Multifunctional Shape-memory Zirconia-reinforced Metal-matrix Composite for Energy Dissipation and High Temperature Applications

Marwa Yacouti, Ph.D. student

Maryam Shakiba, Assistant professor

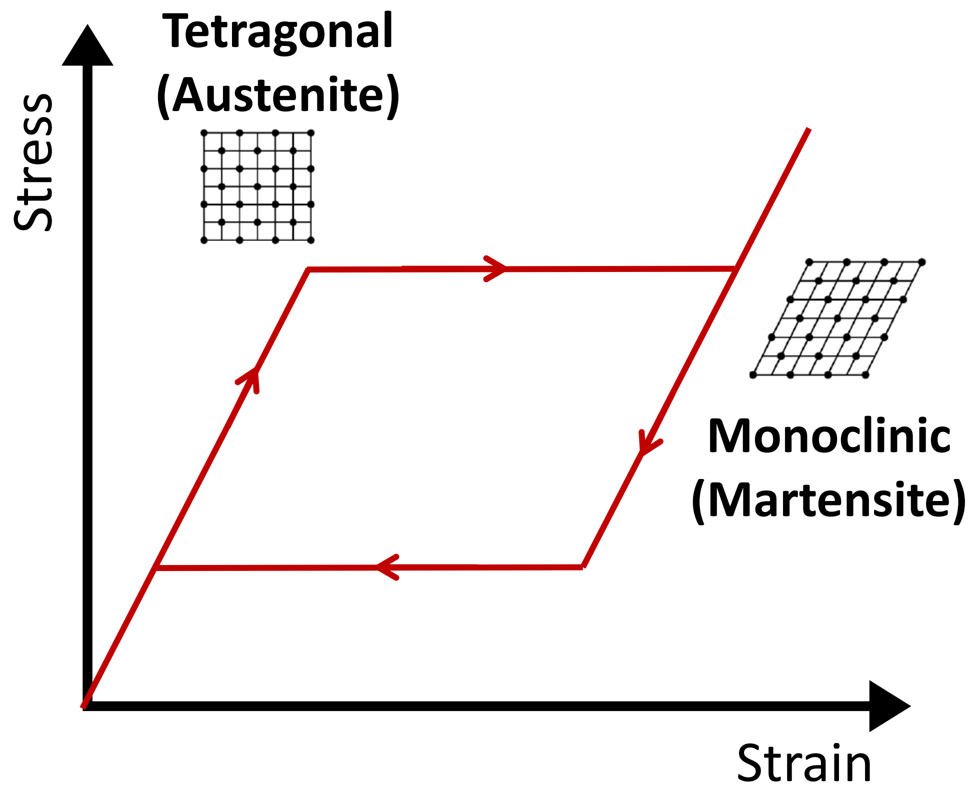
Ann & H.J. Smead Department of Aerospace Engineering Sciences

University of Colorado Boulder

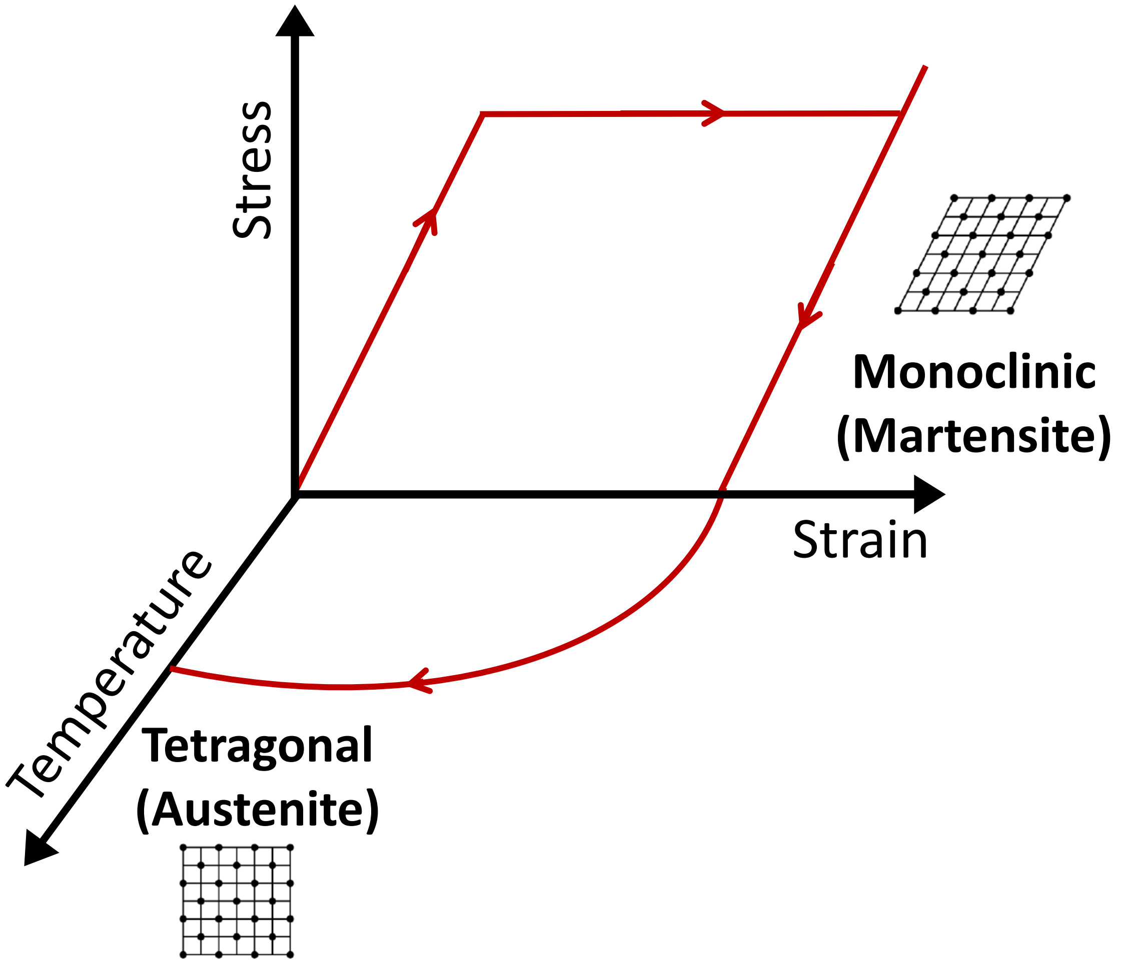
University of Colorado
Boulder

Zirconia is characterized by two unique properties: superelasticity and the shape-memory effect

