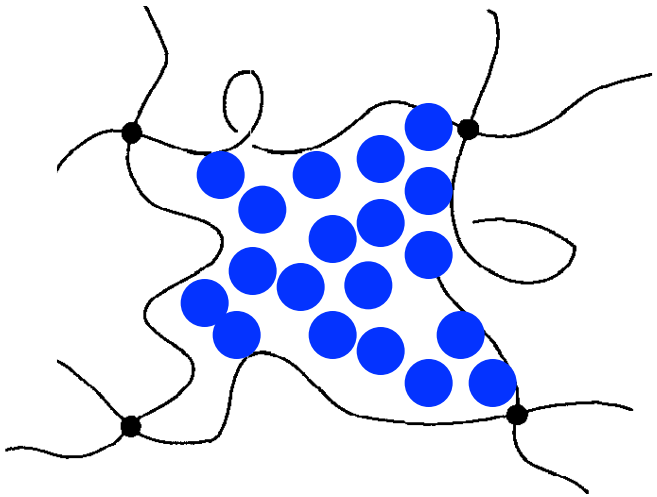
中科院力学所/力学云论坛

advances in the mechanics of soft materials

elastic dissipaters

Zhigang Suo
Harvard University

Soft material 1. Tissue



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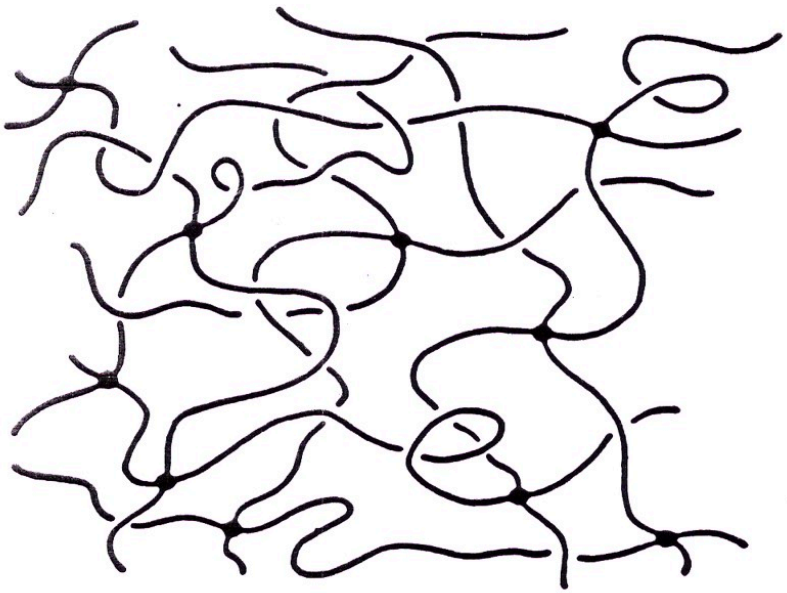
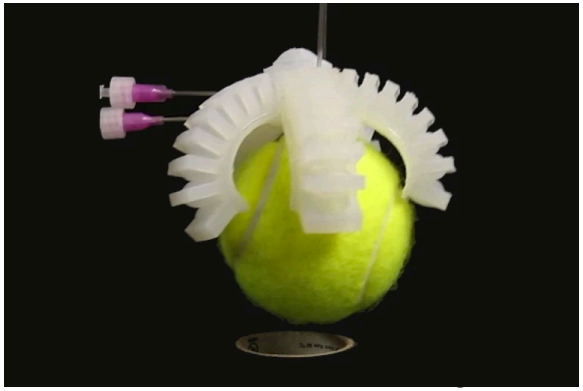
Soft material 2. Elastomer



Polymer chain
Crosslink

Polymer network



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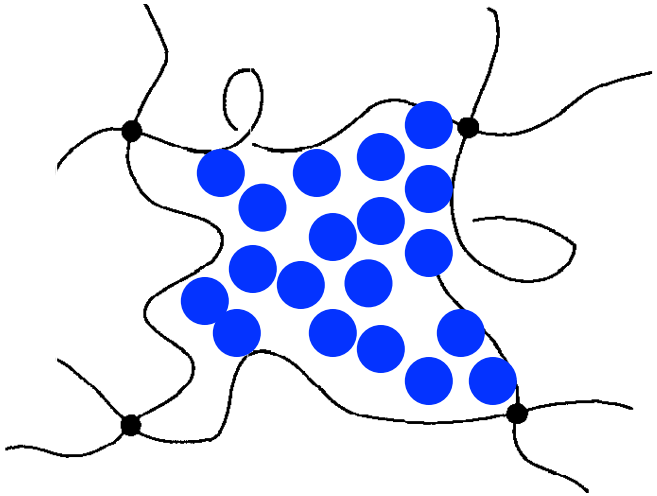
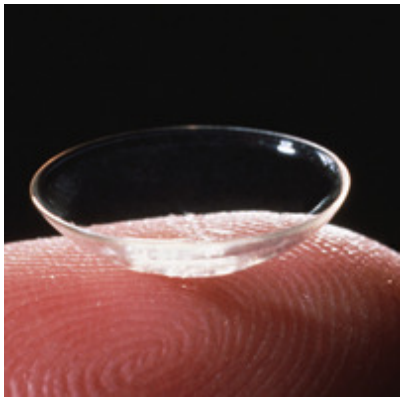
Soft material 3. Hydrogel



Polymer chain
Crosslink

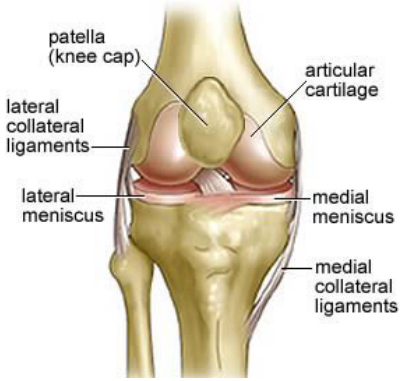
Polymer network

Solvent
Solute



Contact lens
1960s

Superabsorbent diaper
1980s



Artificial tissues
ongoing

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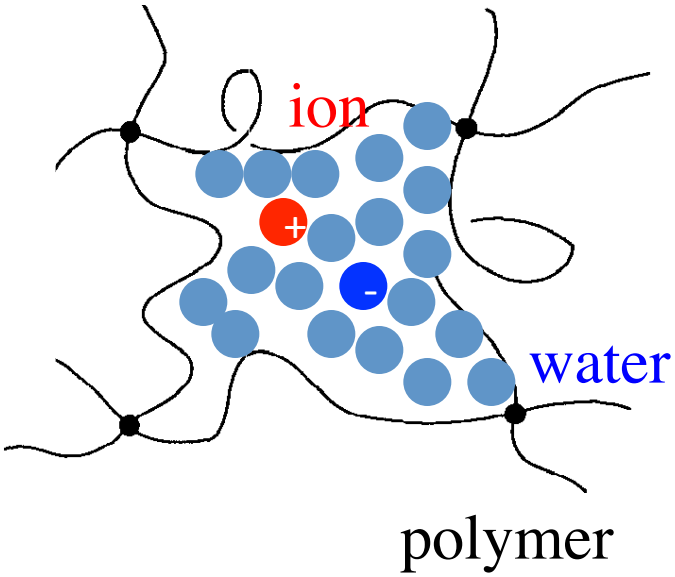
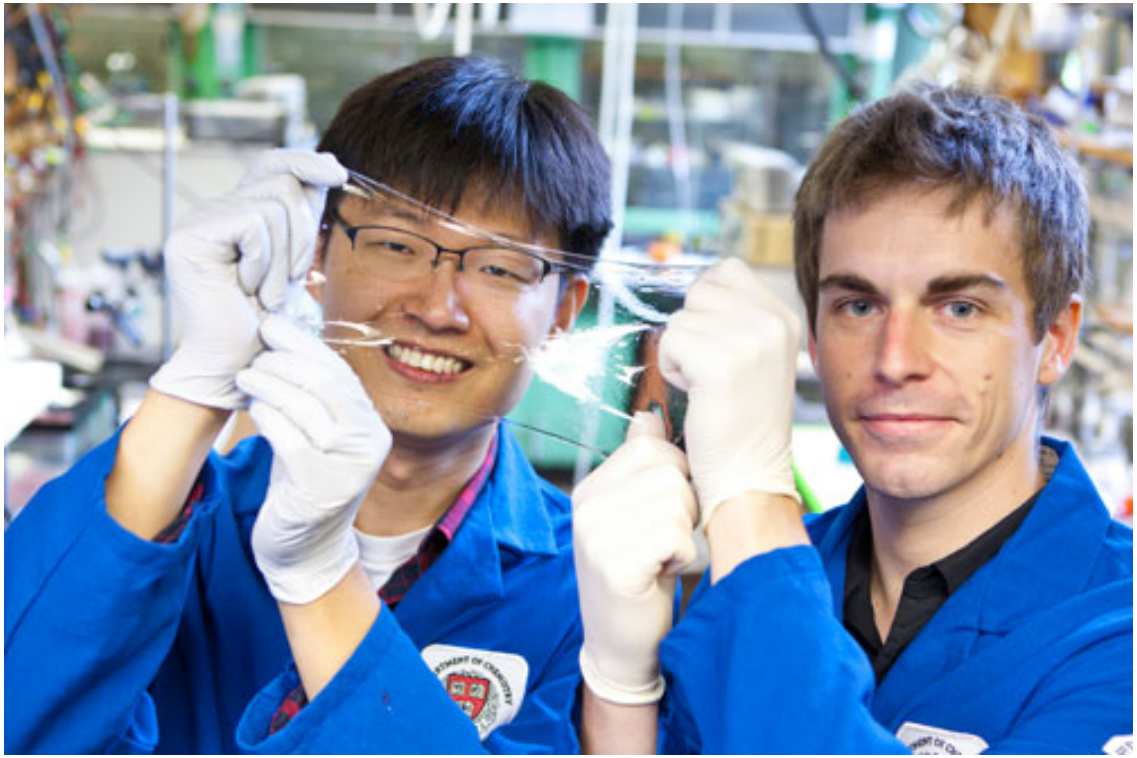
Stretchable, transparent, ionic conductors

Hydrogel





Keplinger, Sun, Foo, Rothemund, Whitesides, Suo. Science 341, 984 (2013)

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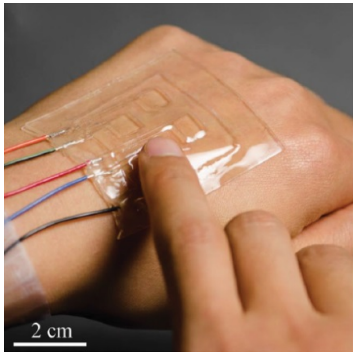
hydrogel ionotronics

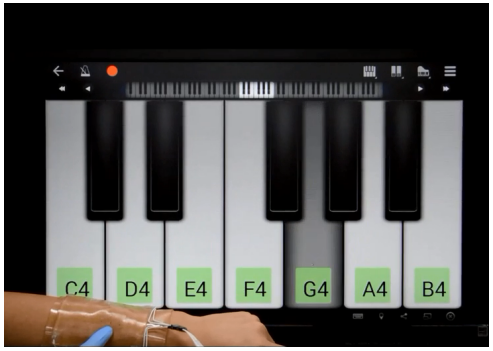
ionic music (iTune)

Science 2013

ionic touchpad (iPad)

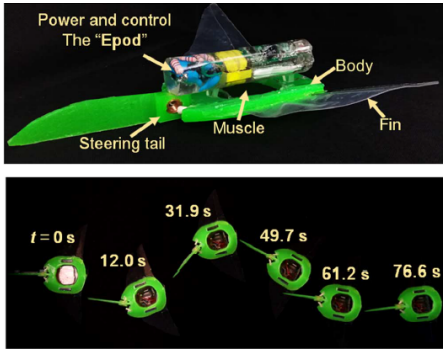


Advanced. Materials 2014



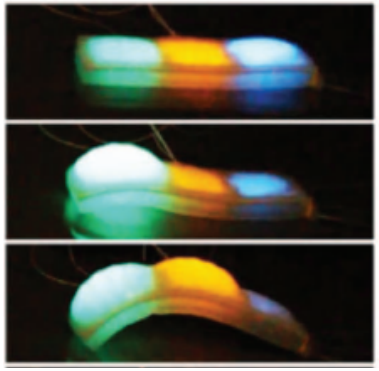
Sun, et al. Science 2016

ionic robot (iBot)

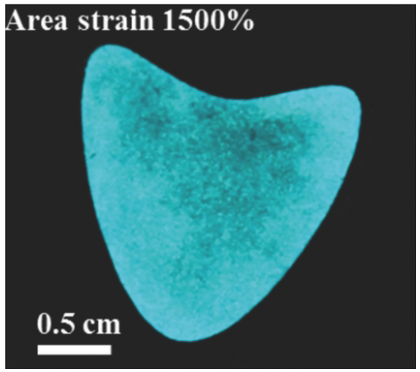


Li, et al. Sci. Adv. 2016

electroluminescence



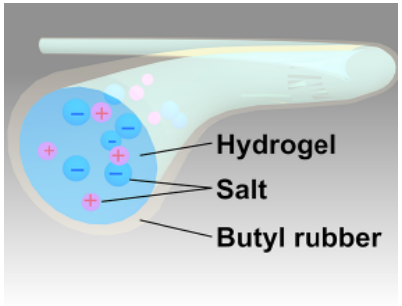
Larson et al. Science 2016



Advanced Materials 2016

artificial axon

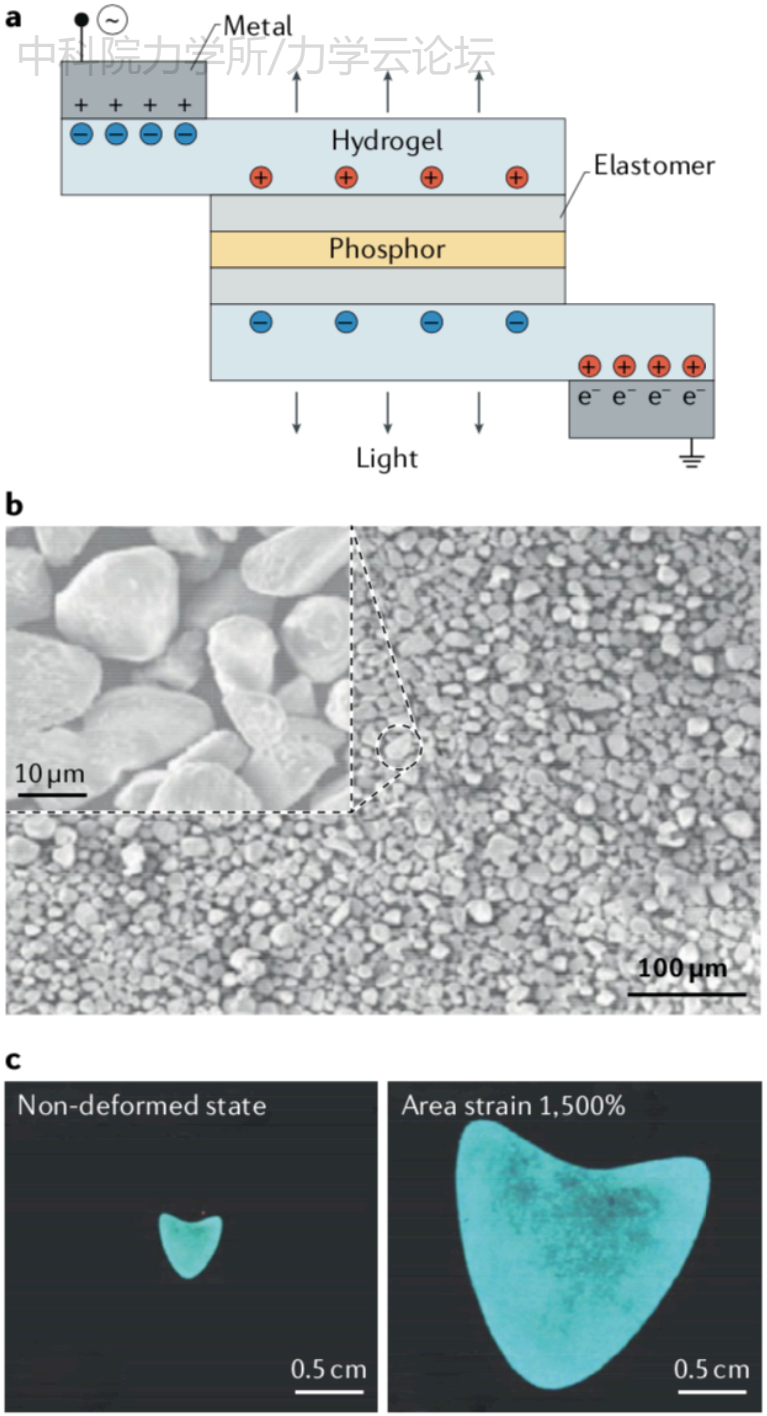
EML 2015



AMI 2017

Yang, Suo. Nature Reviews Materials 2018

Electroluminescence of giant stretchability



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Yang, Suo. Advanced Materials 2016

