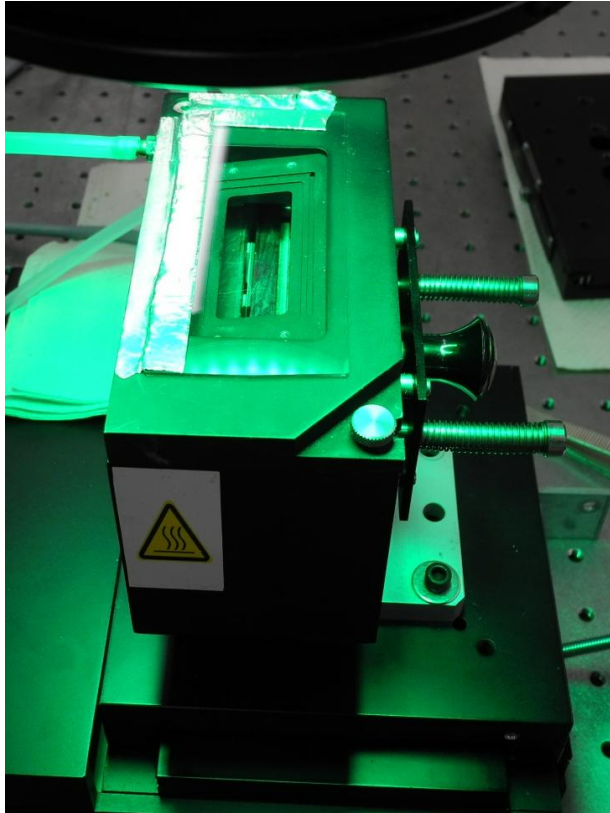


- Input variables for the virtual DOE with varied Tg, CTE and elastic modulus
- Output variable: maximal equivalent strain that occurs in the BGA of level 2 interconnects (solder balls)
  - Dominating influence on the solder ball strain: interposer construction
  - Max. influence: interposer build-up film

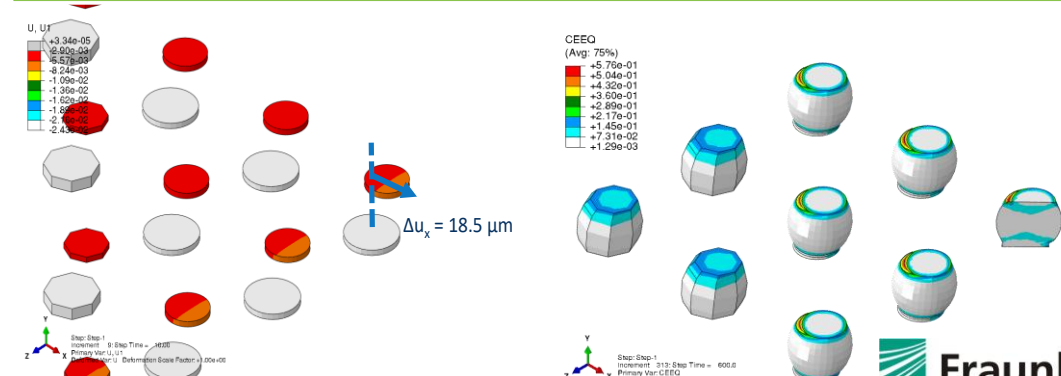
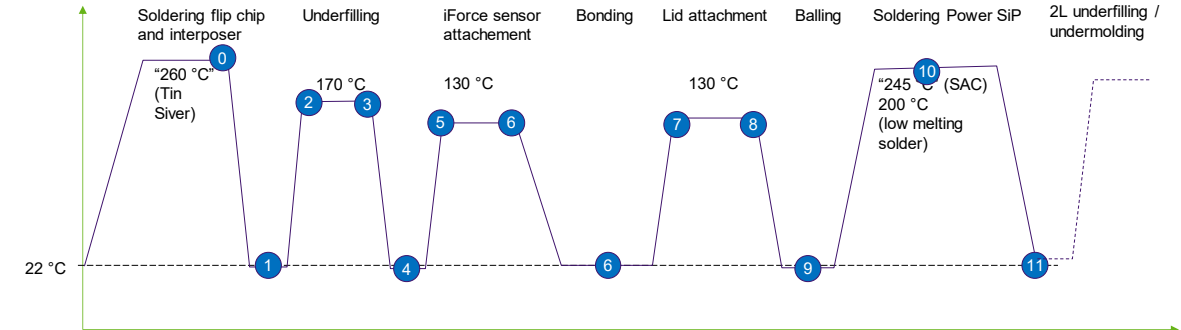
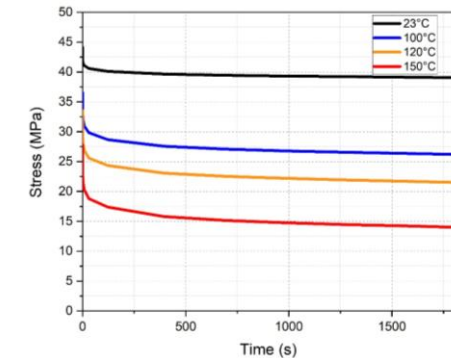
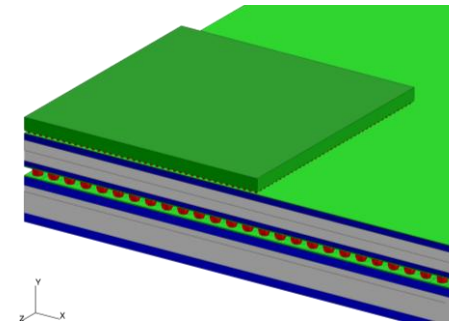


R. Dudek, R. Döring, S. Rzepka, P. Gromala, J. Schindele and B. Vandeveld, "Studies on Thermo-Mechanical Reliability of High Performance Vehicle Computers Based on a Mock-up System," 2021 22nd International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), 2021, pp. 1-12, doi: 10.1109/EuroSimE52062.2021.9410854.

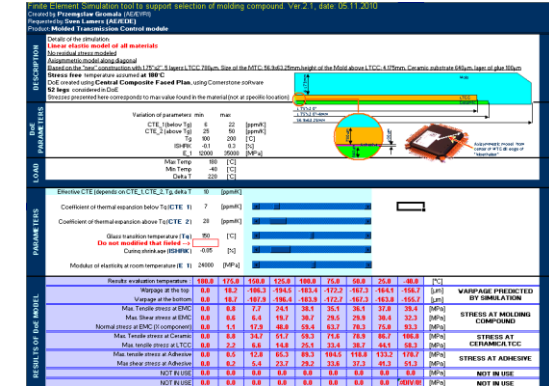
- Thermal deformation investigation of cross sections



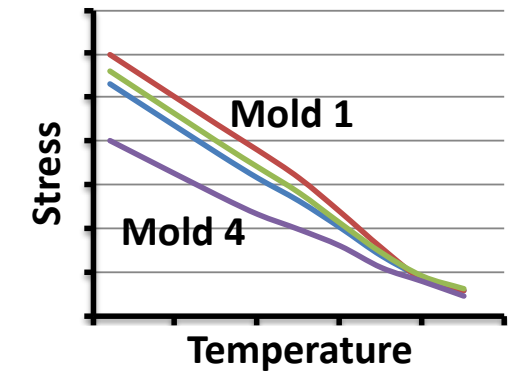
- Simulation can be predictable
  - Geometry
    - Cross-section, X-Ray, CT...
  - Materials
    - Visco-elasticity, visco-plasticity, rate independent plasticity, aging, interfaces...
- Loading and boundary conditions
  - Assembly, coupled domain, inhomogeneous temperature distribution...
- Evaluation criteria
  - Stress, strain, energy, work...
- Standardization
  - Element type, Load steps, SW tools...
- Simulation provide recommendation for robust design



- Virtual DoE → significantly accelerate the design process → lower development costs
- Selection of the molding compound can be supported by numerical simulation.
- Specific applications e.g. LTCC, PCB or DBC substrate require different molding compound → required properties can be defined before first prototype is manufactured
- Because selection of molding compound is done by process engineers → results of virtual DoE should be available in easy to use tool, e.g. in Excel



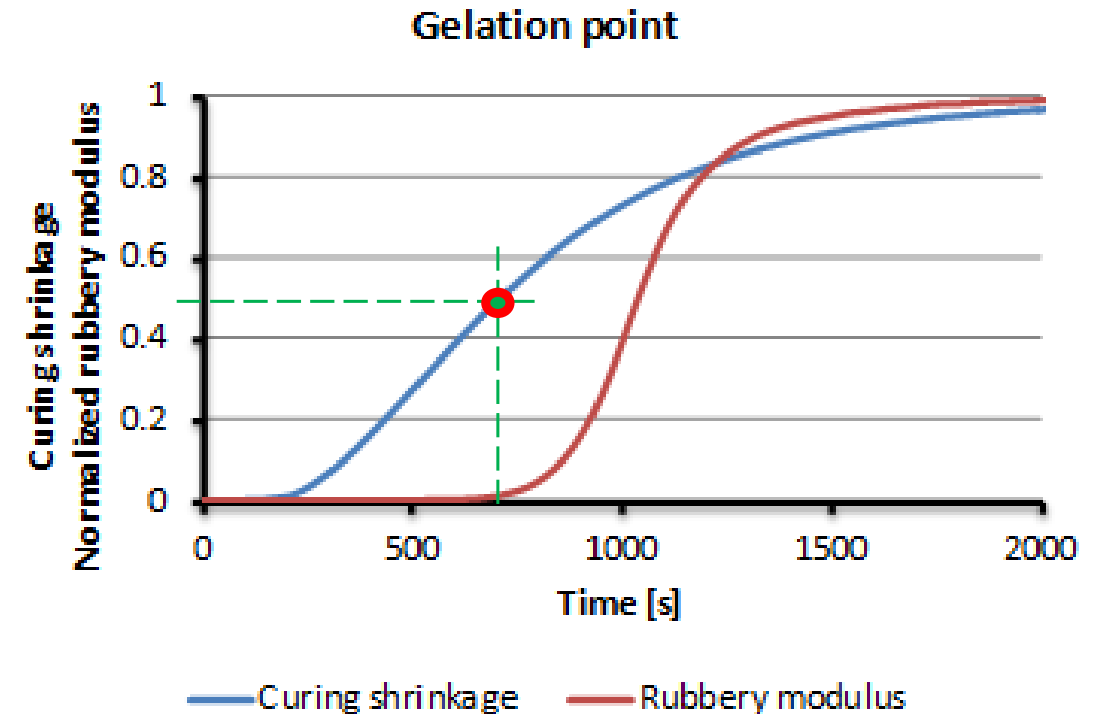
Virtual DoE provides qualitatively reliability prognosis before the first prototype is manufactured.



1. Introduction
2. Material Selection and Key Influencing Mechanisms
- 3. EMC Material Characterization Essentials**
  1. Curing Shrinkage
  2. Coefficient of thermal expansion
  3. Modulus of Elasticity
  4. Bulk Modulus
4. From Material Data to Simulation Models
5. Summary and Key Takeaway

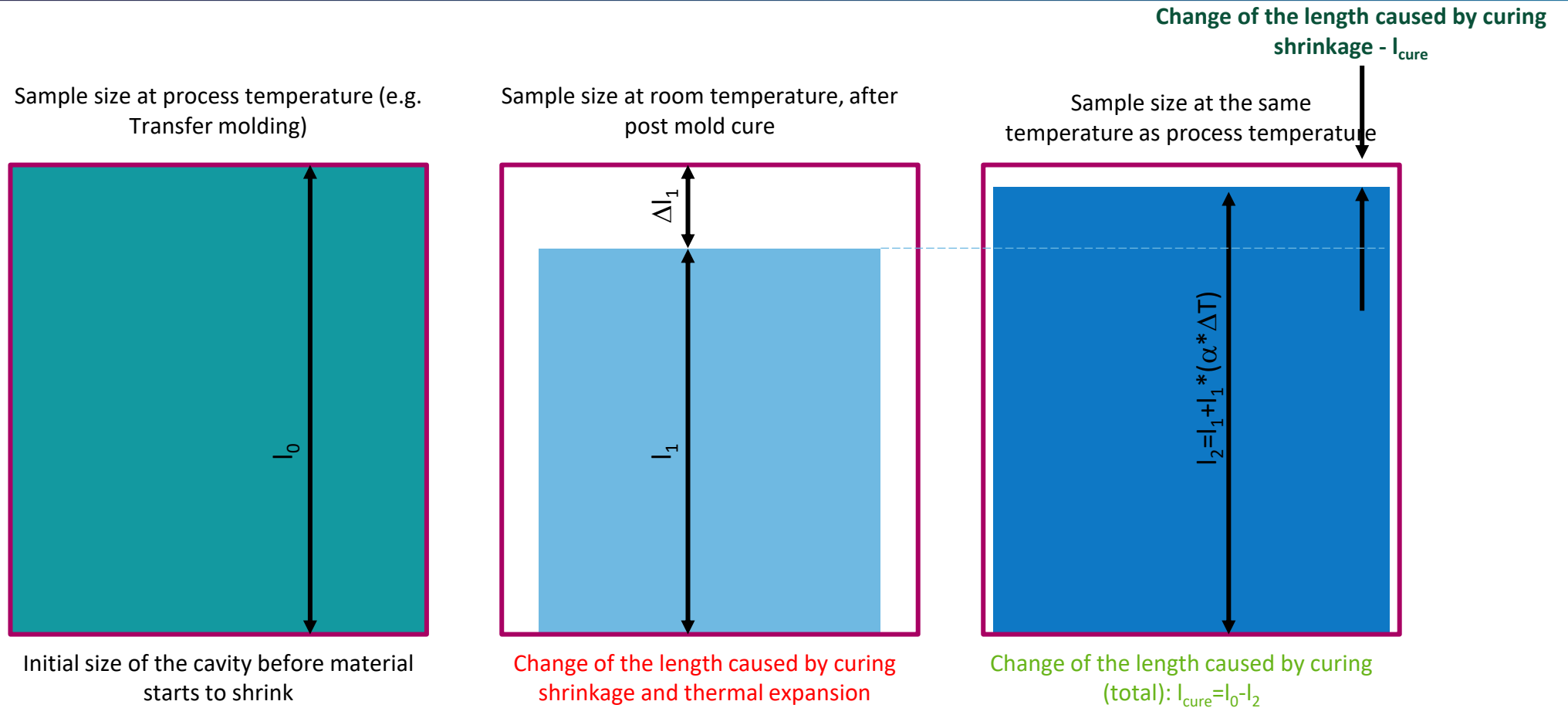
What do we need to quantitatively model material behavior?

- Curing shrinkage happens during polymerization process of epoxy based thermosets
- Curing shrinkage causes:
  - volumetric shrinkage → change of deformation
  - Modulus of elasticity increases with time → stresses
- Change of the deformation and stress build up happens only after gelation point



From thermo-mechanical point of view, only shrinkage after gelation point is important

# Mold shrinkage – what can we get from supplier

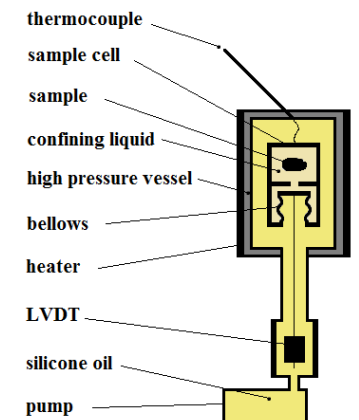
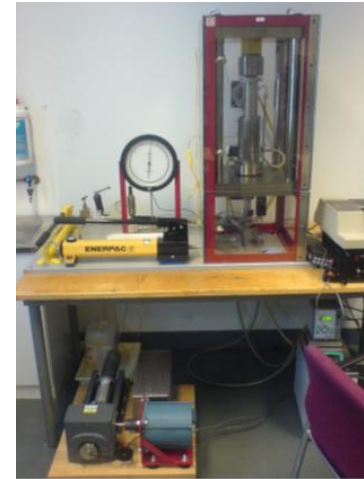
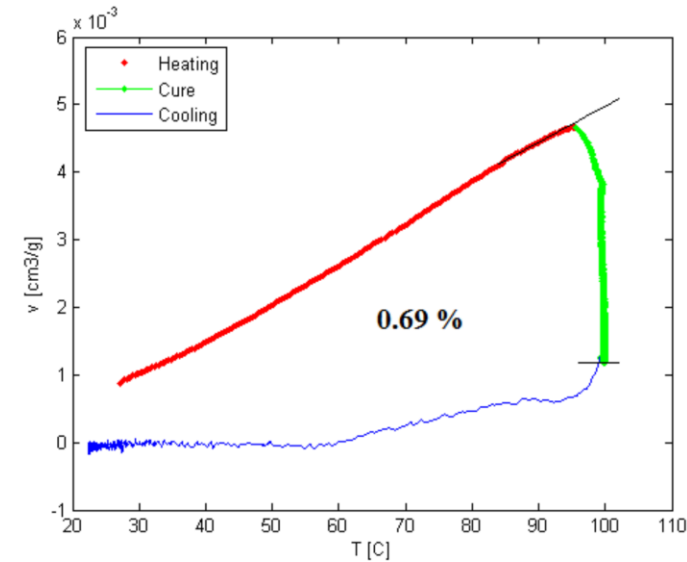


Mold shrinkage (ASTM D2566) → relative change of sample length in respect to mold dimension

\* ASTM. Standard test method for linear shrinkage of cured thermosetting casting resins during cure. ASTM D2566-79.