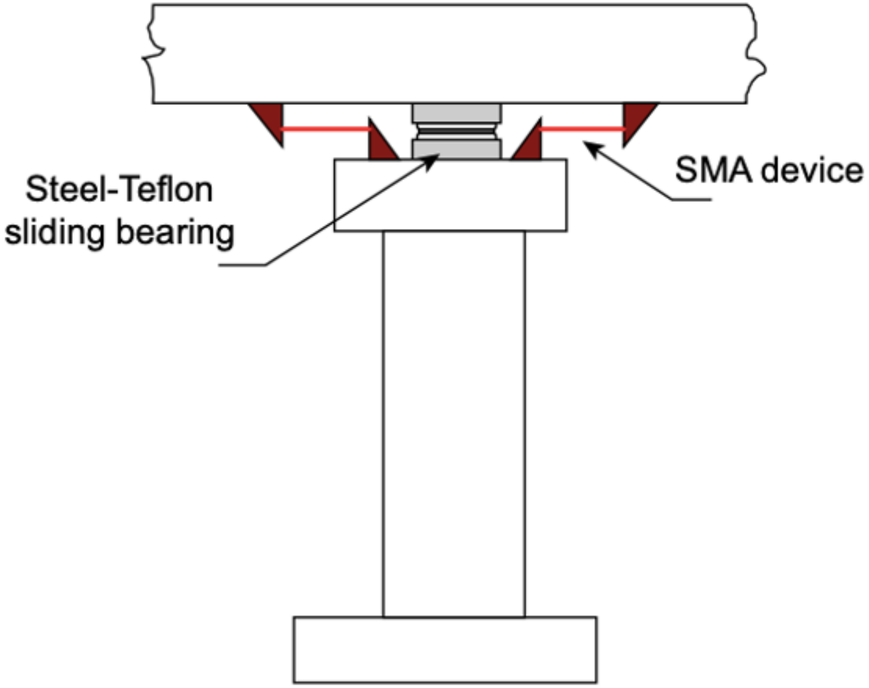
- **Superelasticity**



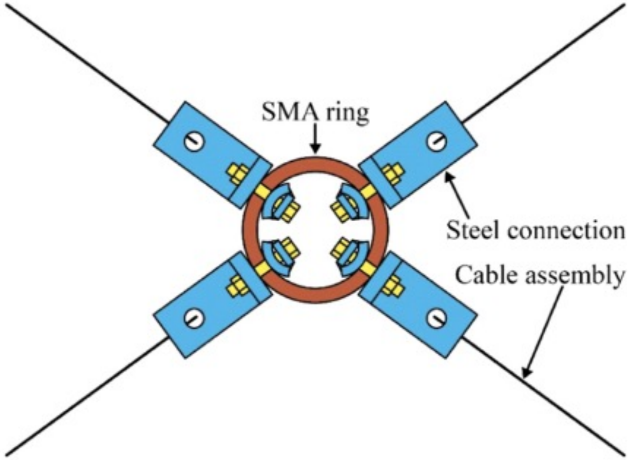
- **Shape-memory effect**



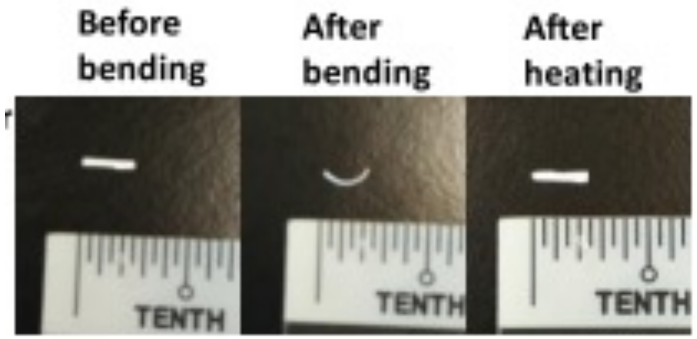
Shape memory materials are multifunctional materials with a variety of applications



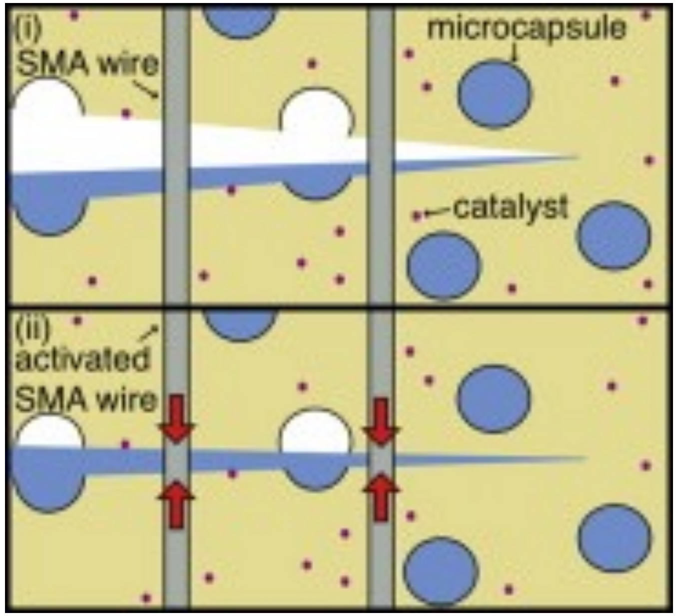
Isolated bridge model with an SMA/rubber isolation system. (Ozbulut and Hurlebaus, 2011)



Cross-braced system based on a SMA ring. (Gao et al., 2016)

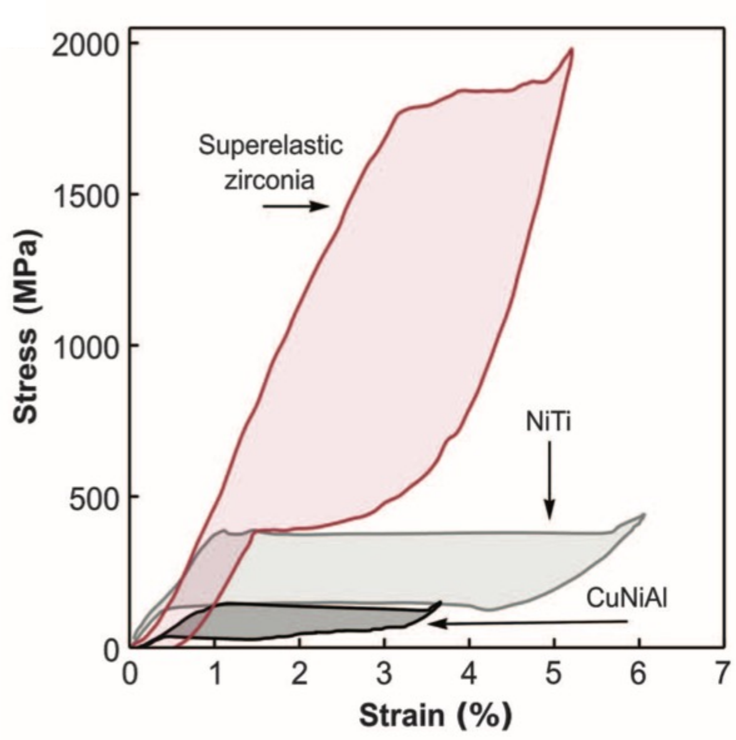


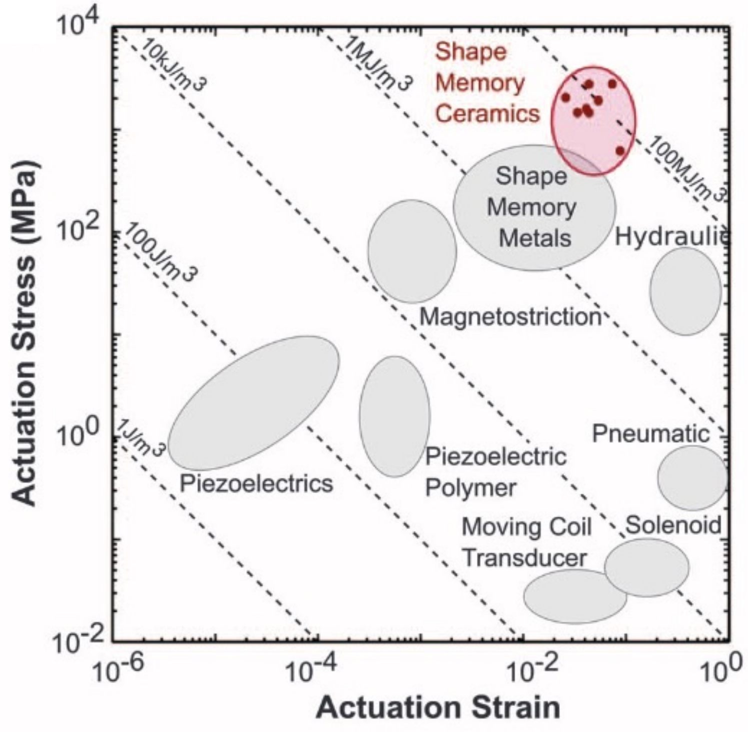
High temperature actuation in zirconia aligned fibers. (Du et al., 2020)

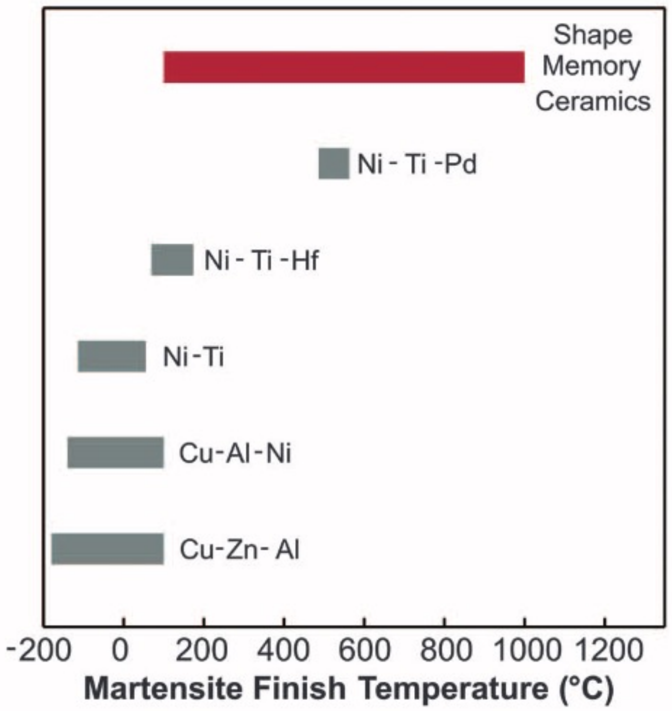


Self-healing mechanism using SMA wires. (Kirkby et al., 2016)

Zirconia is distinguished by higher stresses, larger energy dissipation and wider operational temperature range compared to other widely used Shape Memory Alloys (SMA)







Small scale zirconia-based ceramics are one of the most promising materials for damping systems and high temperature actuation

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(Lai et al., Science 341, no. 6153 (2013): 1505-1508)

Modeling of the behavior of shape-memory zirconia

The thermodynamic based constitutive model proposed by Xu et al. was used to predict the response of shape-memory zirconia

