Self-regulating shape memory alloy robots controlled with soft ionic skin strain sensor

2020. 06. 29

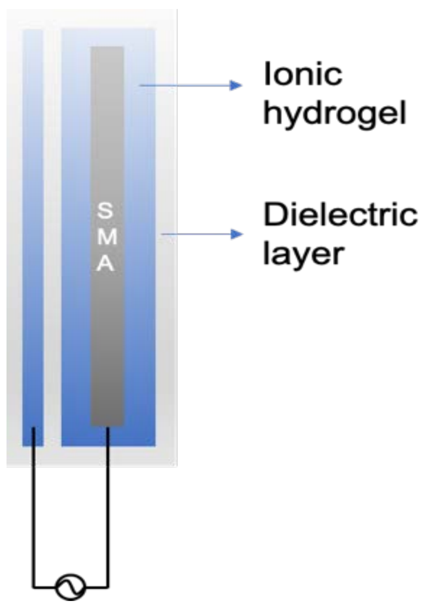
Current status of Structural Materials

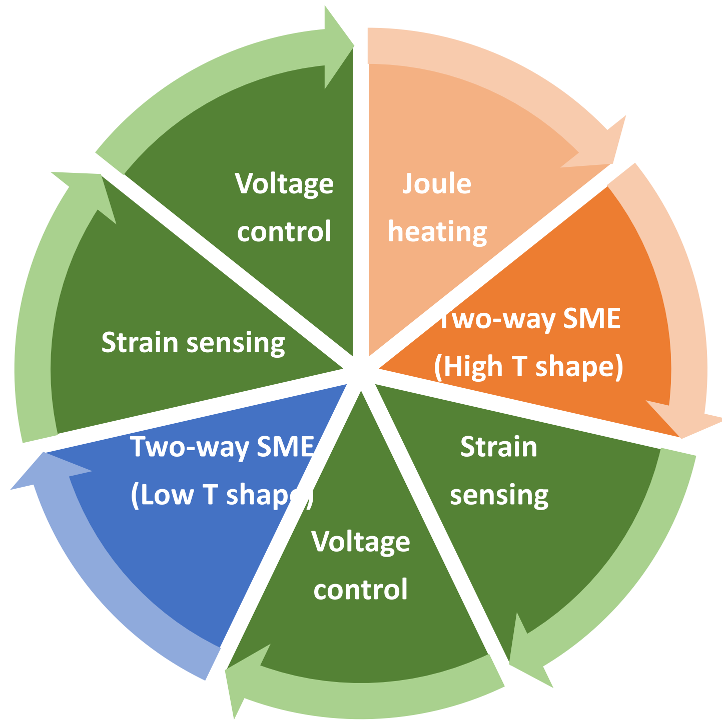
Hyun Wook Na & Ji Young Kim

Contents

- Proposal of Self-regulating SMA strain sensor
- Two-way SMA as electrode of capacitive ionic sensor
  - Material selection & cyclic training for two-way SME
- Fabrication of Capacitive ionic sensor
  - Adhesion of SMA and hydrogel
  - Demonstration of Capacitive ionic sensor operation

- **Scheme of self-regulating shape memory alloy robots with ionic skin**

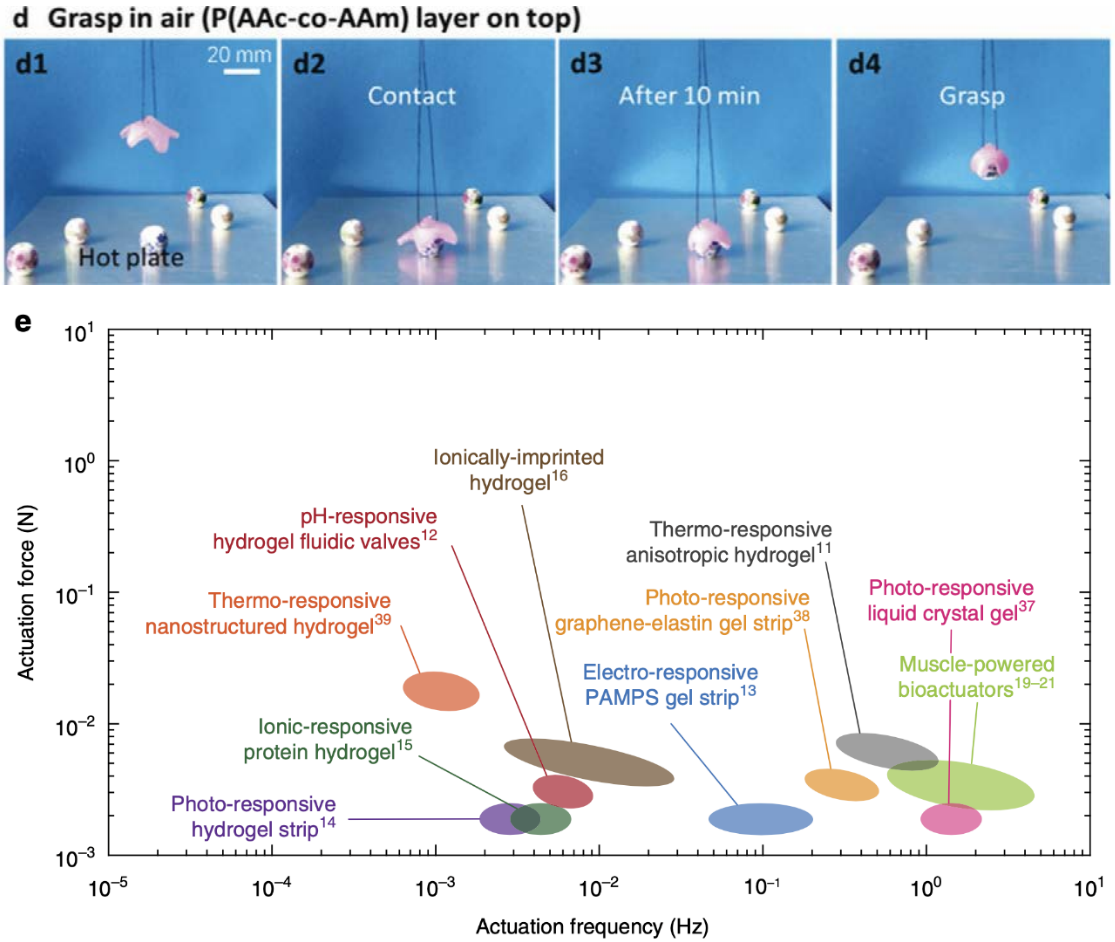




➡ **Fast and strong reversible actuation controlled by joule heating with simple system**