# Existing Techniques for Curing Shrinkage Measurement

- The routinely practiced technique for the chemical shrinkage measurement is the dilatometer [1], which measures the total chemical shrinkage.
- The bi-material strip can be used to measure the total effective shrinkage [2]; although the stress state can be measured directly, the results cannot be used to predict the residual stresses of the actual packaged devices.
- An **FBG-based method** was developed to measure the effective chemical shrinkage [3].
- Piezoresistive stress sensor

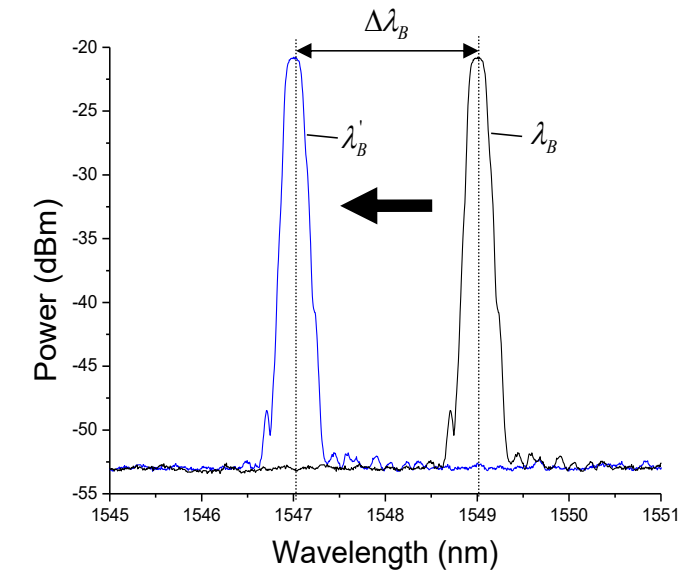
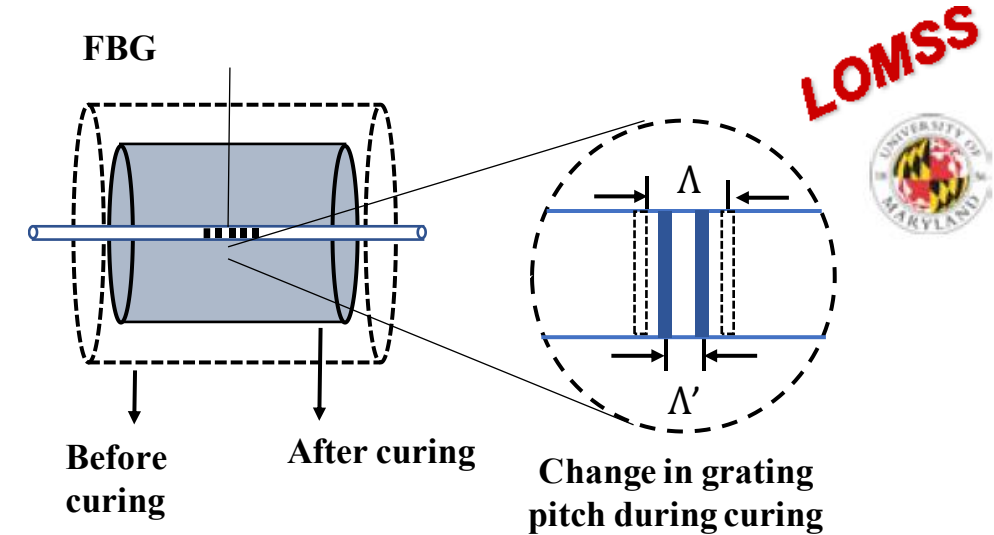


1. Y.-S. Chang, S.-J. Hwang, H.-H. Lee, and D.-Y. Huang, "Study of PVTC Relation of EMC," 2002.
2. W. Zhu, G. Li, W. Sun, F. Che, A. Sun, C. Wang, H. Tan, B. Zhao, and N. Chin, "Cure shrinkage characterization and its implementation into correlation of warpage between simulation and measurement," 2007.
3. Y. Sun, B. Han, E. Parsa and A. Dasgupta, "Measurement of Effective Chemical Shrinkage and Equilibrium Modulus of Silicone Elastomer Used in Potted Electronic System," Journal of Materials Science, Vol. 49, No. 24, pp. 8301-8310 (2014).
4. K. M. B. Jansen, M. Hawryluk, P. Gromala, "Cure dependent characterisation of moulding compounds", Proceedings of the 2011 12th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Linz, Austria, 18-20 April, 2011.

- When a polymer is cured around a fiber, the FBG is compressed axially as the polymer shrinks; the FBG acts like an **optical strain gauge** – the Bragg wavelength changes with the **pitch of this grating**.
- This can be directly used to measure the strain during the evolution of chemical shrinkage and elastic modulus. The governing equation for the wavelength change:

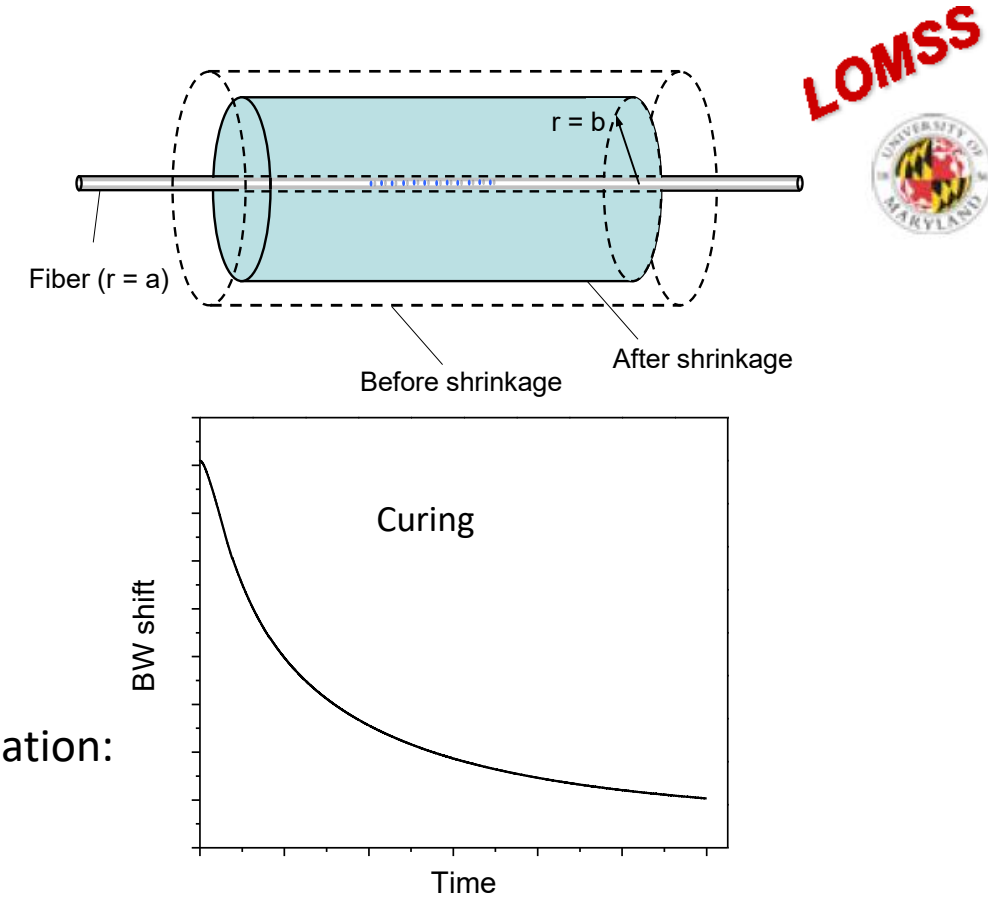
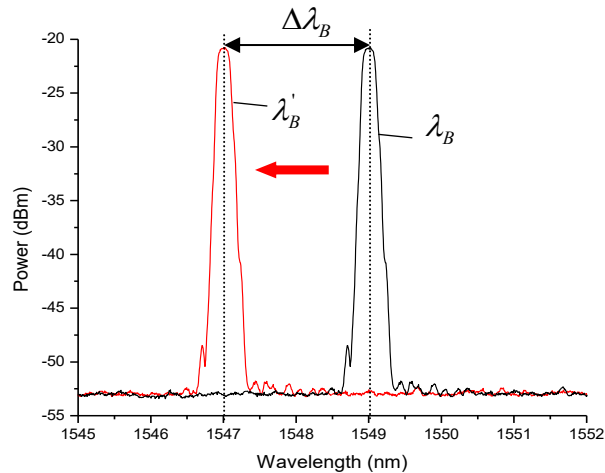
$$\Delta\lambda_b = F(E_s, \beta, \varepsilon_{ch}^{eff})$$

$E_s$  : Modulus at a given instant  
 $\beta$  : Radius ratio of polymer to fiber  
 $\varepsilon_{ch}^{eff}$  : Effective chemical shrinkage



# How to Measure Effective Chemical Shrinkage using FBG?

- A polymer of interest is cured around a glass FBG and the BW shift is documented while curing progresses.



LOMSS



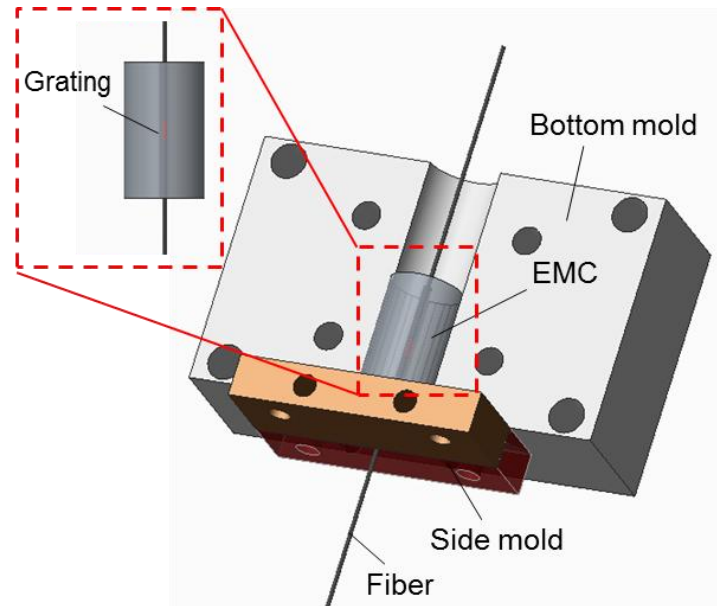
The effective chemical shrinkage can be calculated by the governing equation:

$$\lambda_B = F(E_\infty, \beta) \varepsilon^{eff}$$

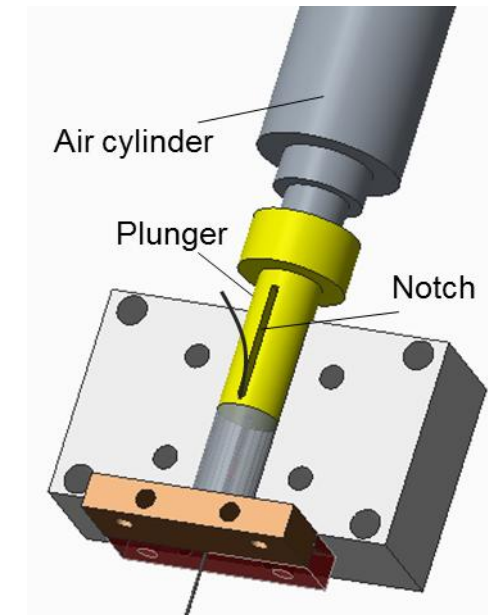
The material properties can be inversely calculated from the measured “deformation” induced BW shift based on the analytical relationship between BW shift and material properties.

# Preparation of EMC Specimen

EMC pellet with a fiber placed at  
the center of the mold



The plunger placed right on  
the specimen

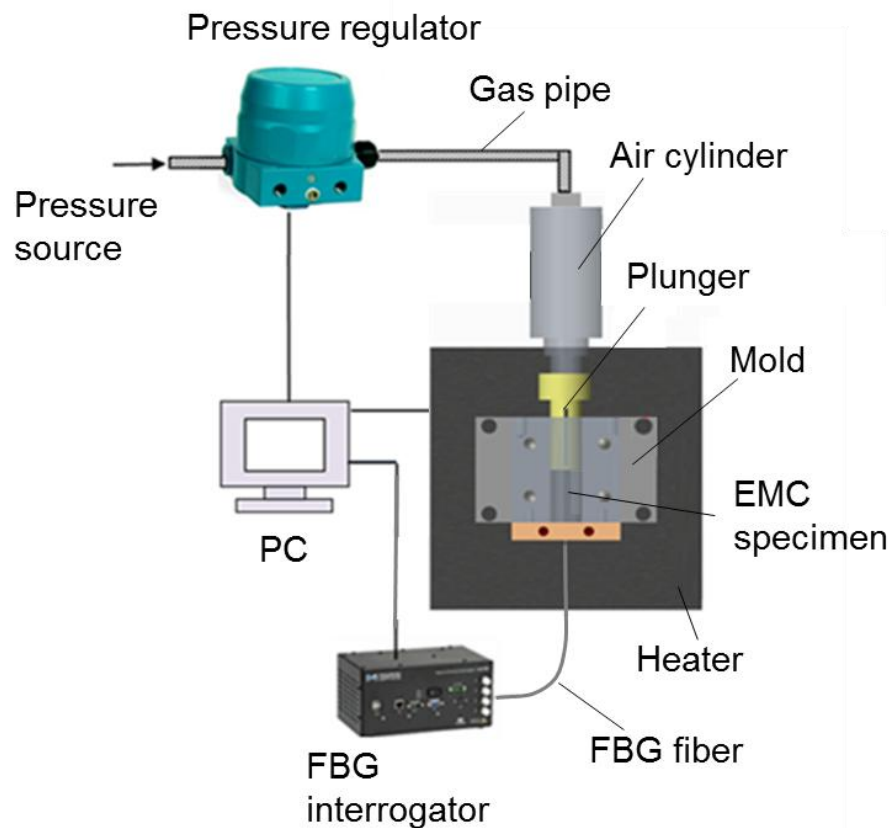


LOMSS

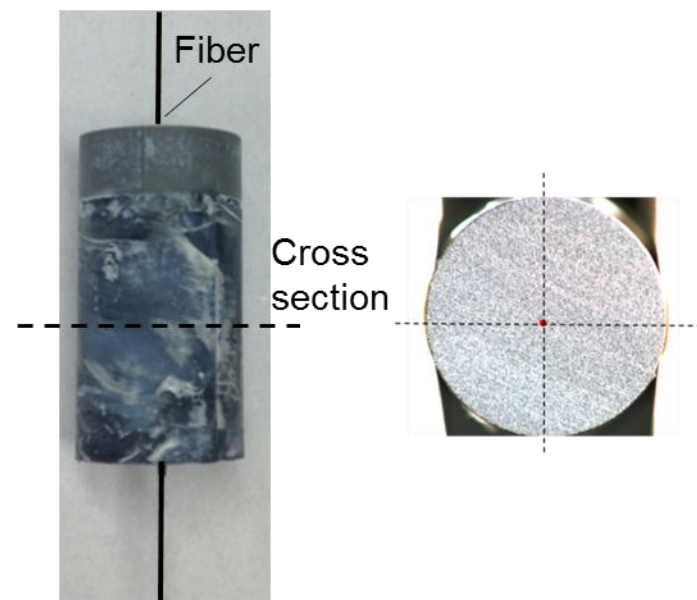


Y. Sun, H.-S. Lee, and B. Han, "Measurement of Elastic Properties of Epoxy Molding Compound by Single Cylindrical Configuration with Embedded Fiber Bragg Grating Sensor," *Experimental Mechanics*, Vol. 57, pp. 313–324, (2017).

# Fabricated EMC Specimen



Cured specimen



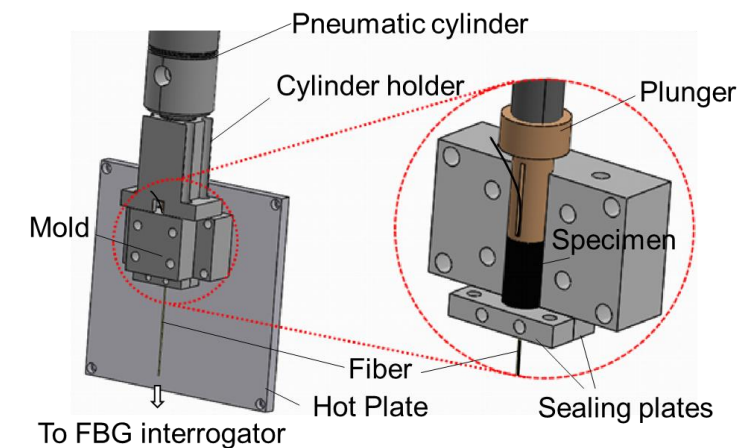
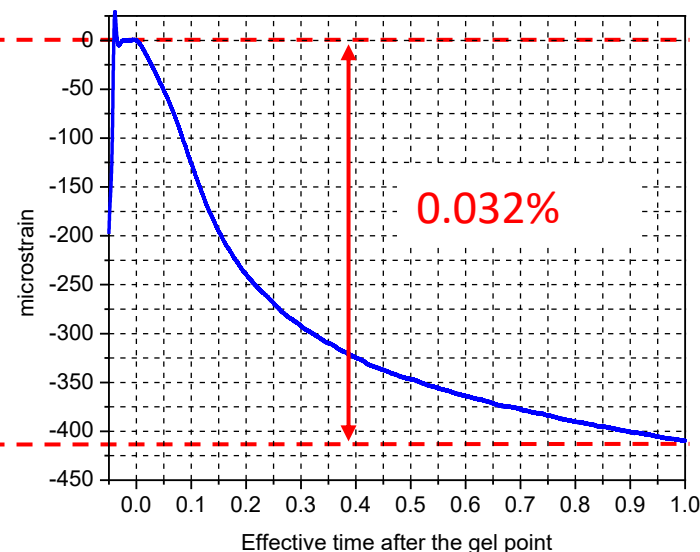
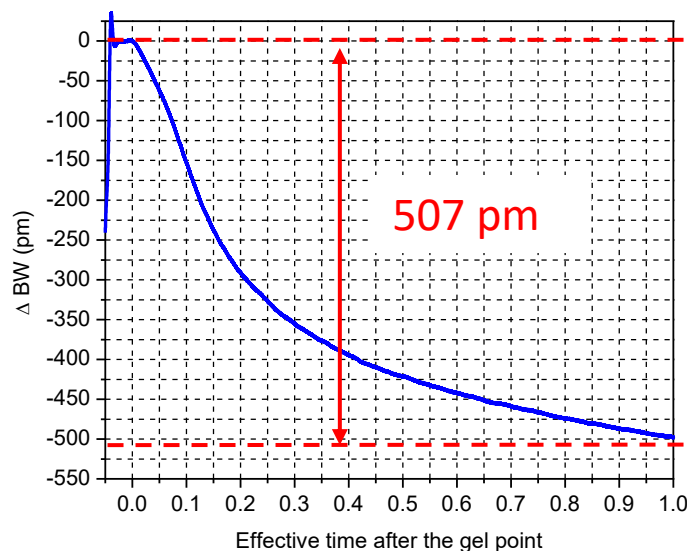
LOMSS