Constitutive relationship

Thermal expansion tensor

Kirchhoff stress tensor

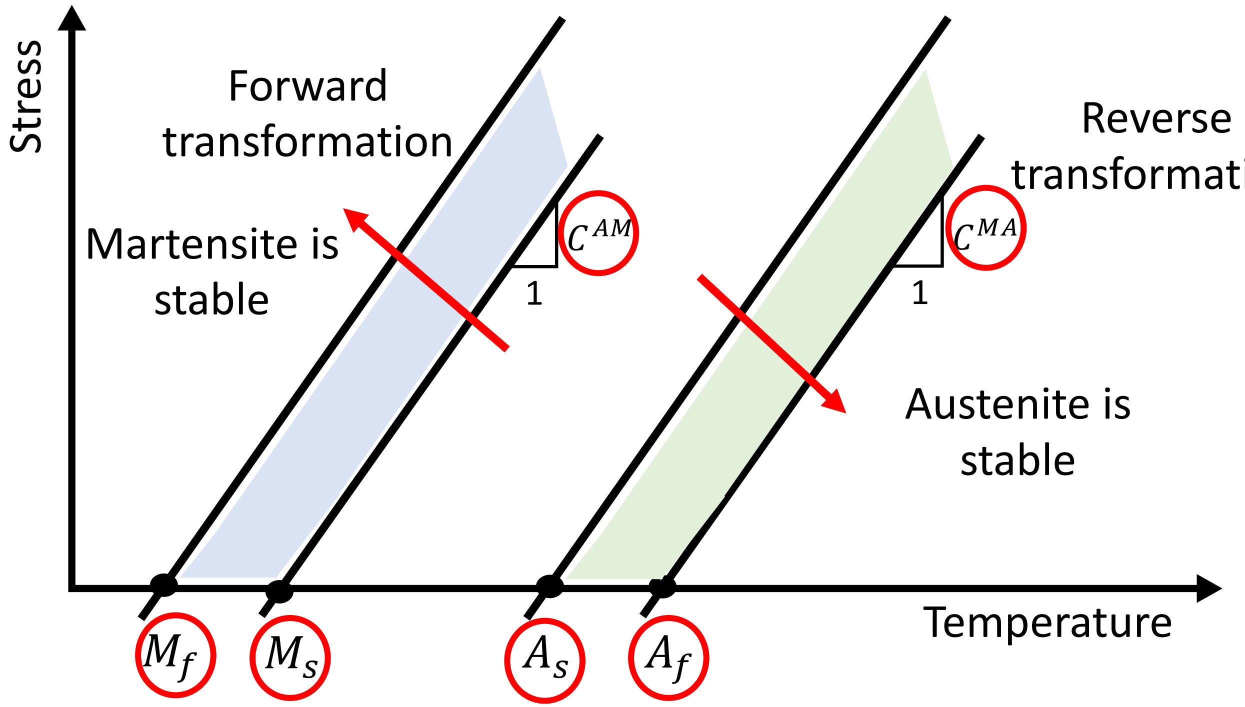
Initial temperature

$$\boldsymbol{h} = \mathcal{S}\boldsymbol{\tau} + \boldsymbol{\alpha}(T - T_0) + \boldsymbol{h}^{tr}$$

Logarithmic strain tensor

Compliance matrix

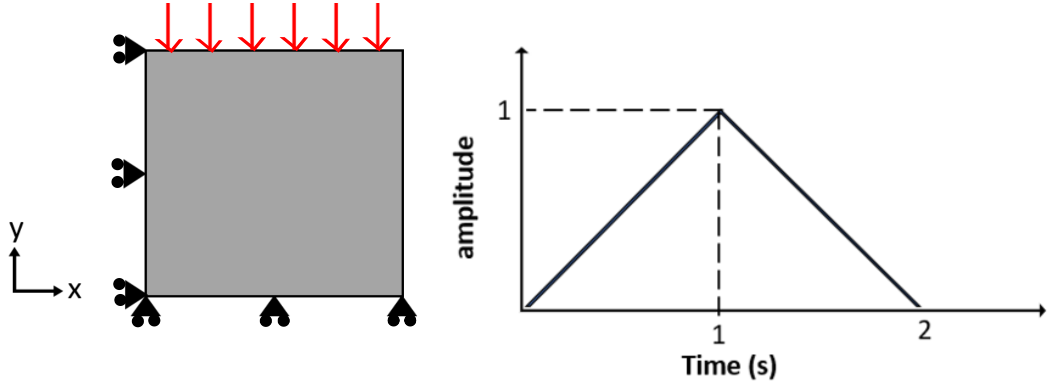
Transformation strain tensor



(Xu, L., T. Baxevanis, and D. C. Lagoudas, 2019, Smart Materials and Structures, 28(7):074004.)

Zirconia parameters were extracted by fitting to the experimental data from the literature (Zeng et al.)

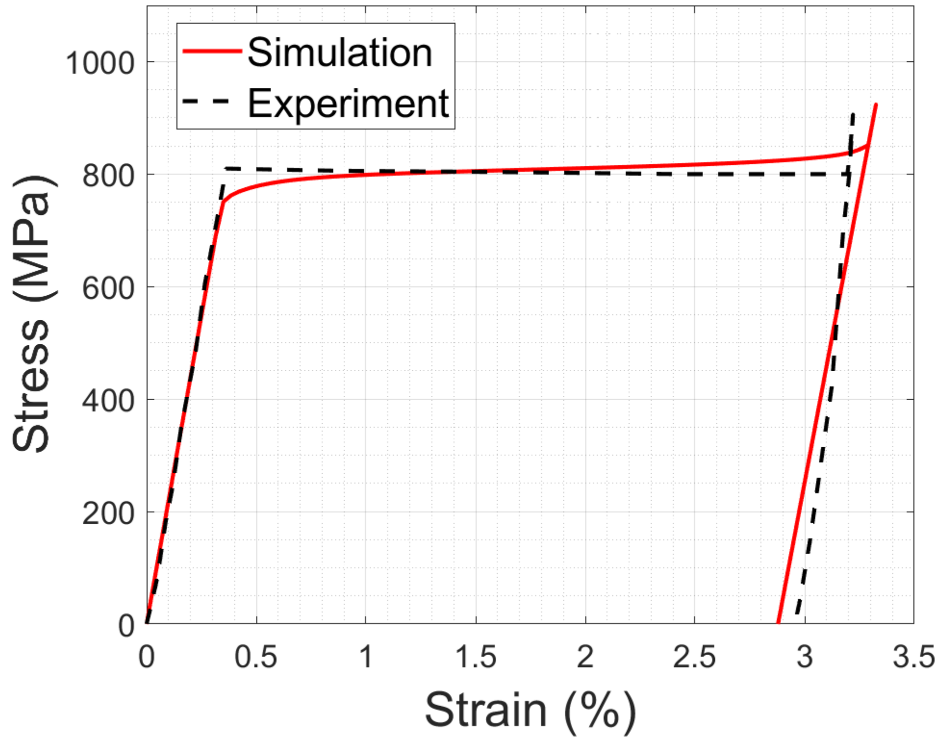
Strain controlled analysis



Zirconia parameters

- $E_M = 200\ GPa$
- $E_A = 200\ GPa$
- $M_s = 165\ K$
- $M_f = 140\ K$
- $A_s = 350\ K$
- $A_f = 450\ K$
- $\varepsilon^L = 0.0325$
- $C^{AM} = 6\ MPa/K$
- $C^{MA} = 6\ MPa/K$
- Temperature : 294 K

Compression test on zirconia particles

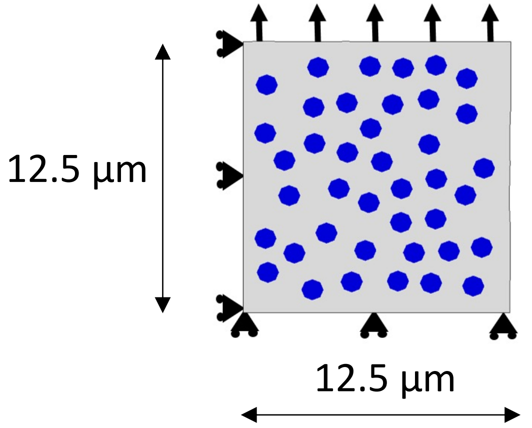


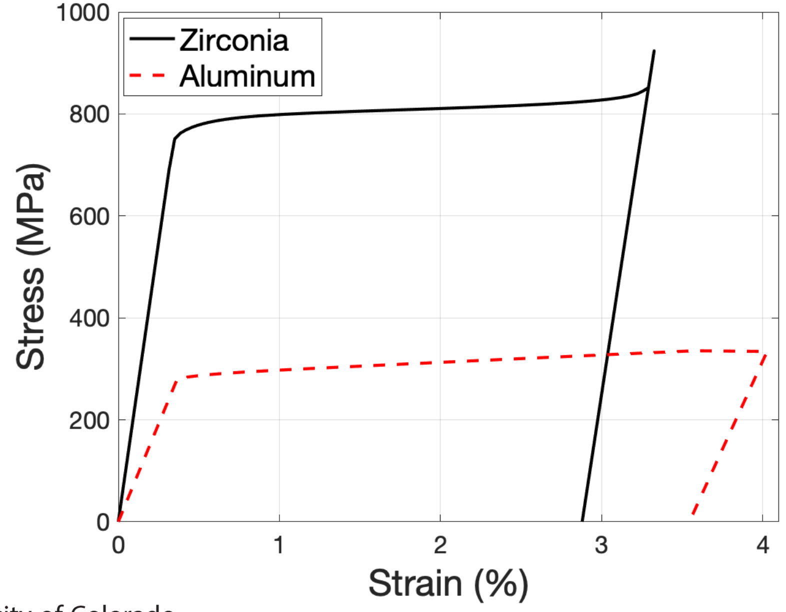
(Zeng et al., MRS Commun 7(4):747-754 (2017))

