In-situ 3D damage visualization and molecular mechanism in fracture toughness enhancement of multiple network elastomers

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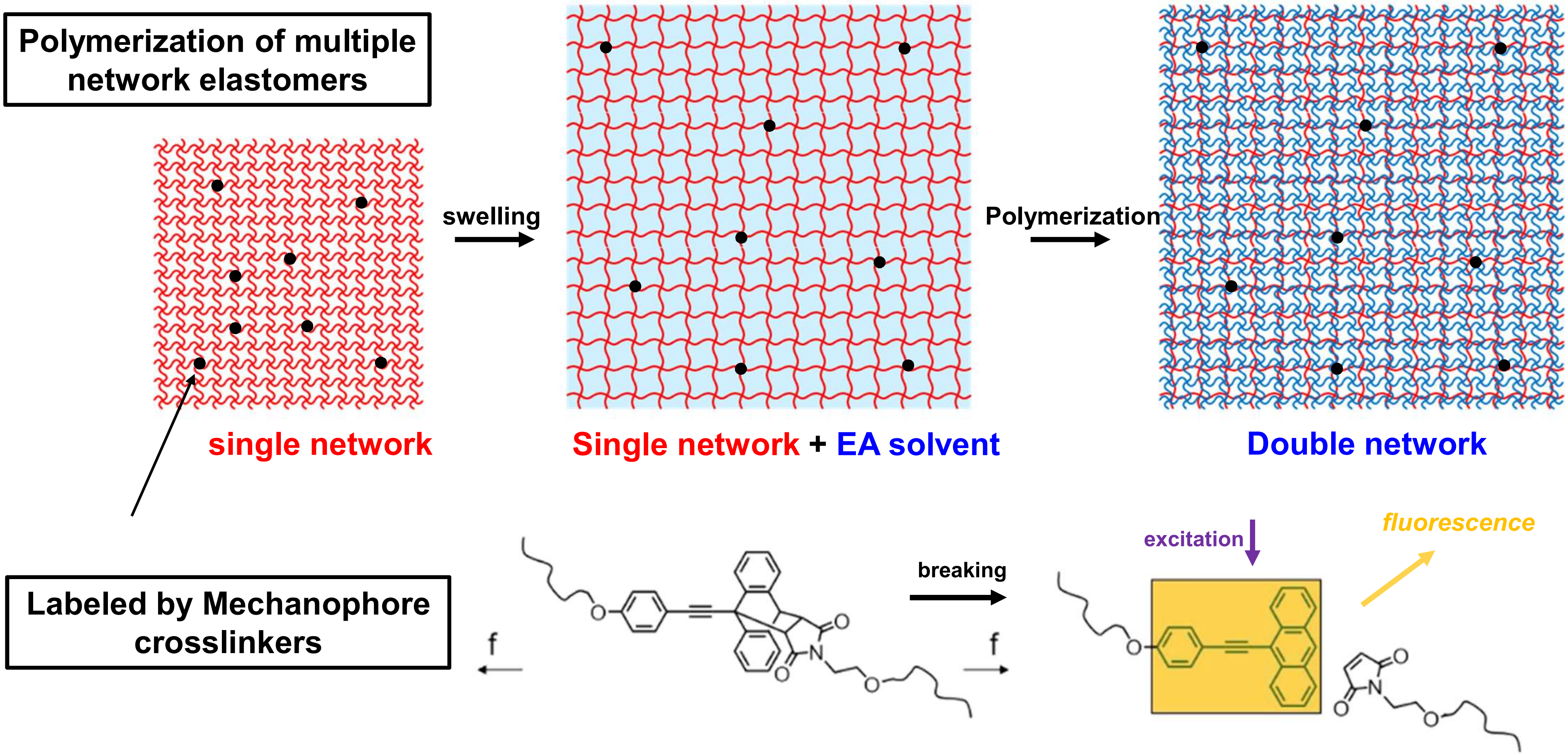
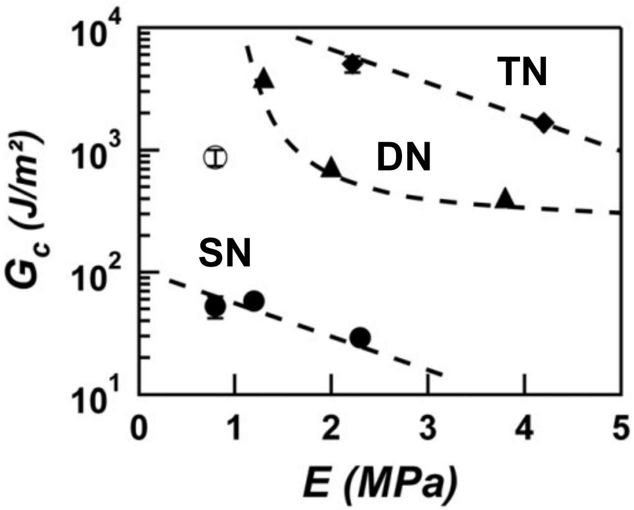
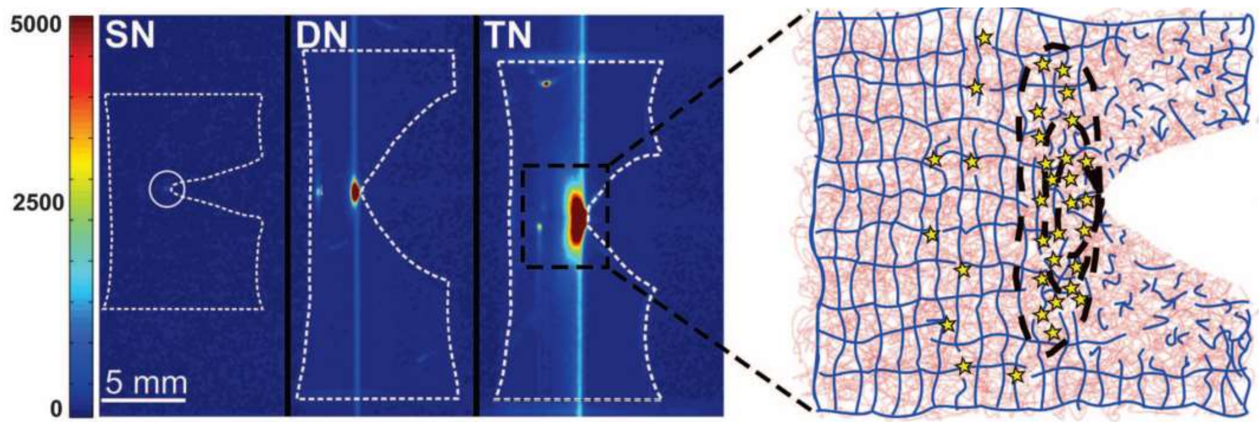
Material: Poly (Ethyl Acrylates) multiple network



Previous work: Toughening Elastomers by Sacrificial Bonds





Enhanced Fracture toughness

Stronger dissipation for multiple network

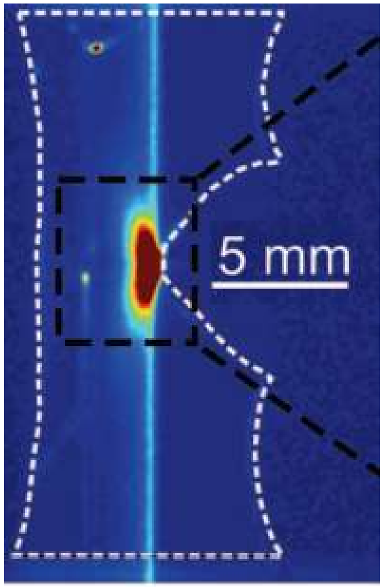
Fluorescence mapping visualized by camera