# Results of Effective Chemical Shrinkage Measurements of EMC

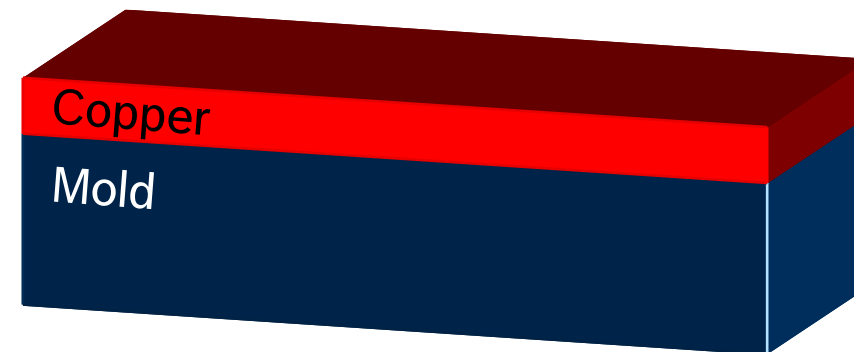
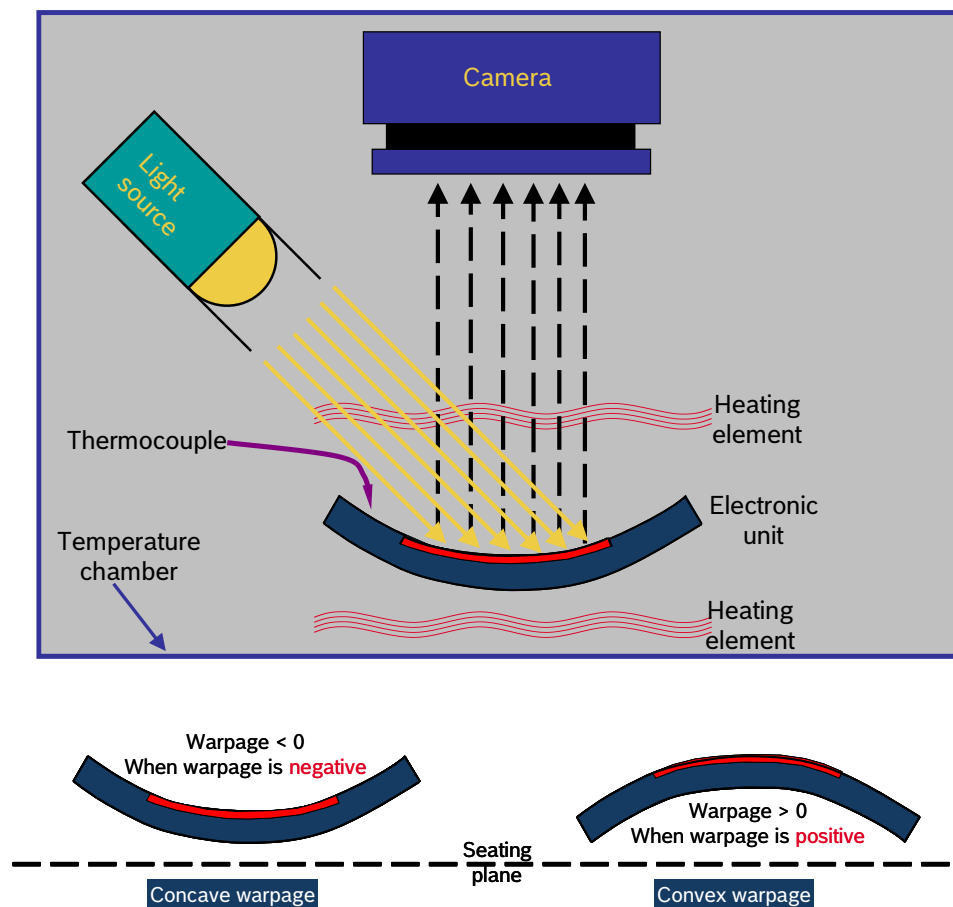
- The measurement was made at 125° C to ensure the condition of “infinite configuration”.
- The pressure was removed before EMC reached the gel point.

LOMSS



C. Kim, S. Phansalkar, H.-S. Lee, and B. Han, “Mold Shrinkage, Chemical Shrinkage or Both?,” *Proceedings of 2019 IEEE 69th Electronic Components and Technology Conference*, Las Vegas, NV, May 29 - 31, 2019.

# Validation – fringe pattern technique

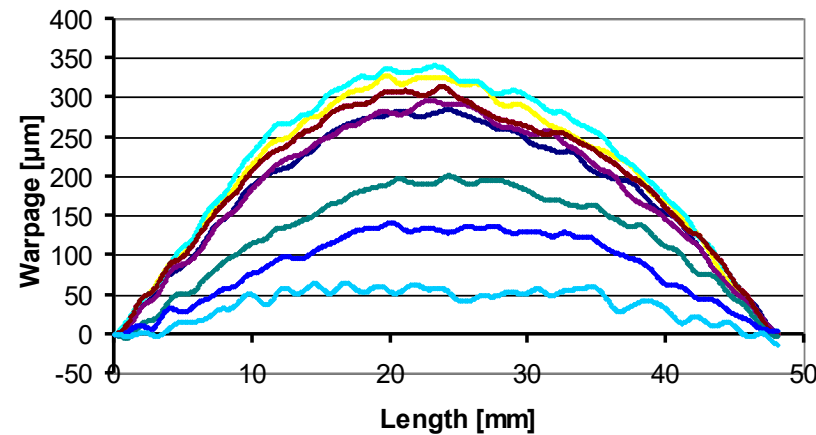


|                         | Length<br>[mm] | Width<br>[mm] | Thickness<br>[mm]         |
|-------------------------|----------------|---------------|---------------------------|
| Sample 1<br>(reference) | 50             | 9             | EMC: 2.0 mm<br>Cu: 0.4 mm |
| Sample 2                | 50             | 9             | EMC: 0.6 mm<br>Cu: 0.4 mm |
| Sample 3                | 50             | 9             | EMC: 0.6 mm<br>Cu: 0.2 mm |

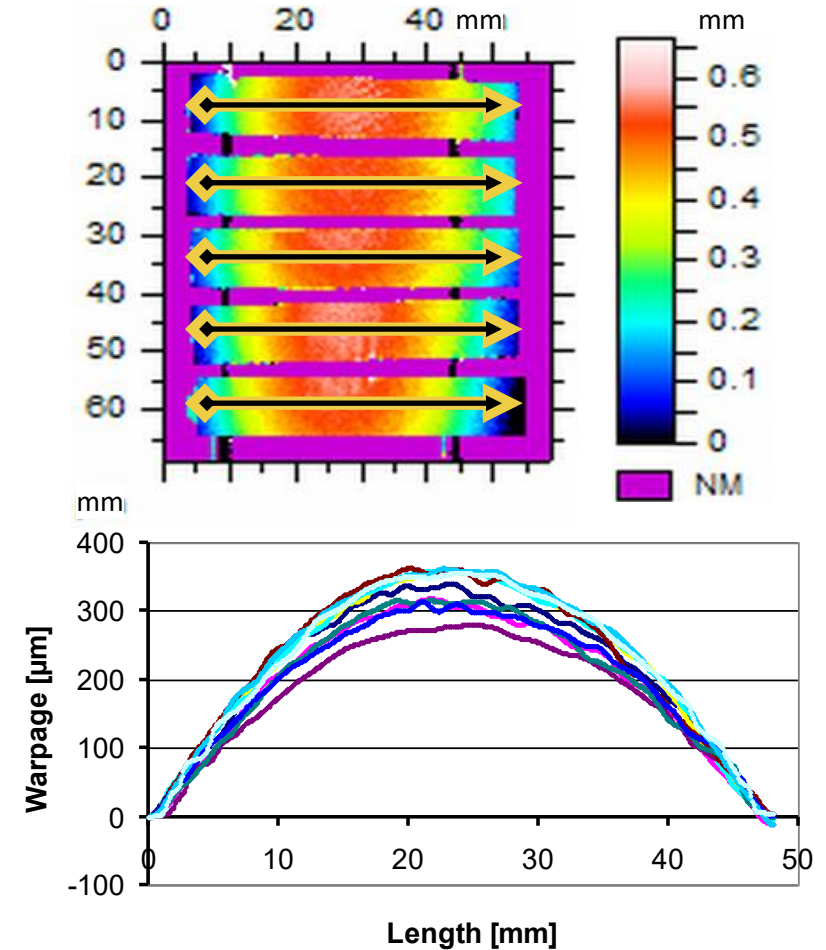
P. Gromala, J. Duerr, M. Dressler, K. M. B. Jansen, M Hawryluk, J. de Vreugd, “Comprehensive material characterization and method of its validation by means of FEM simulation”, Proceedings of the 2011 12th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Linz, Austria, 18-20 April, 2011.

# Validation – warpage experiment

- 10 samples per material
- 5 sample per one run
- From 25...225...25°C
- Every 25K
- Ramp rate 2K/min



• T=25°C • T=50°C • T=75°C • T=100°C • T=125°C  
• T=150°C • T=175°C • T=200°C • T=225°C

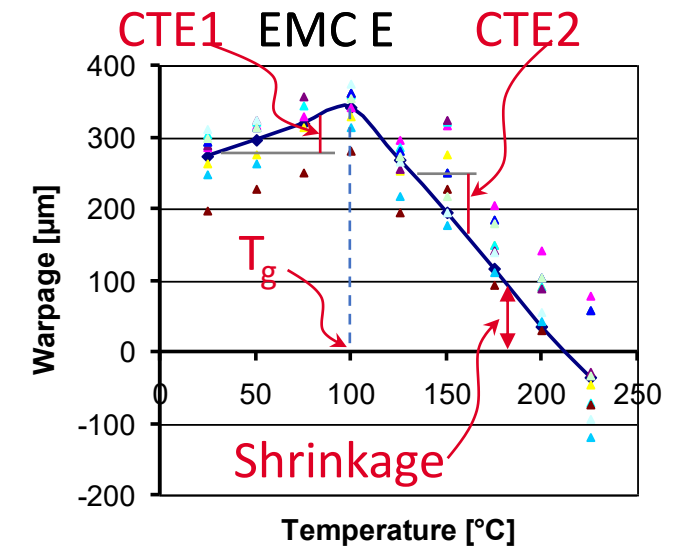
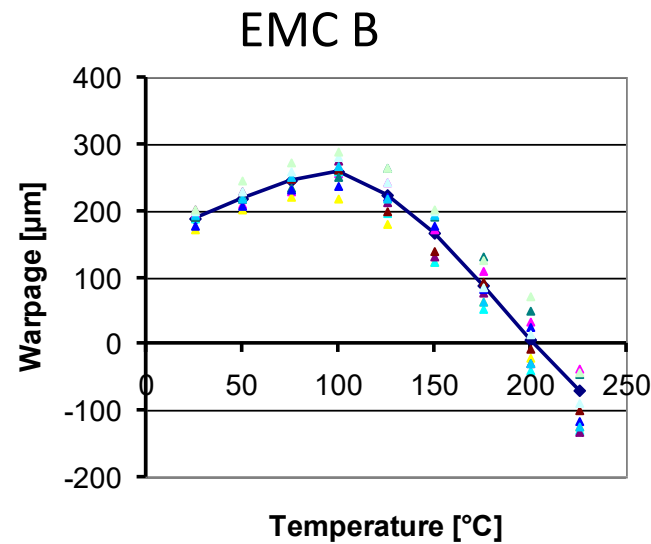
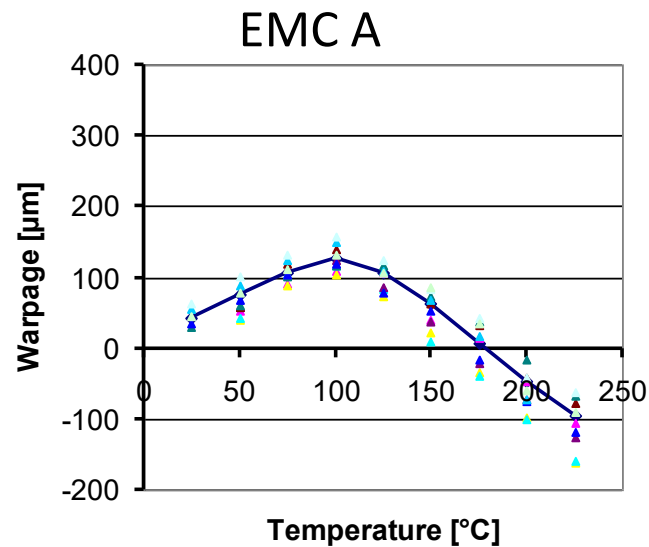
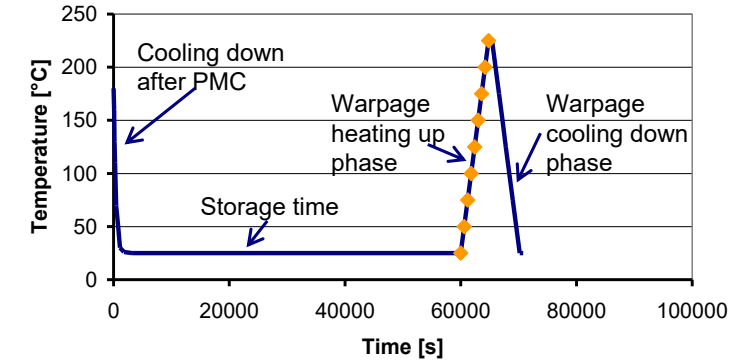


• Sample 1 • Sample 2 • Sample 3 • Sample 4 • Sample 5  
• Sample 6 • Sample 7 • Sample 8 • Sample 9 • Sample 10

# Validation – extraction of parameters

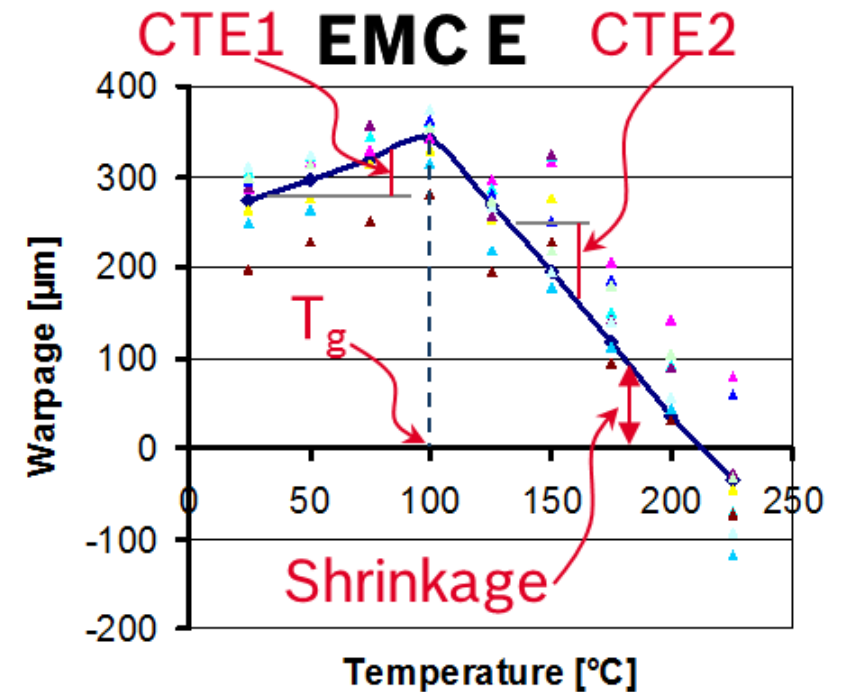
- Goal: minimize error between average warpage of studied samples and calculated by FEM
- FEM: residual stresses implemented

Load profile used in FEM simulation



# Curing shrinkage – implementation in FEM code

- There are four methods approaches commonly used to implement curing shrinkage in FEM code.
- Pre-strain
  - Increase of the CTE of epoxy based thermoset at curing temperature
  - Warpage free temperature as stress free temperature for entire construction
- Shift of reference temperature for epoxy based thermoset
- Swelling
- Direct implementation (only some FEM codes or through user defined model)



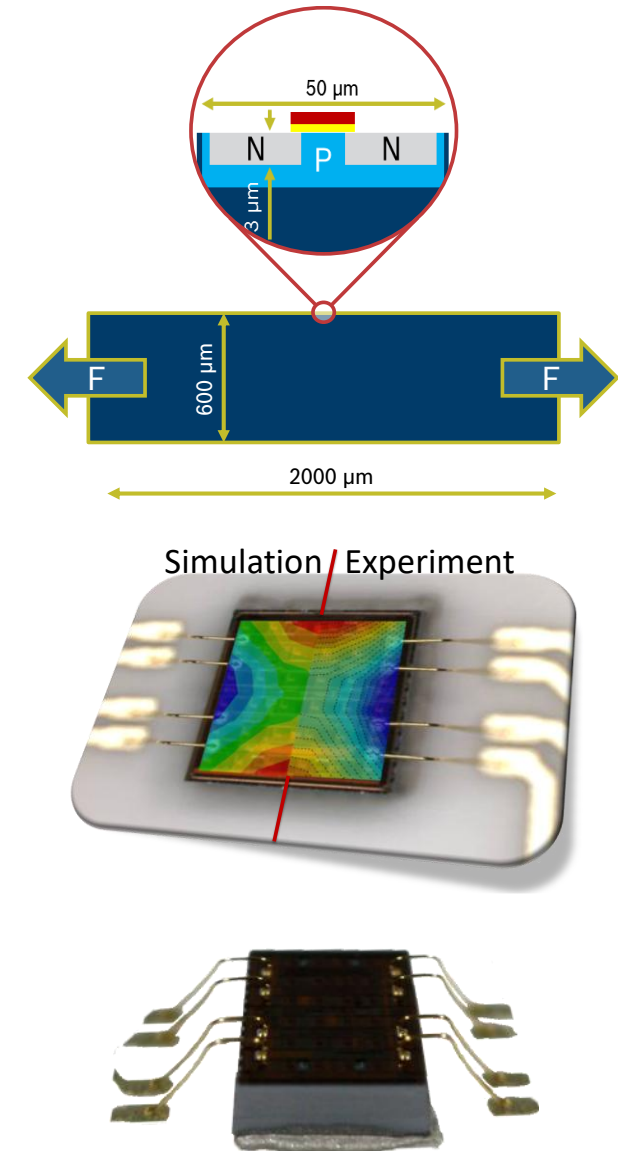
## Piezoresistive silicon based stress sensor: IForce – in-situ measurements of the stress state inside IC package

- Localized mechanical stress measurements during active operation and field condition
- Detection of the crack/delamination during active operation and field condition of the ASICs ad power module
- Understanding the state of health: healthy / unhealthy
- Damage evolution using direct damage relevant quantity:
  - Mechanical stress difference;

$$\sigma_D = (\sigma_x - \sigma_y) \approx \frac{2}{\pi_{44}^{(p)}} \frac{I_{out} - I_{in}}{I_{out} + I_{in}}$$

- Shear stress.