Representative volume element and mesh sensitivity analyses

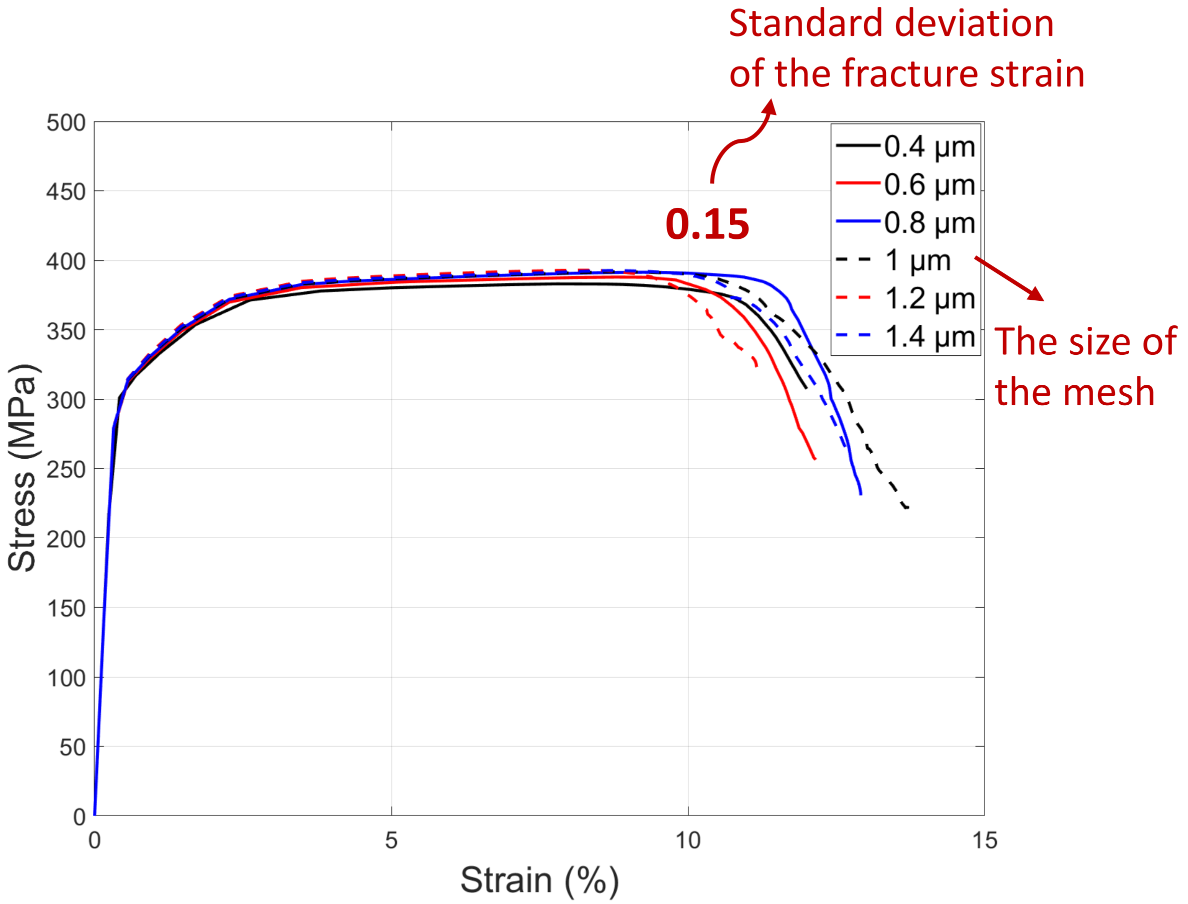
Ductile damage relationships were used to predict matrix behavior in the zirconia-reinforced metal-matrix composite

- Schematic of the particle-reinforced composite and the applied loading and boundary conditions

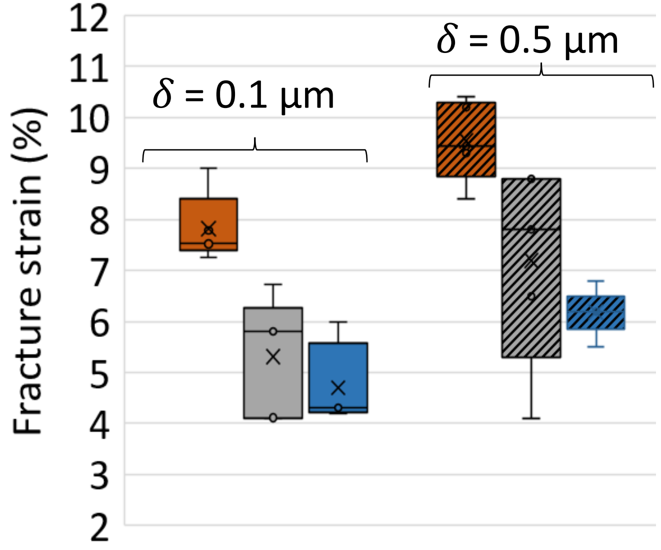


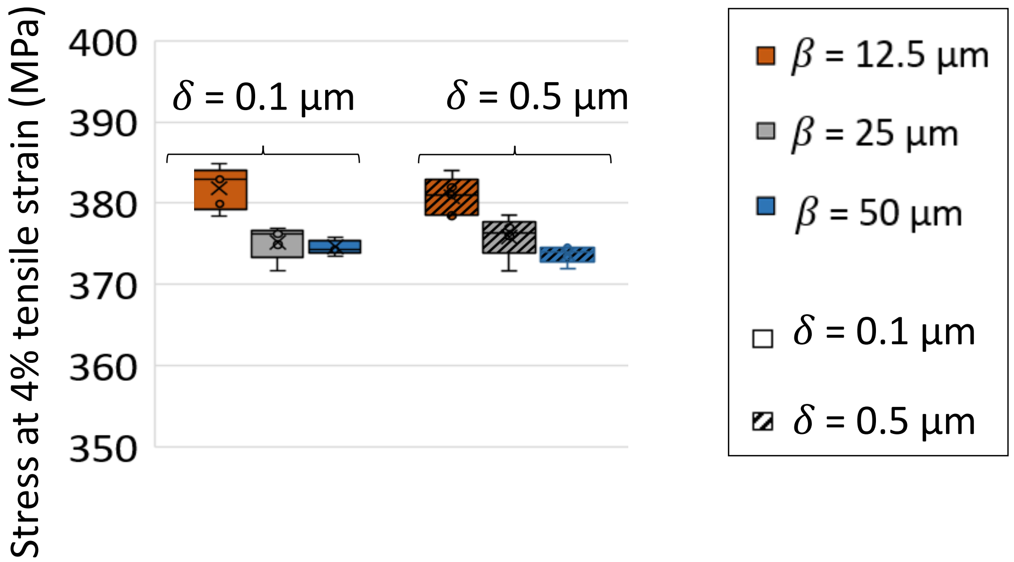


- The stress-displacement formulation proposed in Abaqus reduces effectively the mesh dependency



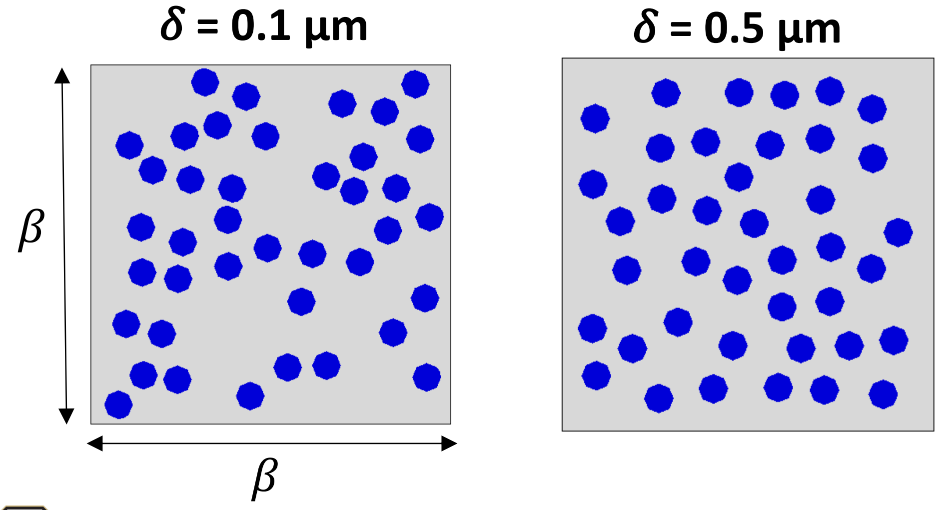
The fracture strain is highly affected by the distance between the particles and the size of the RVE