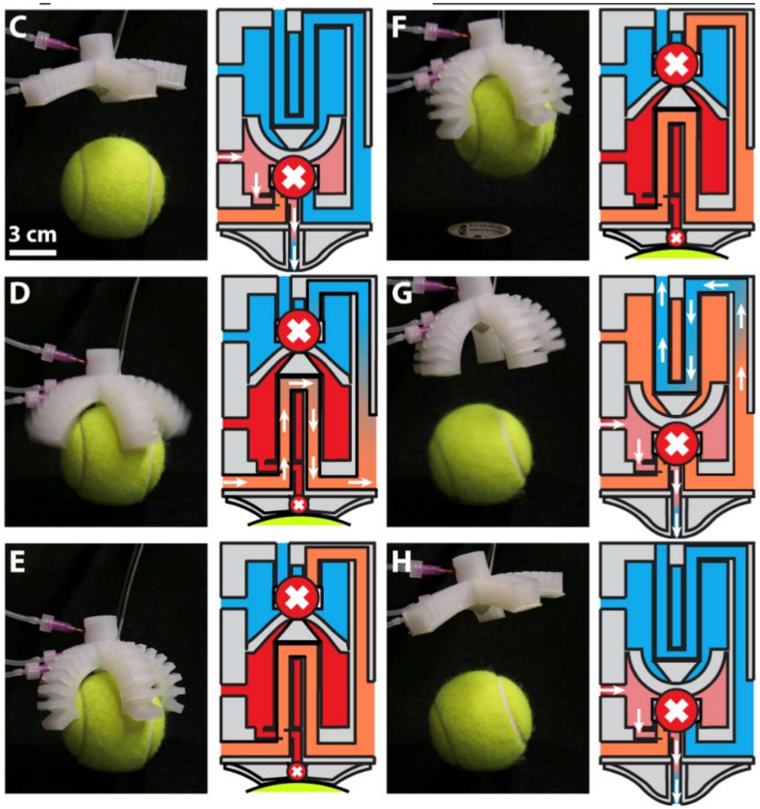
Motivation of developing self-regulating sensor

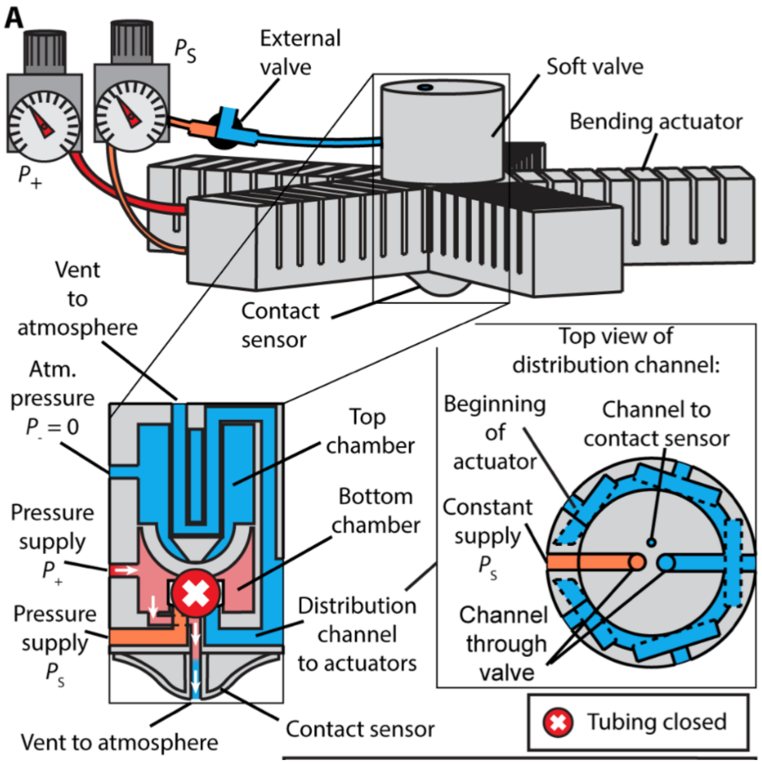
- **Ionic hydrogel gripper**



Zheng, J., et al. (2018). "Mimosa inspired bilayer hydrogel actuator functioning in multi-environments." Journal of Materials Chemistry C 6(6): 1320-1327.

Limitation of Low actuation stress, Low actuation frequency





Rothermund et al, Bistable valve for autonomous control of soft actuators, Science Robotics (2018) p.7986

Limitation of Complex control system for high actuation frequency and stress

Motivation of developing self-regulating sensor

Motivation of this study

Two-way SMA

Temperature sensitive shape change

Rapid response to the situation (Temp.)