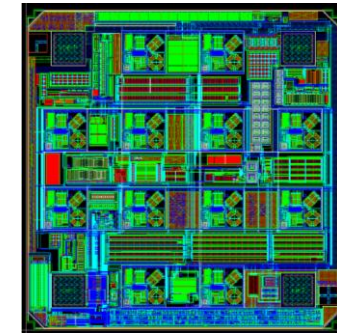
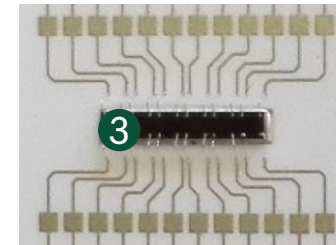
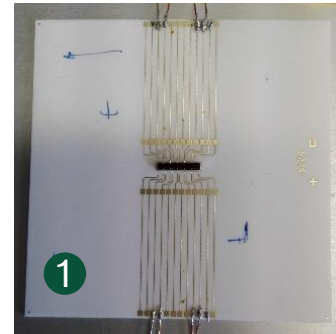
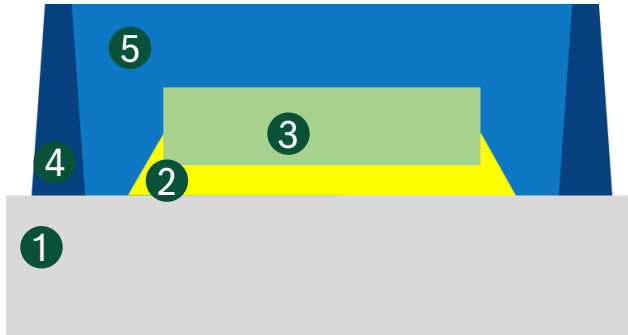
$$\sigma_{xy} \approx \frac{-1}{\pi_{11}^{(n)} - \pi_{12}^{(n)}} \frac{I_{out} - I_{in}}{I_{out} + I_{in}}$$



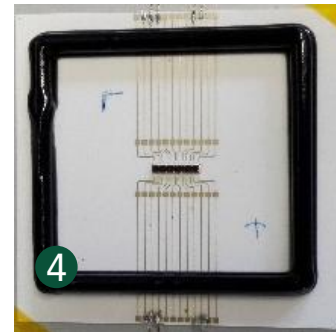
Silicon chip on  
ceramic substrate

Five sensors

In one sensor 12 stress  
sensing cells



- ① LTCC
- ② Die attach
- ③ iForce
- ④ DAM
- ⑤ Epoxy



After DAM  
dispensing

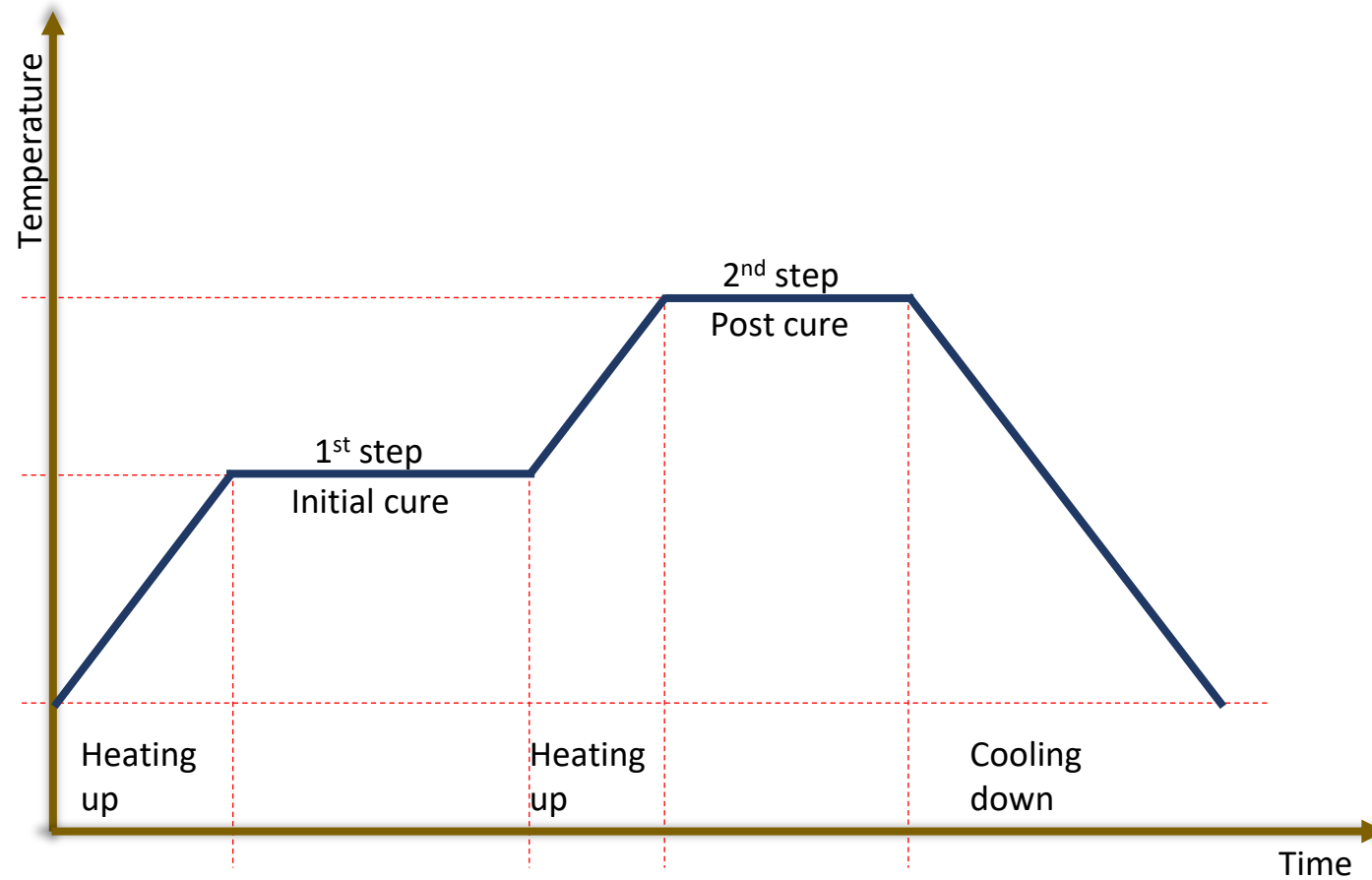


Before curing

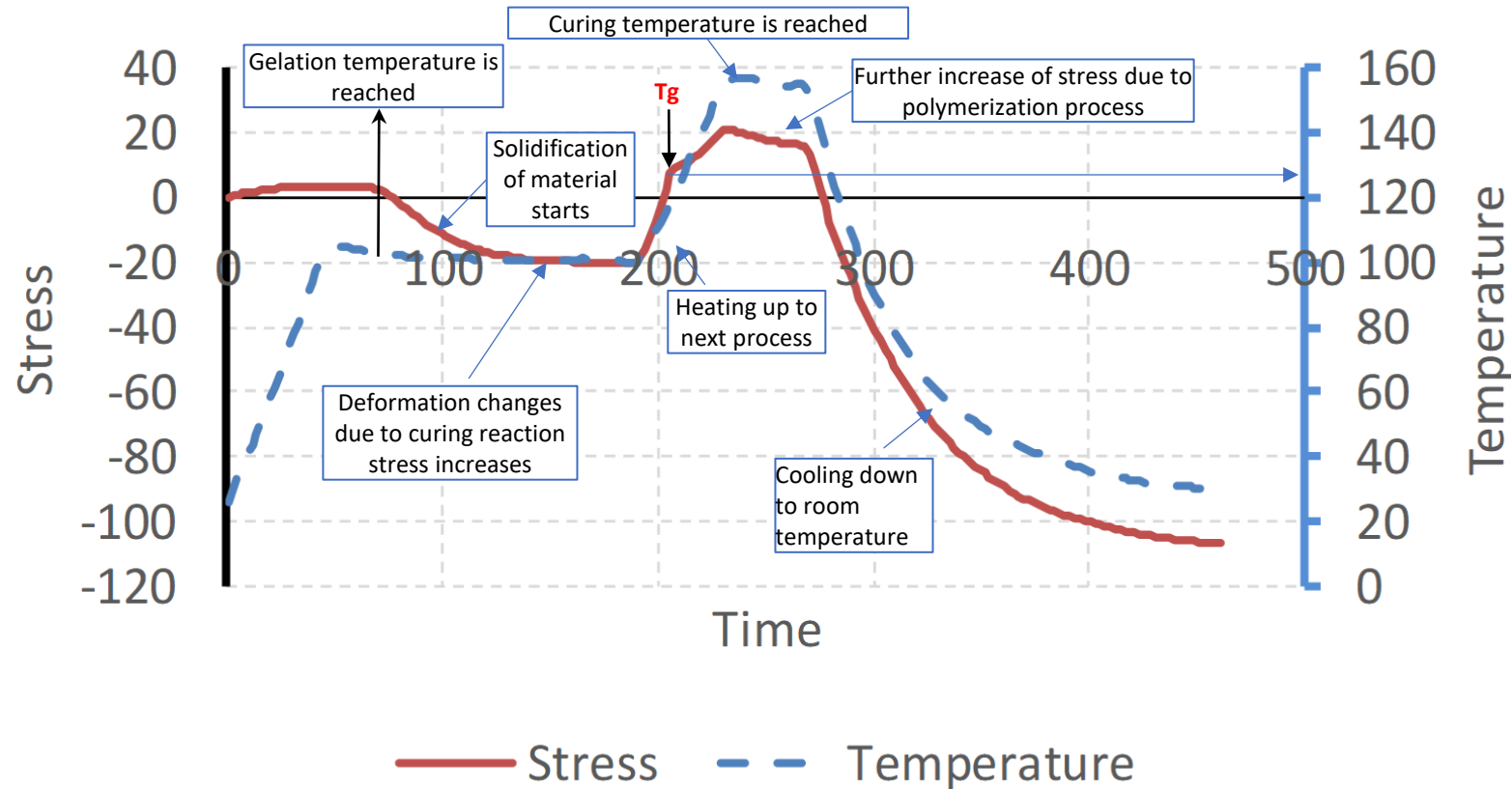


After curing

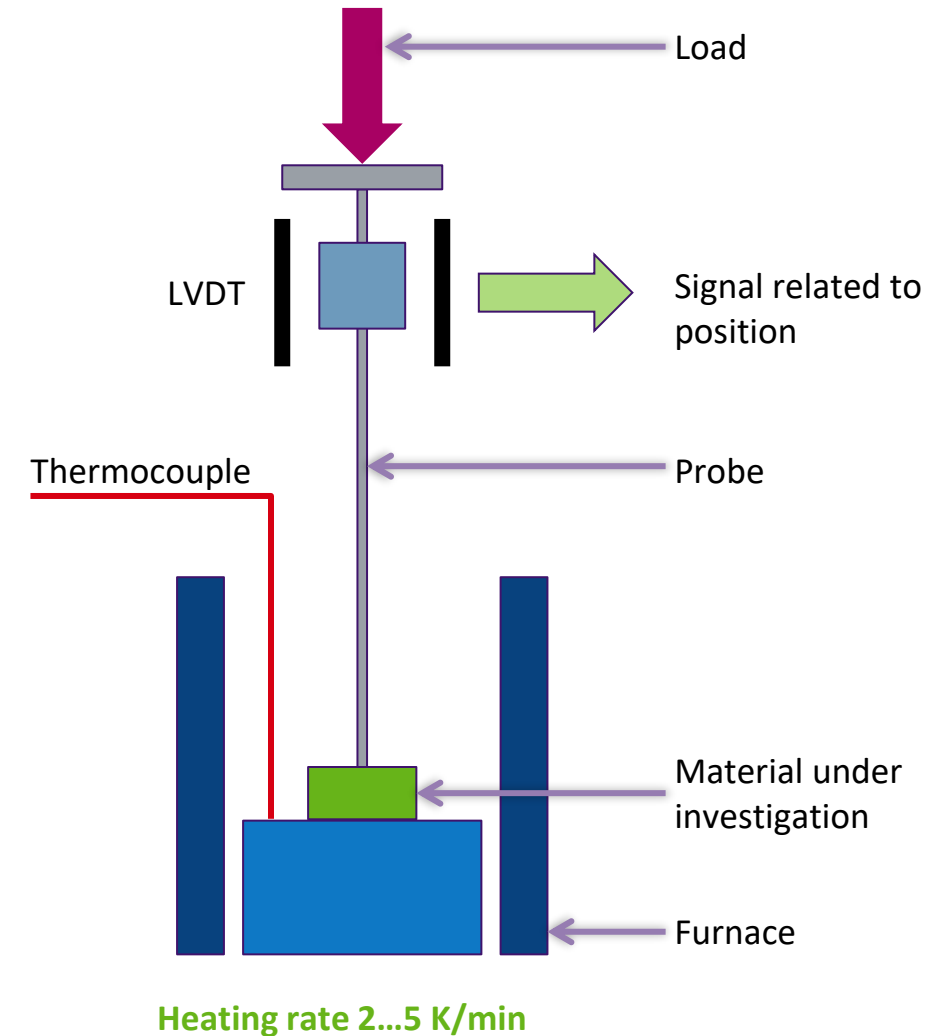
# Curing profile



# Stress induced during curing process

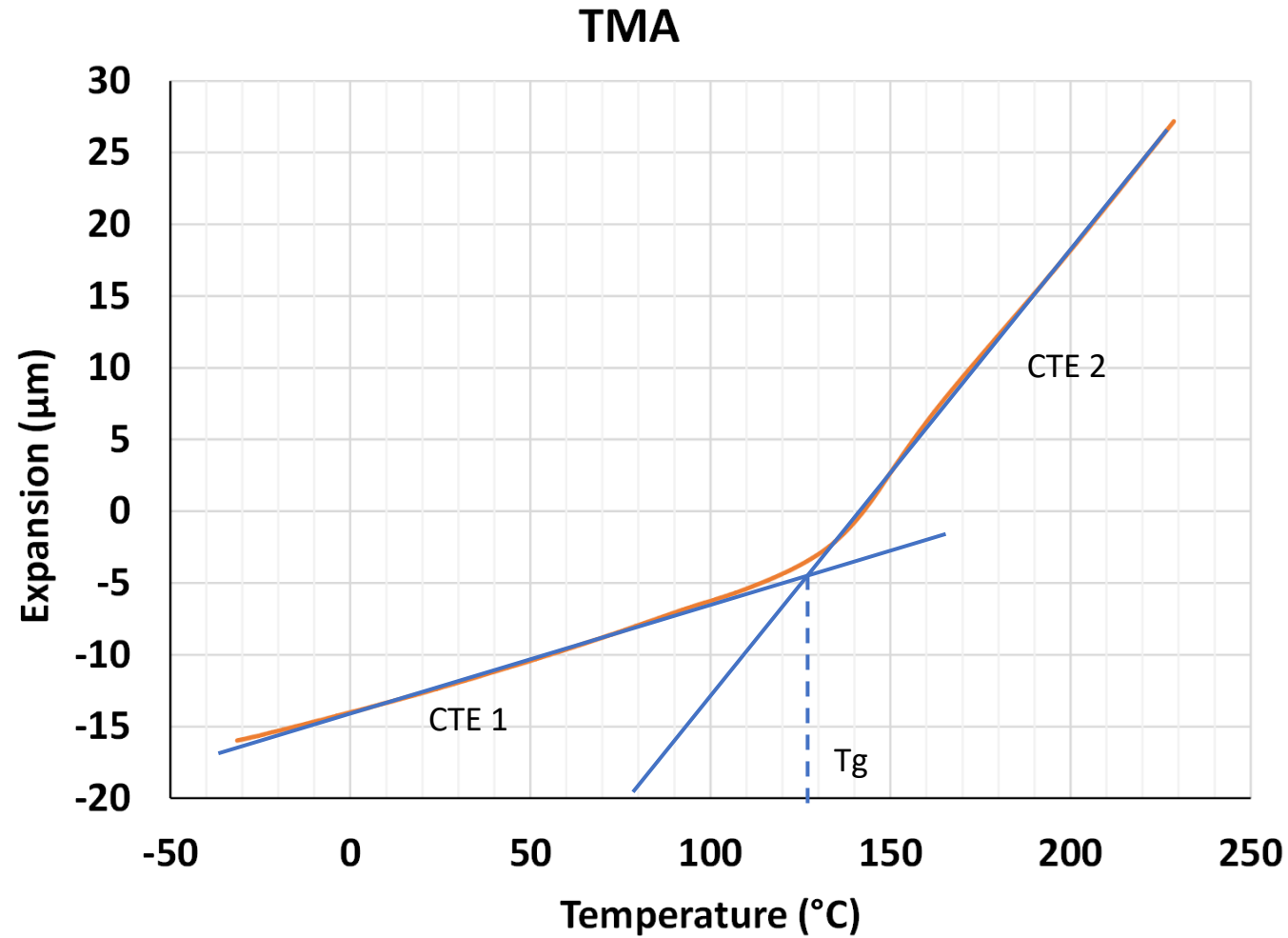


- CTE describes how the size of the sample changes with the temperature
- Most materials have different CTE
- If materials are joined together
  - Warpage → major challenge in microelectronics
  - Mechanical stress
    - In bulk
    - At the interface
- Measurements according to ASTM norm (D696 & E831)
  - Sample pre-conditioning (check manual)
  - Measurements during second heating
  - Thickness of the sample (2...10 mm)
  - Applied load must be negligible → only to provide contact