δ: the minimum distance between the particles

β: side length of the representative volume element (RVE)



- **For the fracture strain**

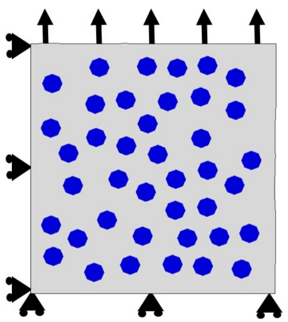
	δ = 0.1 μm			δ = 0.5 μm		
	12.5	**25**	**50**	**12.5**	**25**	**50**
Error	63%	10%	-	54%	14%	-

- **For the stress**

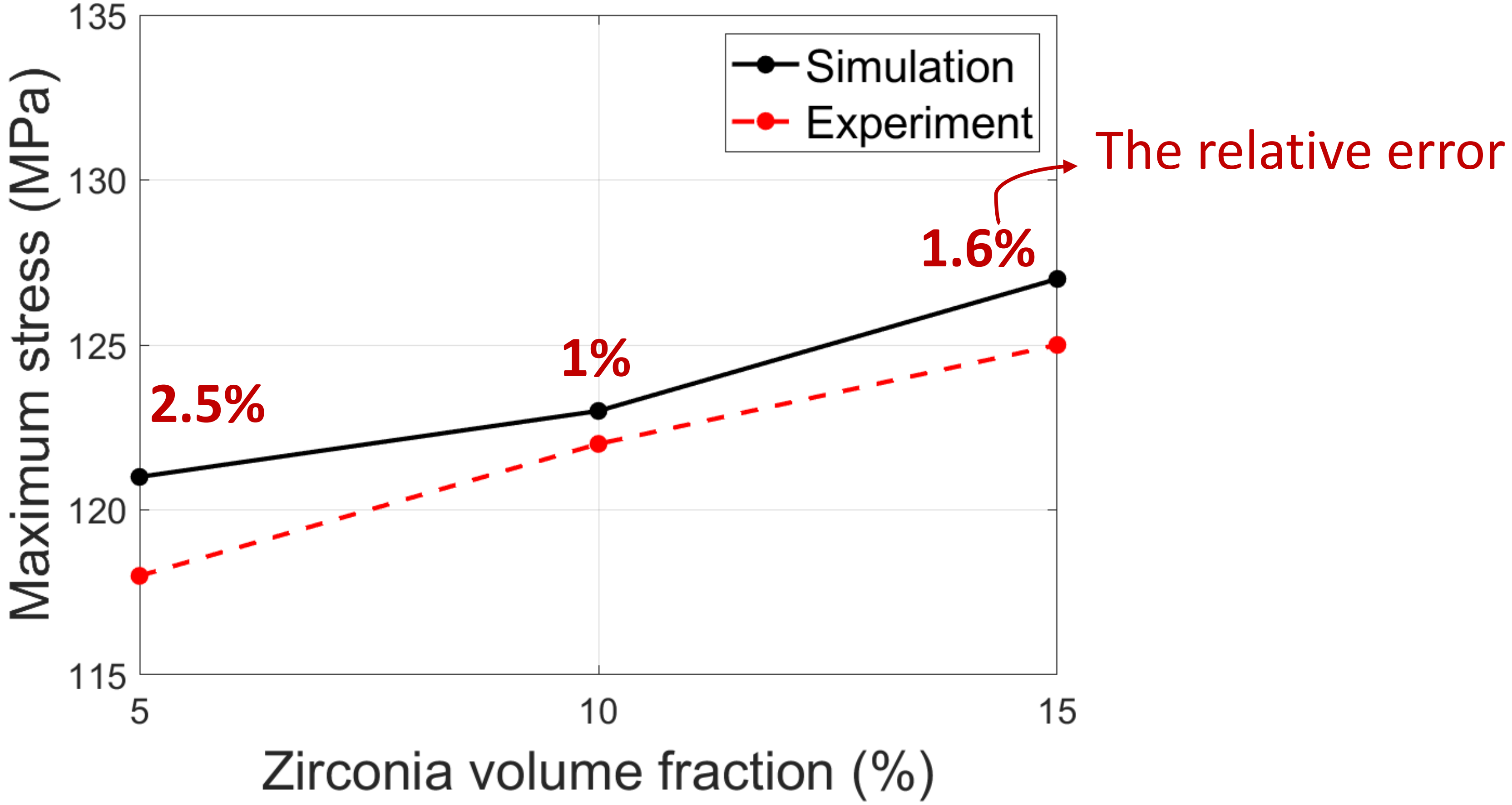
	δ = 0.1 μm			δ = 0.5 μm		
	12.5	**25**	**50**	**12.5**	**25**	**50**
Error	2.3%	1.8%	-	1.9%	0.5%	-

Validation of the numerical results versus experimental data

The composites simulations results were validated versus independent experimental tests in the literature



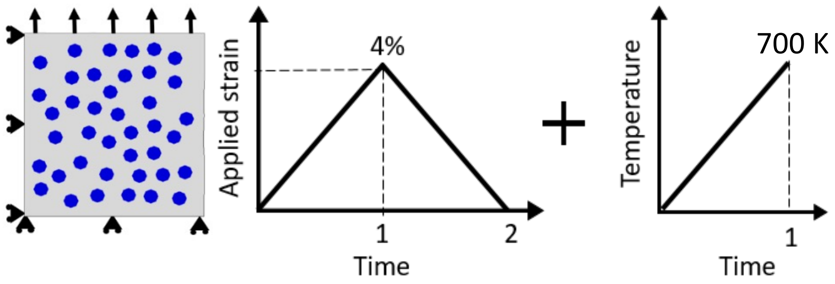
Al6061 matrix Zirconia-reinforced composite was subjected to a tensile test



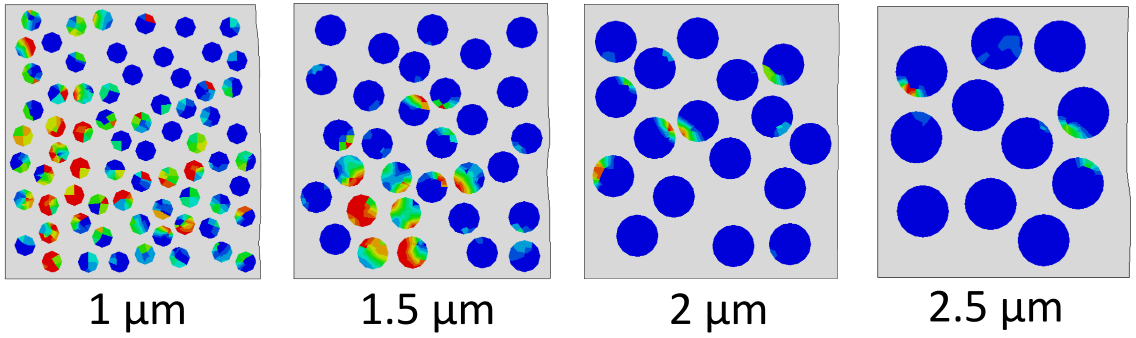
(Roseline *et al.*, *Ann Oper Res* 275, 653–667 (2019))

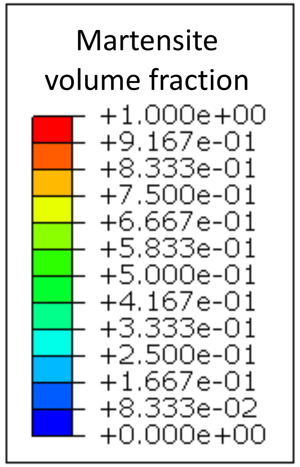
Parametric studies

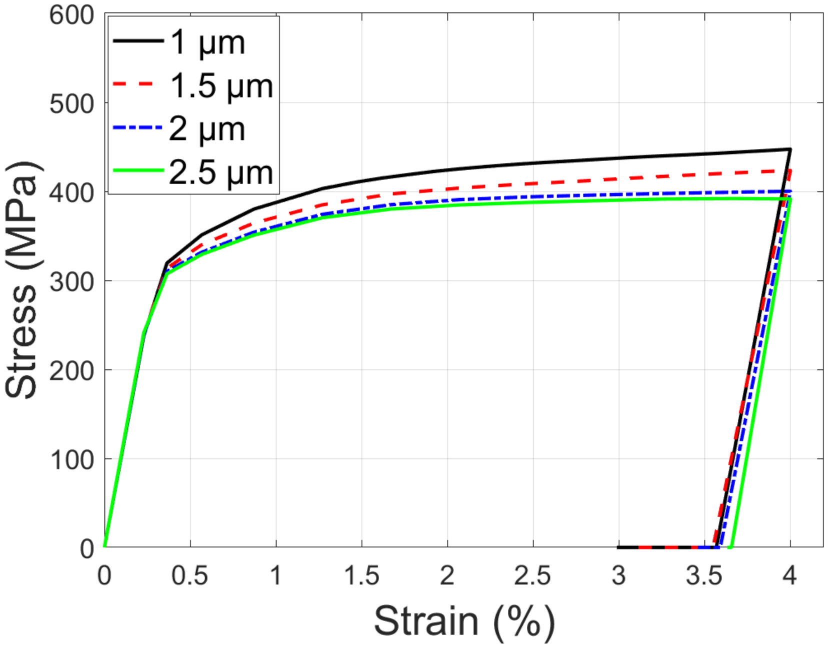
The amount of phase transformation, the maximum strength and the amount of strain recovery increase with the decrease of the particles’ diameter