1. **2D fluorescence of a 3D structure**
2. **High threshold for damage visualization**

Opening question: dissipation mechanism in multiple network elastomers

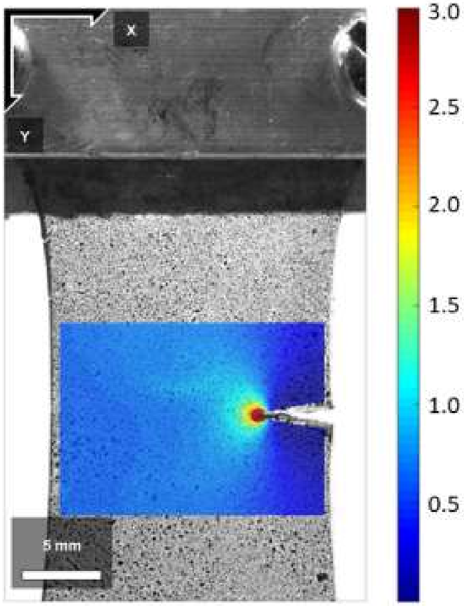
Damage mapping

Energy dissipation by molecular damage



Strain mapping

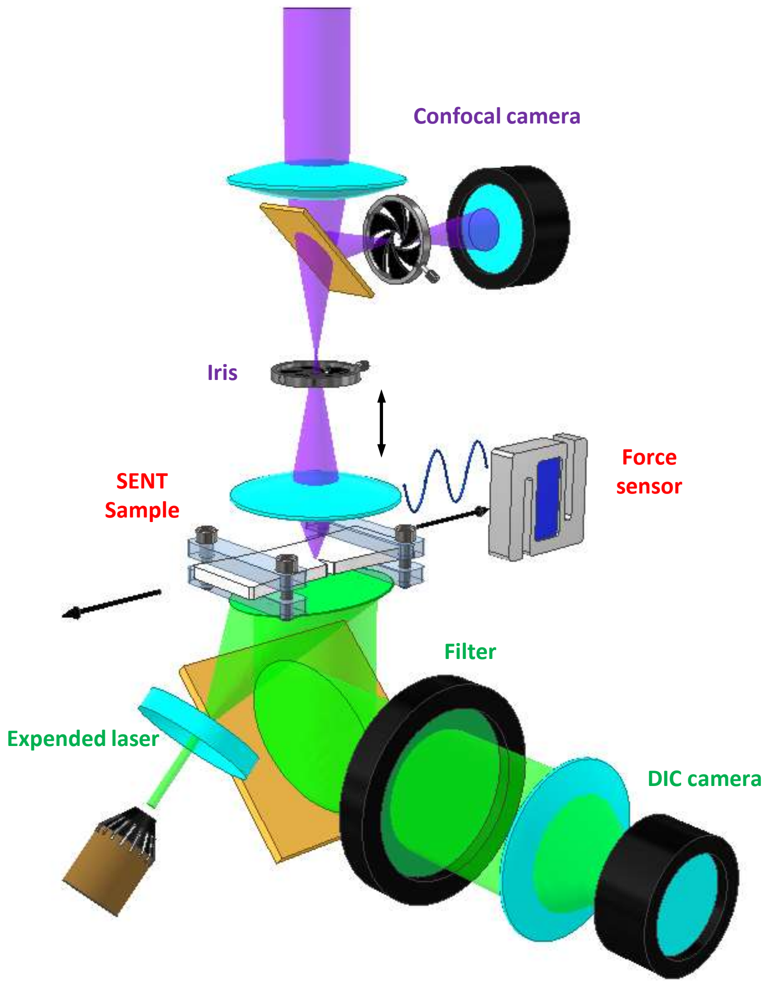
Energy dissipation by deformation localization (crack blunting)



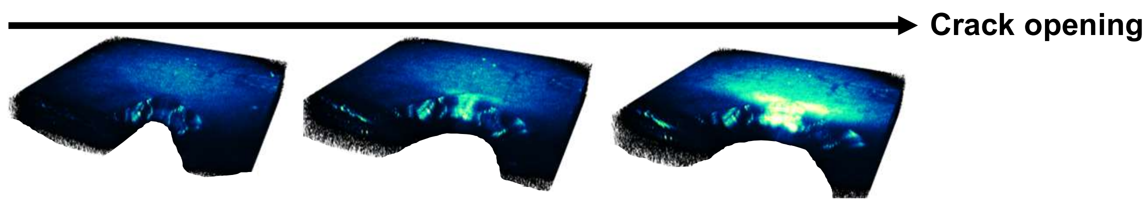
Challenge: Coexisting of different energy dissipation mechanism

Damage + Deformation localization

Solution: Digital image correlation + confocal microscopy mapping

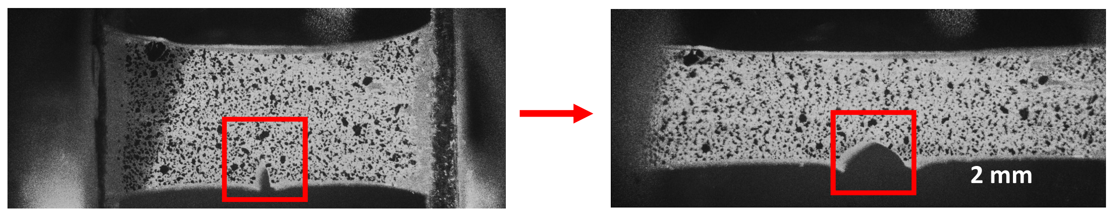


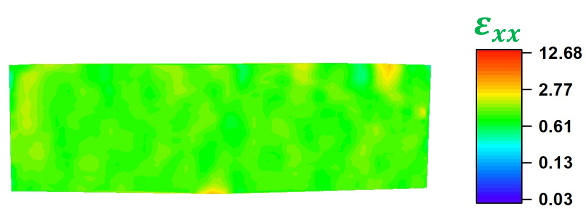
From top: confocal microscopy



damage mapping

From bottom: digital image correlation (DIC)