Structural materials

+

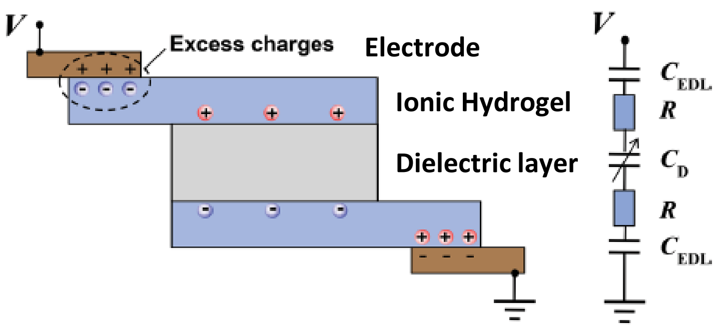
Capacitive ionic sensor

Sensitive **sensing** system

Skin-like soft compliance

Simple layer structure

Capacitive strain sensor



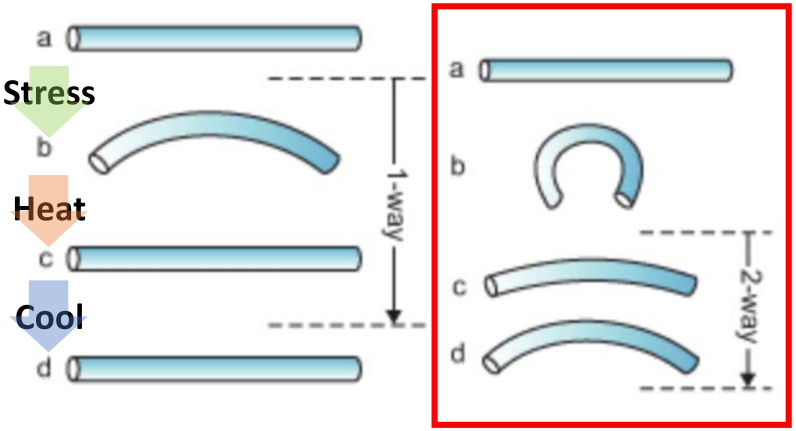
Sandwich structure of

Electrode / Dielectric layer / ionic hydrogel

Electrode metal – ionic hydrogel layer structure

- **Two-way SMA**

https://www.youtube.com/watch?v=xhykVMFDULk



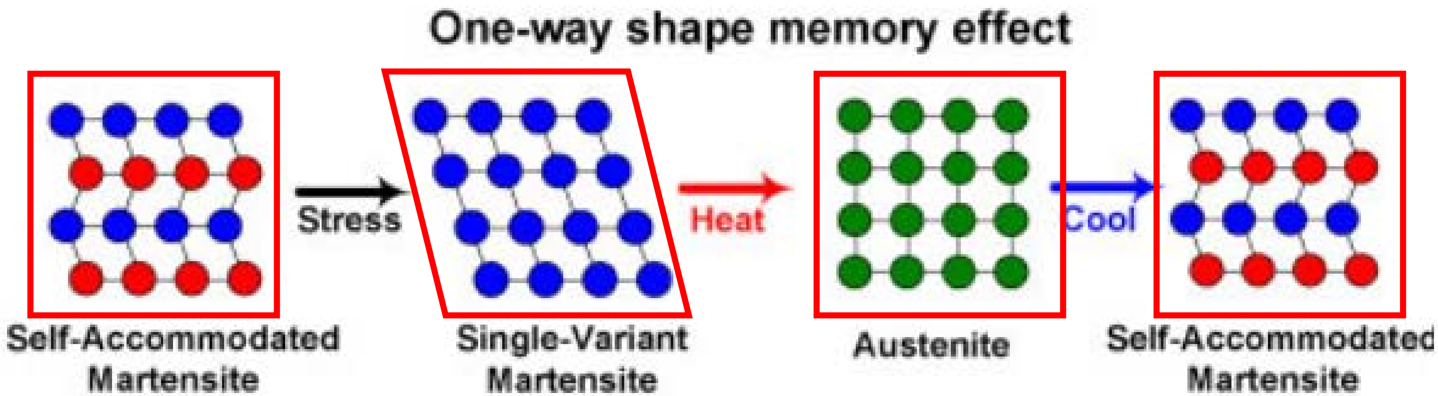
J Ma, I Karaman & R.D. Noebe, Internatinal Materials Reviews 55 (2010)

https://en.wikipedia.org/wiki/Shape-memory_alloy

Various Application as temperature sensitive sensor / grabber

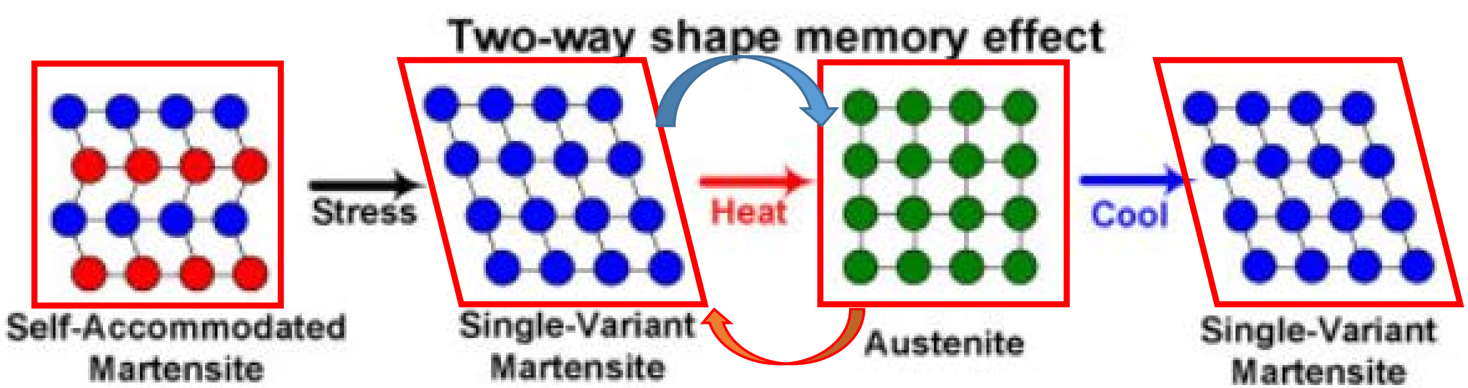
Two-way Shape memory alloys

— Macroscopic shape, size



Thermally-induced martensite
(Various variants, Twinned M)

Stress-induced martensite
(Single variant, Detwinned M)



J Ma, I Karaman & R.D. Noebe, Internatinal Materials Reviews 55 (2010)

https://en.wikipedia.org/wiki/Shape-memory_alloy

Material selection for Two-way SMA as Capacitive sensor

- **Condition : Low T (Room temperature) ↔ High T (Joule heating)**

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Letter

Temperature profiles in a Ti–45Ni–5Cu (at%) shape memory alloy developed by the Joule heating

Seung-yong Yang[a], Seok-won Kang[b], Yeon-Min Lim[b], Yun-jung Lee[c], Jae-il Kim[d], Tae-hyun Nam[b,*]

electric power input : 12.09 W

1.338V, 9.04A

(Resistance SMA wire : 4.933Ω/m)

"Temperature gradient from 504K to 413K is developed by the Joule heating"