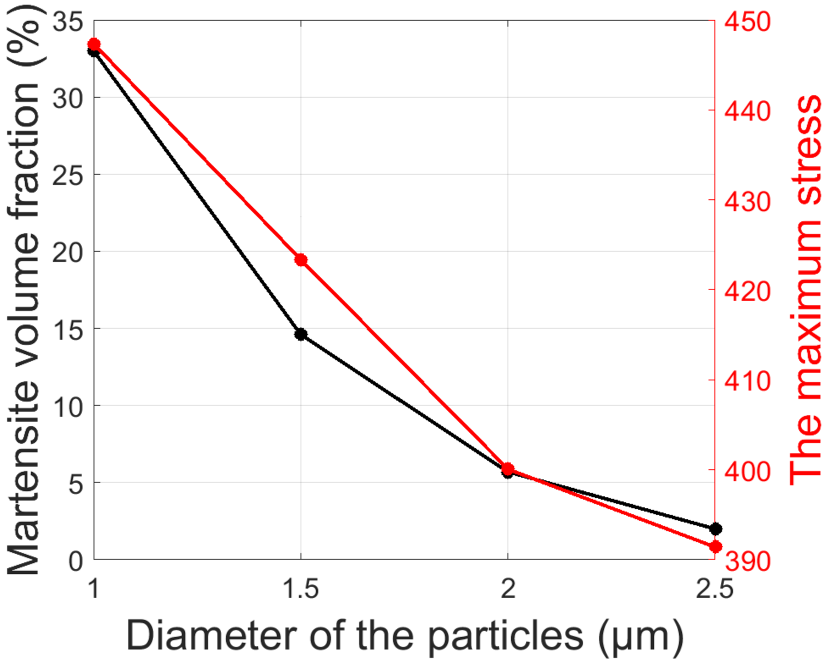


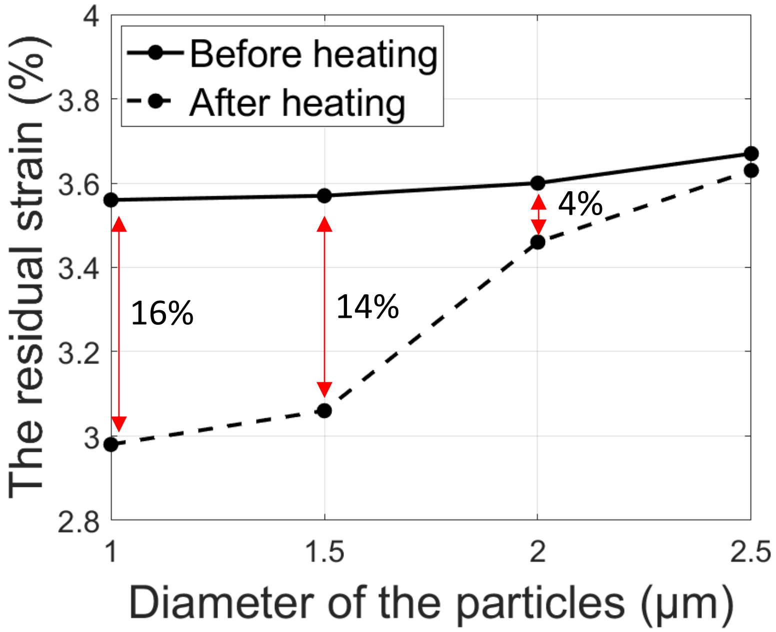
Zirconia volume fraction = 35%
Matrix yield stress = 250 MPa