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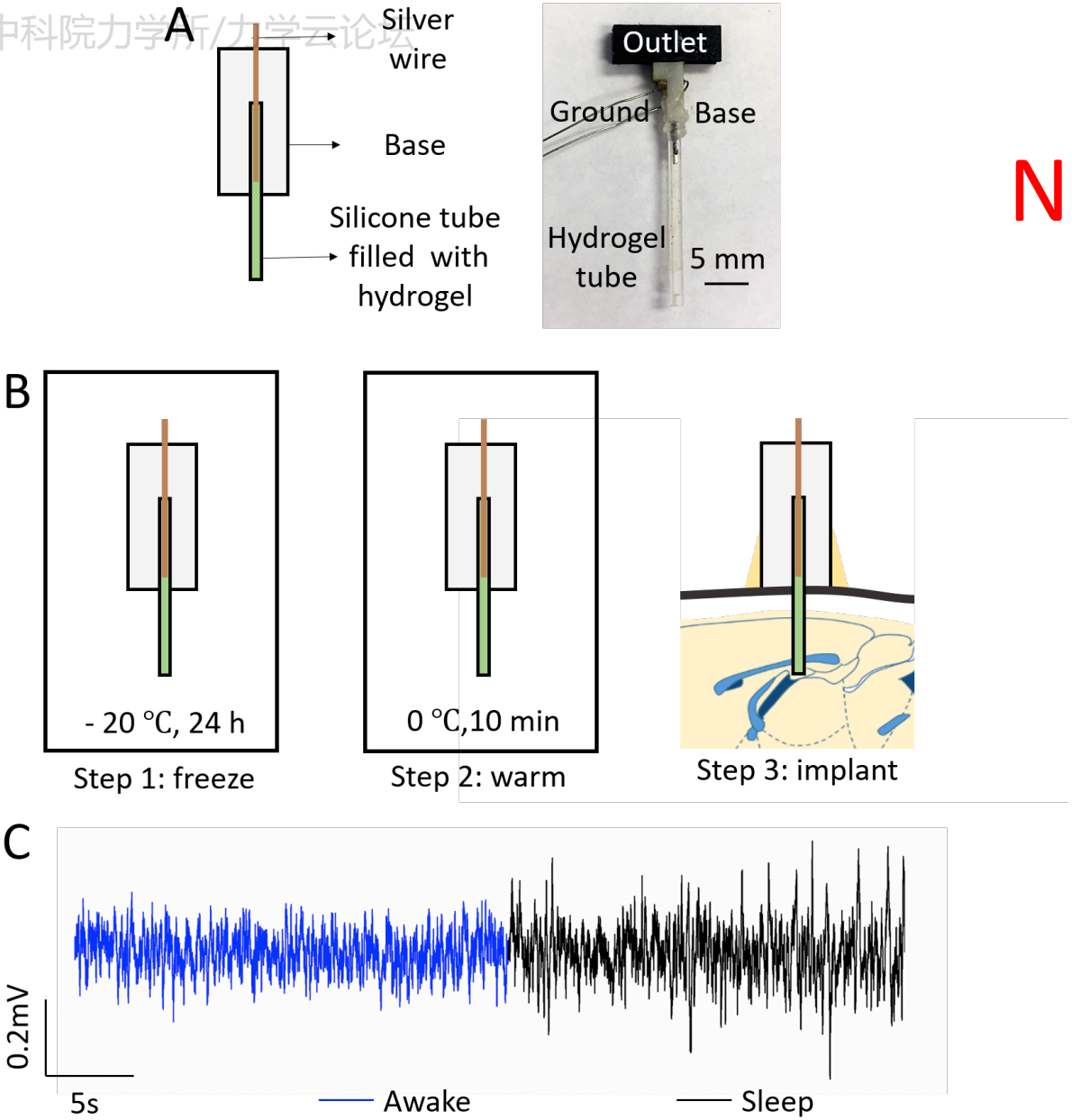
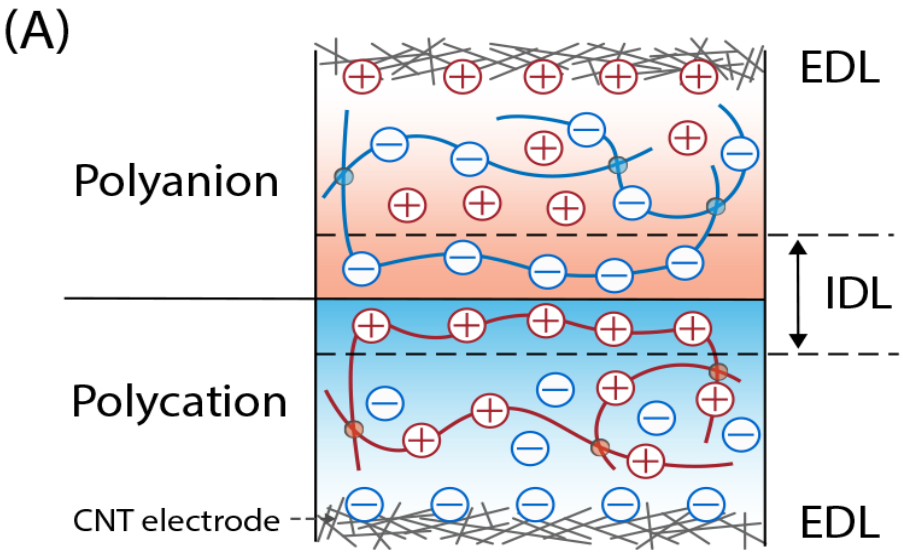
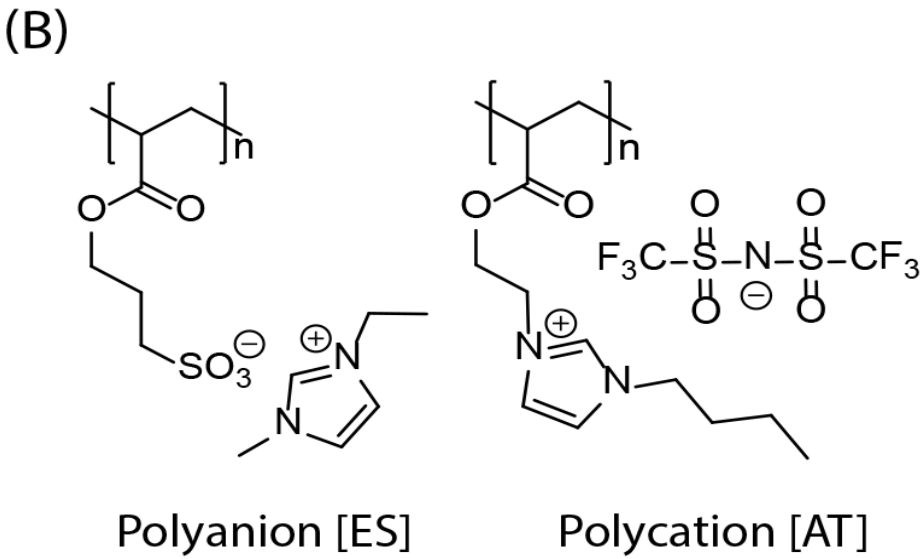
Neurohydrogel



Sheng, Wang, Kong, Xi, Yang, Wu, Wu, Li, Hu, Tang, Zhou, Duan Wang , Suo. Neural Interfaces by hydrogel. Extreme Mechanics Letters 2019.

ionoelastomer diodes and transistors





Kim, Chen, Suo, Hayward. Science 2020

Glass is elastic but brittle.

Metal is inelastic but tough.

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elastic dissipater

Wang, Xiang, Yao, Le Floch, Mendez, Suo, PNAS 2019
Xiang, Wang, Yang, Yao, Wang, Suo. Materials Today 2019
Liu, Yang, Yin, Wang, Qu, Suo, JMPS 2019

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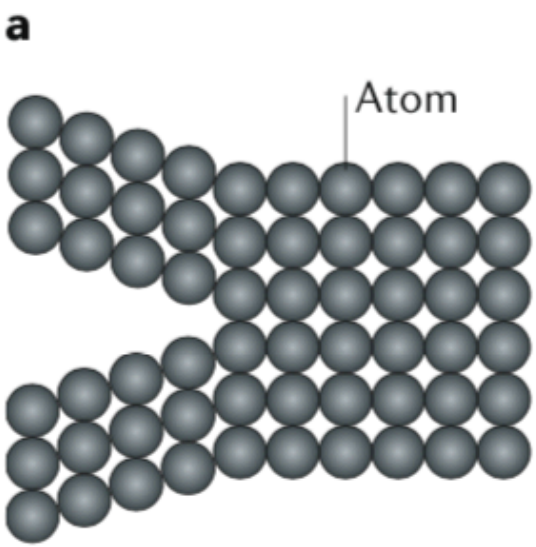
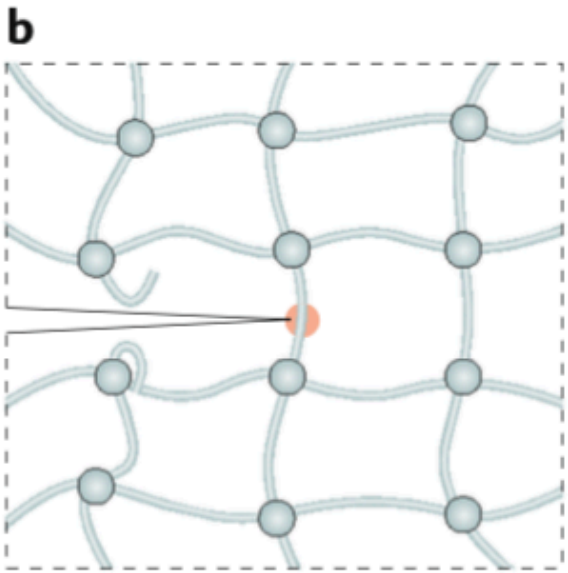
Toughness

Griffith 1921



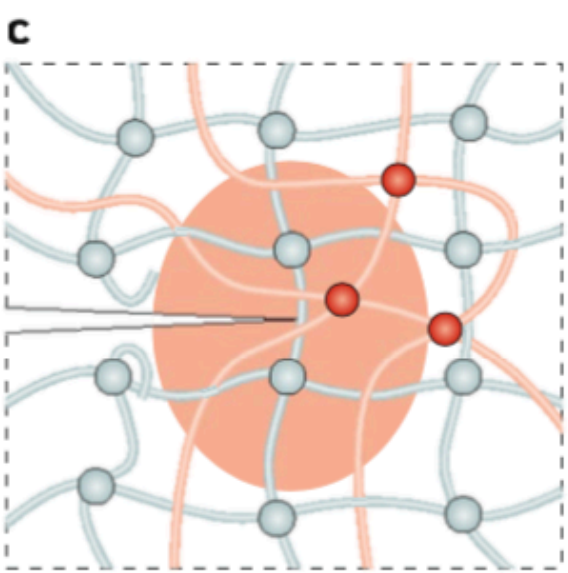
Break a layer of bonds
Toughness ~ 1 J/m^2

Lake-Thomas 1967



Snap a layer of chains
Toughness ~ 10-1000 J/m^2

Irwin-Orowan 1940s



Dissipate energy in the bulk
Toughness ~ 100-10000 J/m^2

Yang, Suo. Nature Reviews Materials 2018

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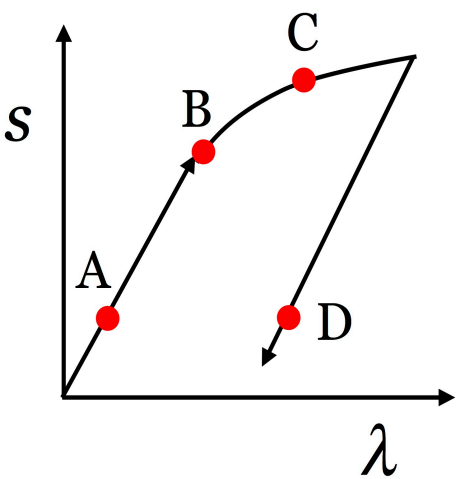
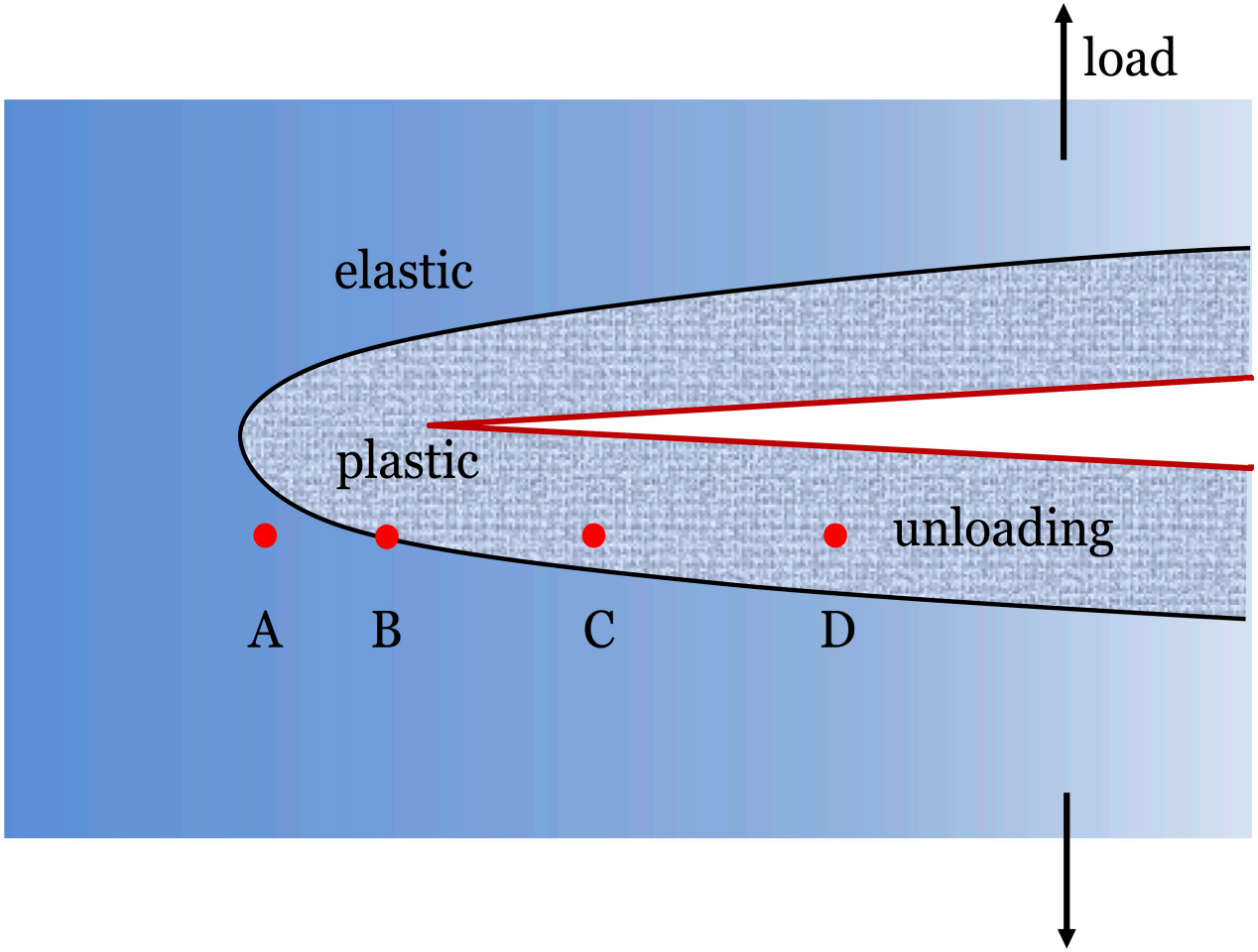
Irwin–Orowan toughness