ASTM E1545 - 11(2016): Standard Test Method for Assignment of the Glass Transition Temperature by Thermomechanical Analysis

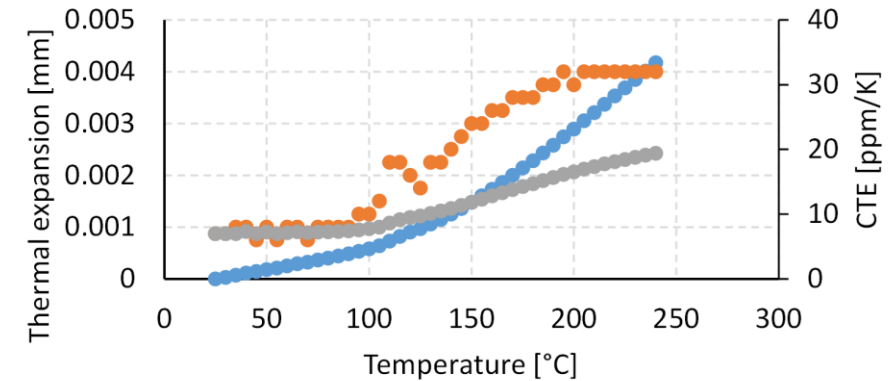
# Typical curve



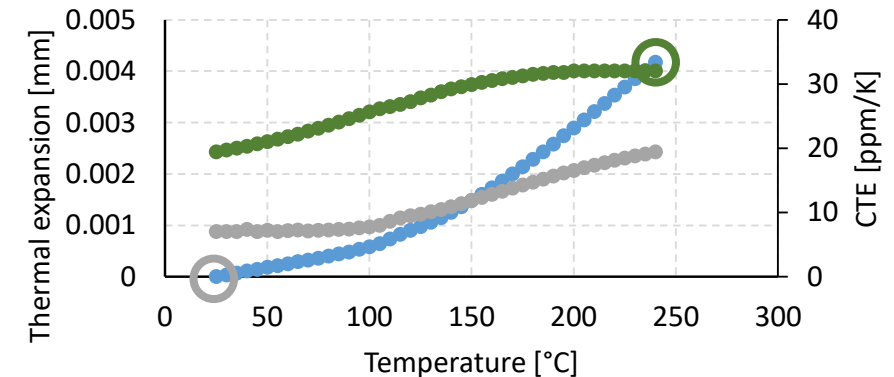
# How we can implement CTE in FEM code

- In Ansys CTE can be defined as:
- Thermal strain (**THSX**)
- Instantaneous coefficient (**CTEX**)
- Secant coefficient (**ALPX**)
  - **MPAMOD,MAT\_NUMB,T<sub>0</sub>**
- All methods provide accurate results
- For epoxy based thermosets, in the data sheet, typically instantaneous coefficient is defined e.g.:
  - **CTE<sub><T<sub>g</sub></sub>=7 ppm/°C, CTE<sub>>T<sub>g</sub></sub>=32 ppm/°C, T<sub>g</sub>=125°C**
- For metals, in the data sheet, CTE is quite often defined as secant coefficient e.g.:
  - **CTE<sub>(20-200)</sub> = 12 ppm/°C**

Definition of thermal expansion in Ansys



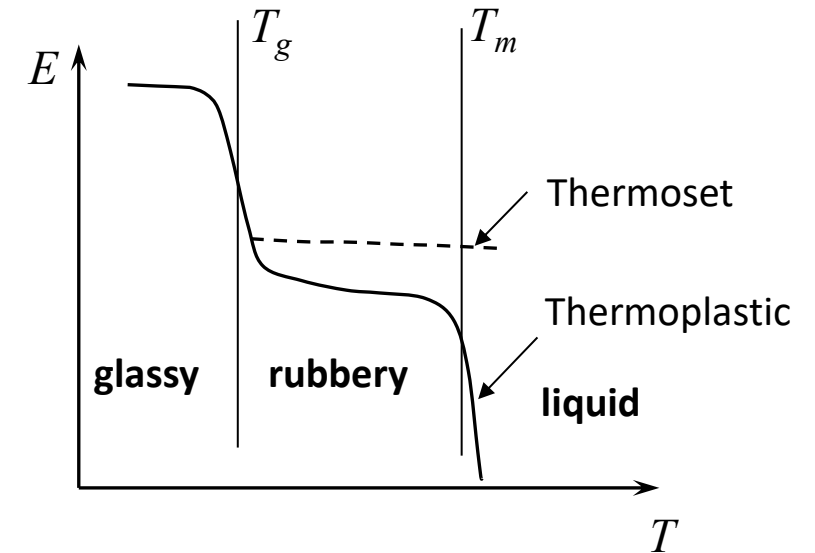
Definition of the CTE using secant coefficient



● Thermal expansion ● Reference at 240°C ● Reference at 25°C

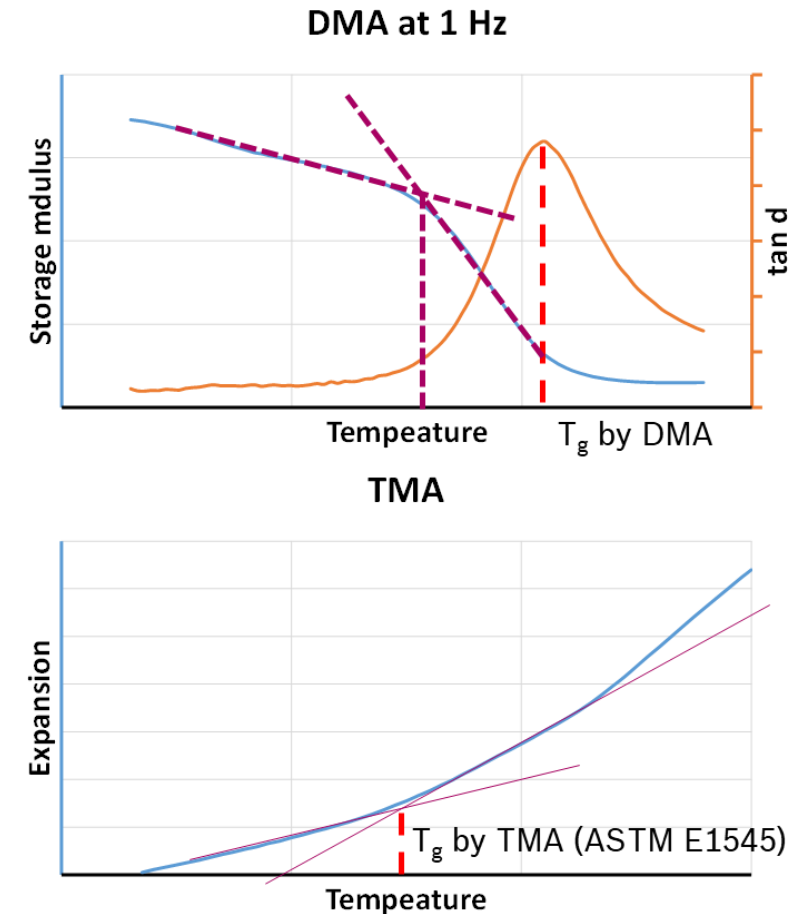


- The glass transition is a reversible transition of polymer material from a hard and relatively brittle state to a molten rubber like state; this temperature can also be defined as the temperature at which the forces holding distinct segments together are overcome by thermally-induced motions.
- Glass transition temperature  $T_g$ : from glassy state to rubber-like state;
- Melting temperature  $T_m$ : from rubber-like to liquid state (for thermoplastic only)



Glass transition temperature – temperature region in which polymer transition from glassy material to rubbery material

- **NOT A FIXED POINT...**
- Different measurements methods (DMA, TMA, DSC...) will lead to different values → difference can be as high as 30 °C
- Even the same DMA produces different  $T_g$  depending upon the frequency → the higher frequency is the higher  $T_g$
- The ASTM E1545 standard describes a method to extract  $T_g$  from a TMA measurement.
- $T_g$  shift during moisture absorption as well as aging of material

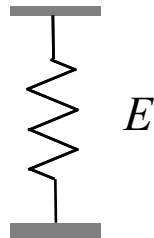


Always ask how it was measured and defined

- Elasticity
  - the property of materials that deform reversibly under stress
- Viscoelasticity
  - the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation
- **Linear viscoelasticity can be modeled by the combination of the spring and dashpot for small deformation.**

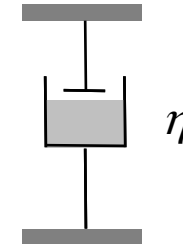
## Stress by elasticity

$$\sigma = E\varepsilon$$

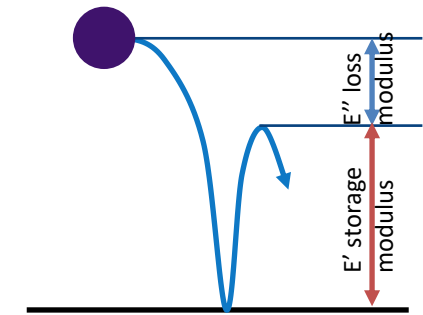
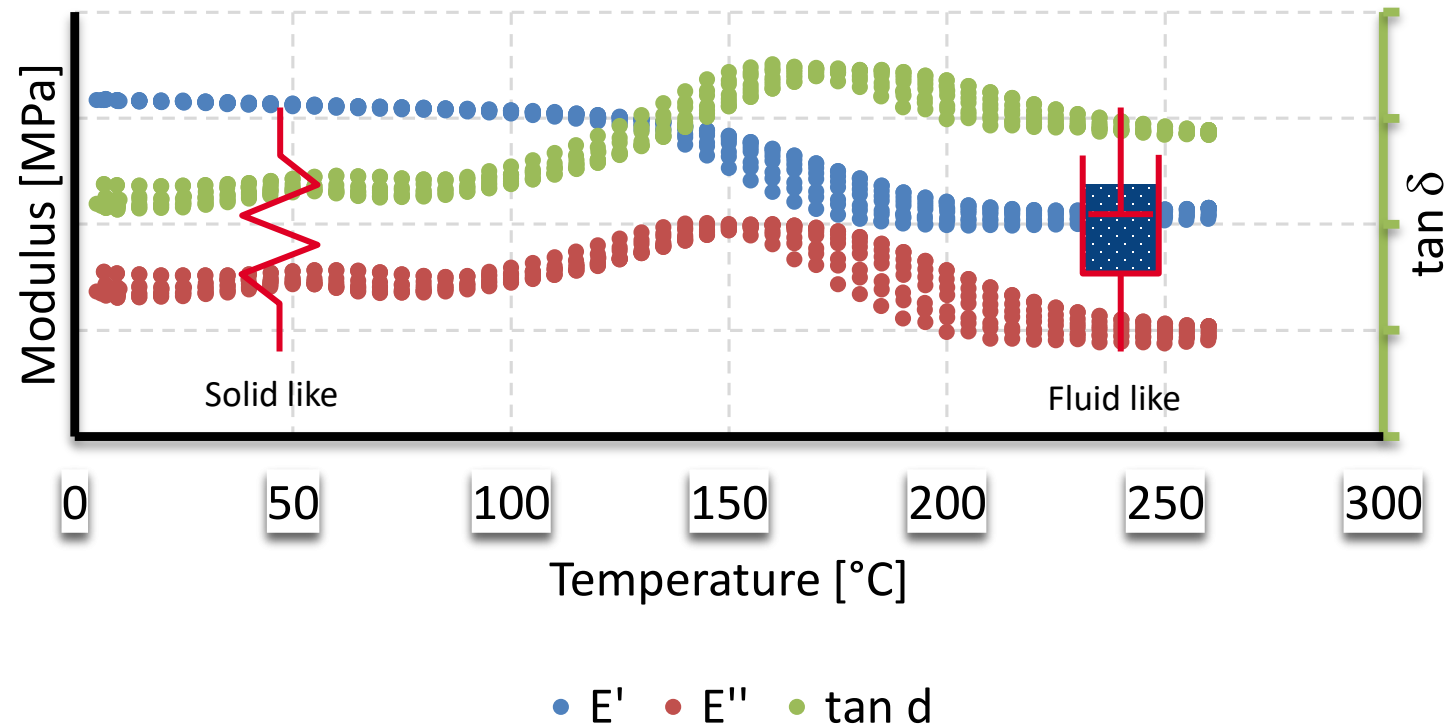


## Stress by viscosity

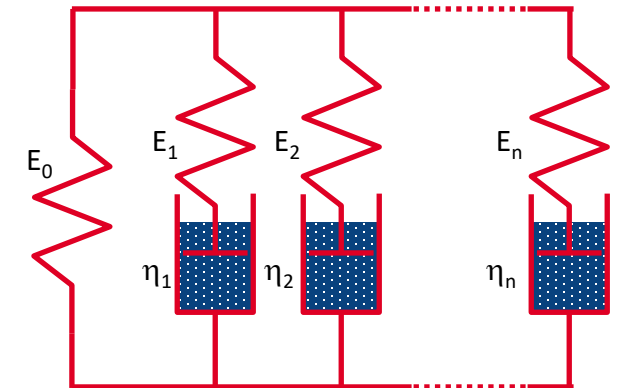
$$\sigma = \eta \frac{\partial \varepsilon}{\partial t}$$



## Epoxy based thermoset



### Generalized Maxwell model



P. Gromala, B. Muthuraman, B. Oeztuerk, K. M. B. Jansen, L. Ernst, "Material characterization and nonlinear viscoelastic modelling of epoxy based thermosets for automotive application", Proceedings of the 2015 16th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Budapest, Hungary, 19-22 April, 2015.

- Creep takes place when a viscoelastic material subjected to constant stress.

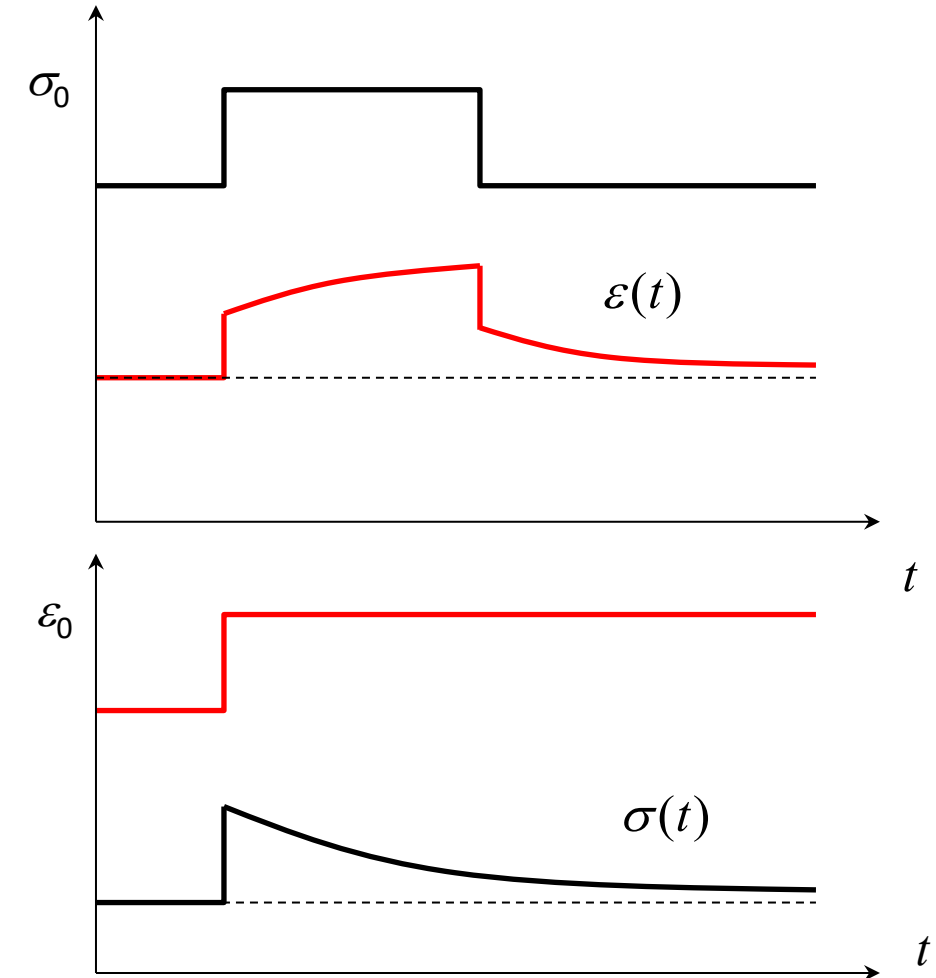
$$\frac{\varepsilon(t)}{\sigma} = J(t)$$

$J(t)$ : creep compliance

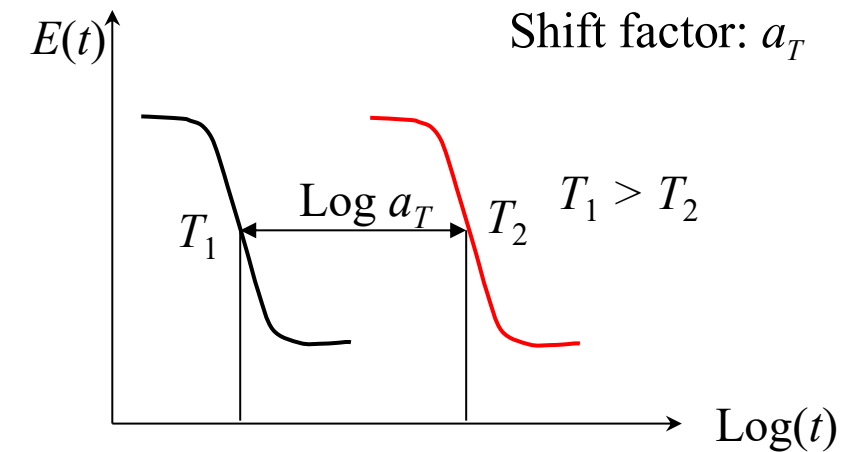
- Stress relaxation happens when a viscoelastic material subjected to constant strain.

$$\frac{\sigma(t)}{\varepsilon} = E(t)$$

$E(t)$ : reduced modulus



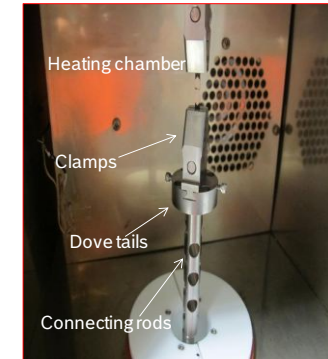
- Assumption of **thermorheologically simple (TRS)**: no change in relaxation (creep) mechanism occurs with temperature  $\rightarrow$  time-temperature superposition principle
- Relaxation modulus at different temperatures can be shifted to one reference temperature on the logarithmic x-axis to create a *master curve*.