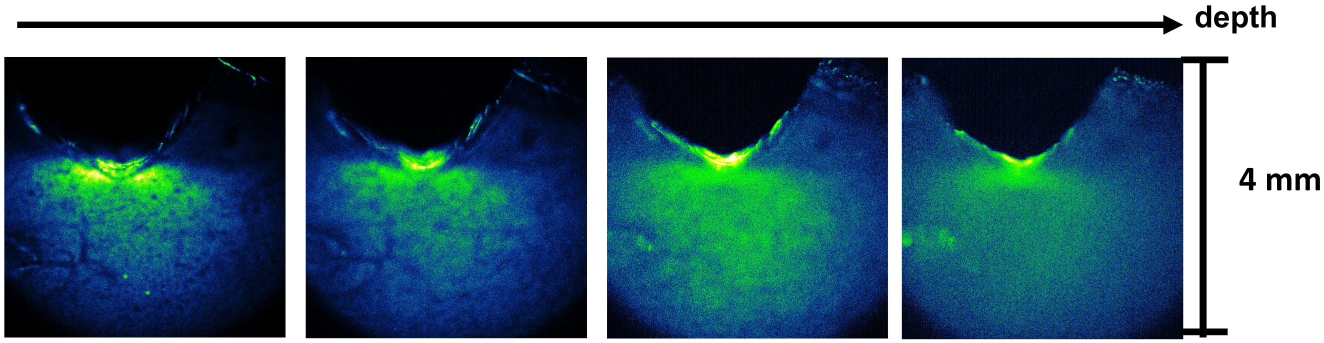




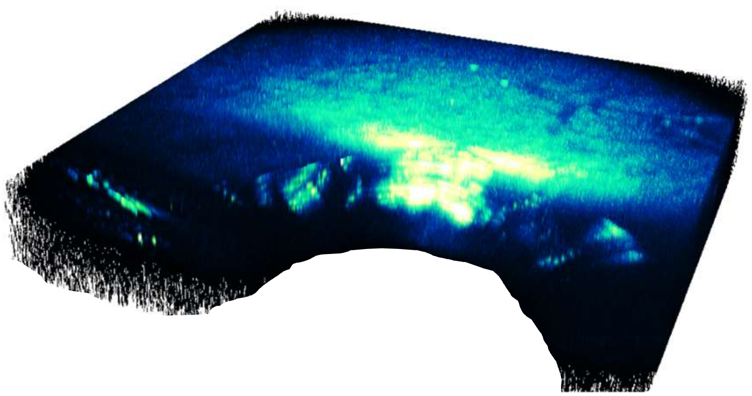
Strain mapping

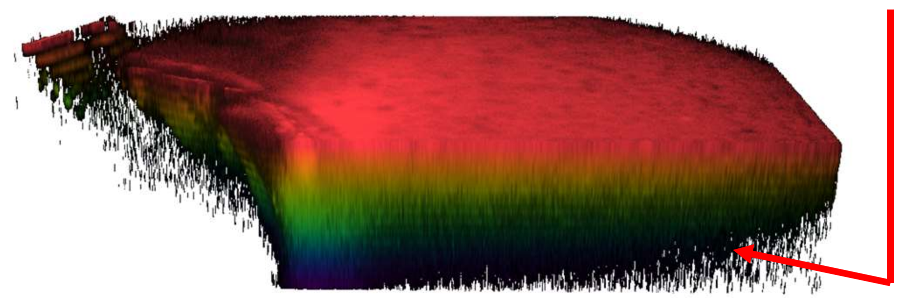
Generation of 3D images

Slices after renormalization



Information lost due to absorption





3D images
(maximum intensity projection without renormalization)

Side view with normalization
(different depth in different color)

Strictly, damage mapping in elastomers is a 3D mapping, but ***highlights surface (both top and lateral) change***

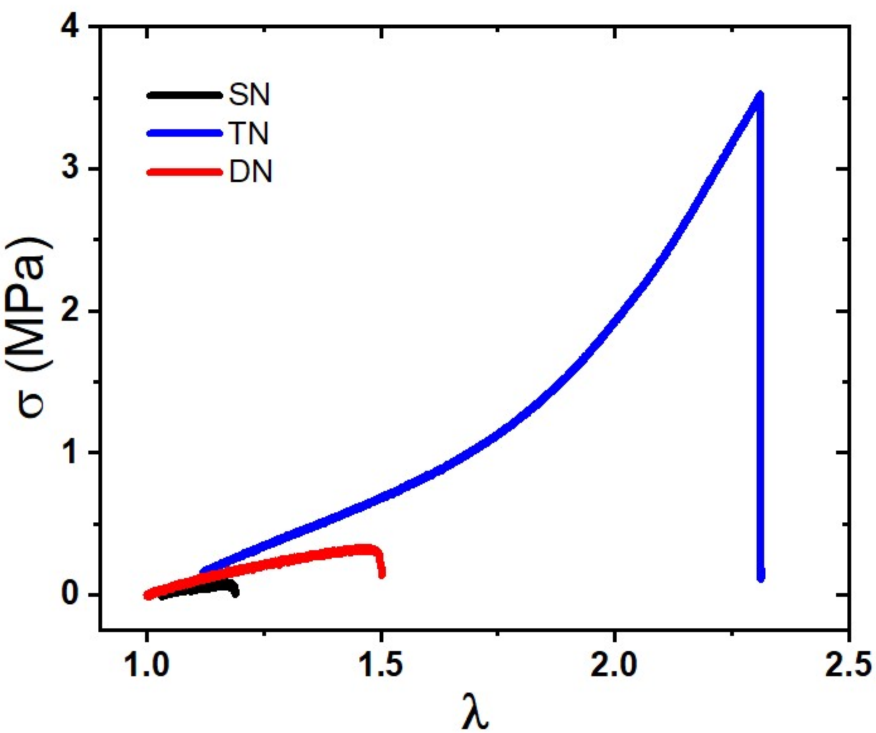
Enhancement mechanism of fracture toughness

I. Fast fracture

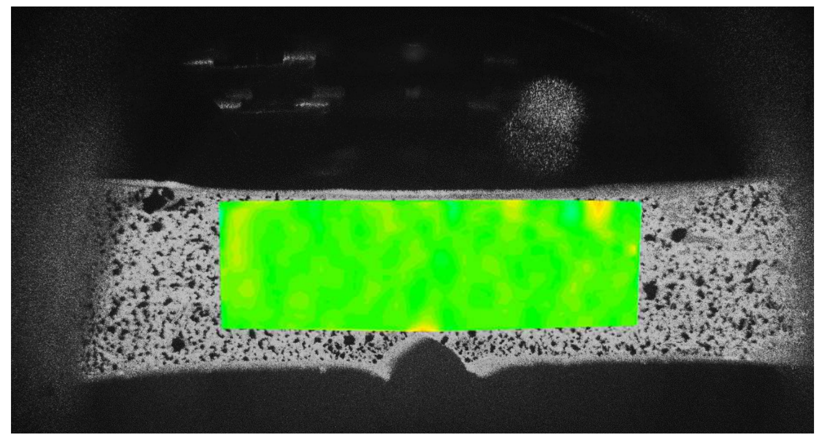
(stretch to break)