Inelasticity
Hysteresis
Toughness





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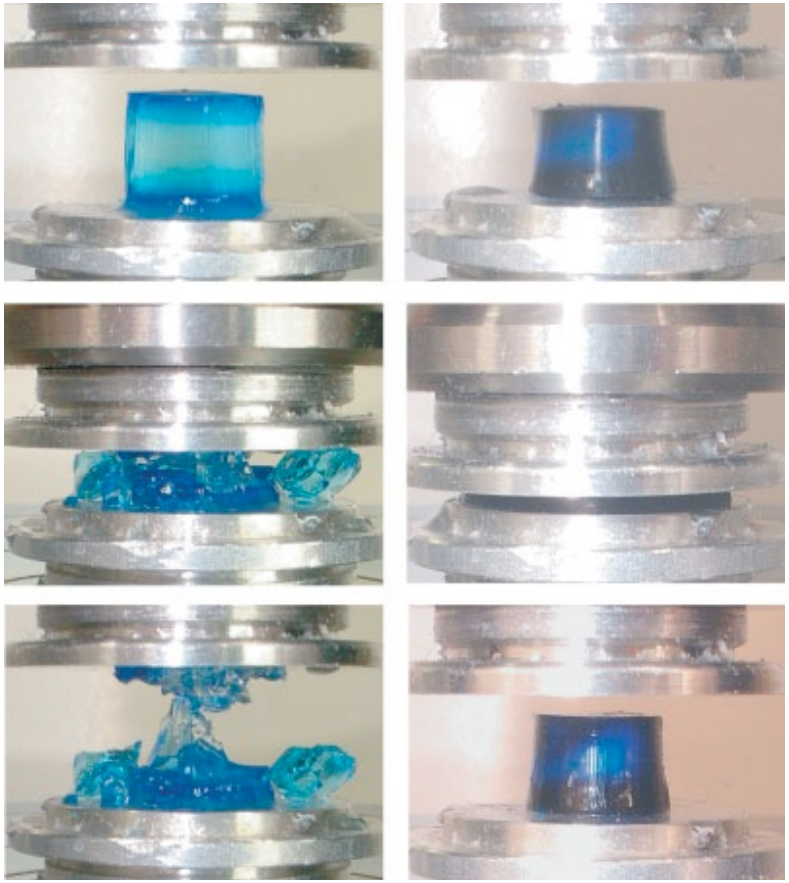
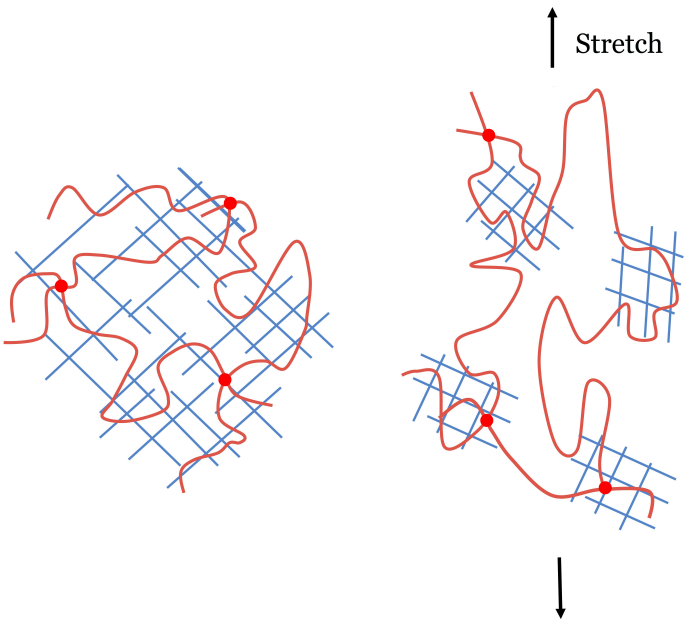
Double-network gels



Single-network gel Double-network gel



Gong, Katsuyama, Kurokawa, Osada, Advanced Materials 15, 1155 (2003)

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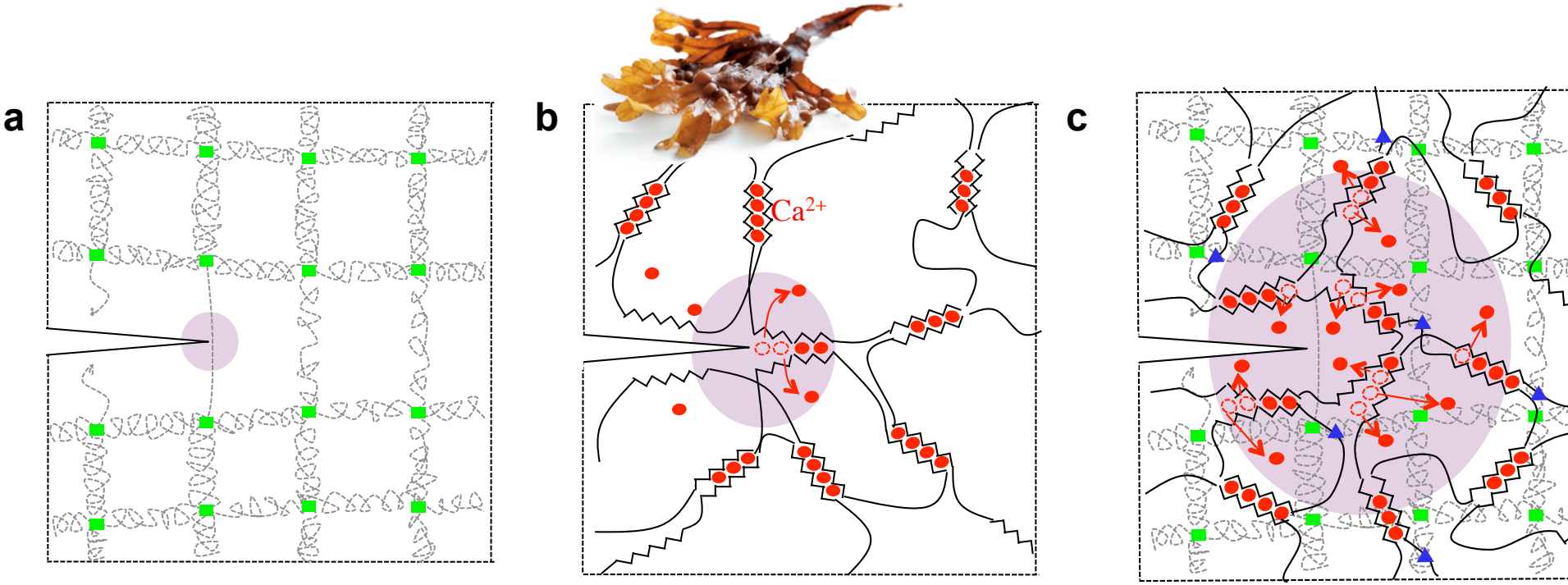
brittle + brittle = tough



Polyacrylamide gel

100 J/m^2

Alginate gel

10 J/m^2

Hybrid gel

9000 J/m^2

Plastic zone near the crack tip

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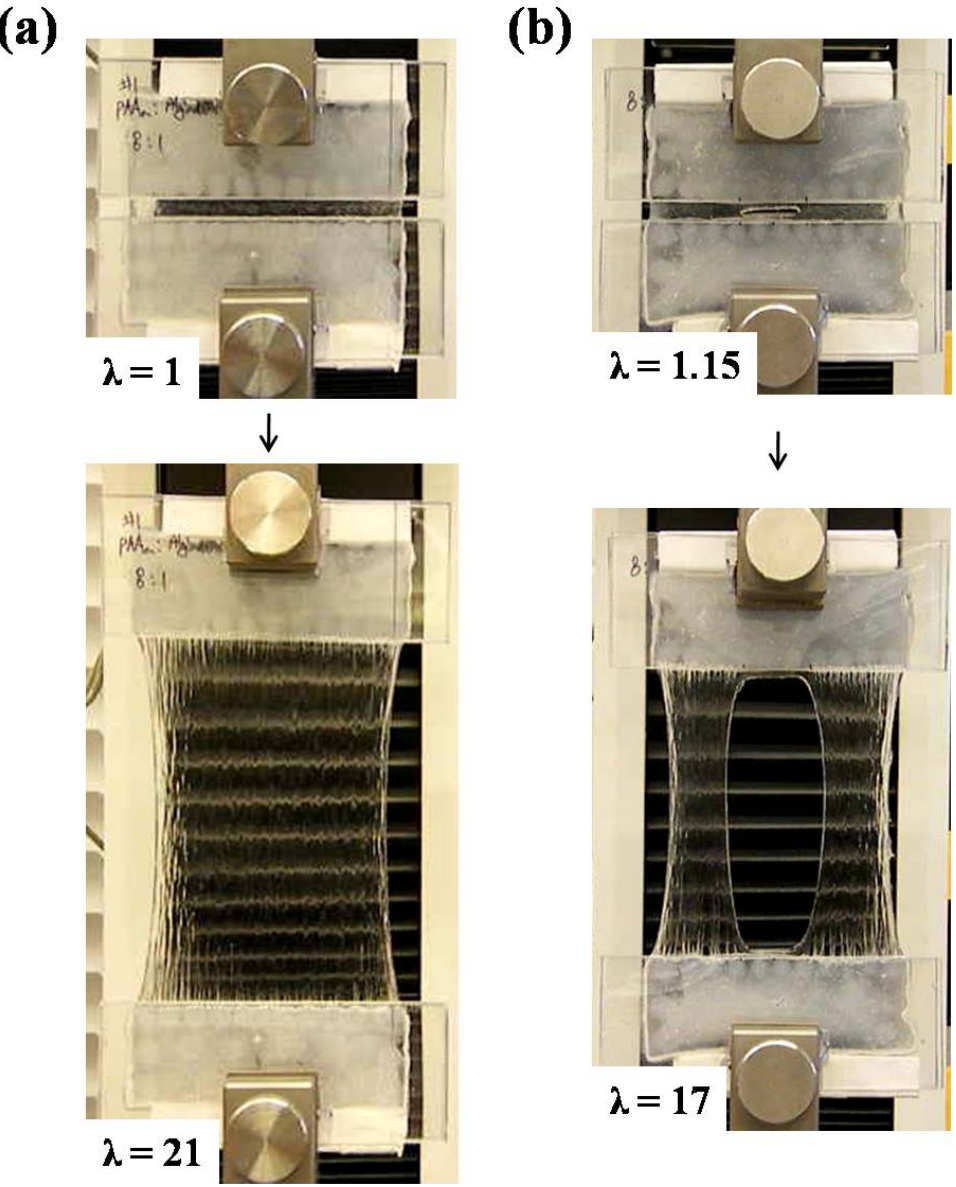
Highly stretchable and tough hydrogels



- Water: 90%
- Stretch: 21
- Fracture energy: 9000 J/m^2

~10 J/m^2, tofu, jello
~10 J/m^2, most gels
~100 J/m^2, contact lenses
~1000 J/m^2, cartilage
~1000 J/m^2, double network gels (Gong 2003)
~1000 J/m^2, VHB
~10,000 J/m^2, natural rubber

Sun, Zhao, Illeperuma, Chaudhuri, Oh, Mooney, Vlassak, Suo. Nature 489, 133 (2012)

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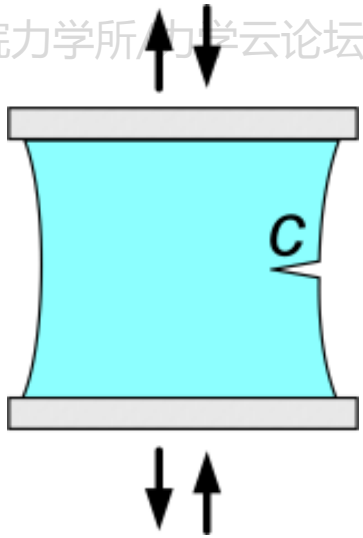

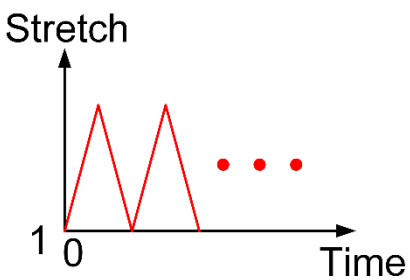

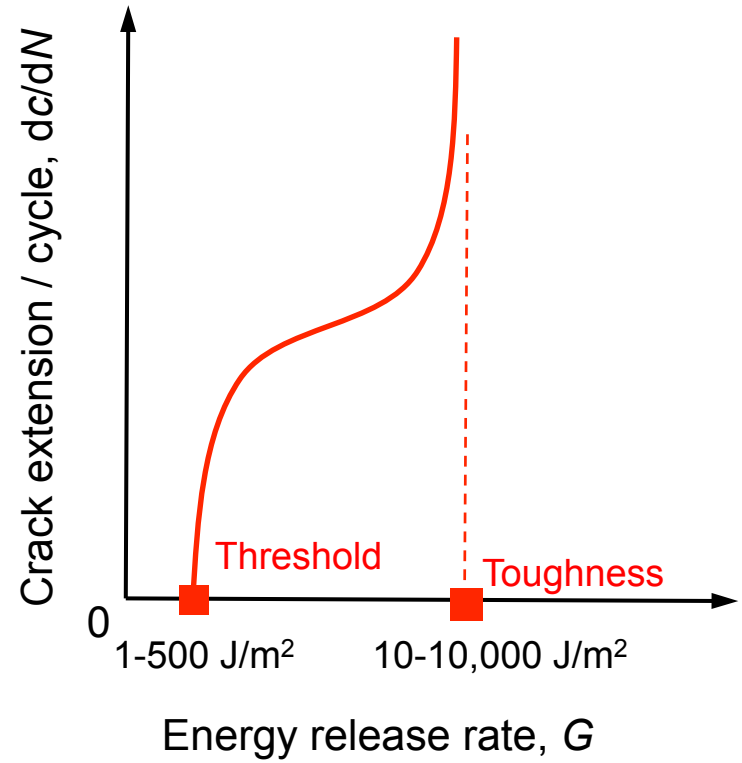

- Toughness of hydrogels has been extensively studied in last 17 years.
- Threshold of hydrogels is a new game in last 3 years.

Bai, Yang, Suo. Fatigue of hydrogel. European Journal of Mechanics A. Solids 2019

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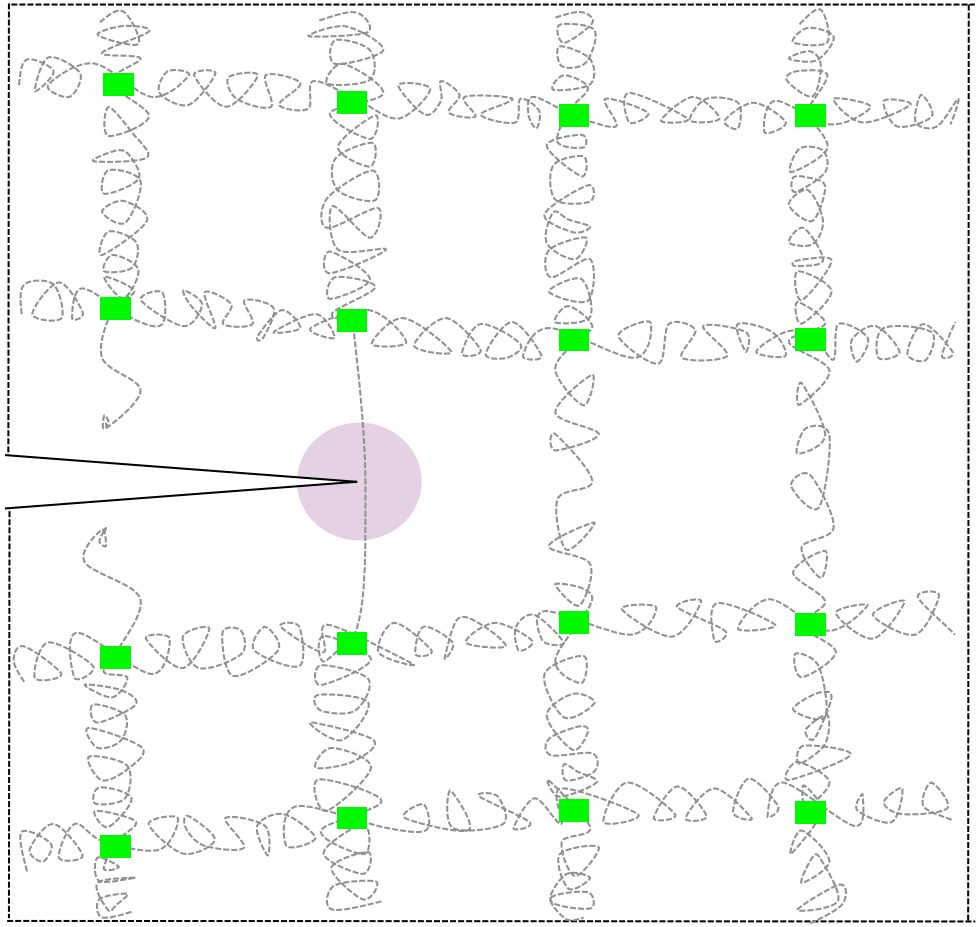
Hypothesis: an elastic network will *not* suffer fatigue



This hypothesis is wrong!