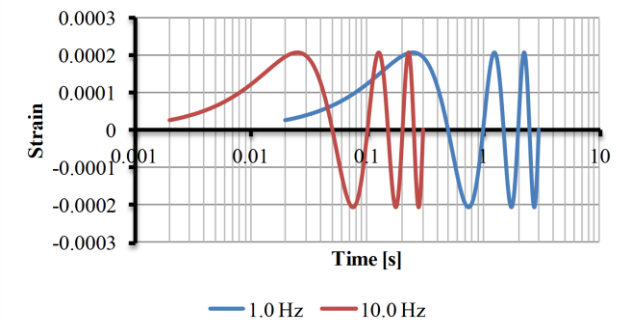
## Dynamic mechanical analysis (DMA) –

is a technique used to study and characterize materials, such as studying viscoelastic behavior of epoxy based thermosets

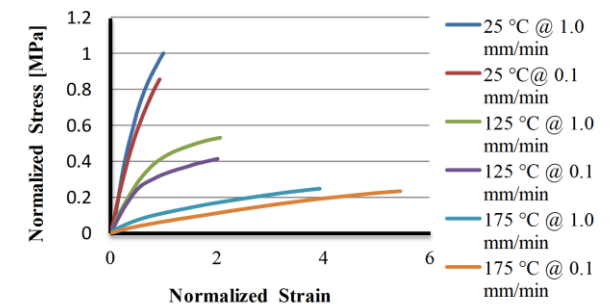
- Temperature range: -60 to 260 °C
- Fatigue investigation
- Typical load application in tensile mode or in three point bending mode
- Material characterization:
  - Modulus of elasticity (storage and loss modulus)
  - Glass transition temperature
  - Critical stress at break



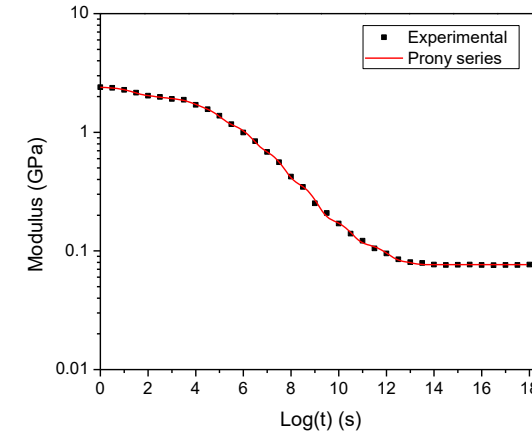
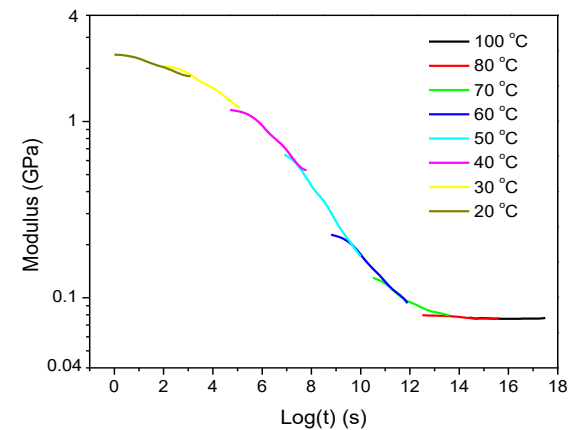
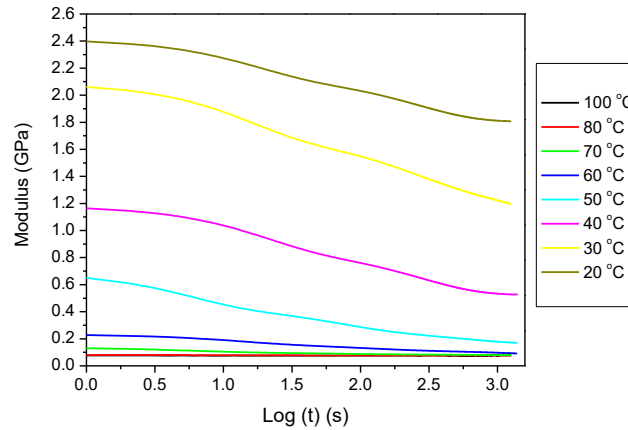
Harmonic load applied during DMA test



Effect of different load rate



# Master Curve and Prony Series



LOMSS



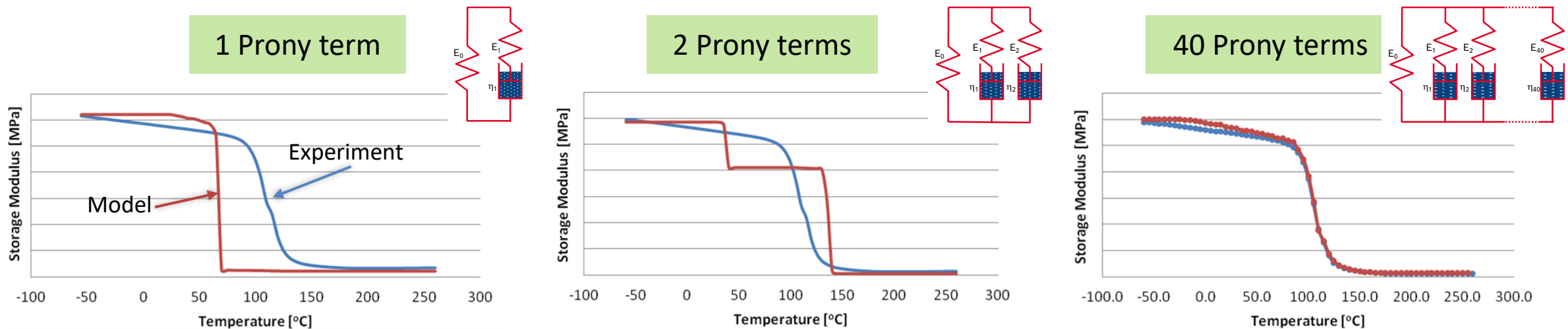
- A master curve can be obtained by shifting the relaxation modulus.
- The master curve can be expressed analytically using the Prony series.

$$E(t) = E_{\infty} + \sum_{i=1}^{10} E_i \exp\left(-\frac{t}{\tau_i}\right)$$

|              | i = 1 | i = 2 | i = 3 | i = 4          | i = 5          | i = 6          | i = 7          | i = 8             | i = 9             | i = 10            |
|--------------|-------|-------|-------|----------------|----------------|----------------|----------------|-------------------|-------------------|-------------------|
| $E_i$ (GPa)  | 0.323 | 0.122 | 0.245 | 0.50           | 0.456          | 0.355          | 0.212          | 0.076             | 0.033             | 0.008             |
| $\tau_i$ (s) | 22    | 202   | 6800  | $9 \cdot 10^4$ | $2 \cdot 10^6$ | $4 \cdot 10^7$ | $1 \cdot 10^9$ | $3 \cdot 10^{10}$ | $1 \cdot 10^{12}$ | $1 \cdot 10^{13}$ |

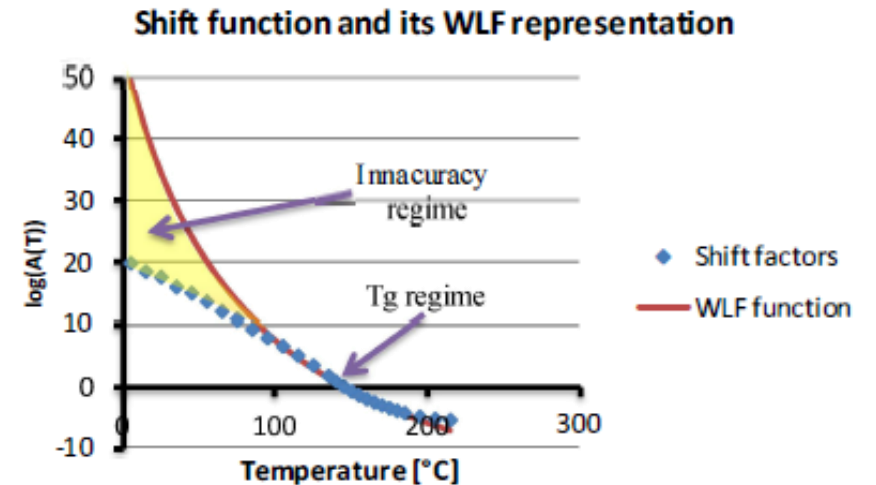
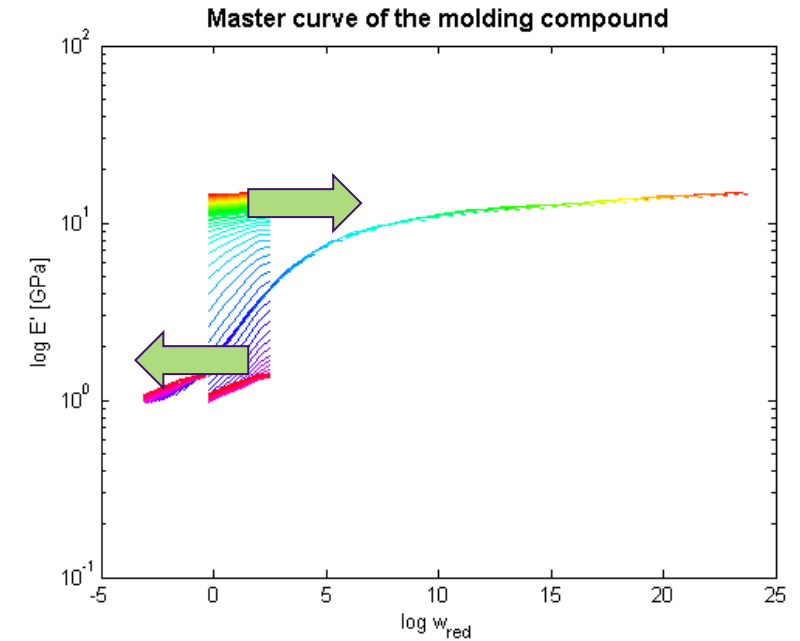
# More about Prony terms

- Each Maxwell element defines relaxation time and “a depth of transition” at a specific relaxation time.
- Typically, numerous Maxwell elements are required to describe the transition from glassy to rubbery correctly.

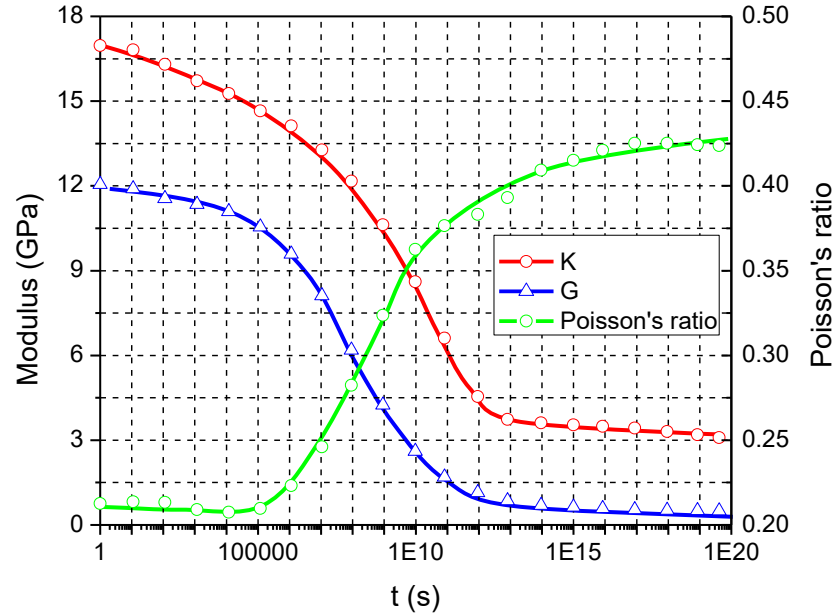


Minimum 15 prony terms required

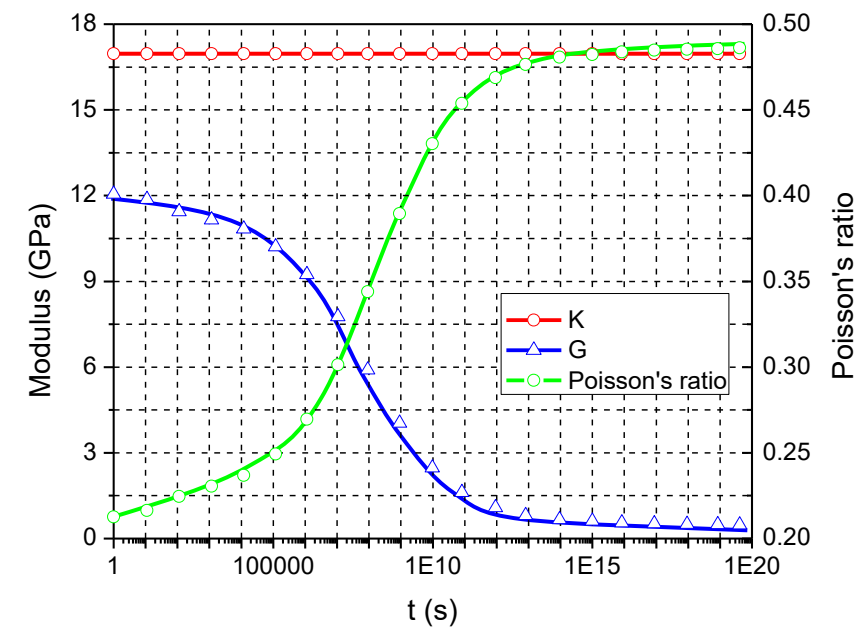
- Implementation in FEM
  - WLF function → accuracy only in  $T_g$  regime
  - Piecewise shift function (user defined model)
  - As temperature dependent prony terms (look-up table)



Master curves from the measurements



Master curves with the constant bulk modulus assumption



$$K(t) \approx K = \frac{E(0)|_{T=25^{\circ}C}}{3(1-2\nu(0)|_{T=25^{\circ}C})}$$

$$G(t) = \frac{3K_0 E(t)}{9K_0 - E(t)}$$

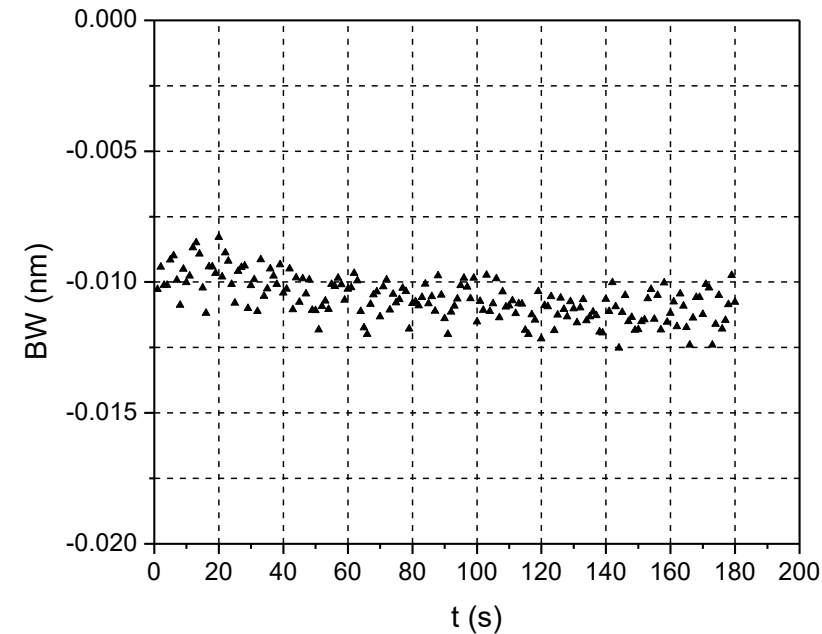
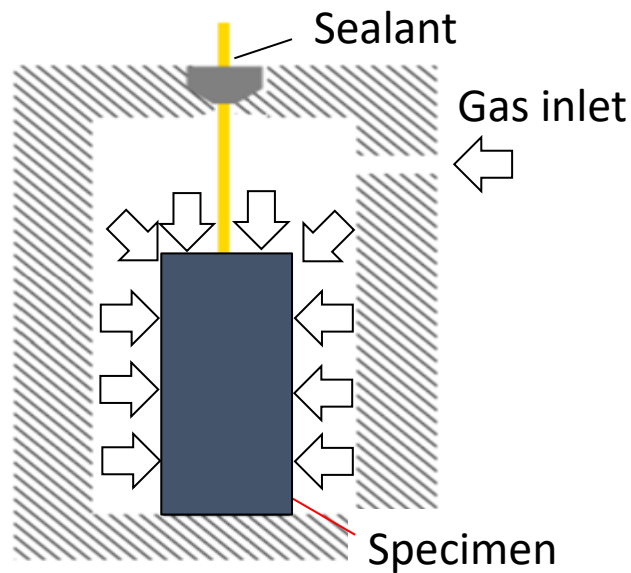
$$\nu(t) = \frac{1}{2} - \frac{E(t)}{6K_0}$$

H.-S. Lee, Y. Sun, C. Kim, and B. Han, "Characterization of Linear Viscoelastic Behavior of Epoxy Molding Compound Subjected to Uniaxial Compression and Hydrostatic Pressure," *IEEE Transactions on CPMT*, Vol. 8, no. 8, pp. 1363-1372, Aug. 2018.