Macroscopic measurement

Stress-strain curve



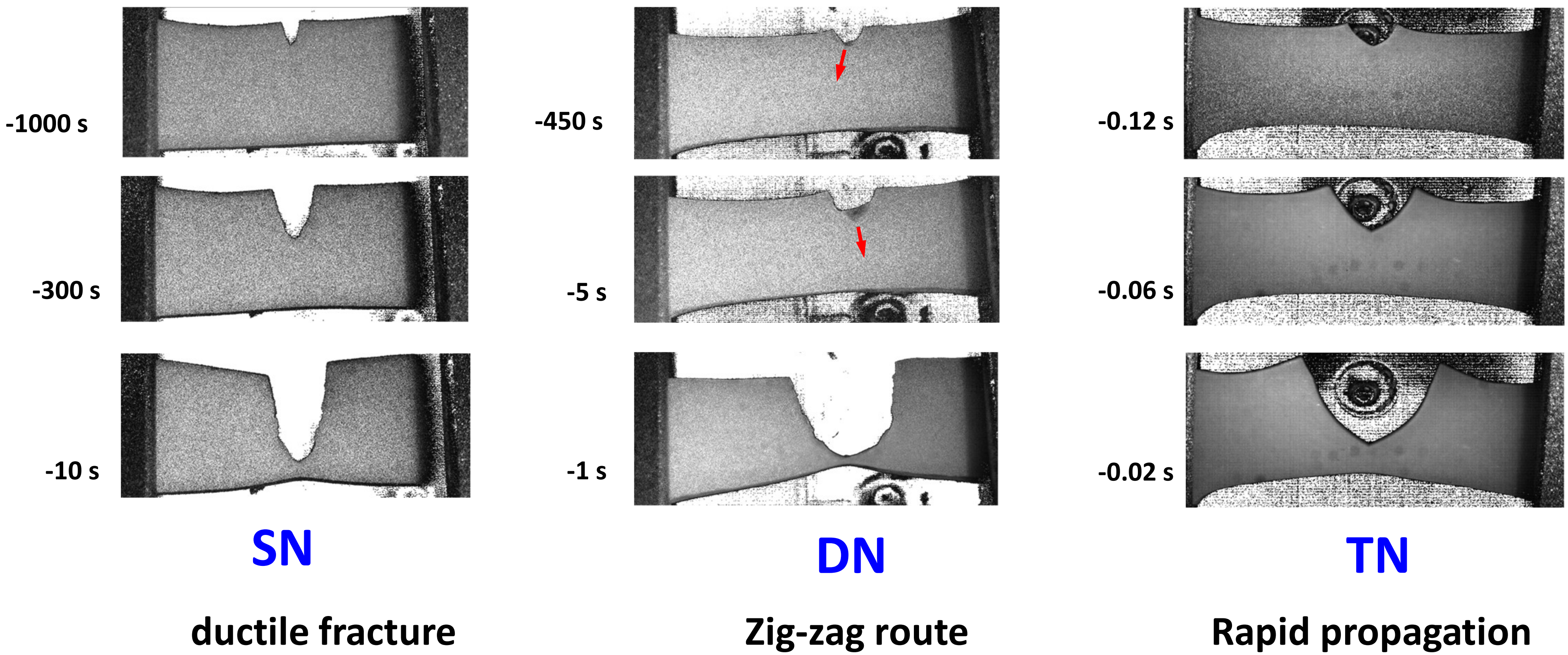
enhanced strength and fracture toughness



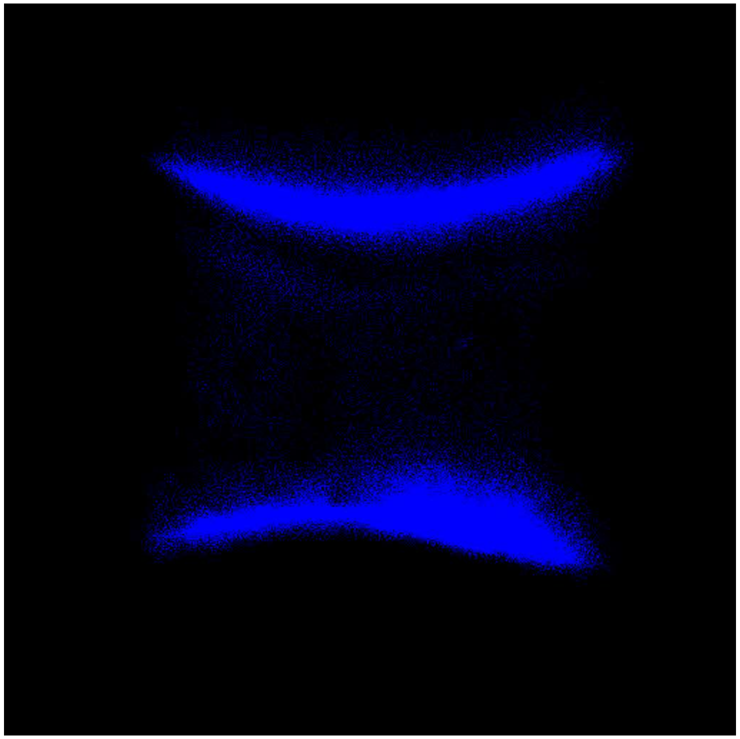
Sample parameter

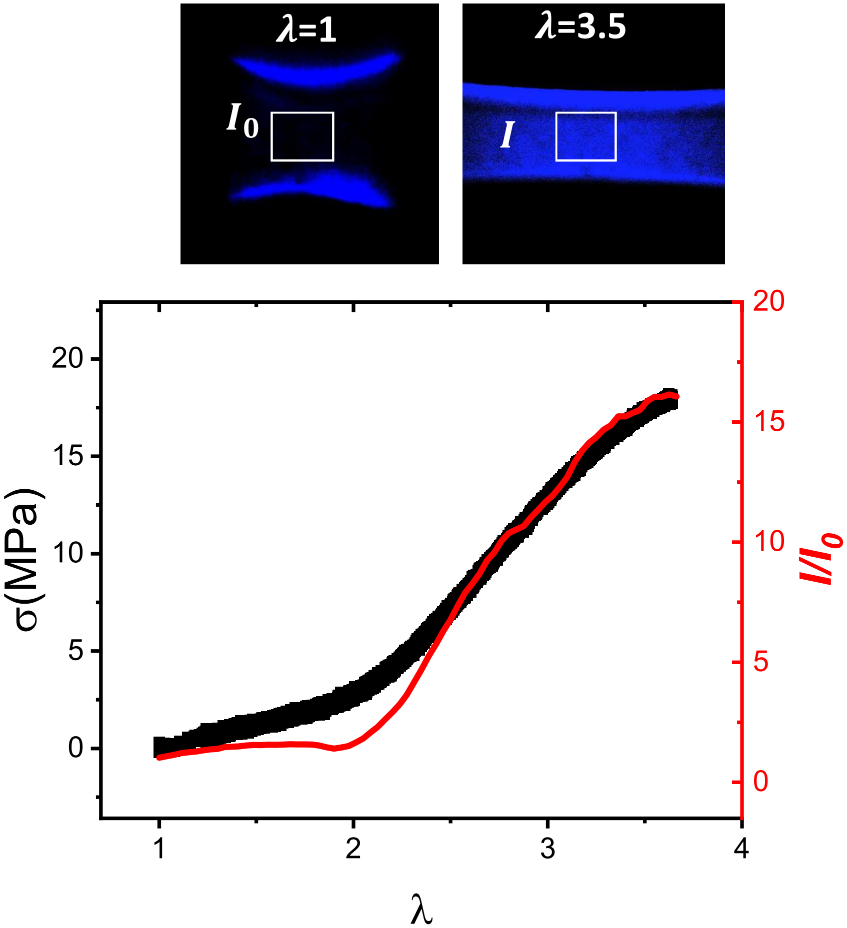
L x W: 15 mm x 6 mm
Crack length: 1.5 mm
Thickness: 0.8 mm-SN 1.3 mm-DN 1.9 mm-DN
Nominal strain rate: 10^{-4} s^{-1}