Tang, Li, Vlassak, Suo. Extreme Mechanics Letters (2017)

Fatigue fracture of hydrogel

Tang, Li, Vlassak, Suo. Extreme Mechanics Letters (2017)

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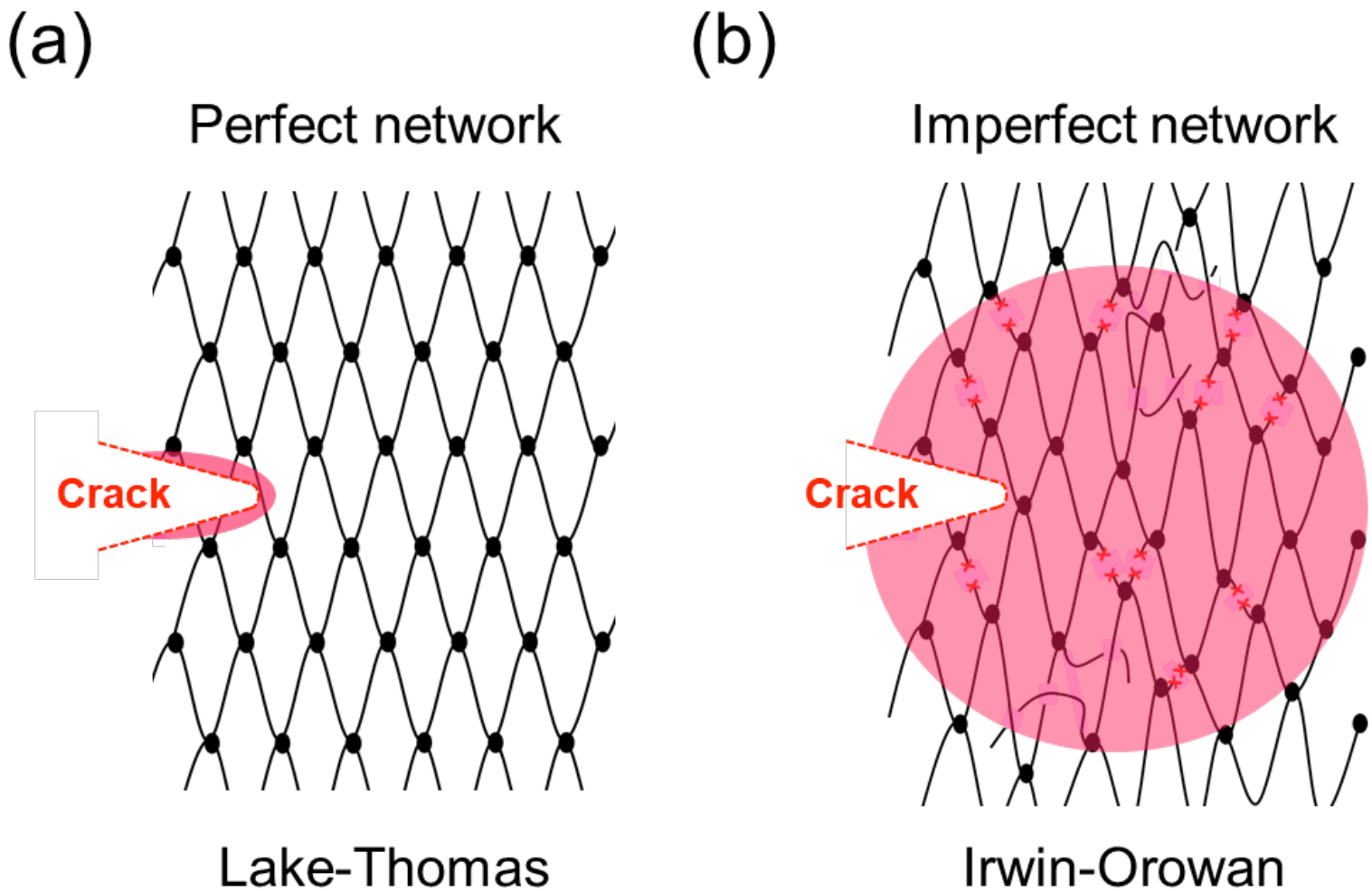
A mechanism of fatigue in an elastic network



Yang, Yin, Suo. Journal of the Mechanics and Physics of Solids 2019
Yin, Yang, Suo. unpublished

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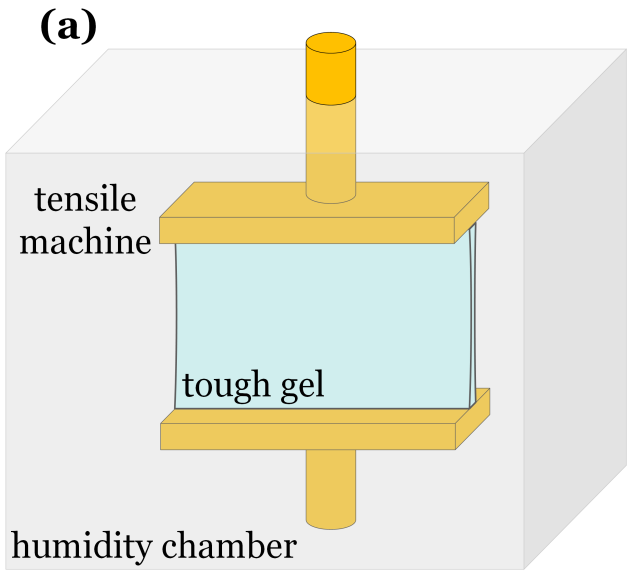
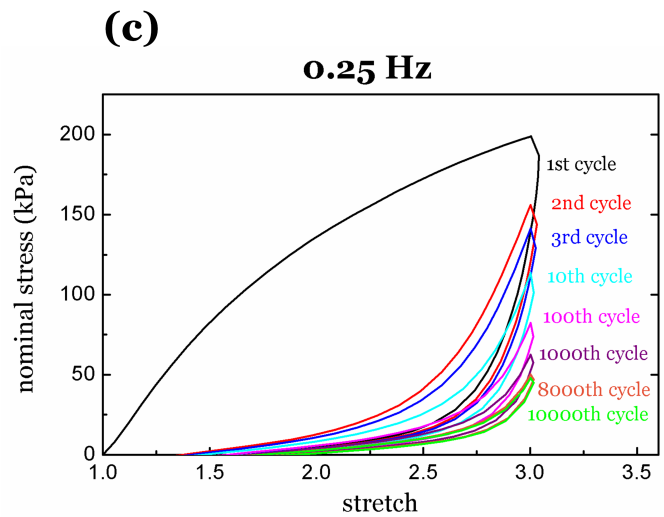
Shakedown of tough gel





Bai, Yang, Tang, Morelle, Vlassak, Suo. Extreme Mechanics Letters (2017)

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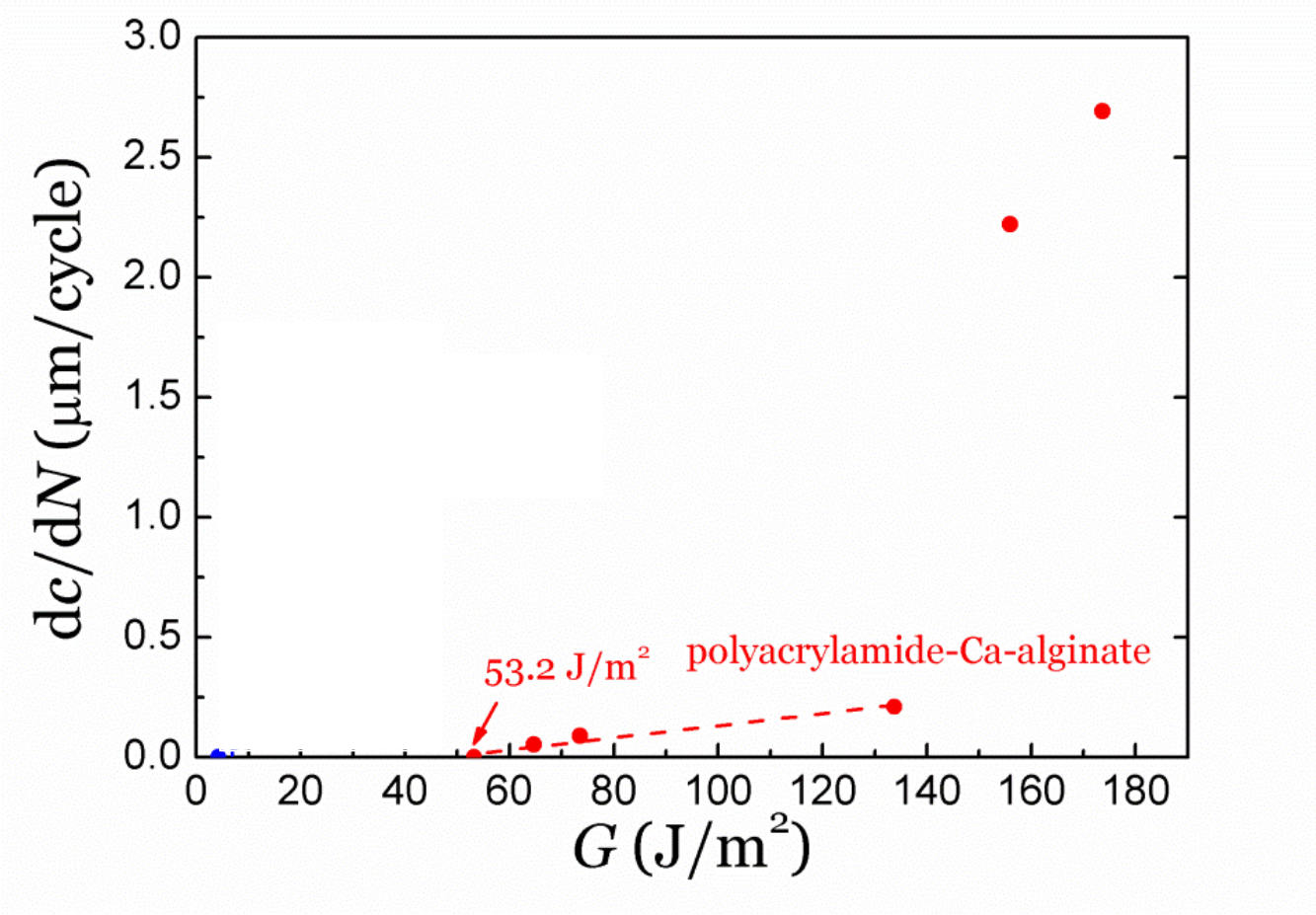
Alginate-polyacrylamide hydrogel



Tough for the first loading.
But suffers fatigue fracture.

Bai, Yang, Tang, Morelle, Vlassak, Suo, Extreme Mechanics Letters (2017)

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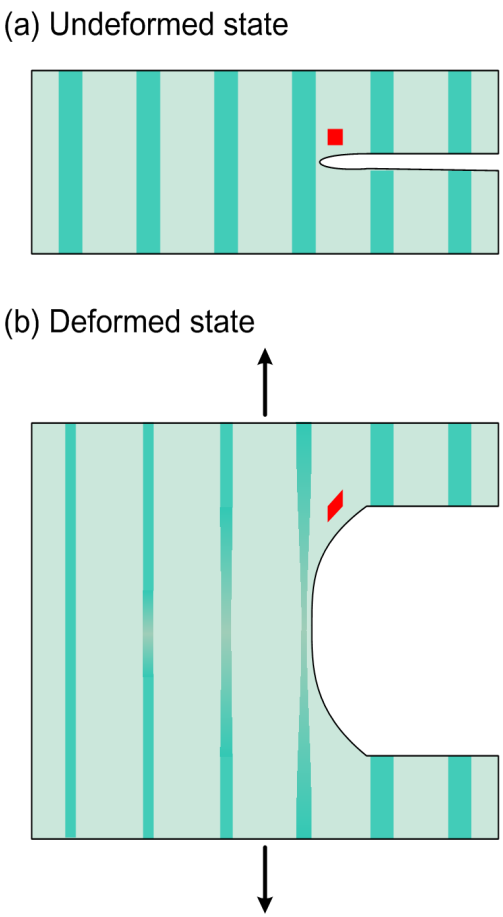
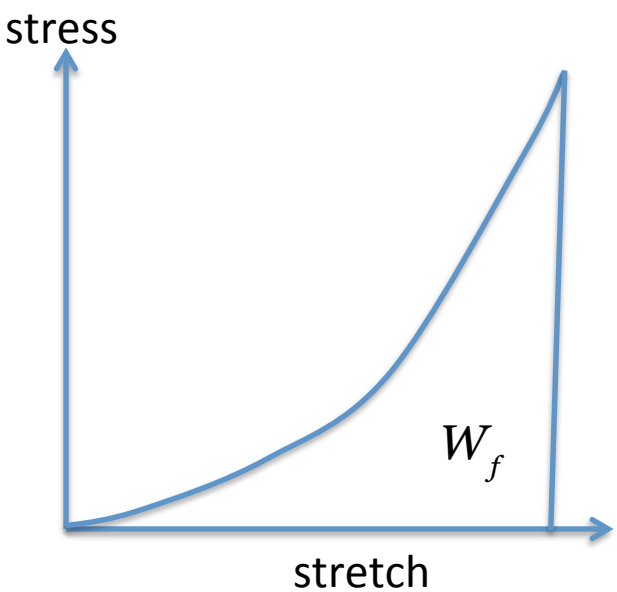
Elastic dissipater

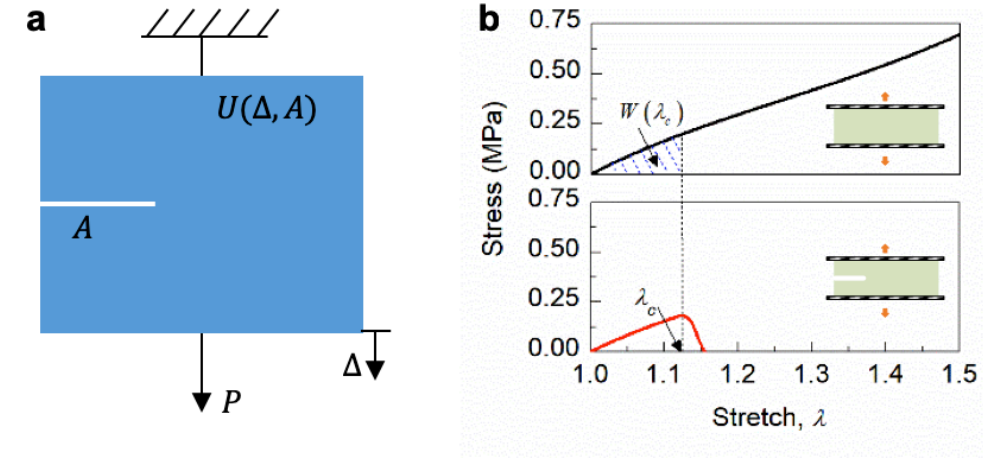




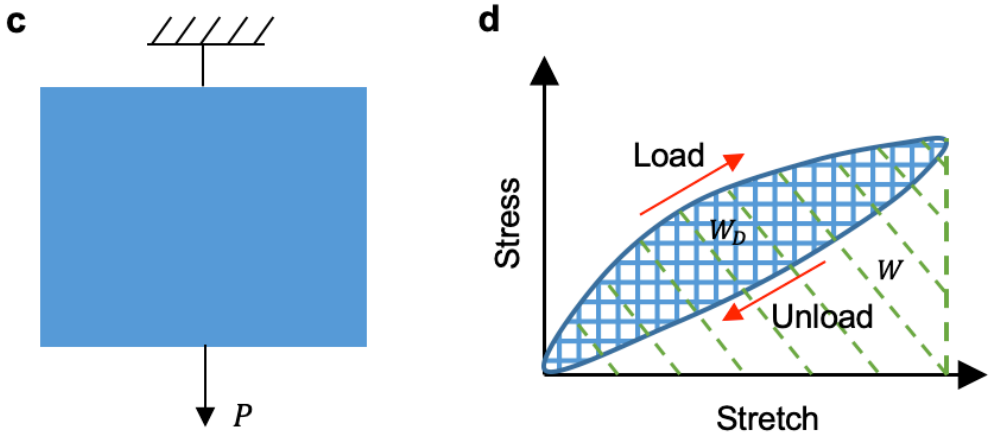
$$\Gamma_o = HW_f$$

Wang, Xiang, Yao, Le Floch, Mendez, Suo, PNAS 2019
Xiang, Wang, Yang, Yao, Wang, Suo, Materials Today 2019

Toughness and hysteresis



$$\text{Toughness} = HW(\lambda_c)$$



$$\text{Hysteresis} = W_D / W$$

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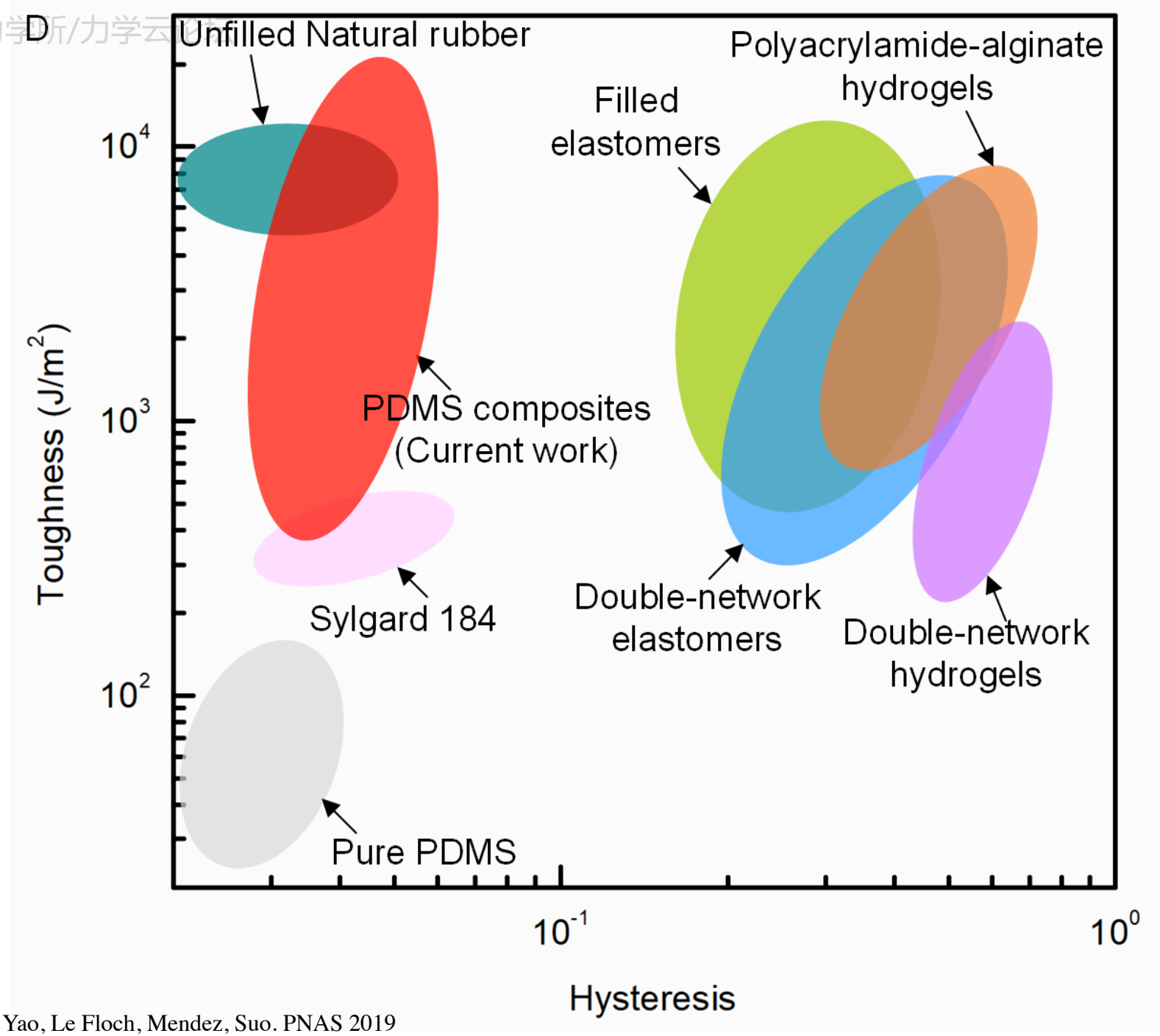