Table 1
Alloy compositions and transformation temperatures

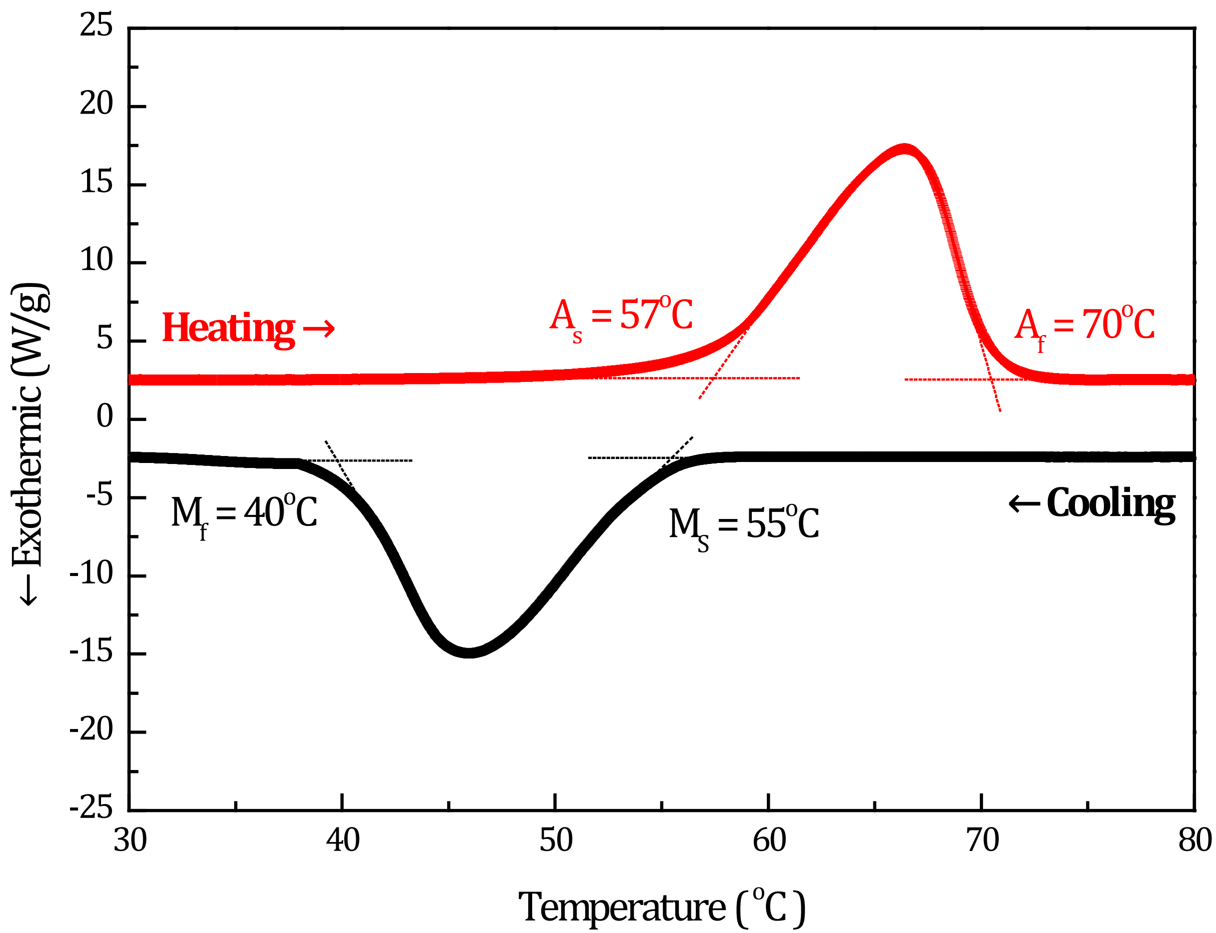
Alloy	Composition (at.%)			Transformation points (°C)			
	Ti	Ni	Cu	M_f	M_s	A_s	A_f
A	49.1	50.9	—	−115.8	−30.7	1.9	44.6
B	49.5	50.5	—	−77.8	−18.5	9.0	53.0
C	50.0	50.0	—	−28.0	37.5	48.2	77.8
D	49.0	41.0	10.0	7.6	29.8	34.5	50.0
E	50.0	40.0	10.0	20.9	41.4	52.7	66.6
F	48.5	41.5	10.0	14.4	37.5	42.6	60.0

S.Y. Yang et al., Journal of Alloys and Compounds 490 (2010) L28-L32

B . Stranadel et al., Materials Science and Engineering A 202 (1995) 148-156

Phase transformation temperature of $Ti_{50}Ni_{40}Cu_{10}$

- **DSC analysis** (10K/min)



To reach the phase transformation temperature via joule heating

Thermomechanical Cyclic training

"**Training** is a procedure to develop **dislocation arrangements**

which guide the formation of martensite variants of a preferred orientation"

- **Diverse cyclic training method to apply two-way SME**

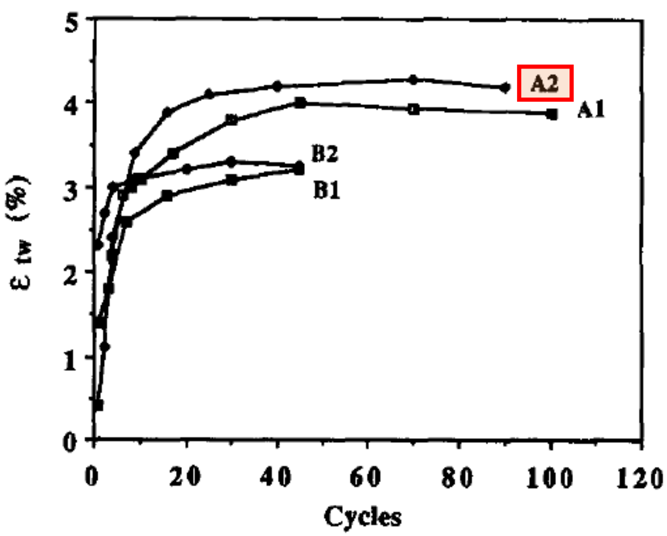


Fig. 8. Effect of training procedure on two-way strain.

With procedures A1 and A2 the load was applied at $T > A_f$ and maintained during cooling to below M_f, thus causing stress induced martensite to form. With A1 the stress was maintained throughout the cycle, while with A2 the load was removed prior to heating and the reverse transformation occurred under zero stress.

The specimens were cooled to below M_f under no load and the stress was applied, causing reorientation of the thermal martensite

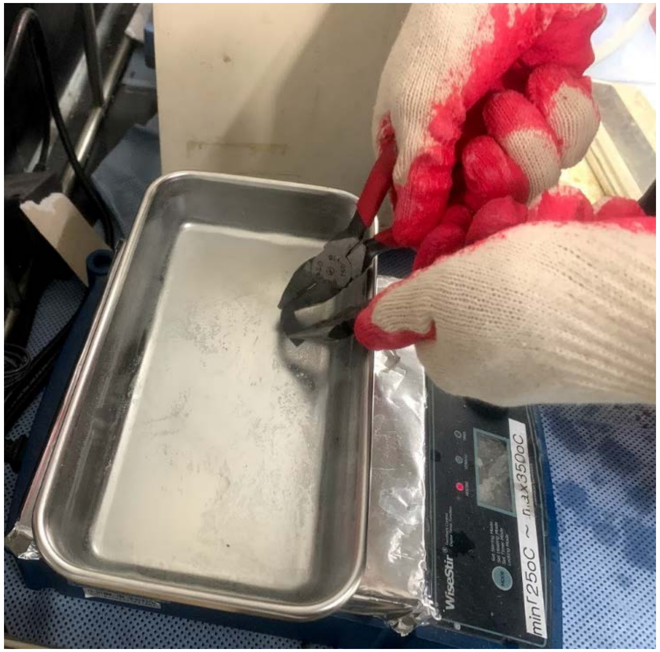
With B1 the load was then removed prior to heating, while with B2 the load was reduced to the same value as used with procedures A1 and maintained at that value during heating to above A_f.