Propagation behavior



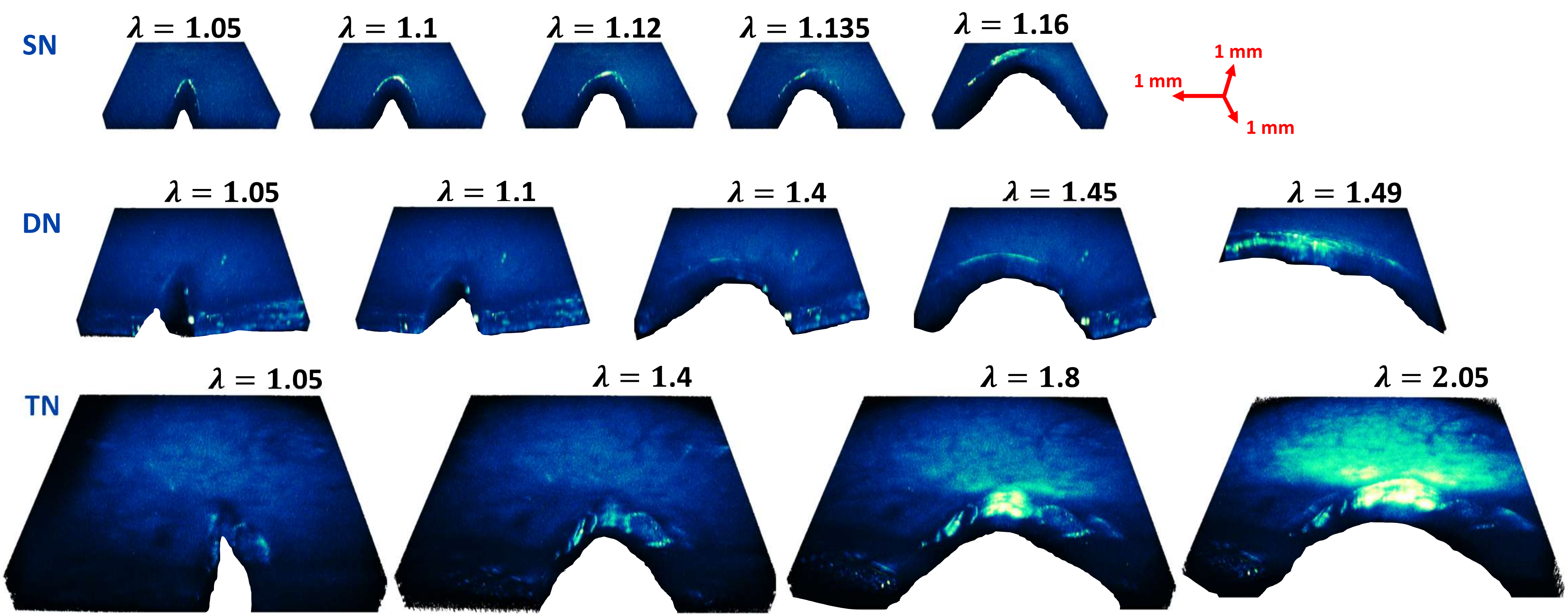
Bulk damage and strain hardening





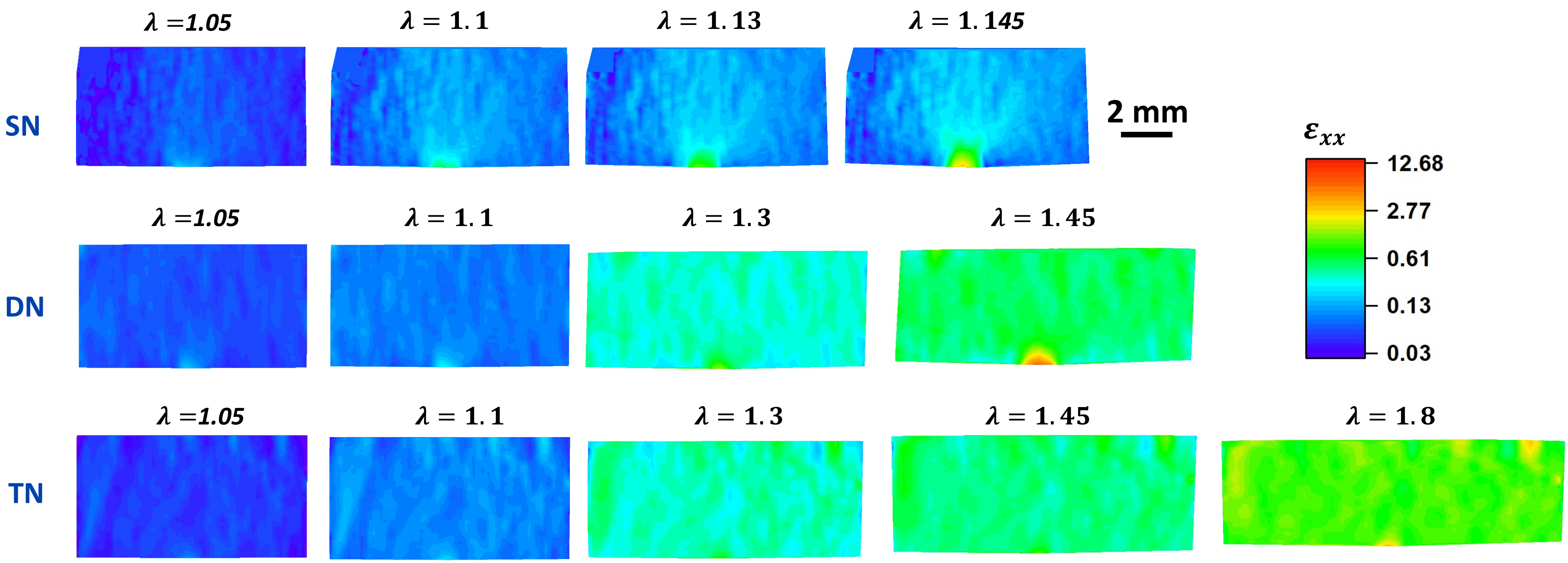
Dogbone sample (unnotched): random damage starts with strain hardening

Damage mapping



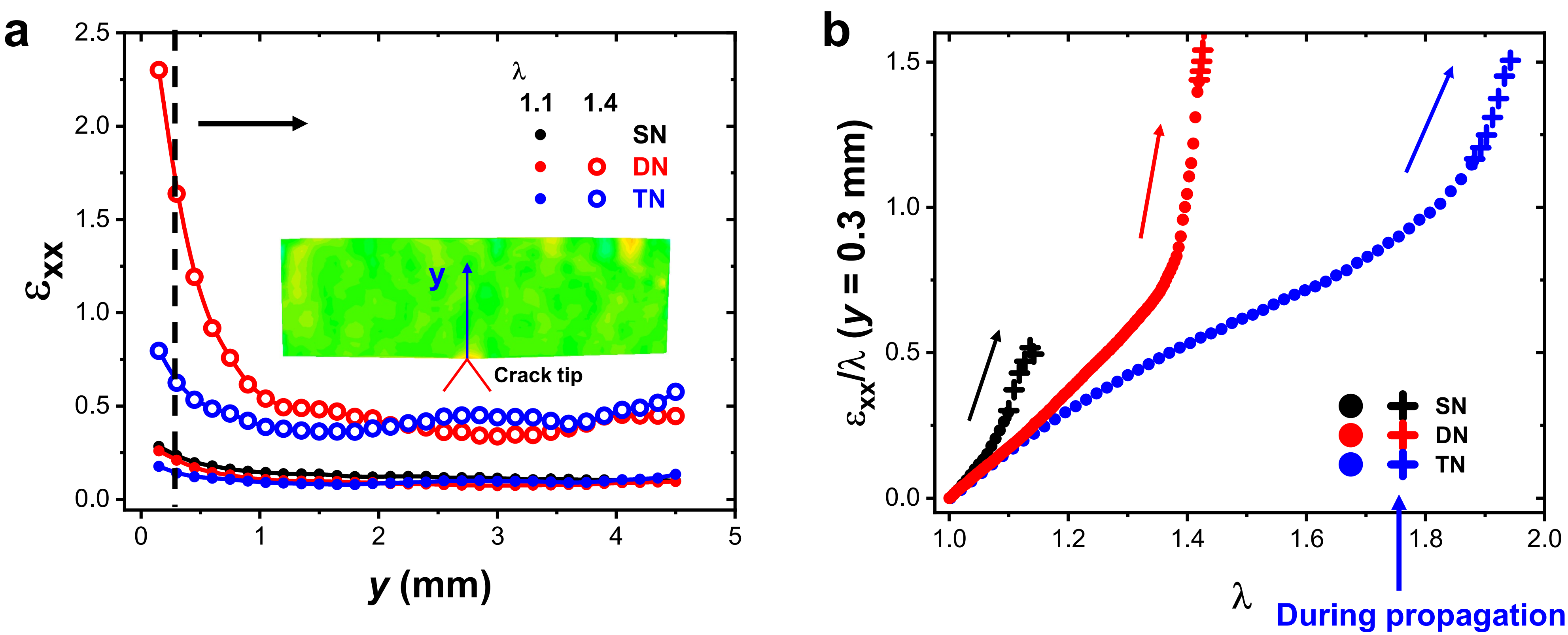
Increasing damaged region (without breaking) in higher level network