Wang, Xiang, Yao, Le Floch, Mendez, Suo. PNAS 2019

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(a) λ_m =2.303, G =4,441 J/m^2, N=1

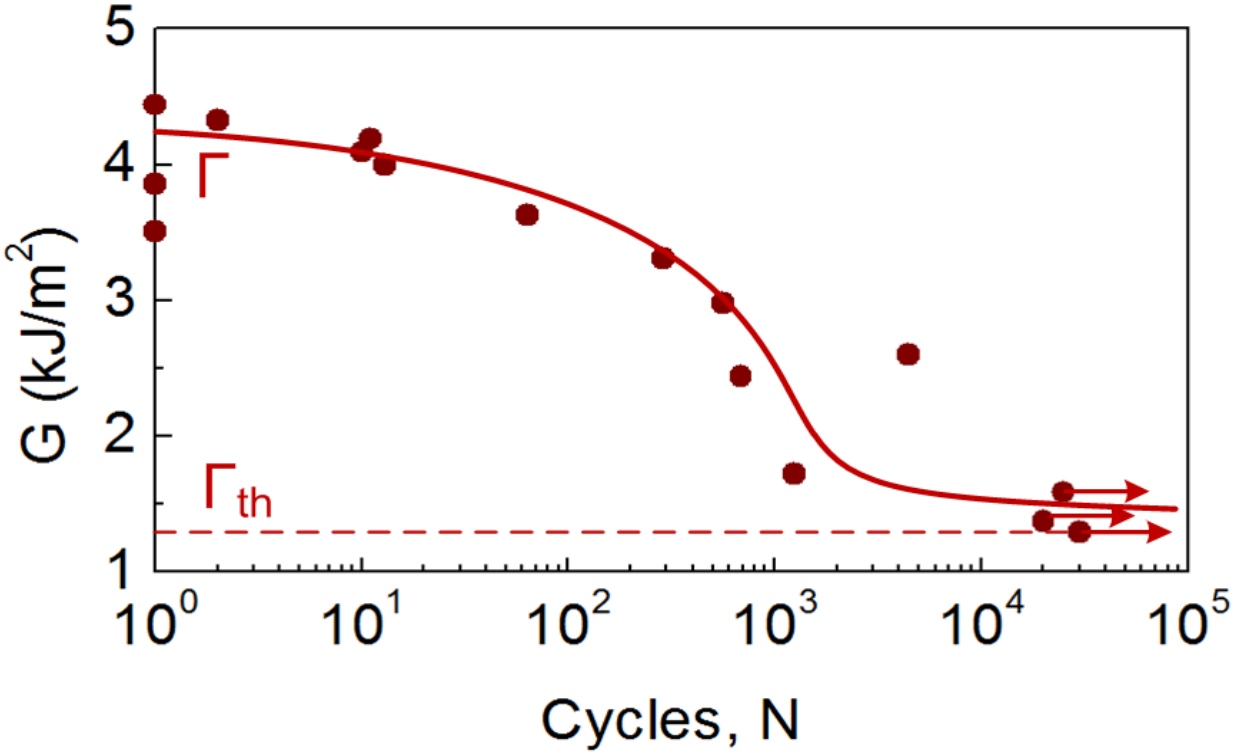
(b) λ_m =2.261, G =4,092 J/m^2, N=10

(c) λ_m =2.107, G =2,978 J/m^2, N=565

(d) λ_m =1.780, G =1,372 J/m^2, N=20,000

(e) λ_m =1.725, G =1,290 J/m^2, N=30,000

- Matrix: PAAm hydrogel
- Fibers: PDMS elastomer



Xiang, Wang, Yang, Yao, Wang, Suo. Materials Today 2019

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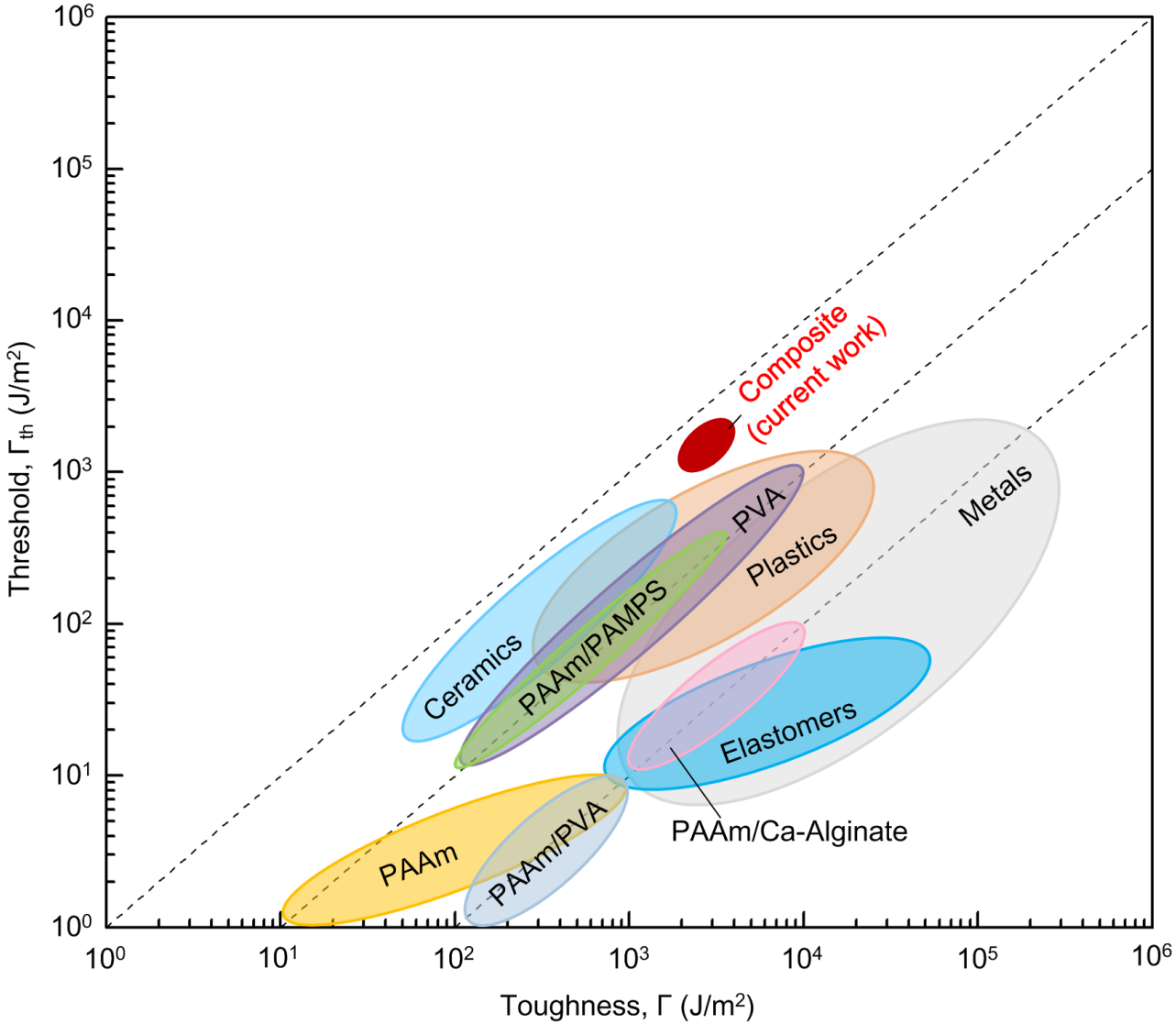
Fatigue-resistant hydrogel-elastomer hybrid



Xiang, Wang, Yang, Yao, Wang, Suo. Materials Today 2019

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Hydrogel-elastomer

ionic cable (artificial axon)

Yang, Li, Yang, Pan, Yin, Tang, Qi, Suo. Advanced Functional Materials (2019)

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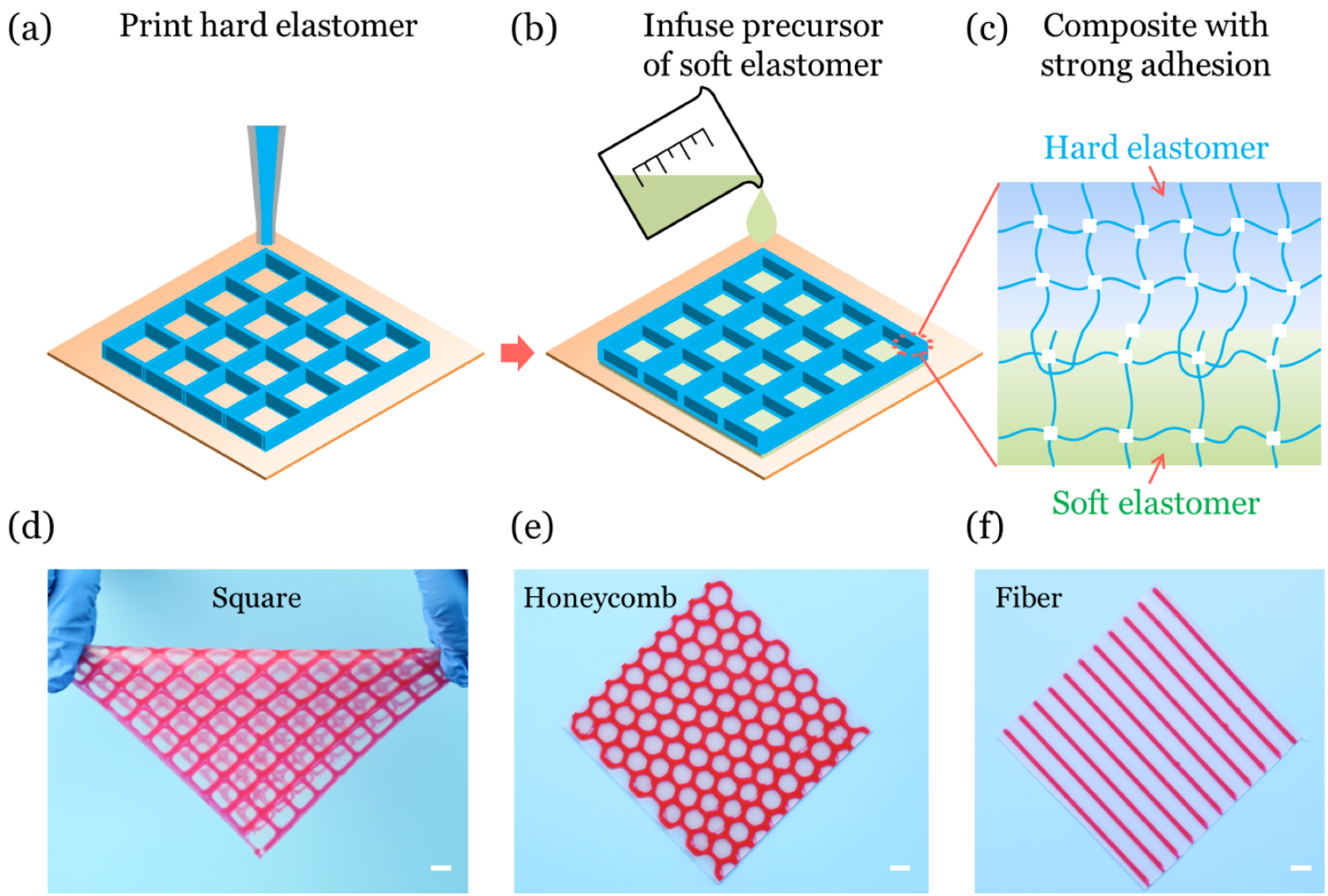
Elastic dissipater of any architecture



Li, Yang, Suo, Tang, JMPS 2019

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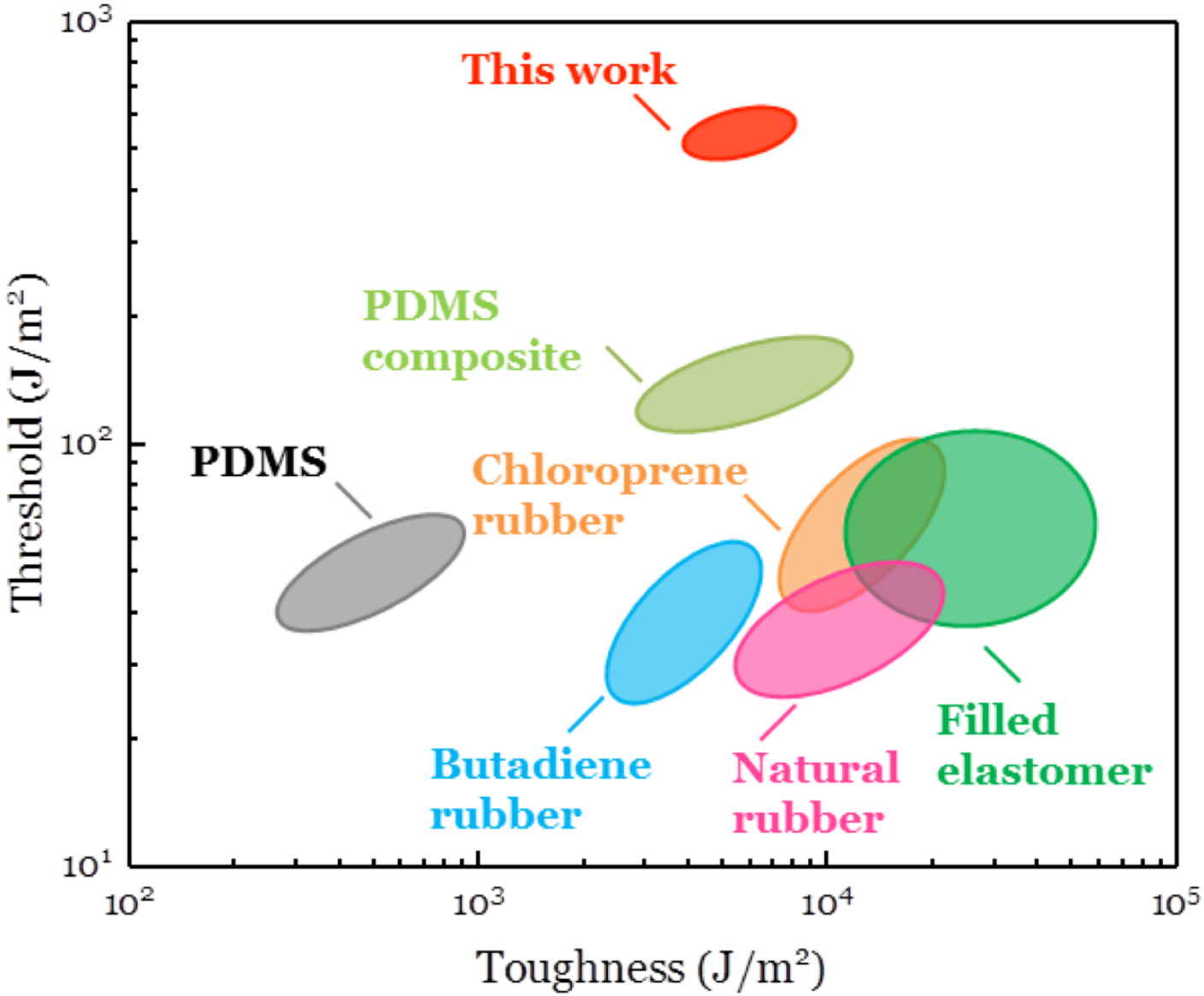
Fatigue-resistant elastomer