Y. LIU et al., Acta metall. Mater. 38 (1990) 1321-1326.

Select A2 cyclic training method among 4 different method (100 Cycle)

100 cycle

with stress

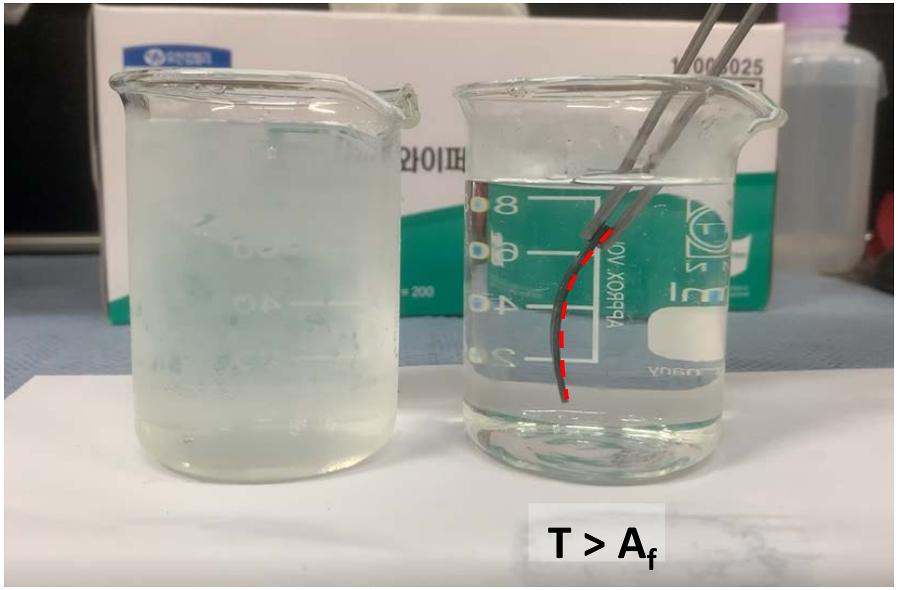


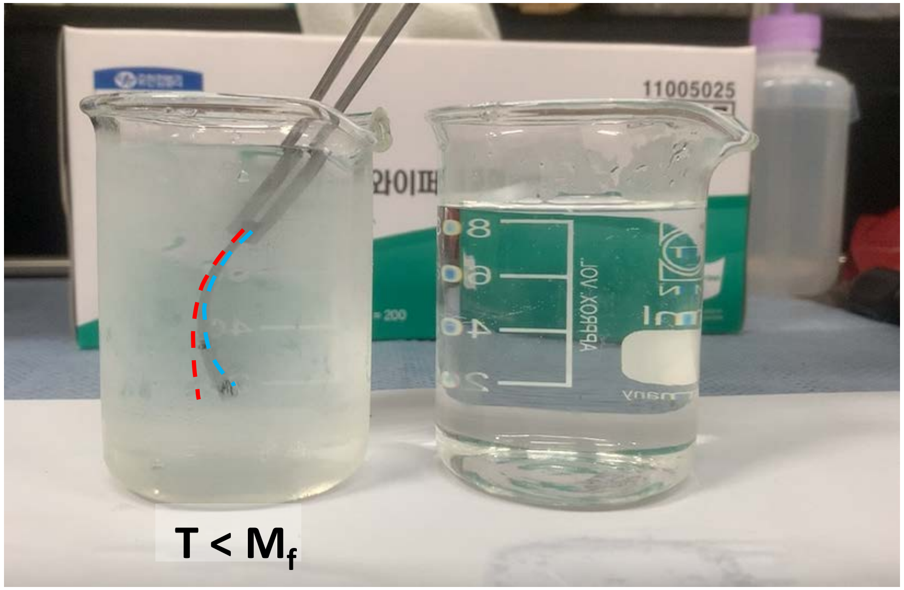
High T ($T > A_f$)

Low T ($T < M_f$)