Strain mapping

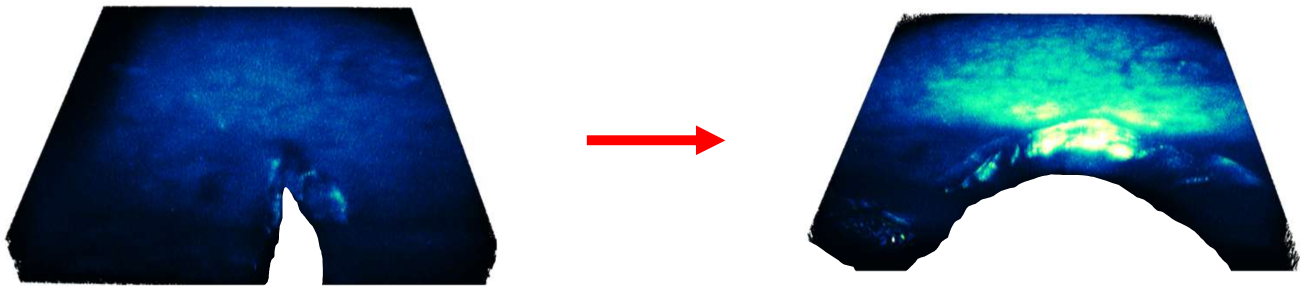


Decreasing strain localization in higher level network

Strain quantification



Responsive protection by sacrificial network



Strain localization → Damage localization —SN→ ***break***

Damage localization —DN,TN↓ Strain hardening (strengthening)

delocalization

Stress localization

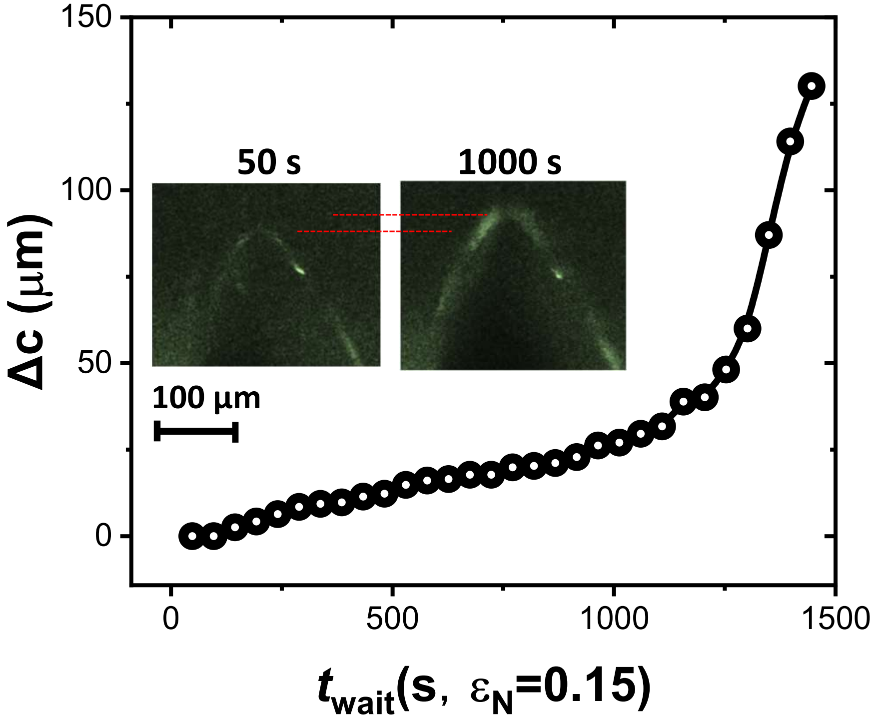
Strain hardening (strengthening)

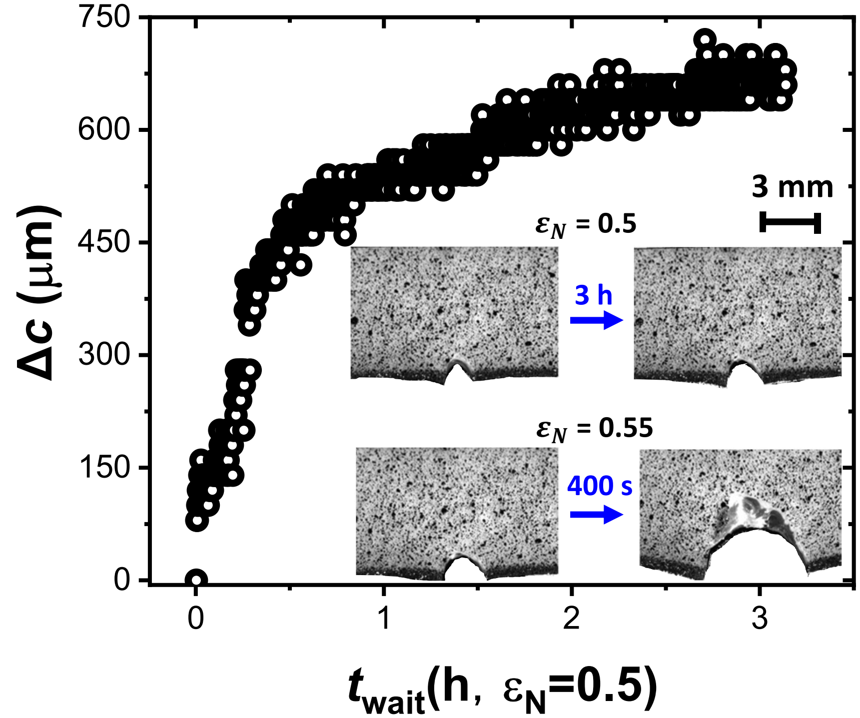
Enhancement mechanism of fracture toughness
II. Delayed fracture

(stretch and hold)

Enhanced resistance to delayed fracture

(increase strain step-by-step, until propagation is observed)