Li, Yang, Suo, Tang, JMPS 2019

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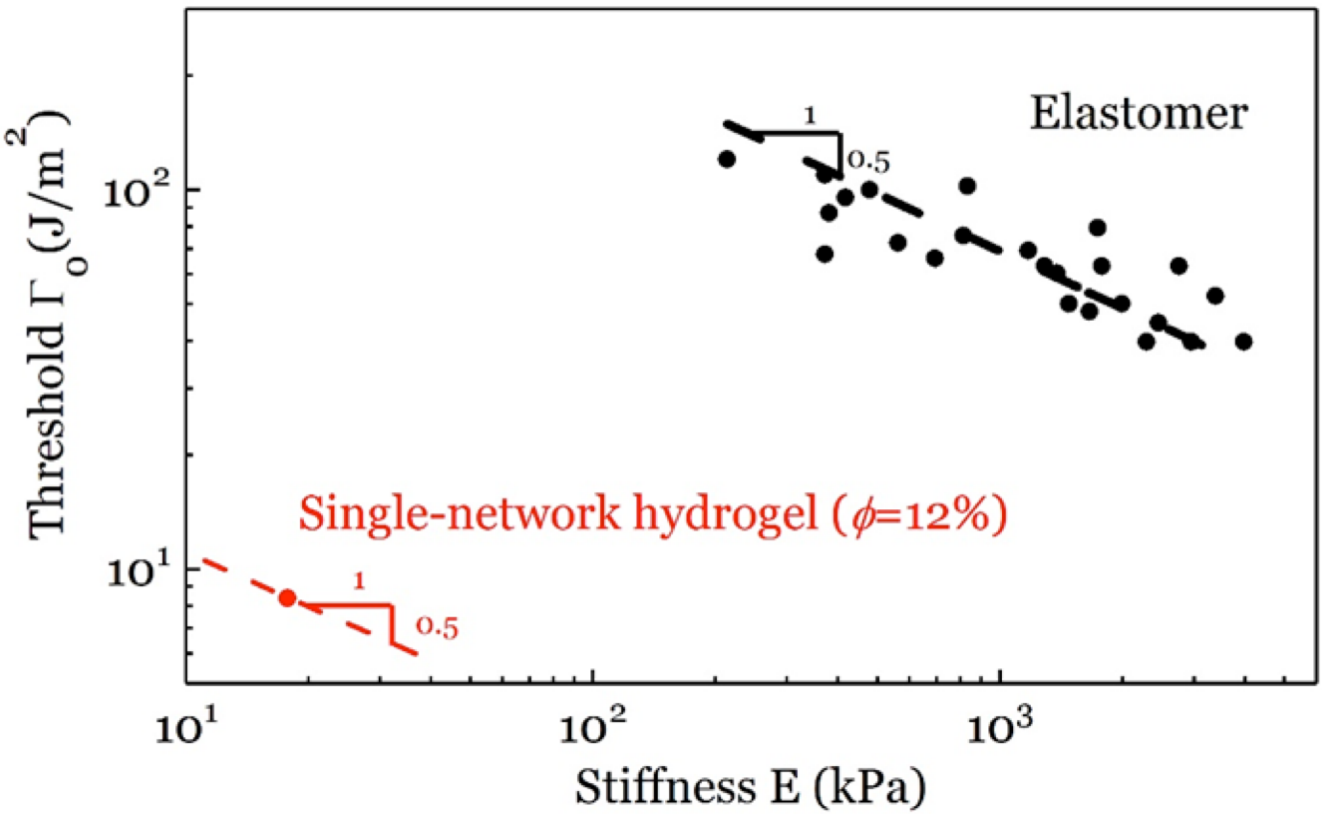
Stiffness-threshold conflict

$$E \sim \frac{1}{n}, \qquad \Gamma_o \sim \sqrt{n}$$

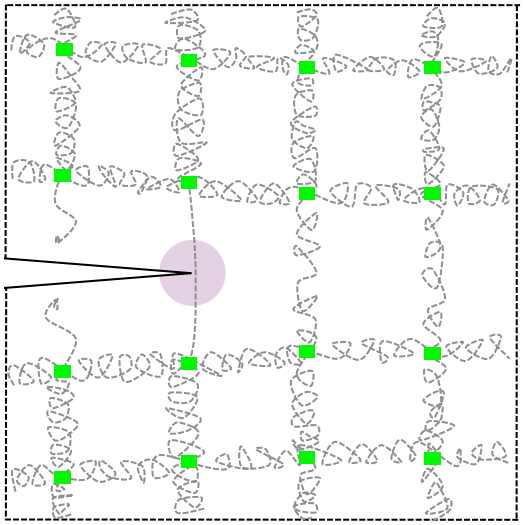


Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019

Remove the stiffness-threshold conflict

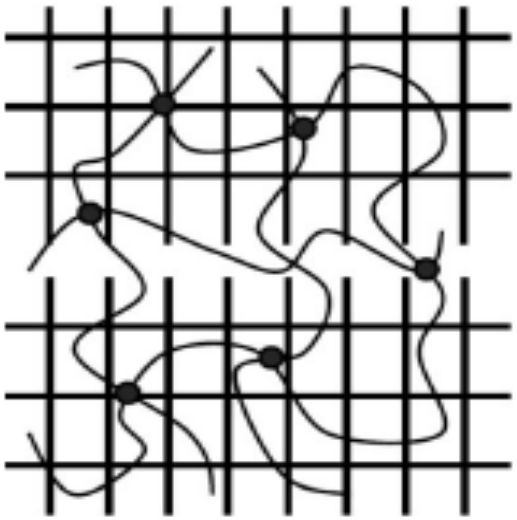
Single network

$$E \sim \frac{1}{n}, \qquad \Gamma_o \sim \sqrt{n}$$

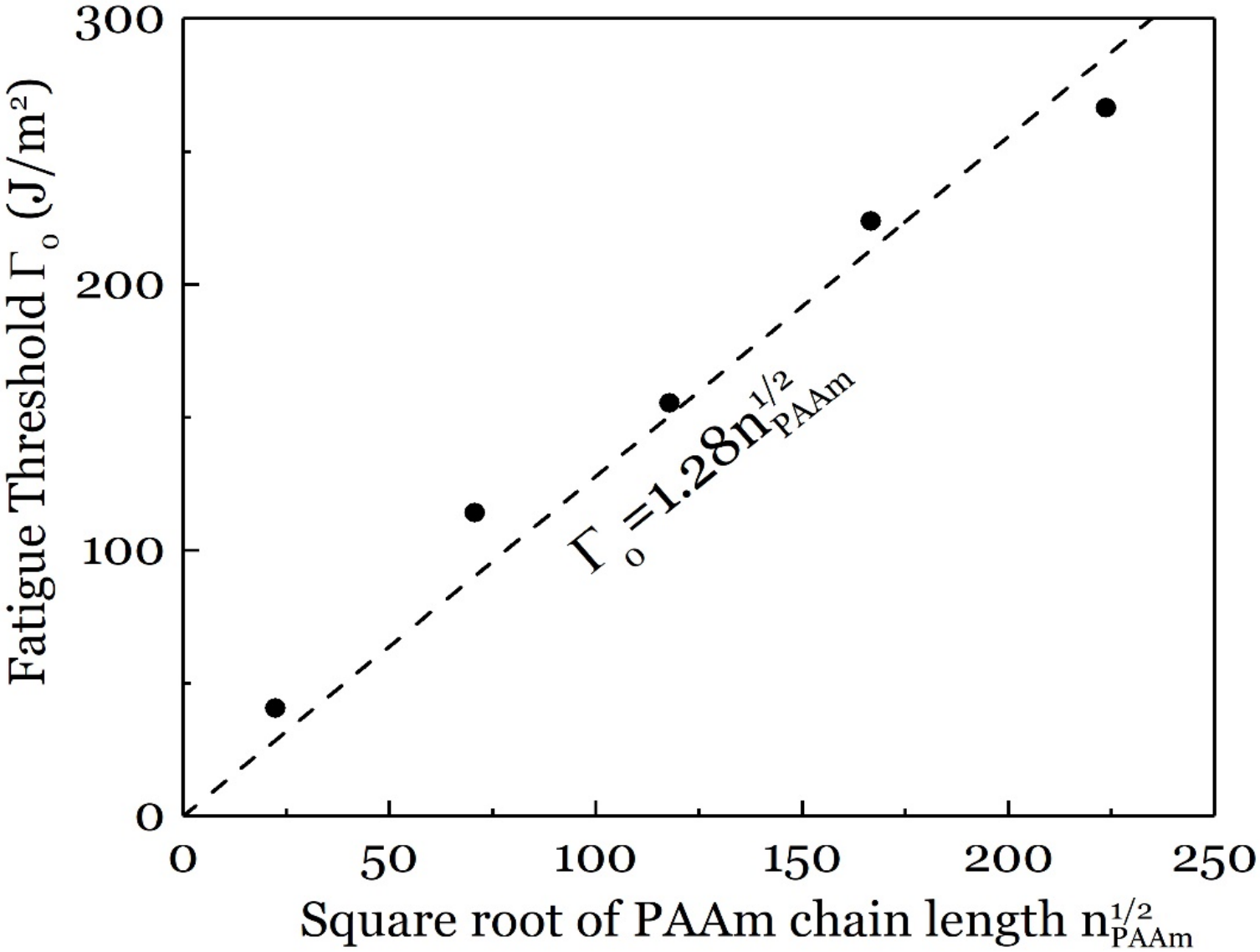


Double network

$$E \sim \frac{1}{n_A}, \qquad \Gamma_o \sim \sqrt{n_B}$$



Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019



Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019

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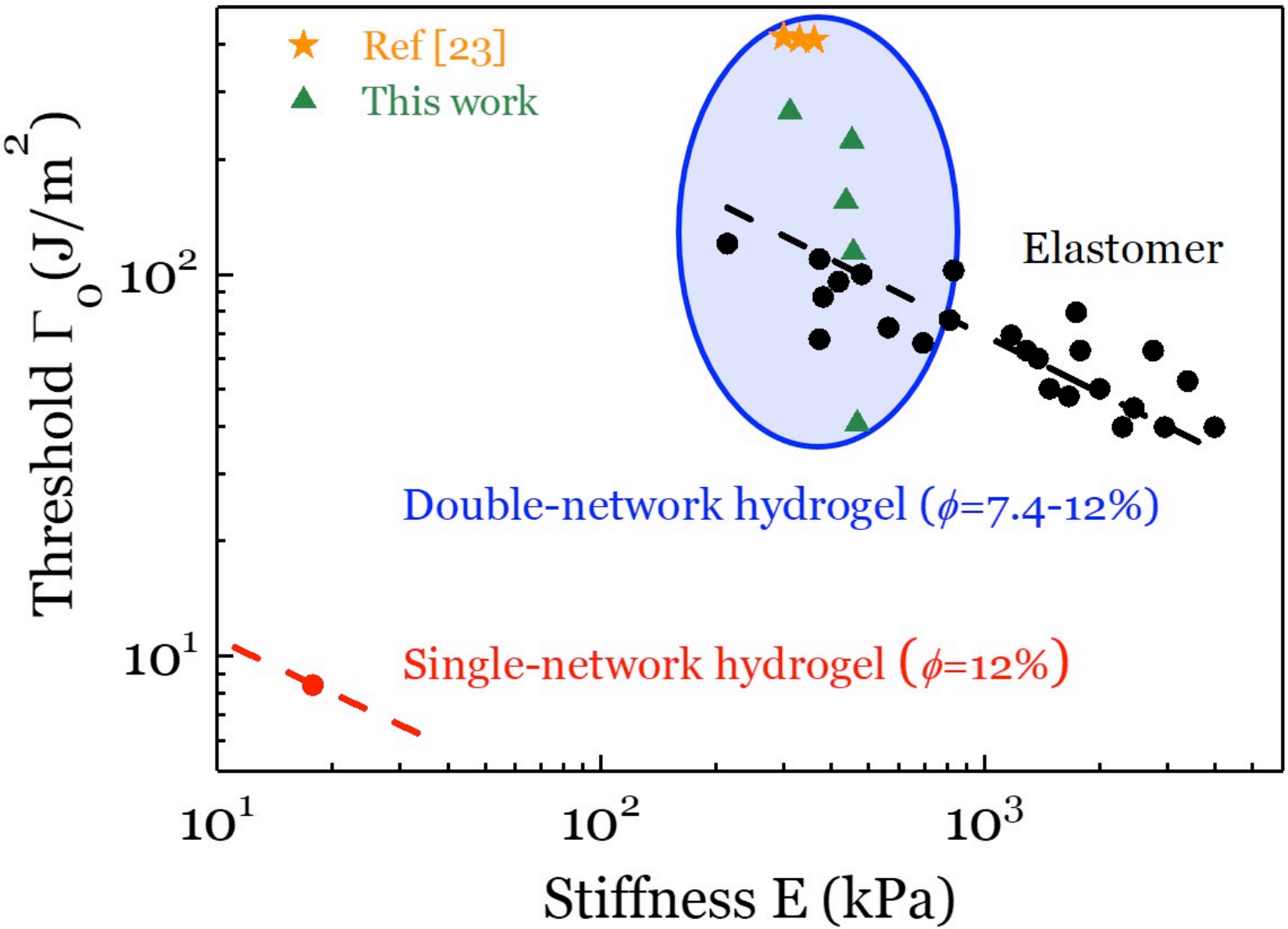

Zhou, Zhang, Hu, Tang, Suo, Lu. JAM 2019
Ref [23] Zhang, Liu, Wang, Tang, Hu, Lu, Suo. Engineering Fracture Mechanics 2018

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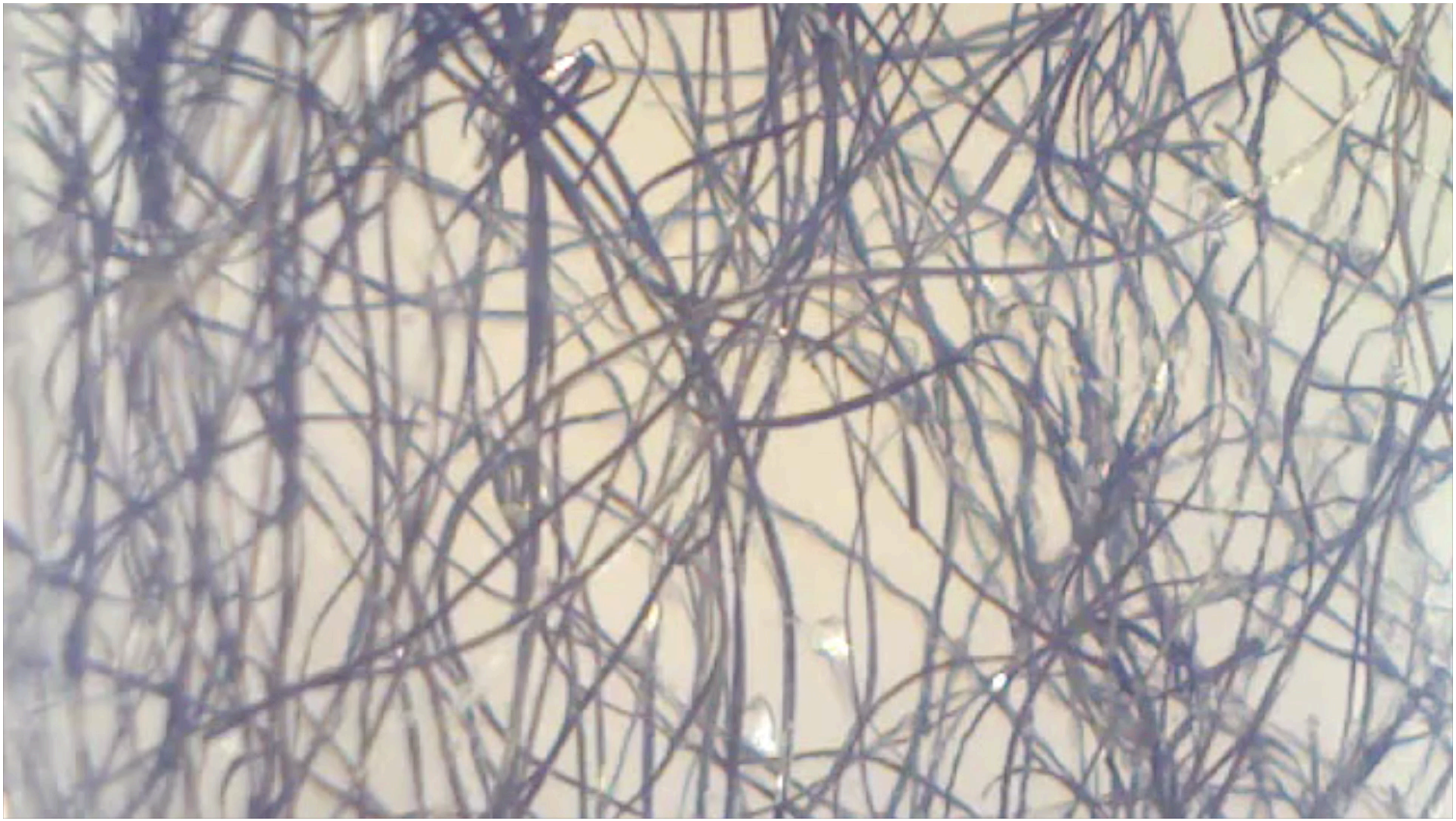
Weak hydrogel-metal adhesion