# Why Higher Pressure for Bulk Modulus?

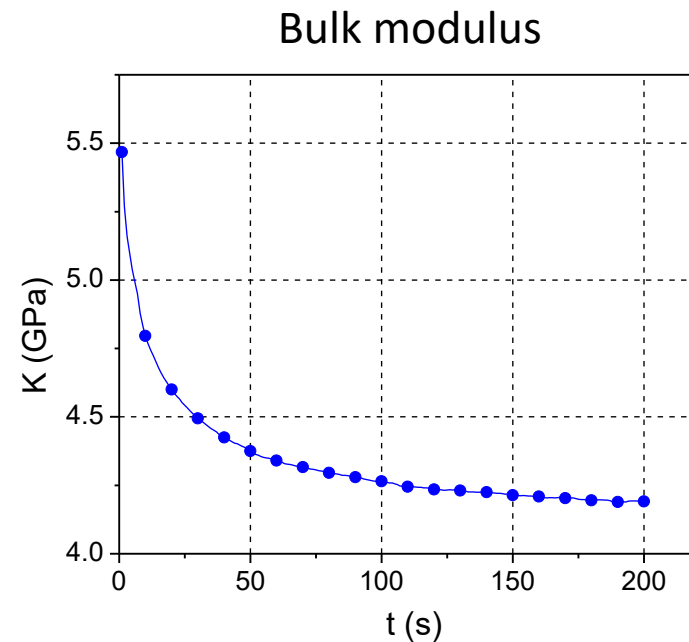
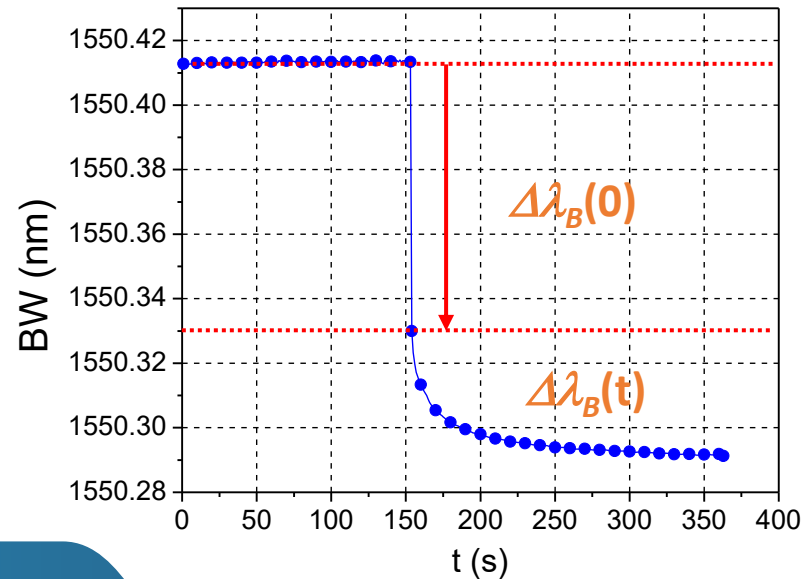
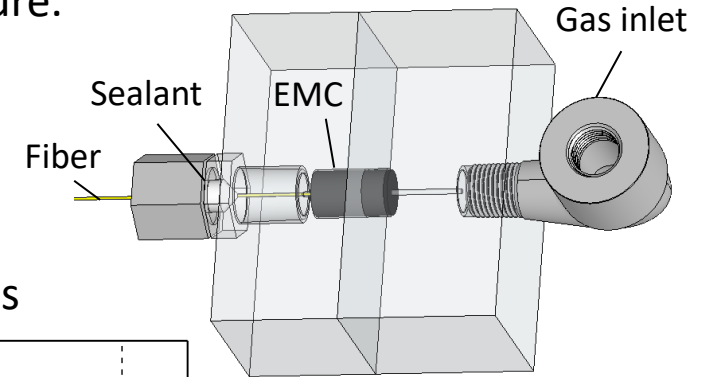
- A higher pressure is required to produce the same strain under hydrostatic loading.
- With the initial attempt using compressed air ( $\approx 100$  psi), the BW shift at low temperature was only around 10 pm, which did not provide a desired S/N ratio of measurement signals (the resolution of the interrogation system of  $\approx 1$  pm).

LOMSS

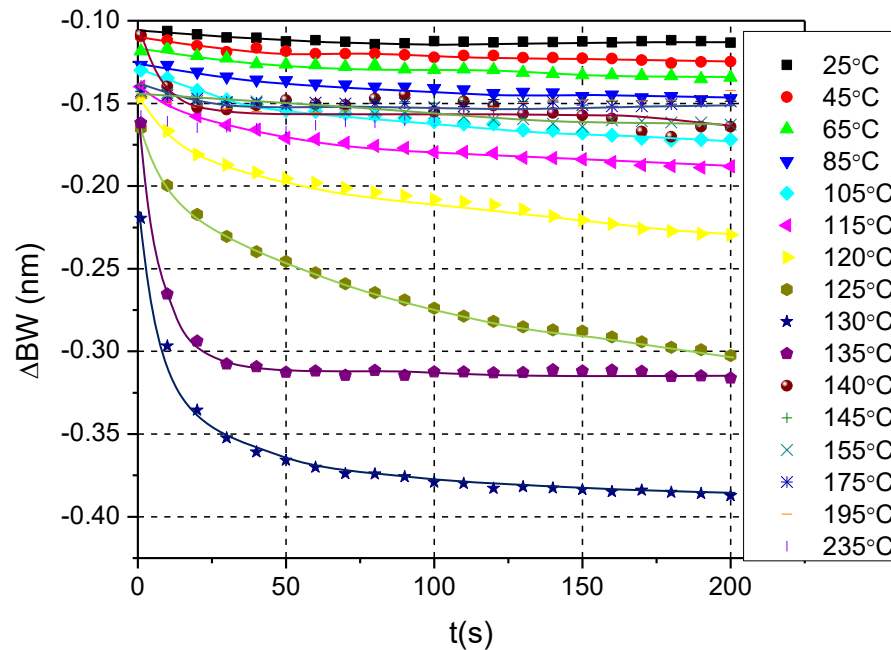


- The initial  $\Delta\lambda_B(0)$  is measured after applying **instantaneous gas pressure**.
- The time dependent  $\Delta\lambda_B(t)$  is measured while maintaining the constant pressure.

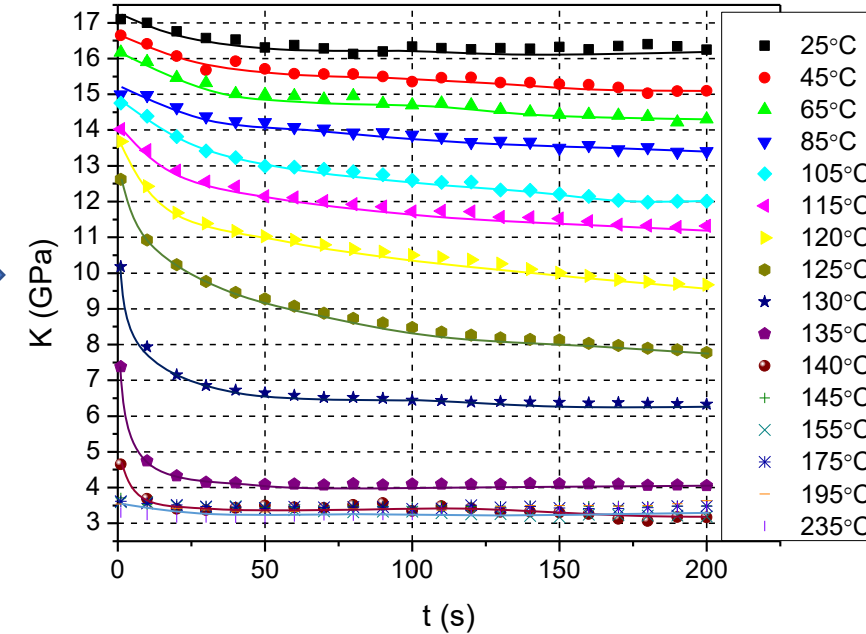
LOMSS



Raw data

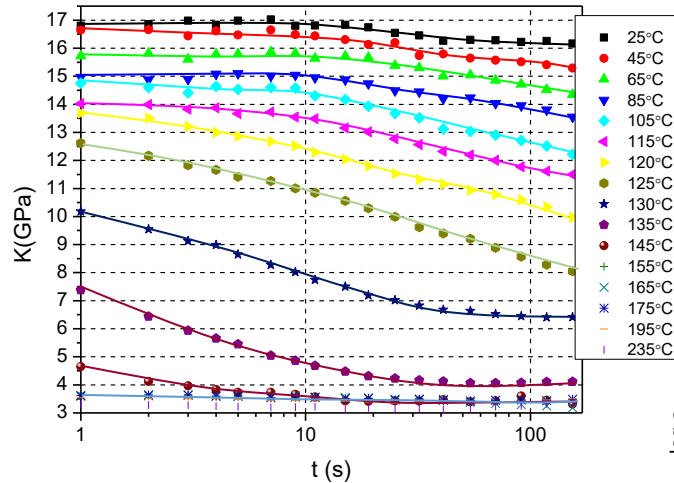


Time/temperature-dependent bulk modulus

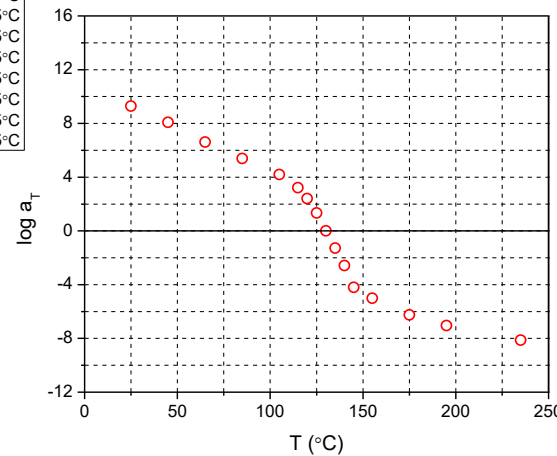


# Master Curve of the Bulk Modulus

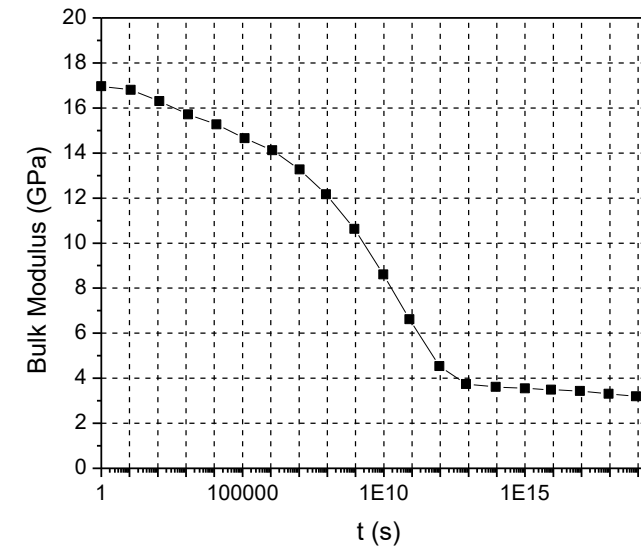
Time/temperature-dependent Bulk modulus in log scale



Shift factors



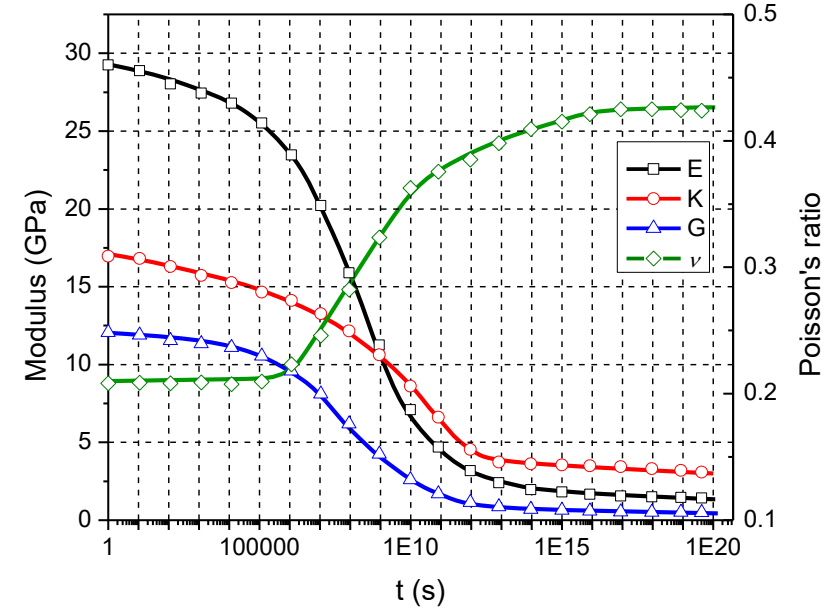
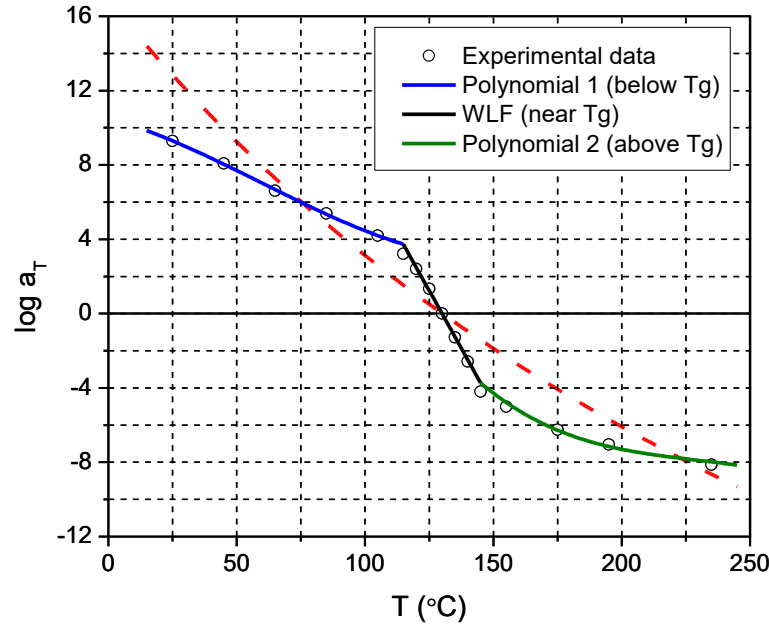
Bulk modulus master curve



Using the same set of the shift factors, the master curve of the bulk modulus was determined.

LOMSS





## Piece-wise shift functions

$$\log a_T^{p1}(T) = a_0 + a_1(T - 115) + a_2(T - 115)^2 + a_3(T - 115)^3 \quad \text{for } T \leq 115^\circ\text{C}$$

$$\log a_T^{WLF}(T) = -\frac{C_1(T - 130)}{C_2 + (T - 130)} \quad \text{for } 115^\circ\text{C} \leq T \leq 145^\circ\text{C}$$

$$\log a_T^{p2}(T) = b_0 + b_1(T - 145) + b_2(T - 145)^2 + b_3(T - 145)^3 \quad \text{for } T \geq 145^\circ\text{C}$$

$$a_0 = \log a_T^{WLF}(115) \quad \text{and} \quad b_0 = \log a_T^{WLF}(145)$$

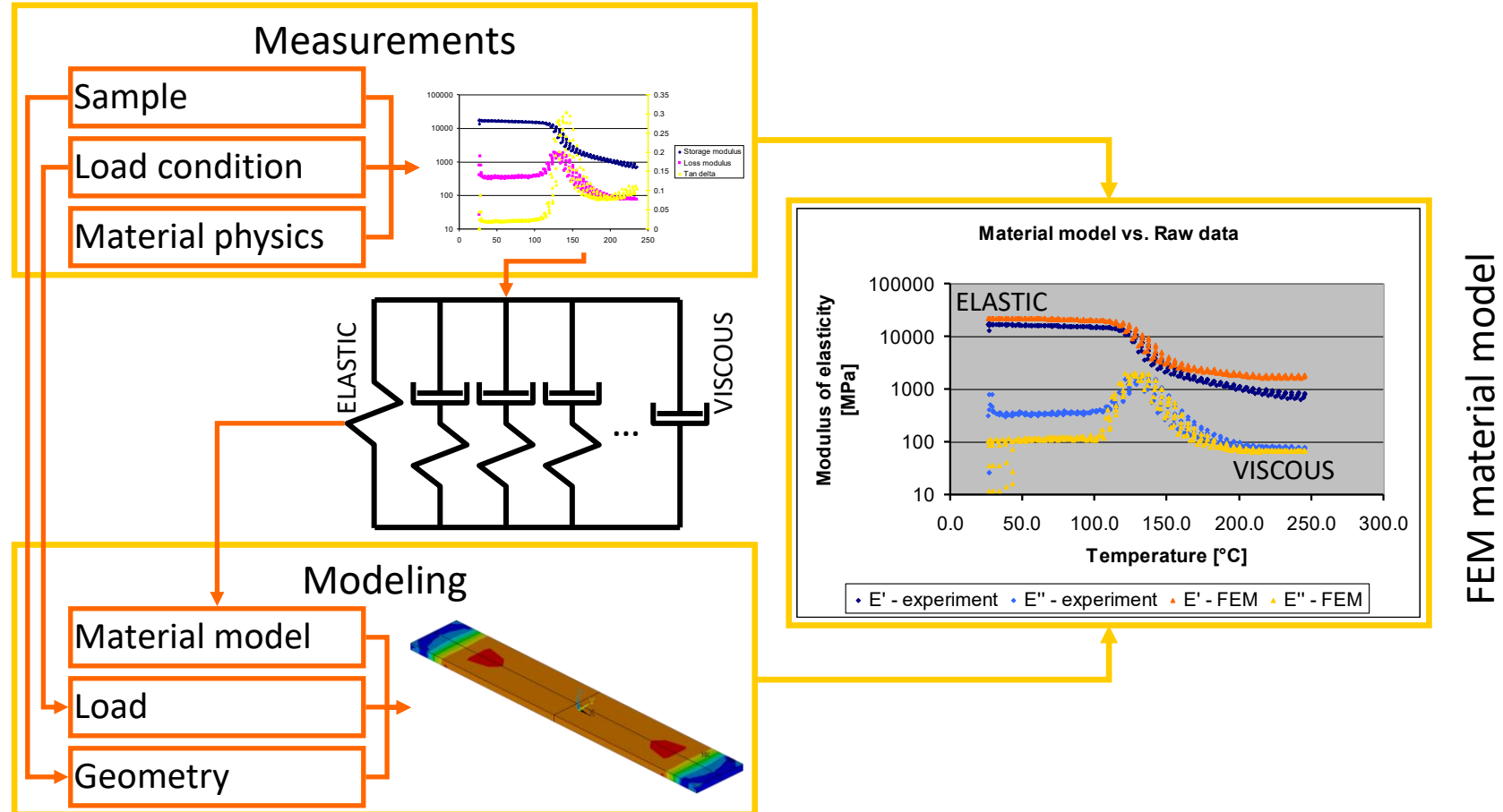
## Prony series

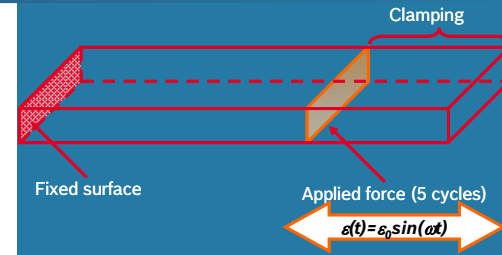
$$K(t) = K_\infty + \sum_{i=1}^{20} K_i \exp\left(-\frac{t}{\tau_i}\right)$$