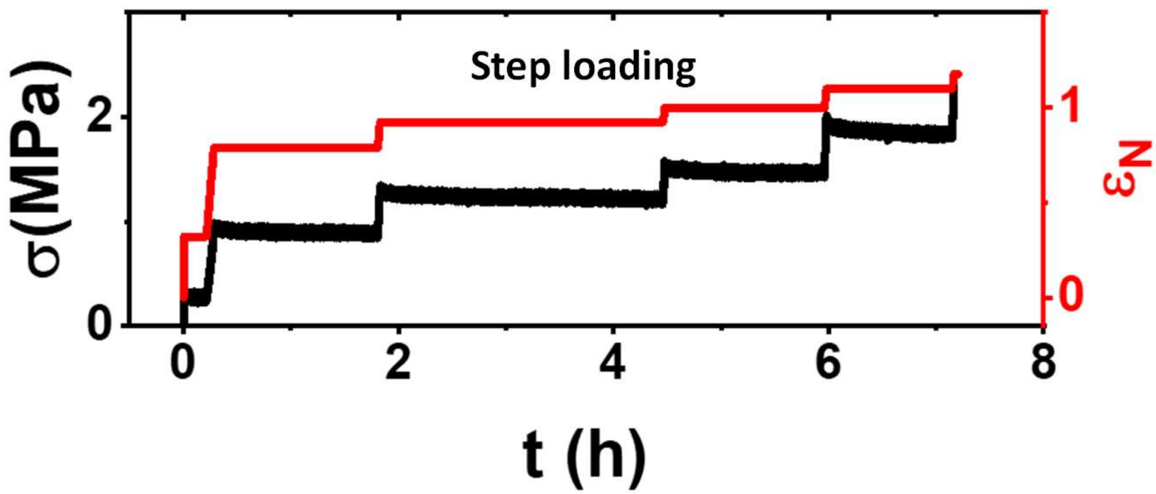


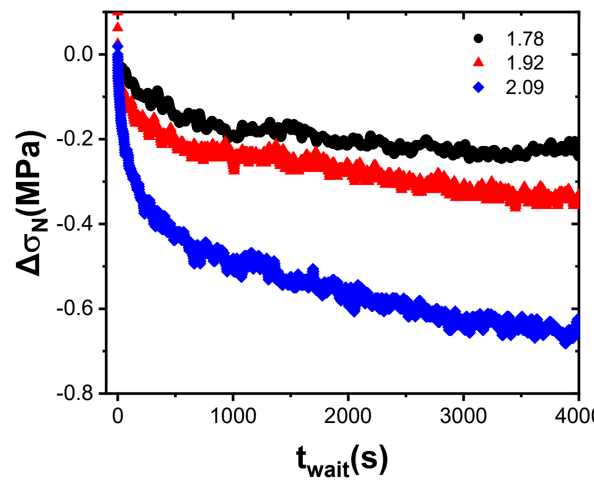
SN: self-acceleration

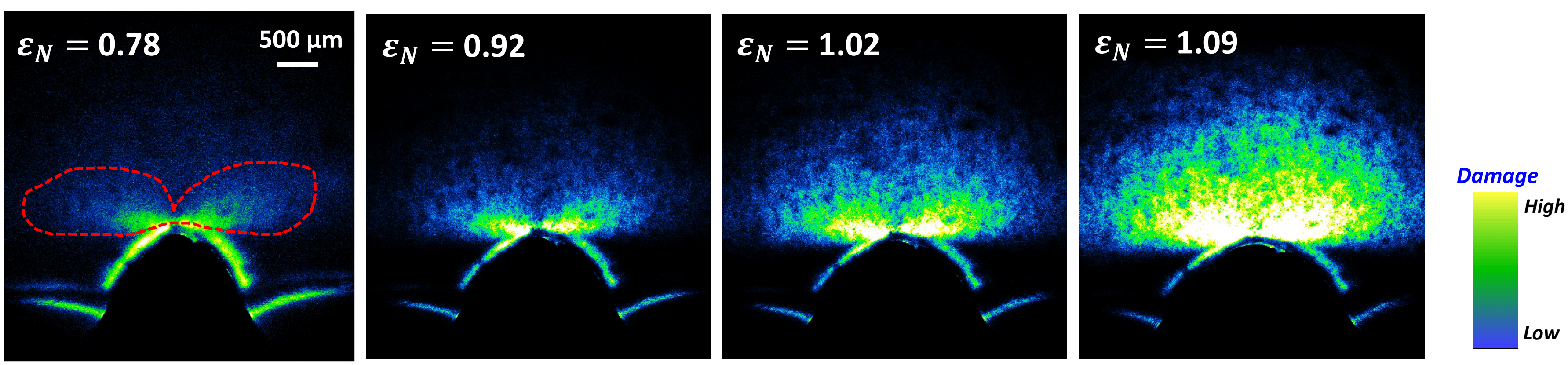
DN: self-stabilization

For TN, delayed fracture never happens: either break during stretching or not

Time-dependent behavior of damaged sacrificial network



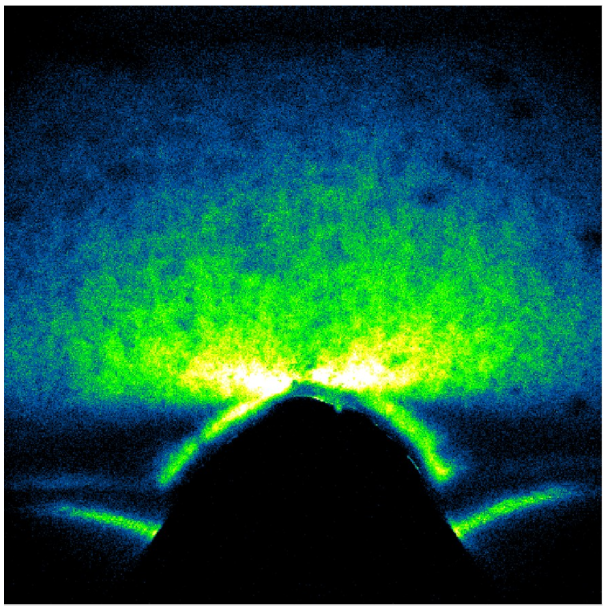




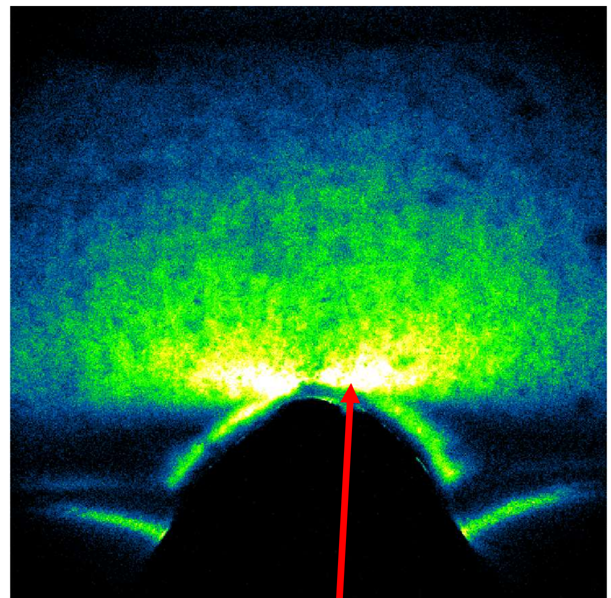
Images right after each steps

Continuous damage accumulation without stretching

Beginning



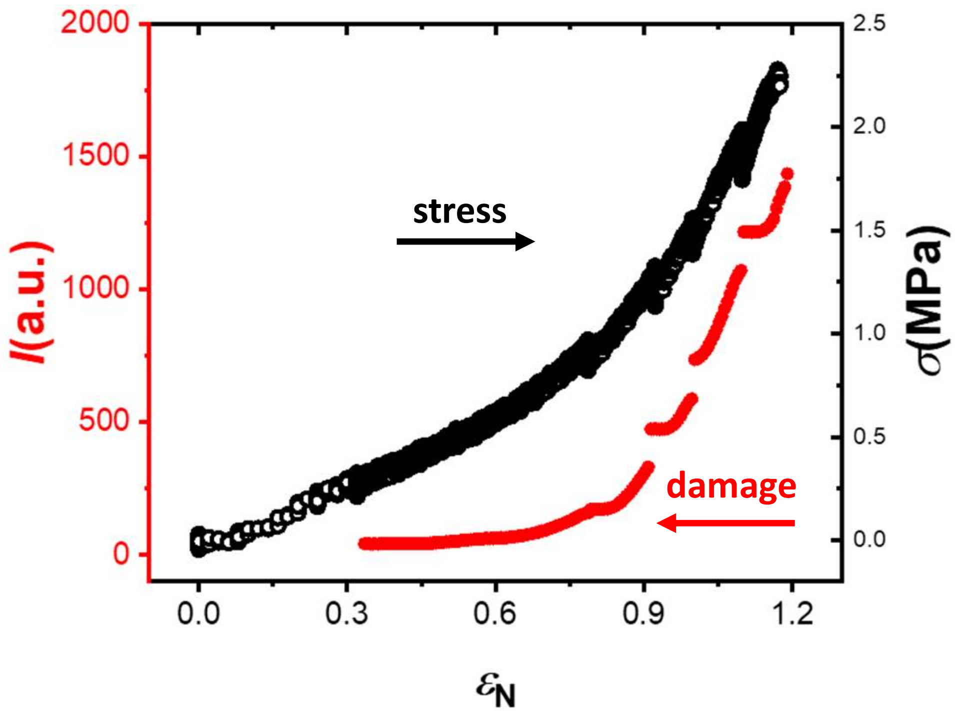
After 2100 s



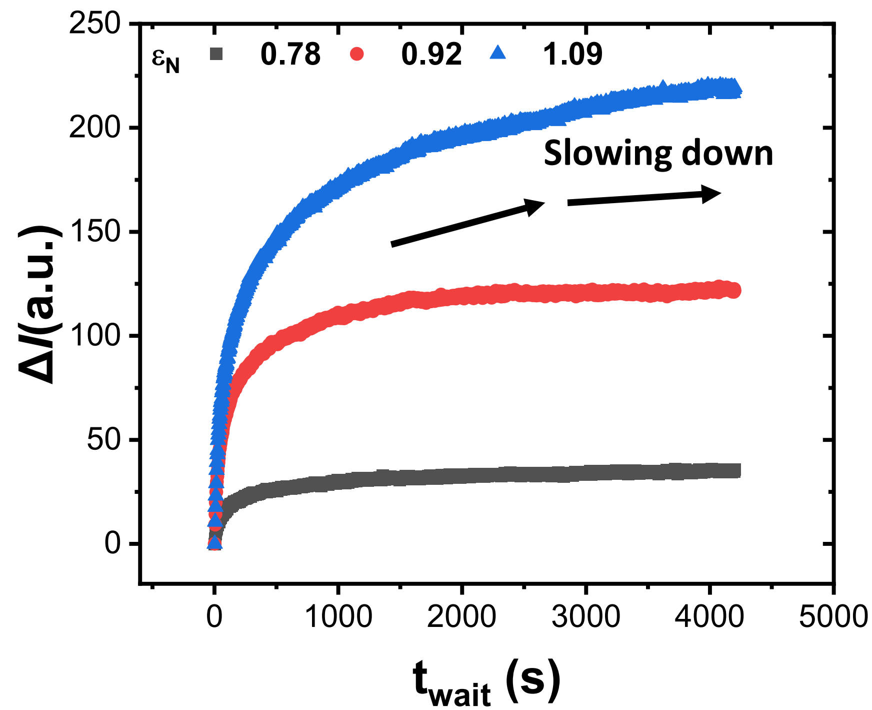