w/o stress

- **After 100 cycle**



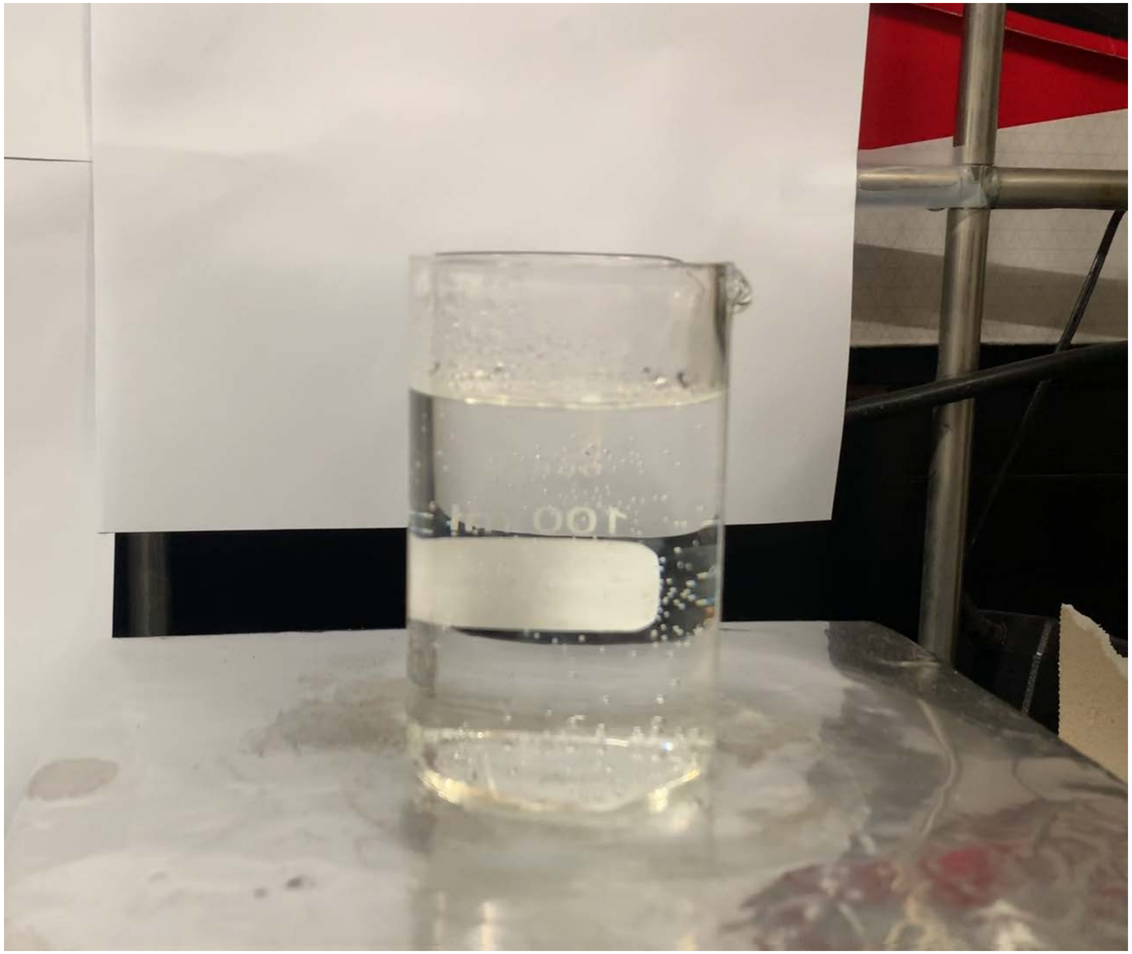


1. To improve change of curvature

➡ Thickness reduction (Cold-Rolling & Heat-treatment)

2. To improve resistance for joule heating ➡ Width reduction

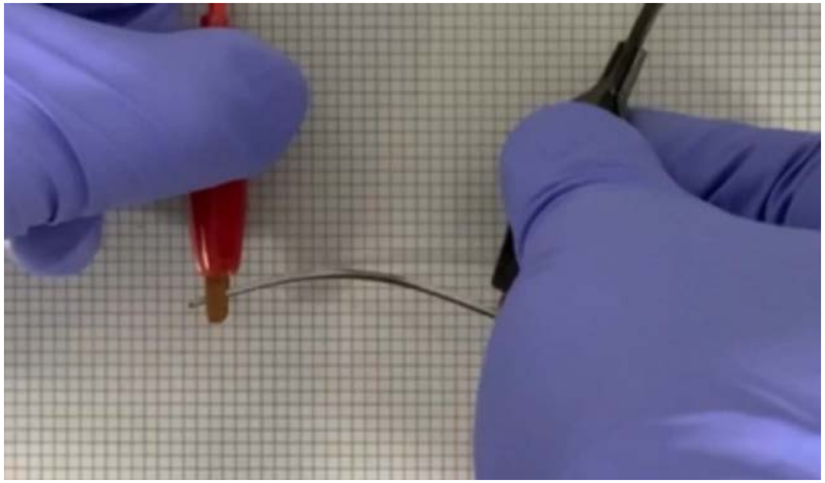
Thickness : 1.1 mm → 0.8mm (27% cold-rolled)



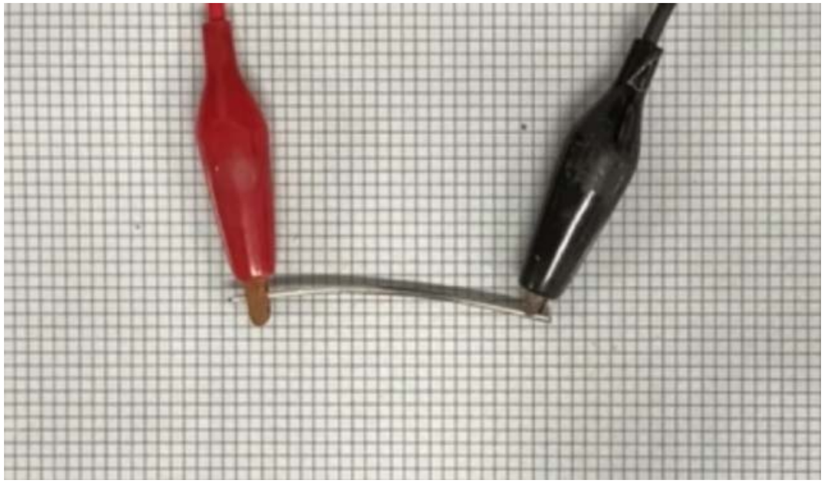
We improved curvature difference by reducing the thickness of specimen.

Two-way Shape memory effect via Joule heating

Movie (x4)



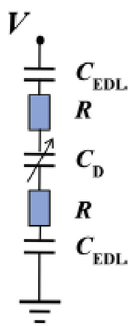
Heating



Cooling

We confirmed the two-way shape memory effect via joule heating.

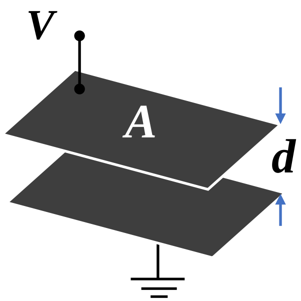
Fabrication of Capacitive ionic sensor



$$\frac{1}{C} = \frac{2}{C_{EDL}} + \frac{1}{C_D}$$

$$C_{EDL}/C \approx 10^5$$

$$\therefore C \approx C_D$$



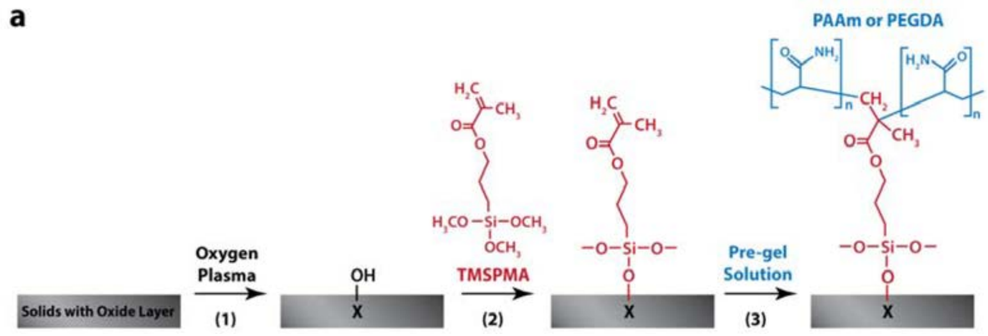
$$C = \frac{\epsilon_0 A}{d}$$

When **uniaxial force** stretches dielectric $\boldsymbol{\lambda}$ **times**,

both **the width and the thickness of the dielectric reduce by a factor of** $\sqrt{\lambda}$,

and the capacitance of the dielectric scales as $\boldsymbol{C = C_0\lambda}$

Adhesion of SMA and hydrogel



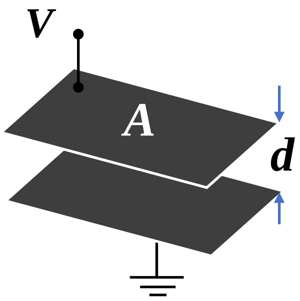
Yuk, H., et al. (2016). "Tough bonding of hydrogels to diverse non-porous surfaces." Nat Mater **15(2): 190-196.**