Illeperuma, Sun, Suo, Vlassak. Extreme Mechanics Letters 2014

Weak hydrogel-elastomer adhesion

Keplinger, Sun, Foo, Rothemund, Whitesides, Suo. Science 341, 984 (2013)
(This video was unpublished)

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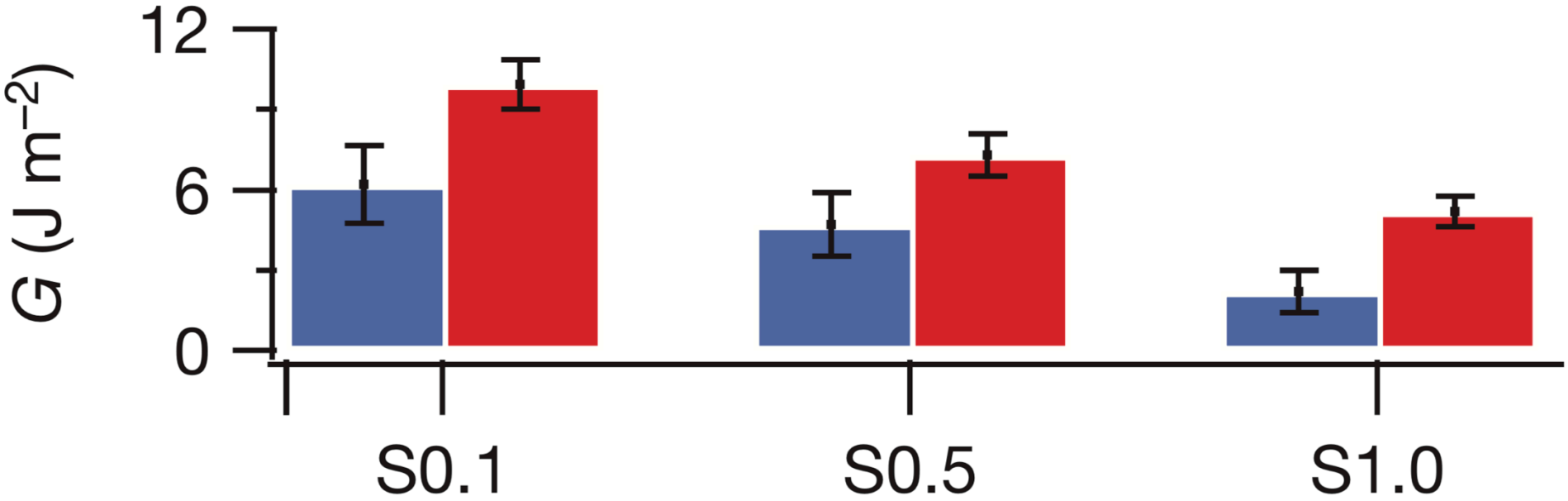
Hydrogel often has weak adhesion



Rose, Prevoteau, Elziere, Hourdet, Marcellan, Leibler. Nature 2014

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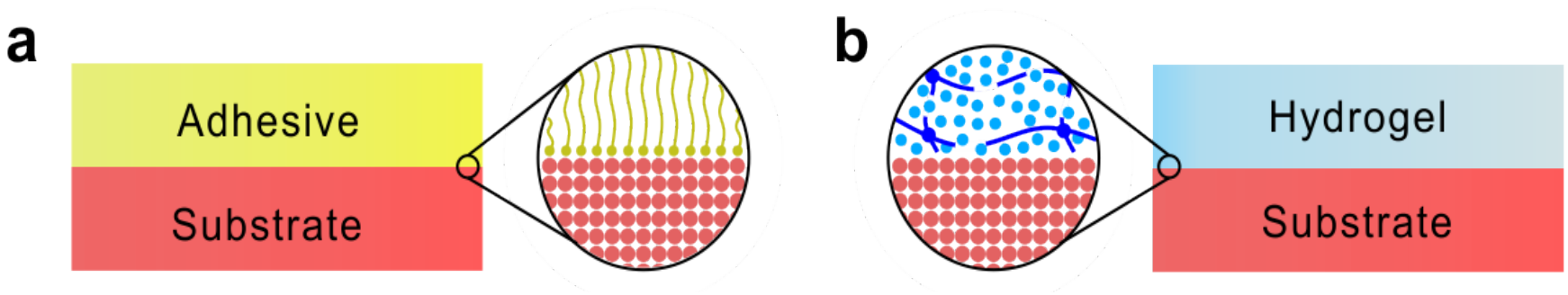
Why is hydrogel adhesion often weak?

It’s water.



Yang, Suo. Nature Reviews Materials 3, 125 (2018)

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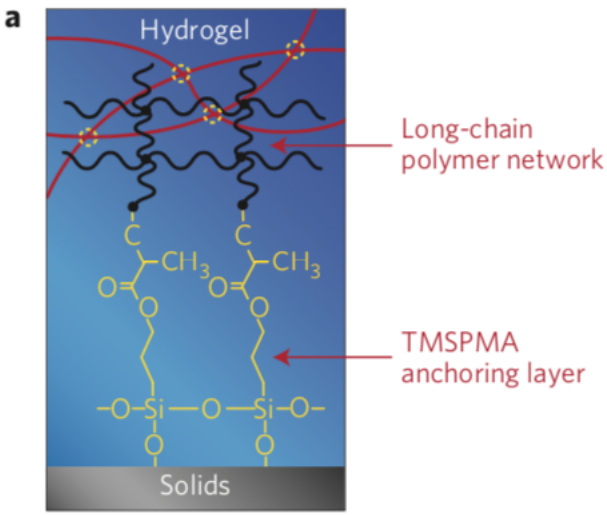
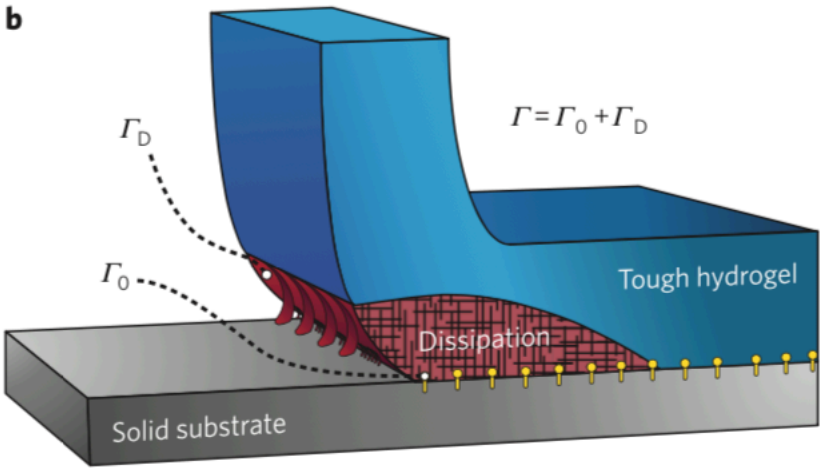
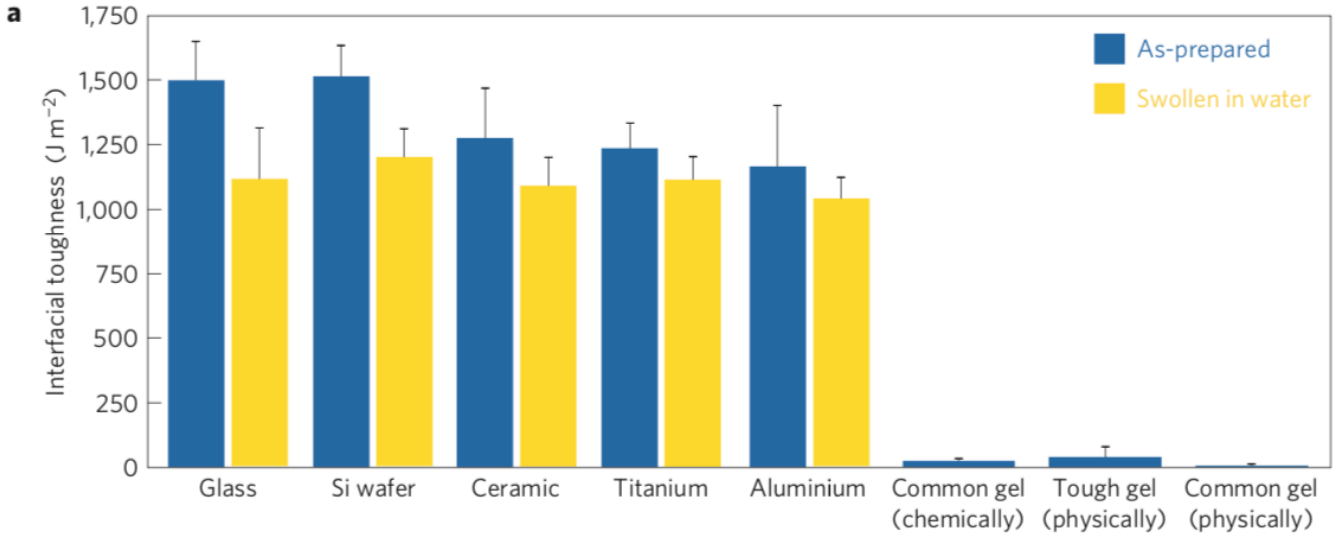
Surface modification







Yuk, Zhang, Lin, Parada, Zhao. Nature Materials 2016.

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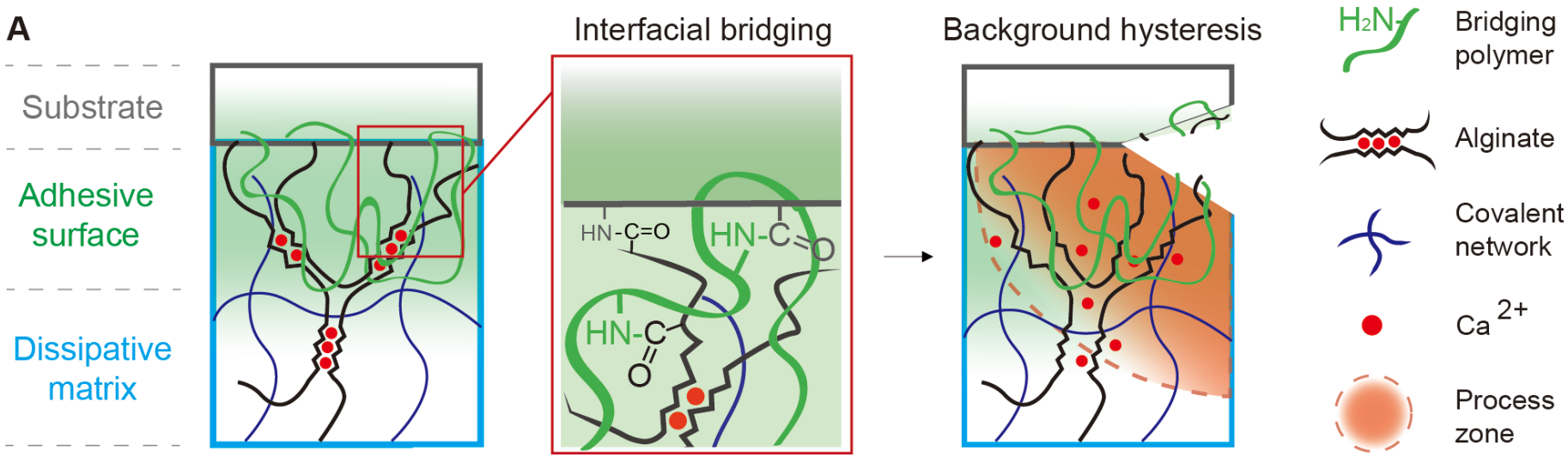
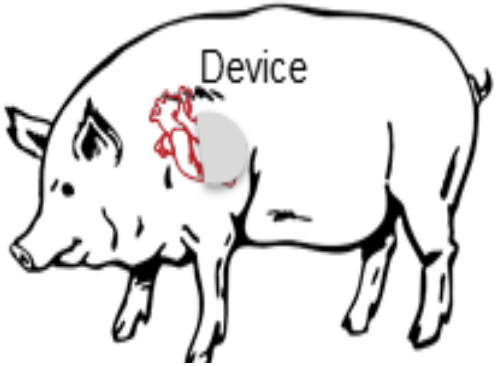
Tough adhesives for wound closure

- Bridging polymers form amide bonds with tissue and hydrogel.
- Weak bonds in the hydrogel dissipate energy.



Li, Celiz, Yang, Yang, Wamala, Whyte, Vasilyev, Vlassk, Suo, Mooney. Science 2017

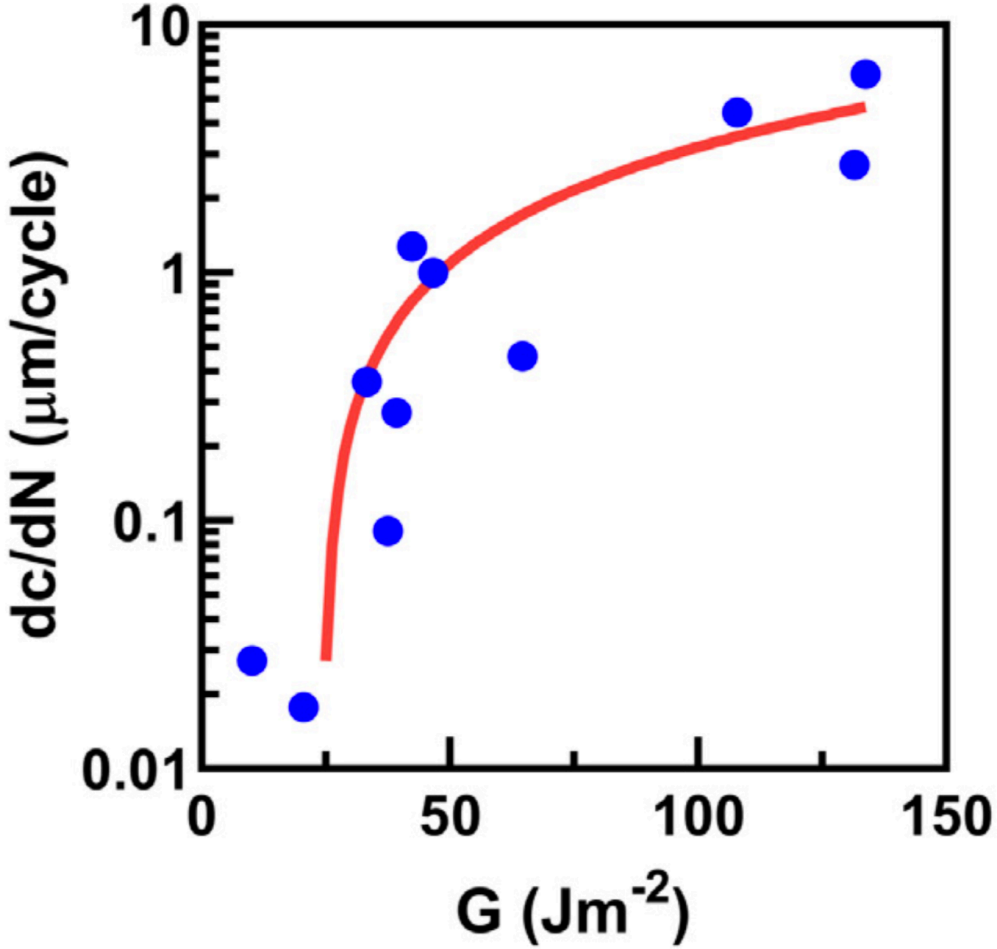


Hydrogel-tissue

- Wound closure
- Drug delivery

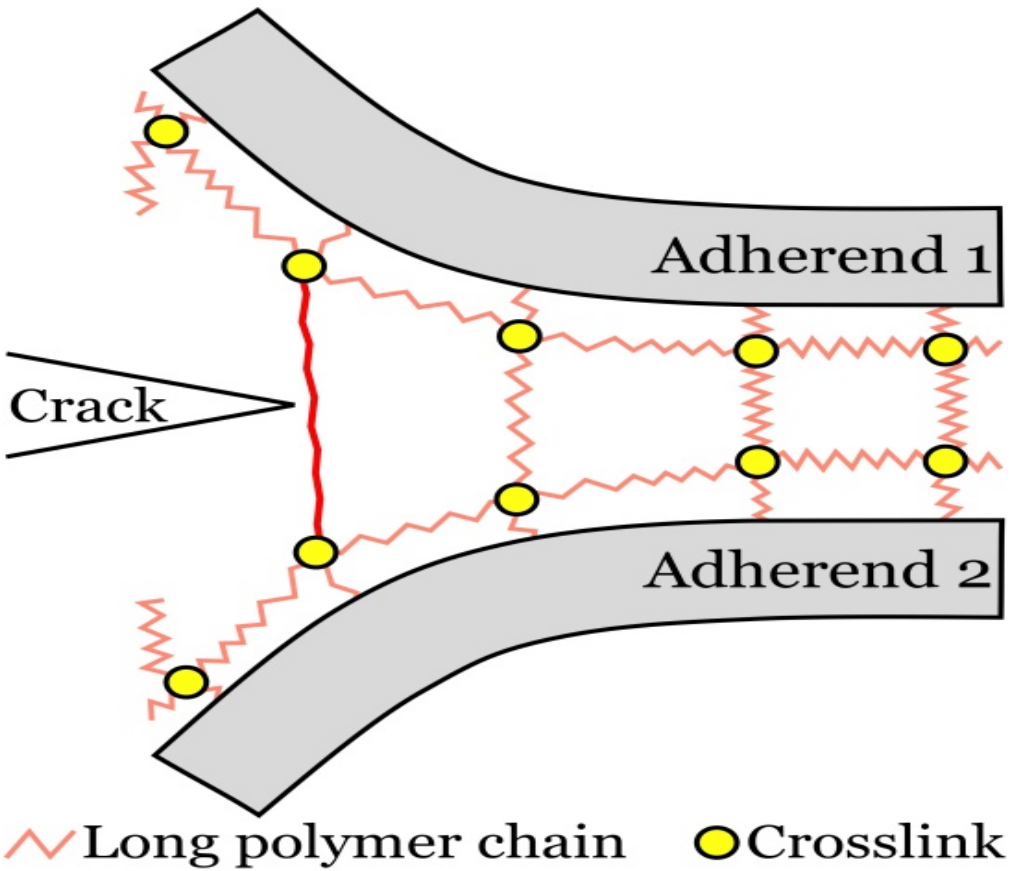
Li, Celiz, Yang, Yang, Wamala, Whyte, Vasilyev, Vlassk, Suo, Mooney. Science 357, 378 (2017)