increase of intensity

Damage accumulation kinetics

Damage accumulating during stretching

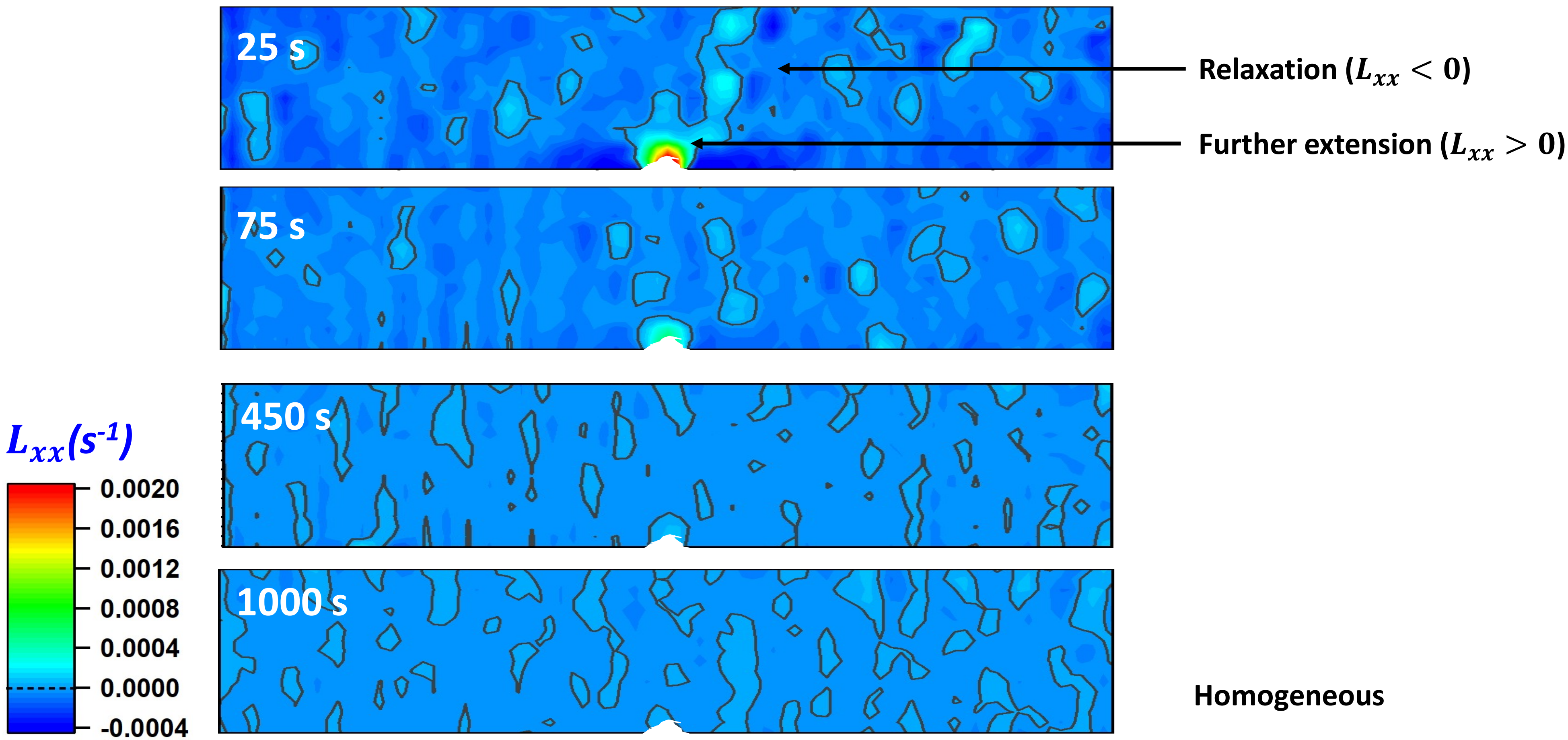


Damage accumulating during delay



Self-stabilized damage accumulation

Homogenization of strain rate distribution



Summary

- **1. 3D confocal mapping provides high-resolution image in the deformed state of crack tip.**

- **2. Multiple network elastomer shows enhanced resistance to rapid fracture and delayed fracture**

- **3. Sacrificial network provides a responsive protection again strain/damage localization.**