Tough bonding between shape memory alloy and hydrogel was achieved by silane coupling reaction

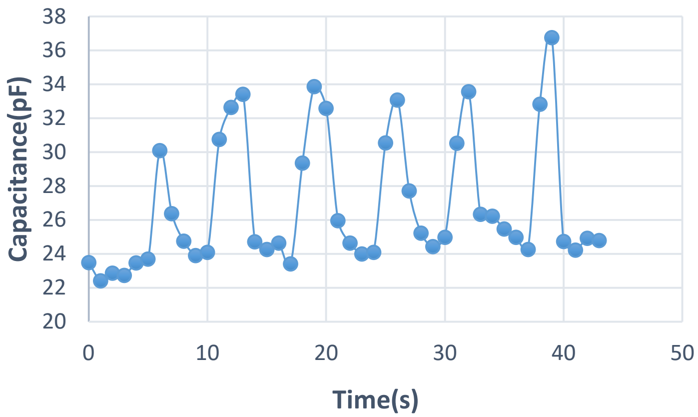
Demonstration of Capacitive ionic sensor operation

(Normal)

(Pressed)

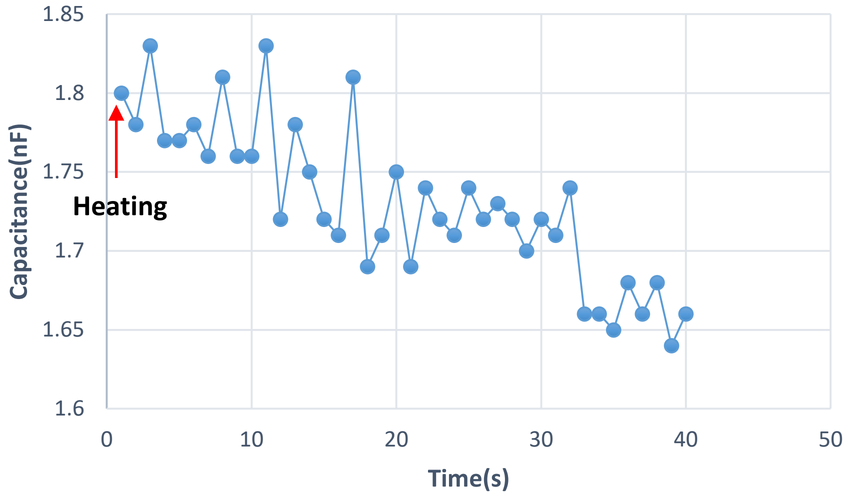


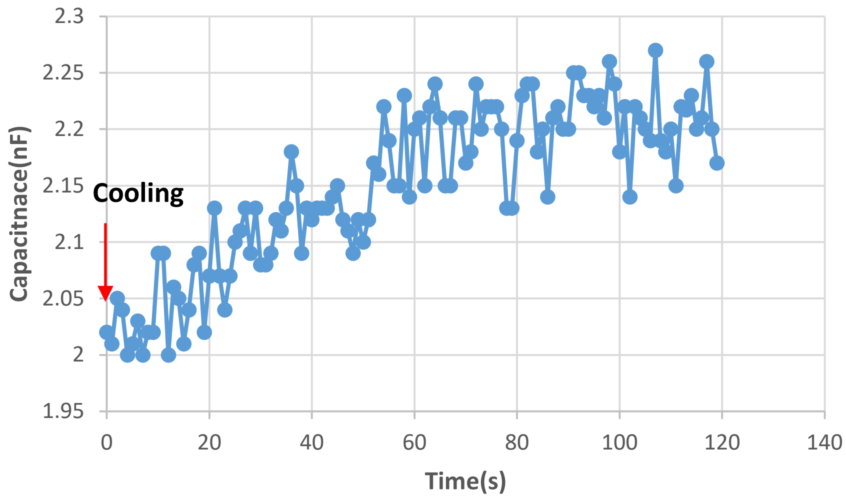
$$C = \frac{\epsilon_0 A}{d}$$



Capacitive ionic sensor with SMA successfully operated by finger pressure

Demonstration of Capacitive ionic sensor operation

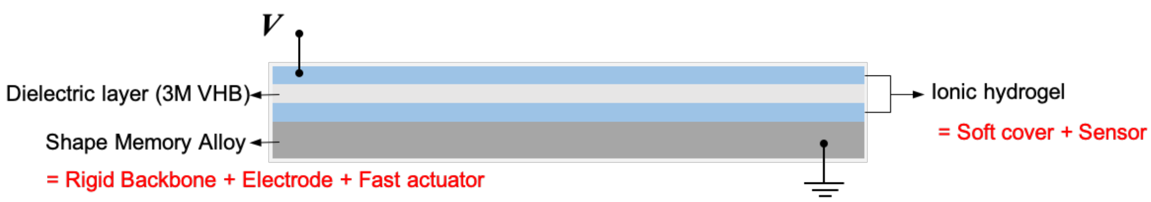


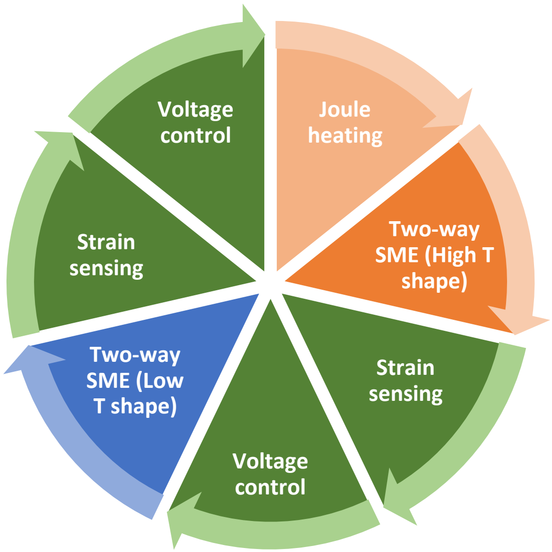


Confirm capacitance change, however very small signal-to-noise ratio, and capacitance changes by contact surface

Summary

Scheme of proposed self-regulating shape memory alloy robots with ionic skin





Significance of this study

Two-way SMA

Temperature sensitive shape change

Rapid response to the situation (Temp.)