Tough adhesion suffers fatigue



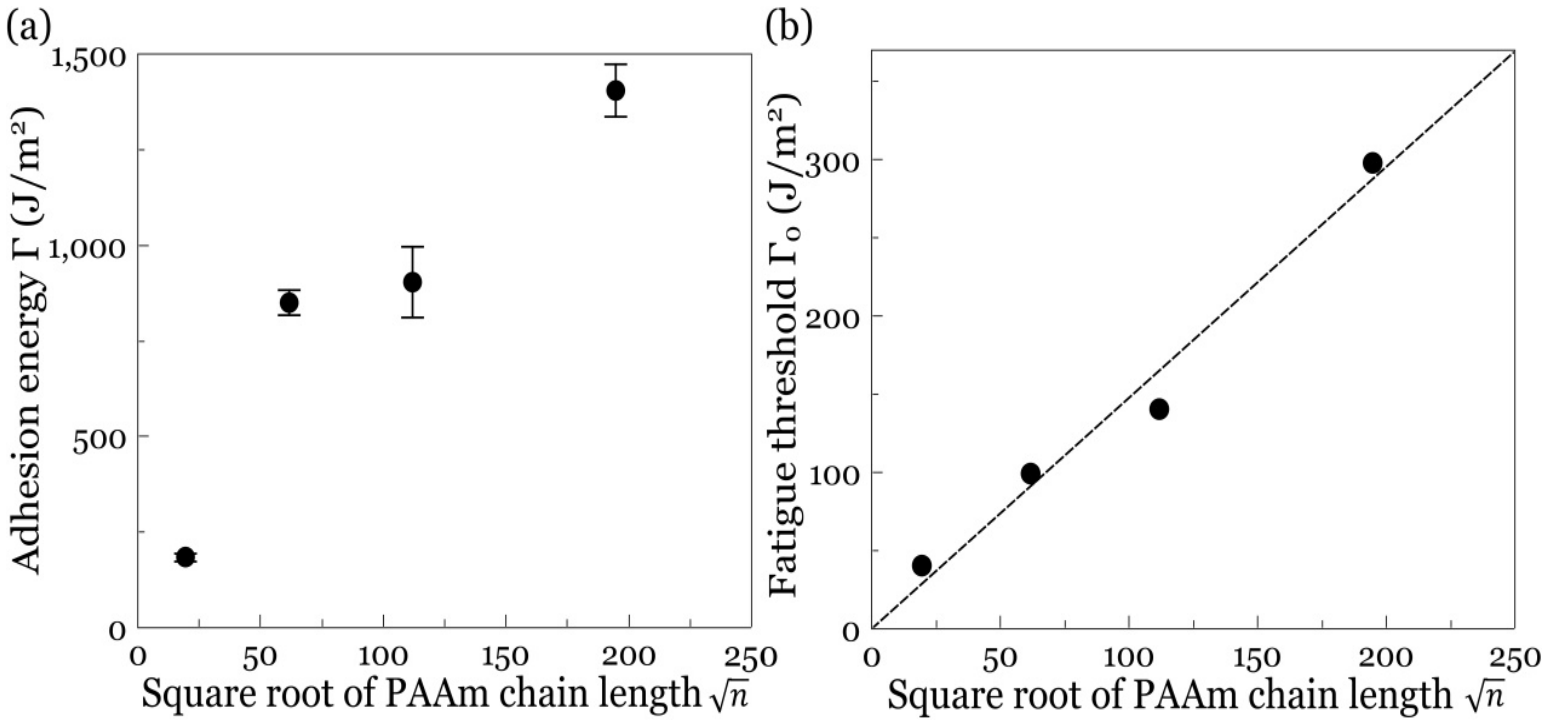
Ni, Chen, Li. Extreme Mechanics Letters 2020

Fatigue-resistant adhesion



Zhang, Gao, Yang Suo, Lu. Submitted

Fatigue-resistant adhesion



Zhang, Gao, Yang Suo, Lu. Submitted

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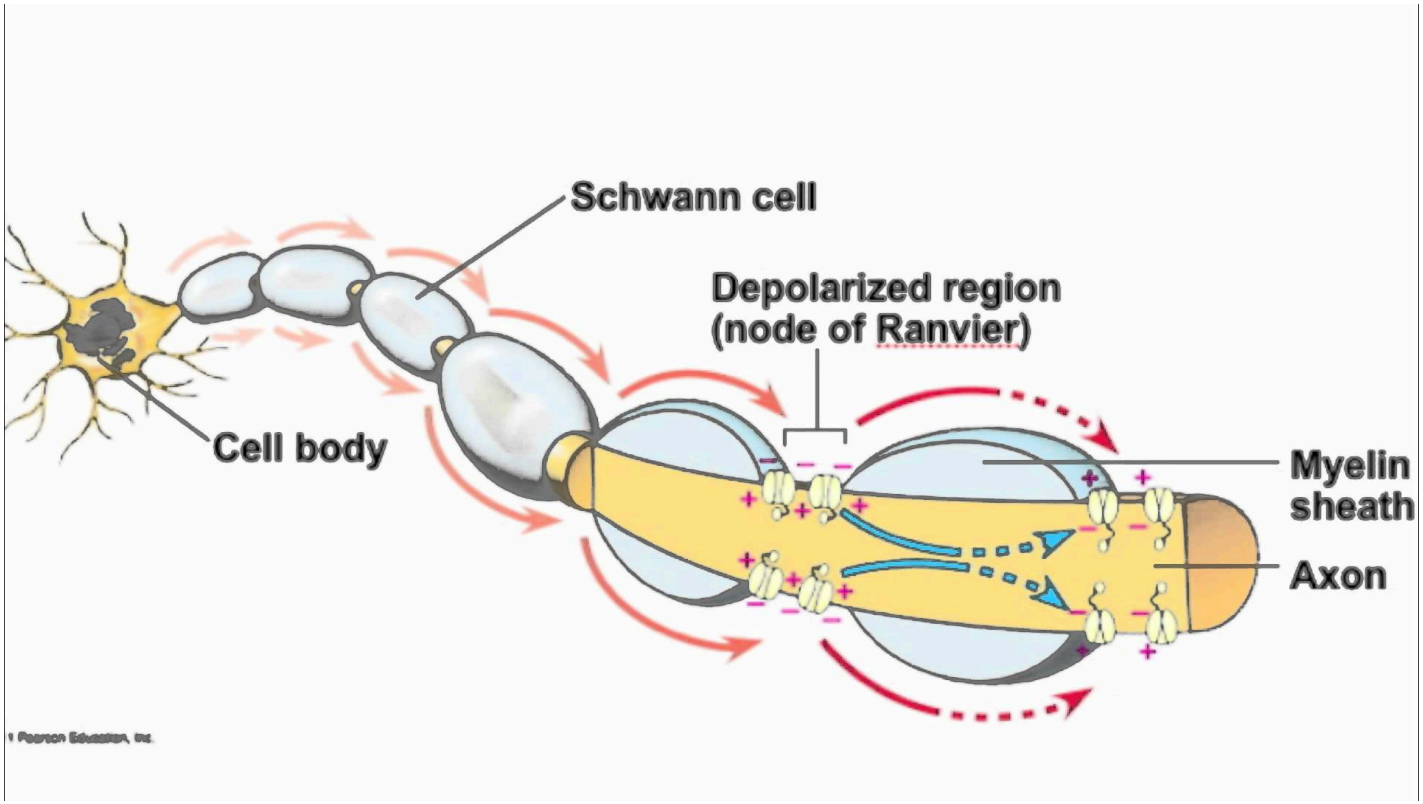
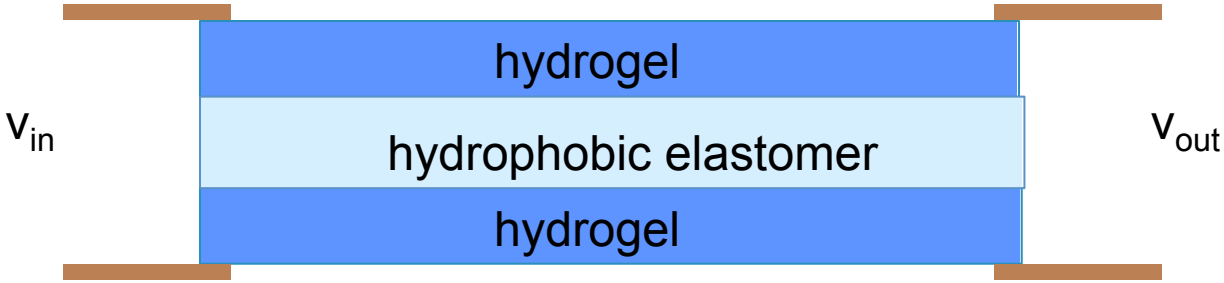
Axon, natural and artificial





Yang, Chen, Lu, Yang, Zhou, Chen, Suo. Extreme Mechanics Letters 3, 59 (2015)

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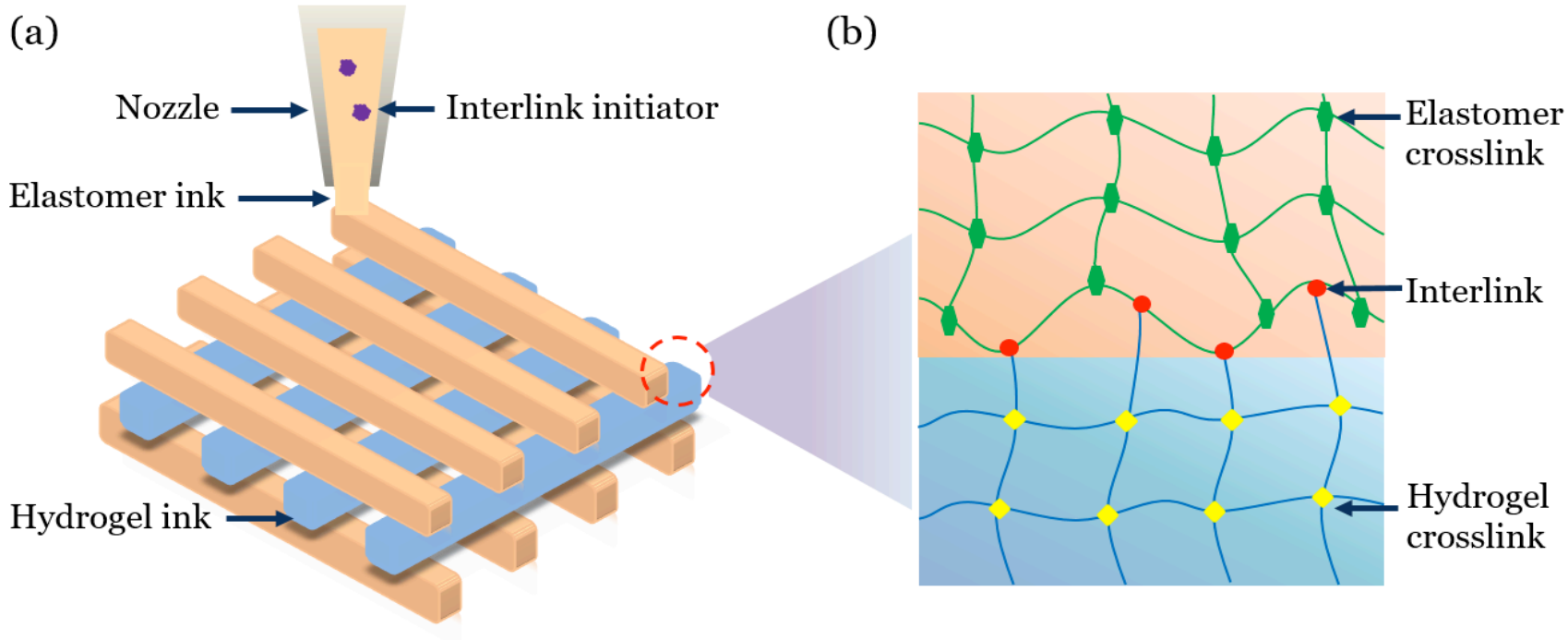
Print hydrogels and elastomers in arbitrary sequence, with strong adhesion



Yang, Li, Yang, Pan, Yin, Tang, Qi, Suo, submitted

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Yang, Li, Yang, Pan, Yin, Tang, Qi, Suo, Advanced Functional Materials 2019

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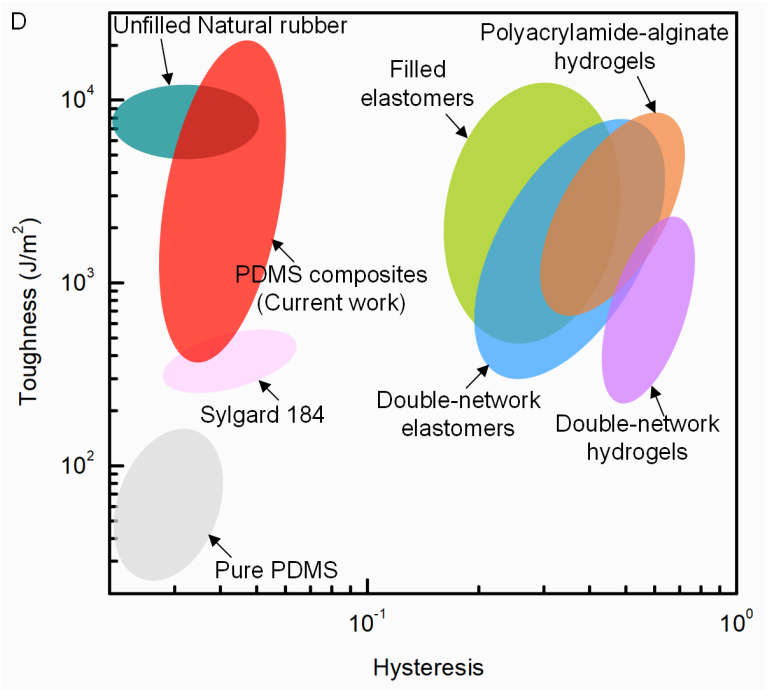
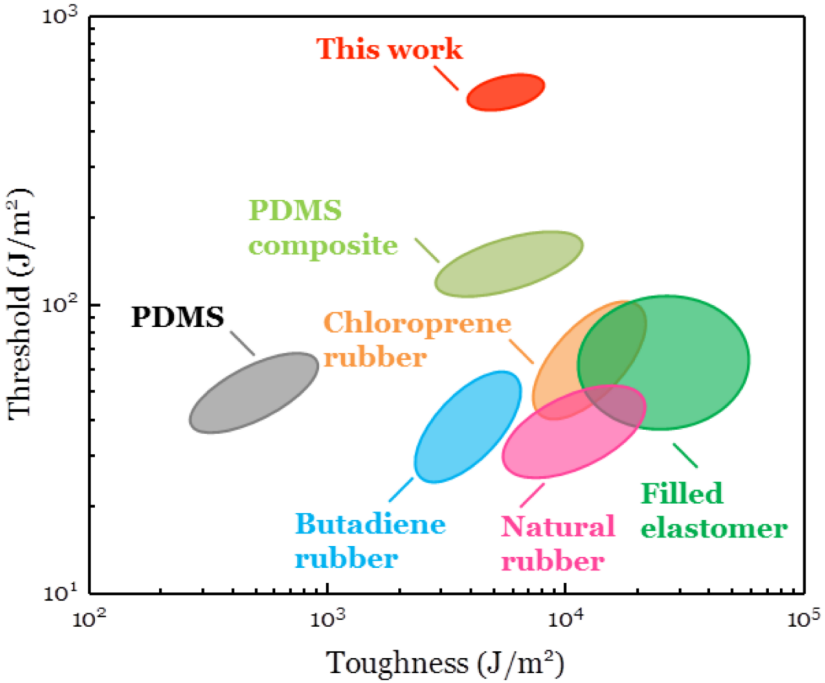
Summary

Elastic dissipater has low hysteresis, high toughness, high threshold.

Let us win the war on fatigue.





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