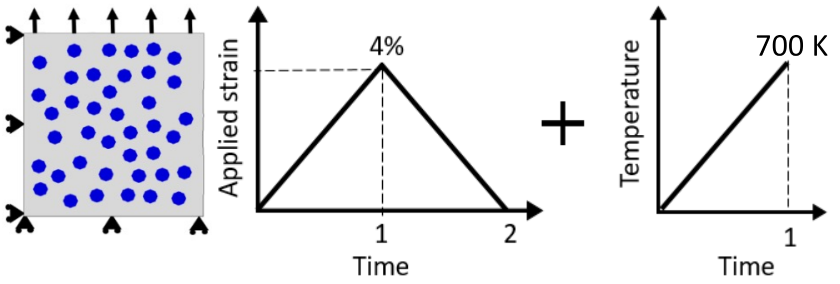




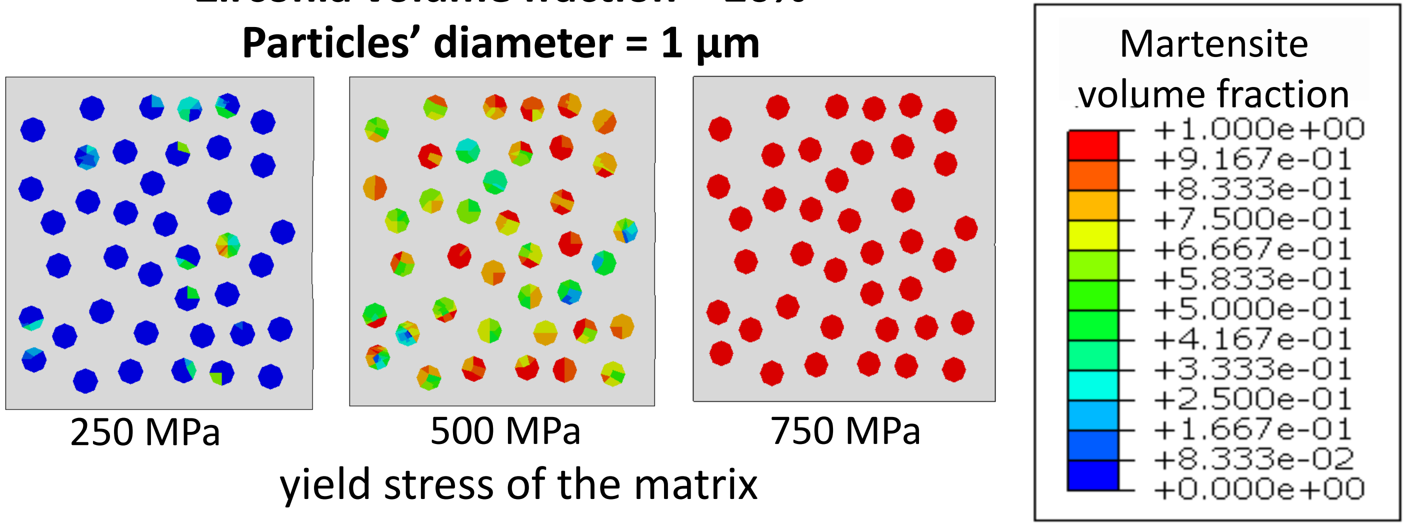


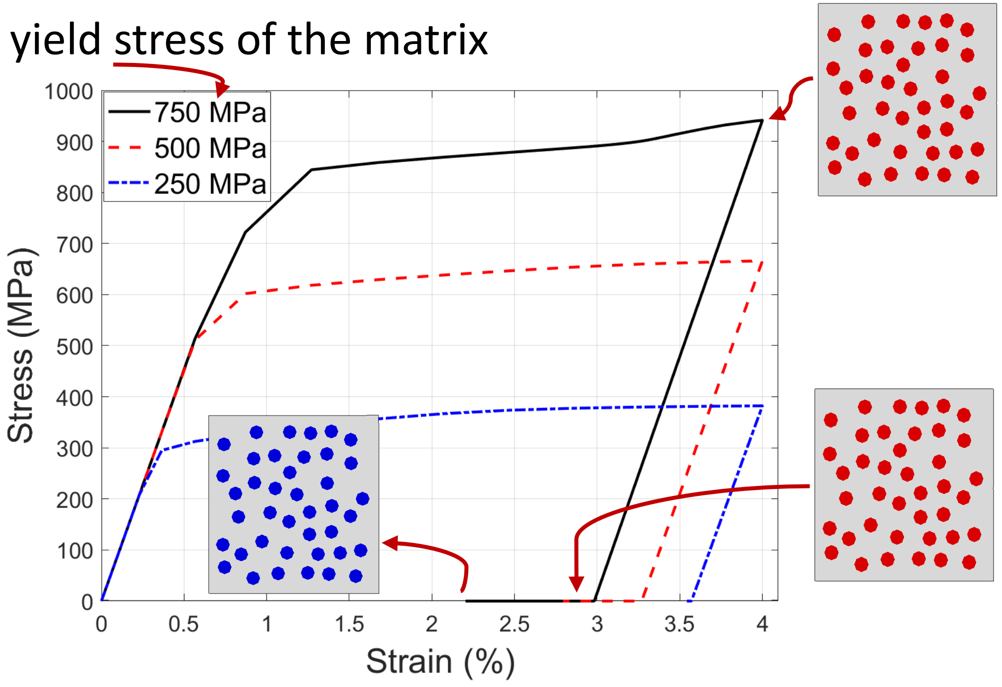


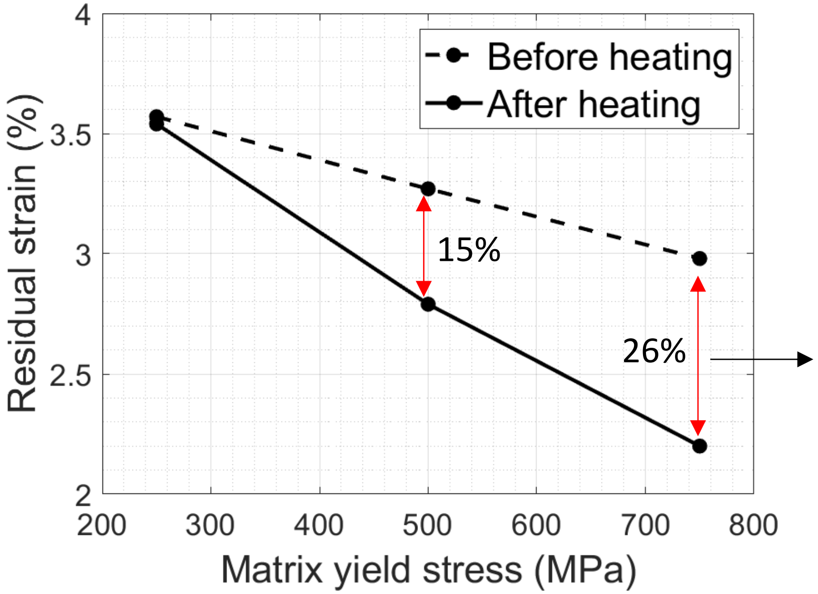
The matrix yield stress should approach or exceed zirconia's critical stress to trigger a significant amount of phase transformation