$$G(t) = G_\infty + \sum_{i=1}^{20} G_i \exp\left(-\frac{t}{\tau_i}\right)$$

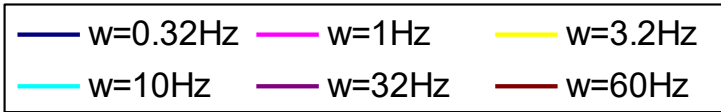
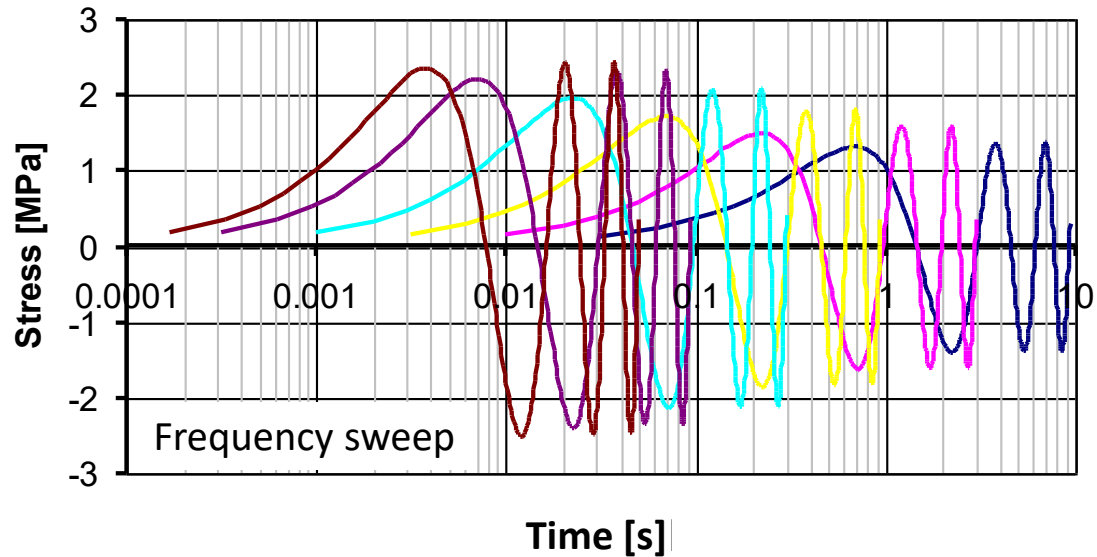
1. Introduction
2. Material Selection and Key Influencing Mechanisms
3. EMC Material Characterization Essentials
- 4. From Material Data to Simulation Models**
5. Summary and Key Takeaway

How to validate visco-elastic models?

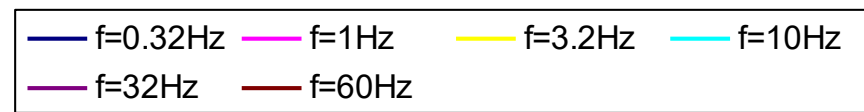
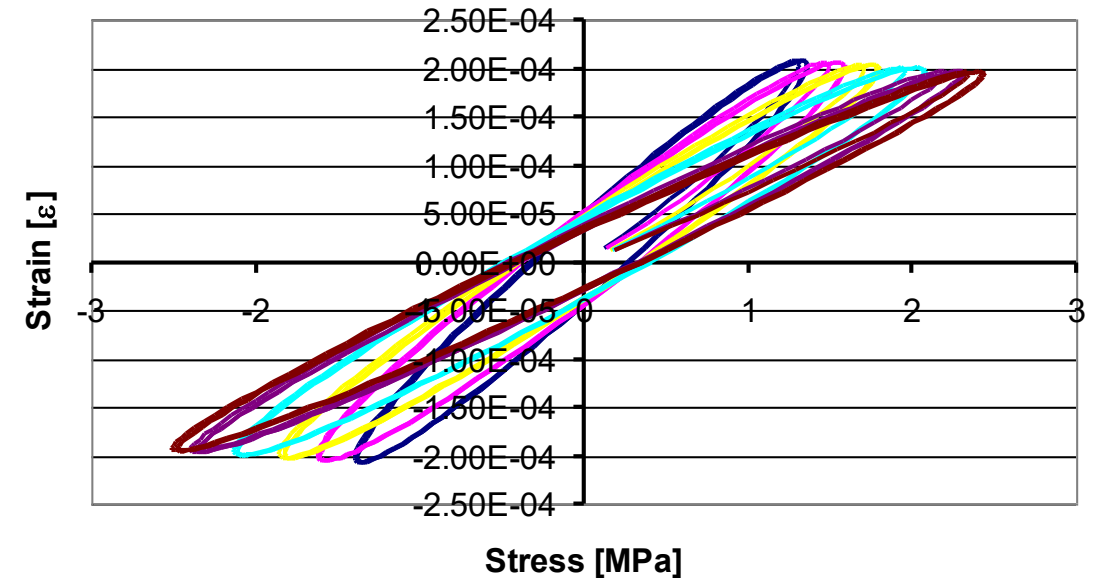




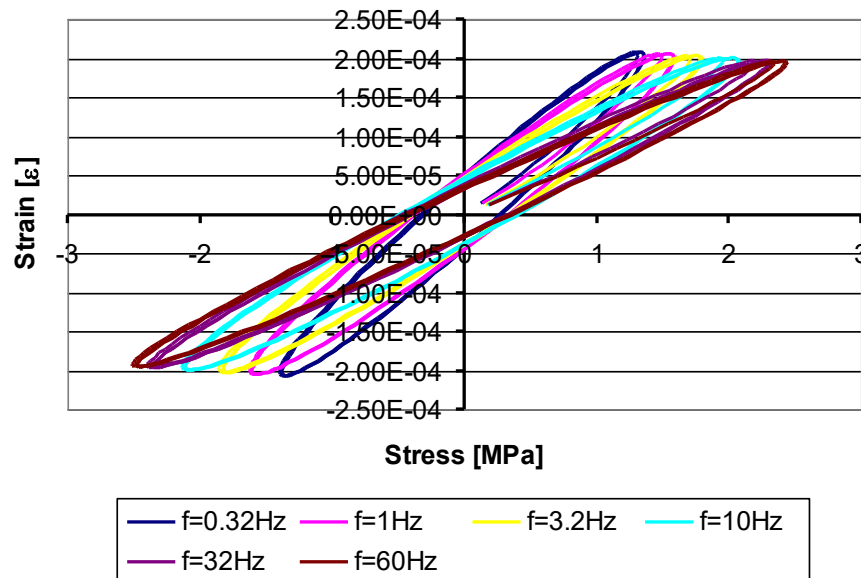
**DMA test: X component of stress for different frequencies**



**DMA test: X component of stress vs. strain**



DMA test: X component of stress vs. strain



$\omega=60.0\text{Hz} \rightarrow \sigma_x=2.47\text{MPa}$

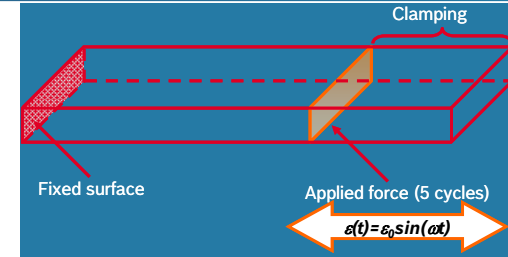
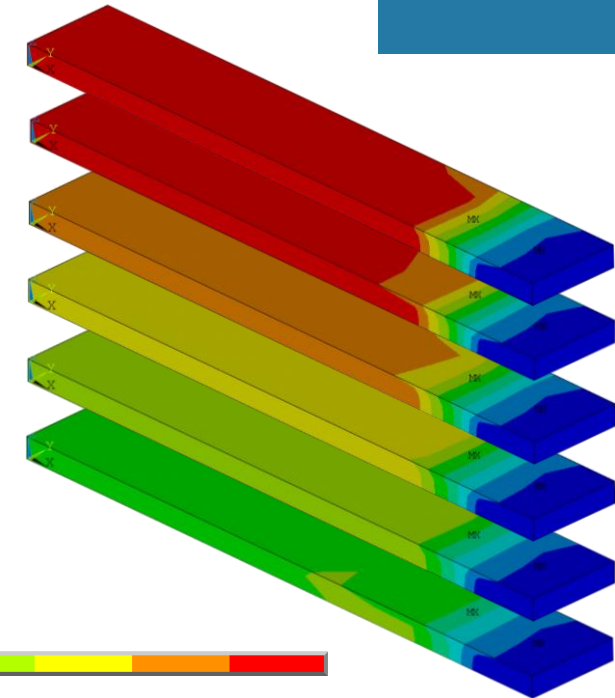
$\omega=32.0\text{Hz} \rightarrow \sigma_x=2.35\text{MPa}$

$\omega=10.0\text{Hz} \rightarrow \sigma_x=2.09\text{MPa}$

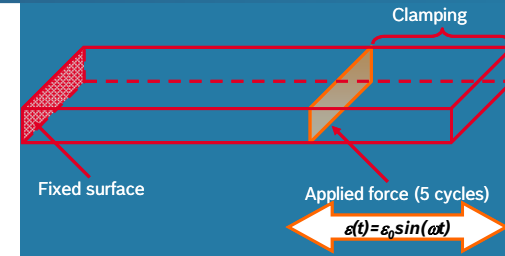
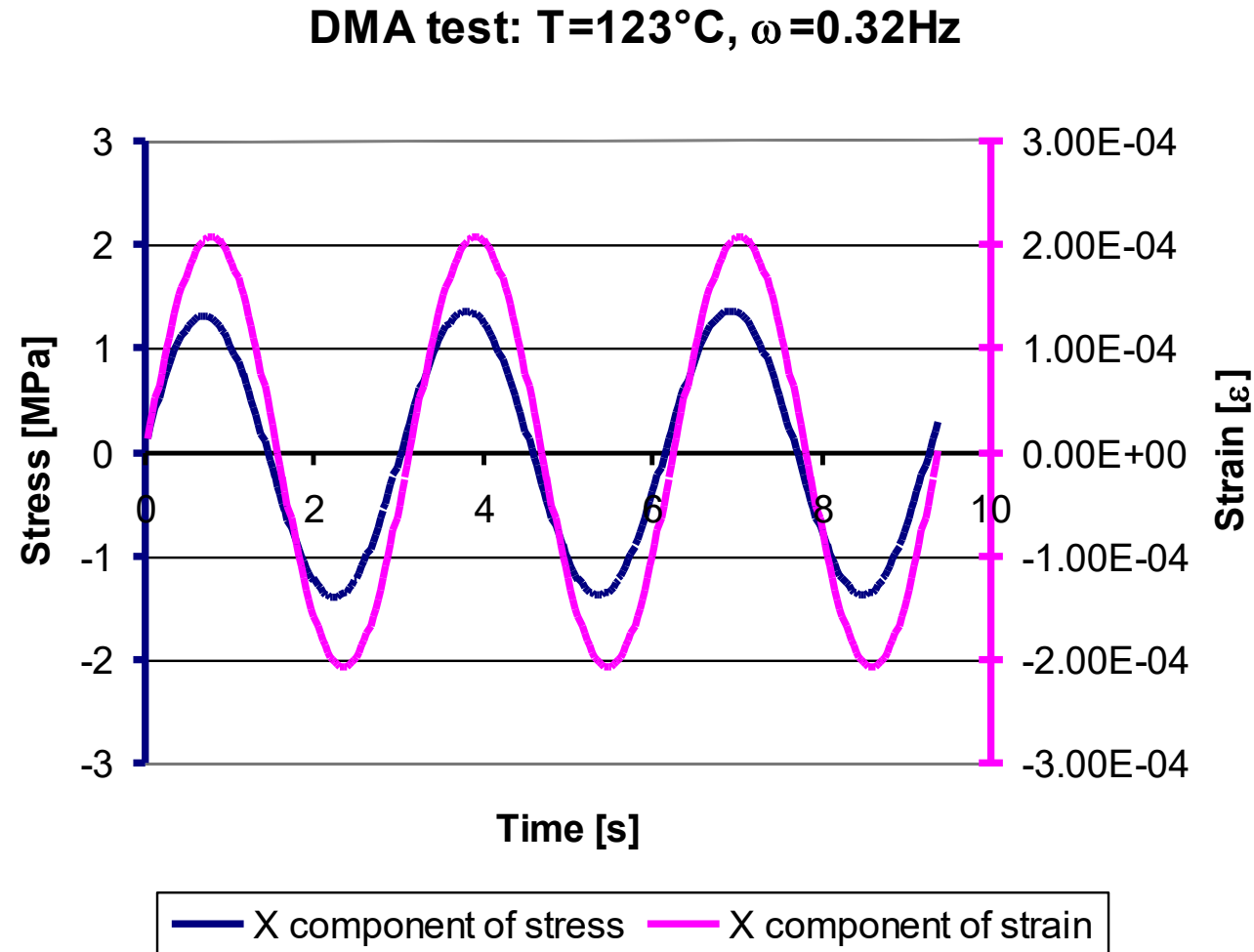
$\omega=3.20\text{Hz} \rightarrow \sigma_x=1.81\text{MPa}$

$\omega=1.00\text{Hz} \rightarrow \sigma_x=1.58\text{MPa}$

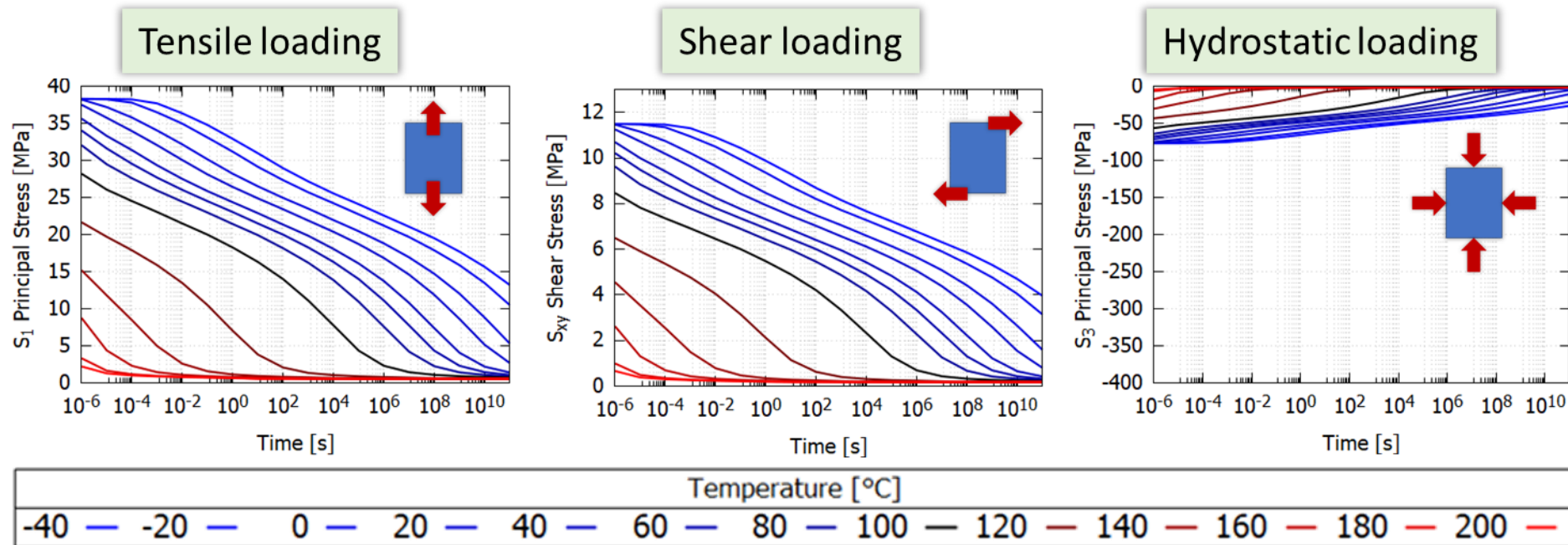
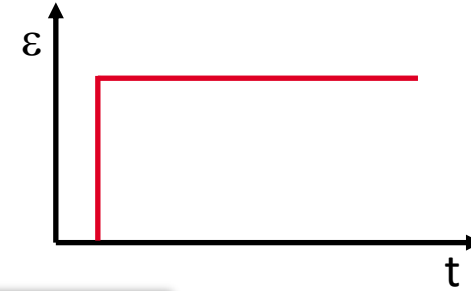
$\omega=0.32\text{Hz} \rightarrow \sigma_x=1.36\text{MPa}$



The higher the frequency the higher the stress



- Goal: study relaxation behavior of molding compound
- One element used



Material modeling is as important as characterization

- Material characterization and modeling are crucial for predictive numerical modeling
- Behavior of an epoxy based thermosets is very complex
  - Temperature dependency
  - Time dependency
  - Non-linear behavior
- Process parameters should not be neglected
- Simulation engineer should lead material characterization and modeling
- Before material is used in product simulation, it should be validated using virtual modeling

## ACKNOWLEDGMENT



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# Thank you very much for your attention!

In case of questions or comments, please contact: [pgromala@ieee.org](mailto:pgromala@ieee.org)