Zirconia volume fraction = 20%
Particles' diameter = 1 µm

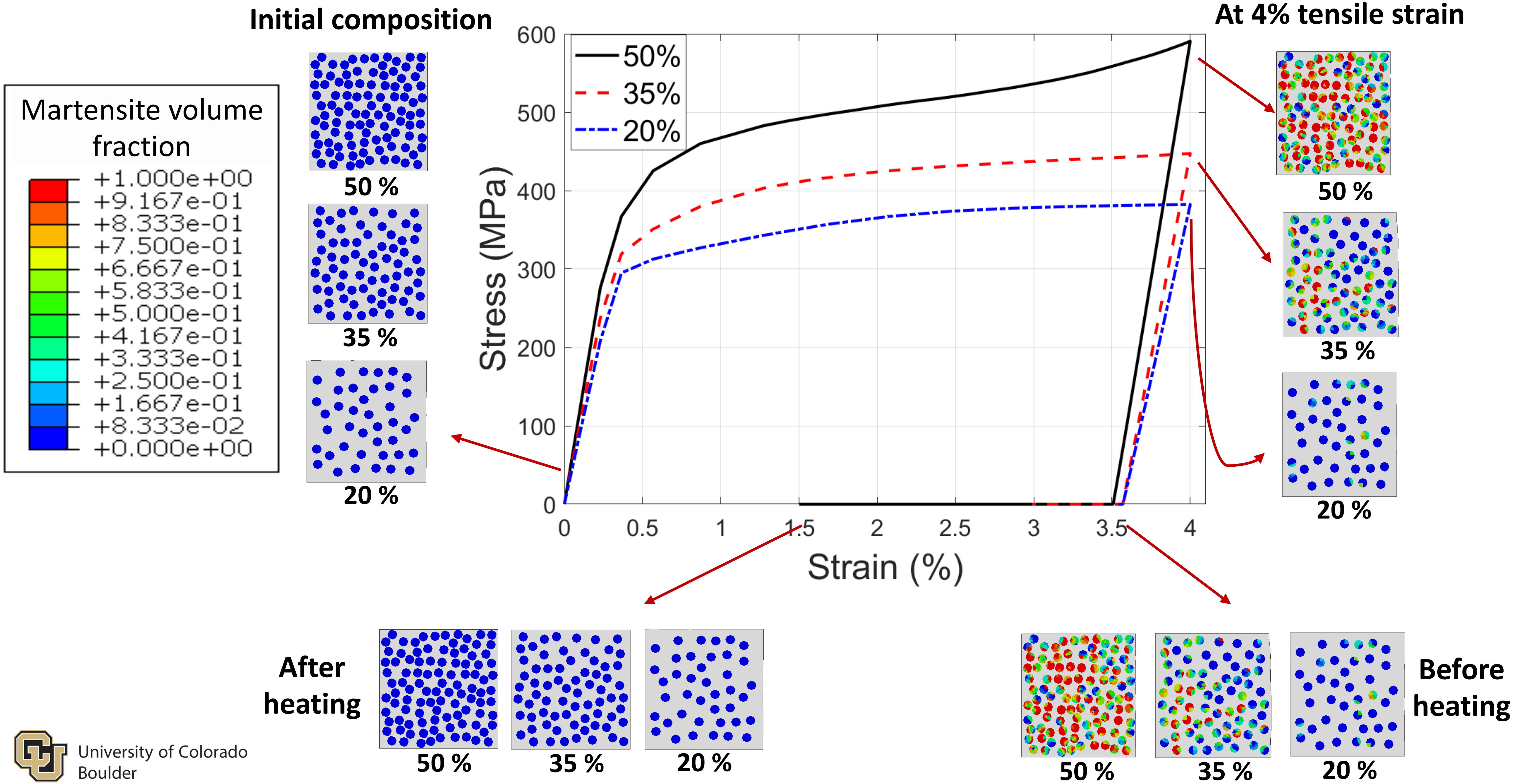




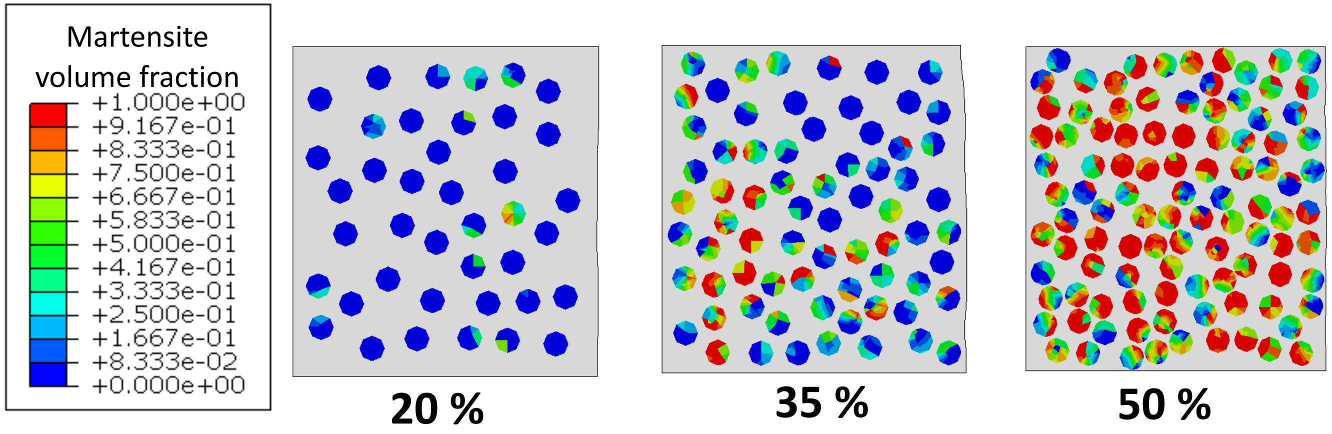


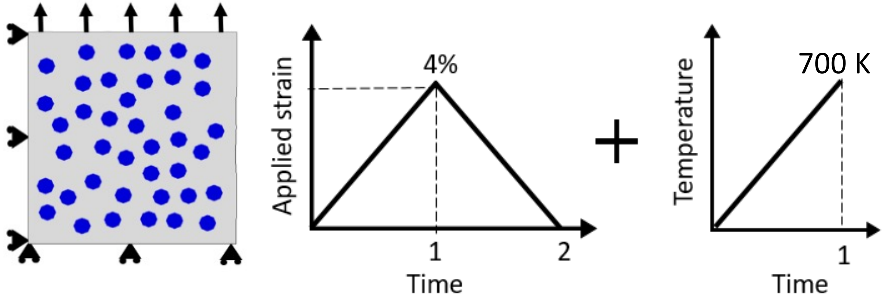
Higher strain recovery was achieved

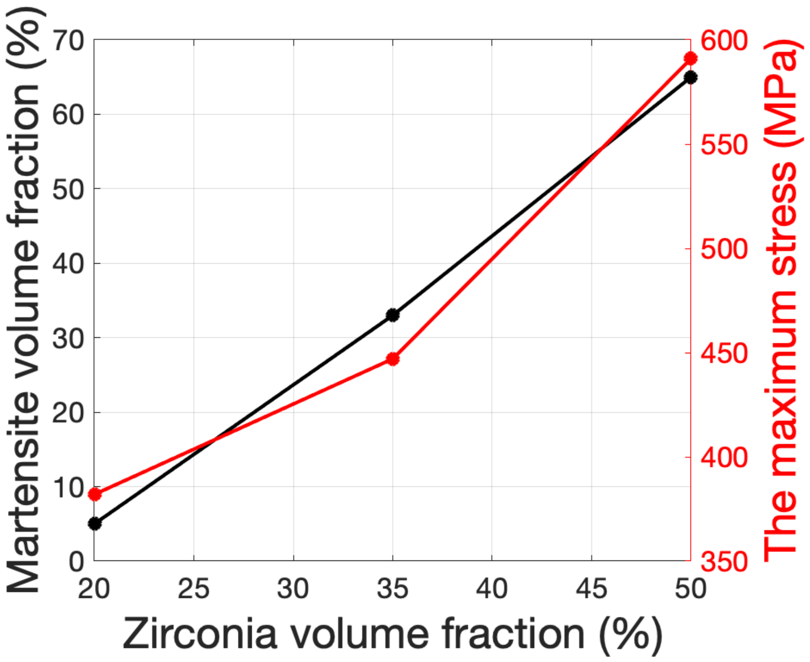
The maximum stress and the strain recovery upon heating increase with the increase of zirconia volume fraction

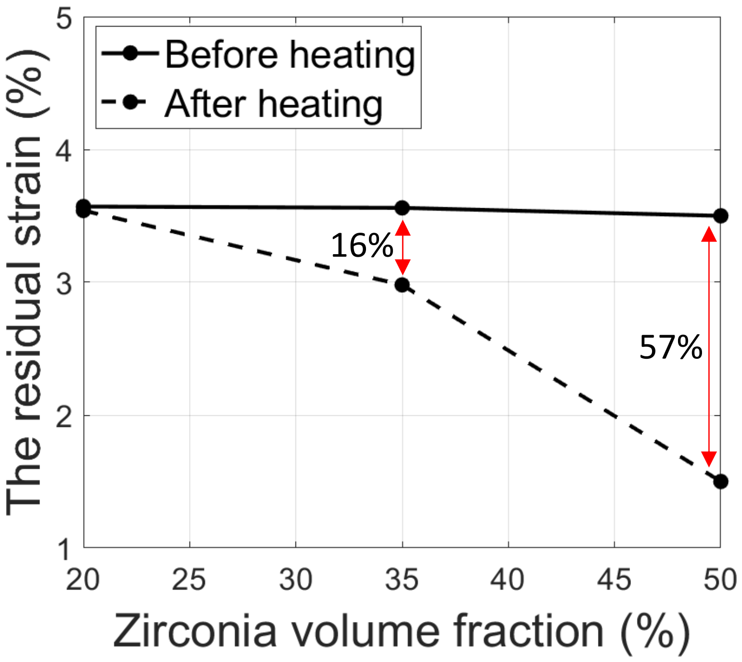


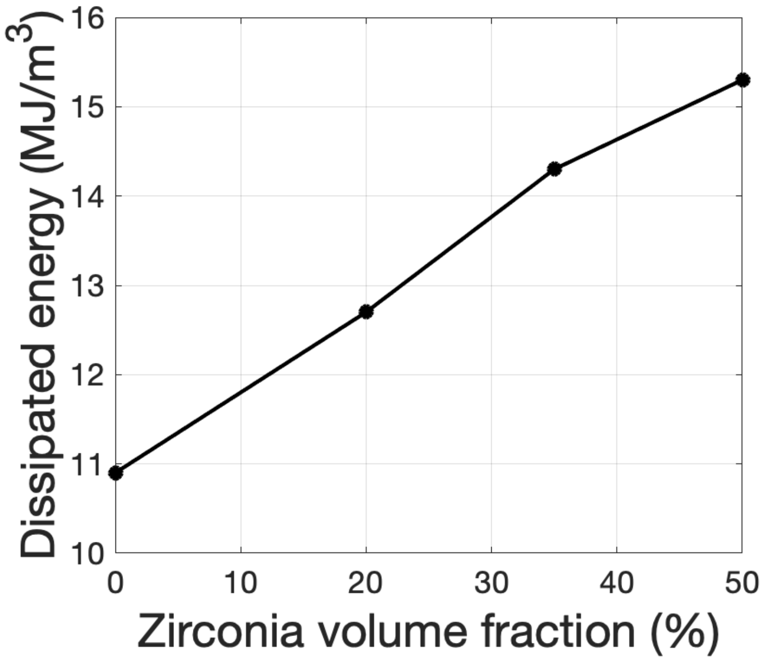
The amount of phase transformation, the maximum strength and the amount of strain recovery increases with the increase of zirconia content





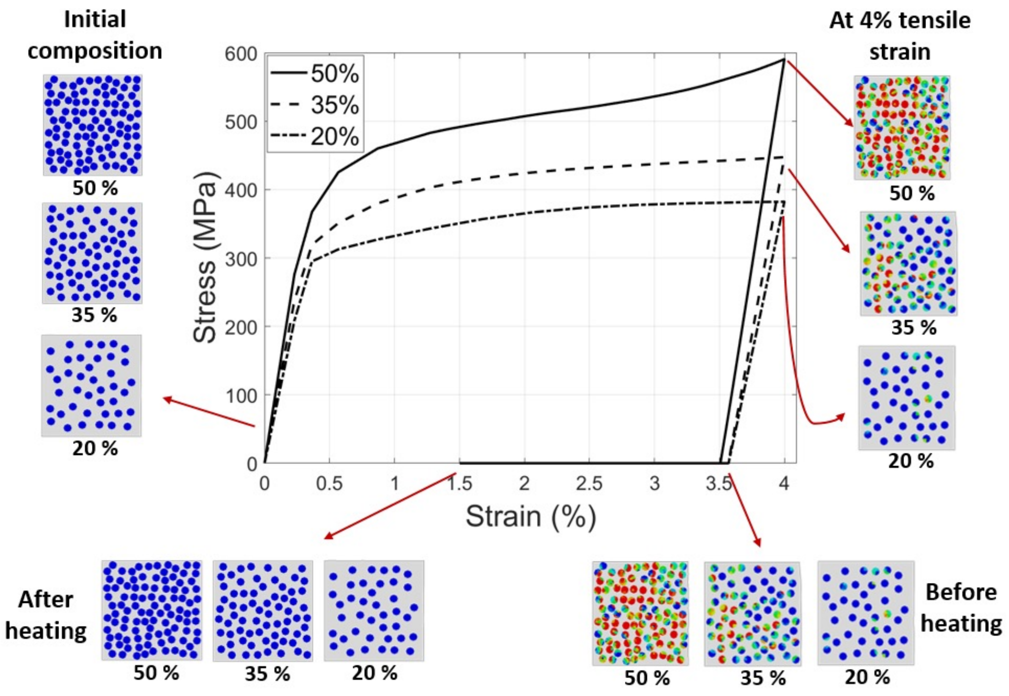






Conclusions

- Zirconia-based ceramics can effectively be used as reinforcing particles to enhance the strength of metal-matrix composites.
- Upon heating, zirconia embedded particles went through reverse phase transformation which results in strain recovery.
- The choice of the combination of the matrix and inclusions plays an important role to maximize the amount of phase transformation and consequently achieve higher stresses and strain recovery upon heating.
- For 50% zirconia volume fraction, the maximum stress and the energy dissipation were increased by 68% and 40% respectively compared to unreinforced aluminum. Upon heating, 57% strain recovery was achieved.



On-going work

- Improve the constitutive relationships (account for the effect of cyclic loading, crystal orientation, residual strain…)

Funded by the National Science Foundation

Any feedback?

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https://tinyurl.com/FSMFeedbackMarwa