Structural materials

+

Capacitive ionic sensor

Sensitive **sensing** system

Skin-like soft compliance

Simple layer structure

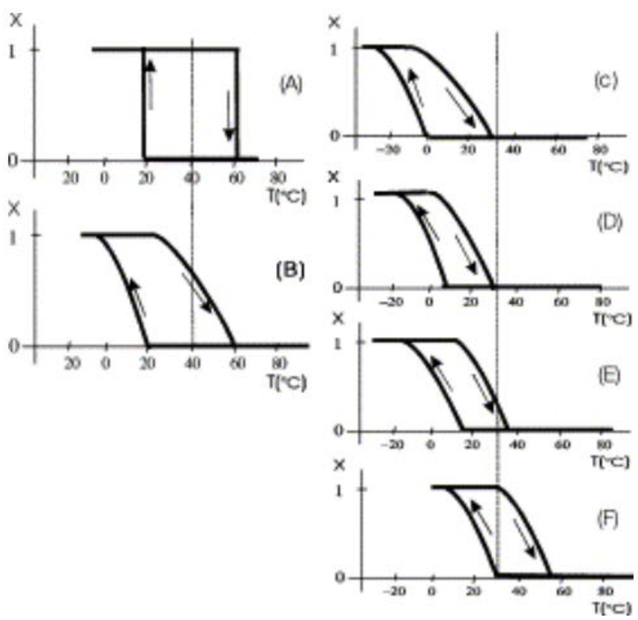
➡ **Fast and strong reversible actuation controlled by joule heating with simple system**

Thank you for your kind attention

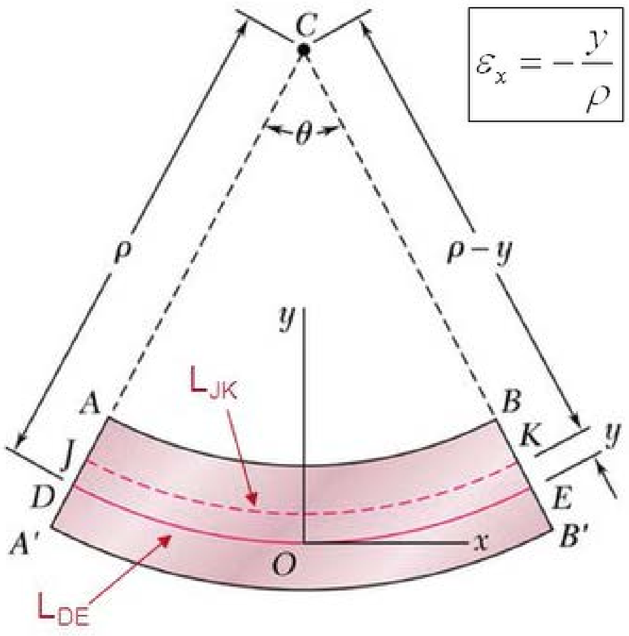
International Journal of Non-Linear Mechanics
Volume 37, Issue 8, December 2002, Pages 1275-1281

Hysteresis in shape-memory alloys

Jordi Ortín [a], Lucas Delaey [b]



from the classical work of Salzbrenner and Cohen [1]. In single crystals, the single-interface transformations (A) take place at two constant temperatures, whose difference characterizes the energy dissipation. The multiple-interface transformations (B), on the contrary, extend in a temperature range, indicative of the build-up and partial storage of elastic strain energy, with a dissipation comparable to the previous case. In polycrystals of various grain sizes, (0.5 mm (C), 1.5 mm (D), 4.0 mm (E)), the transformation takes place via multiple interfaces. The behaviour is then comparable to (B), except that the extension in temperature of the transformations is much larger due to the misorientation between grains and the associated build-up of strain energy. This is demonstrated by the transformations in a single crystal spark-cut from a coarse-grained polycrystal, shown in (F), which behave very similarly to (B).



Thickness : 0.8mm 기준으로,

Diameter = 2cm → 4% Compressive / tensile strain

Diameter = 2.5cm → 3.2% Compressive / tensile strain

Beams: Pure Bending (4.1-4.5) MAE 314 – Solid Mechanics Yun Jing Beams: Pure Bending.

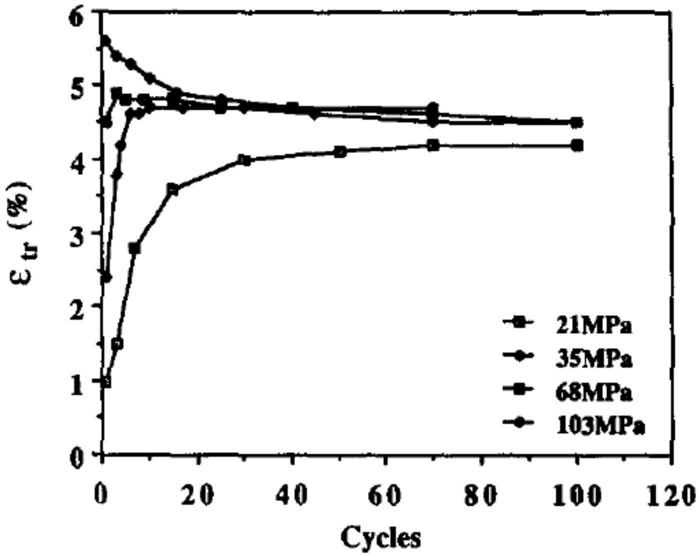


Fig. 3. Effect of number of training cycles and stress on transformation strain.

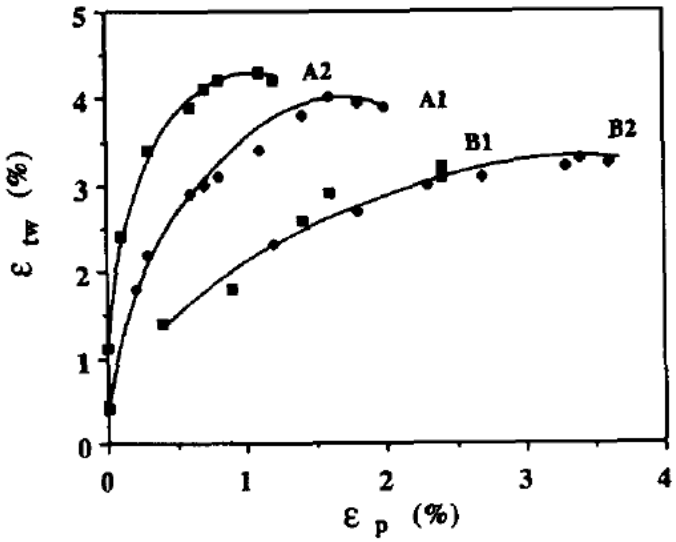
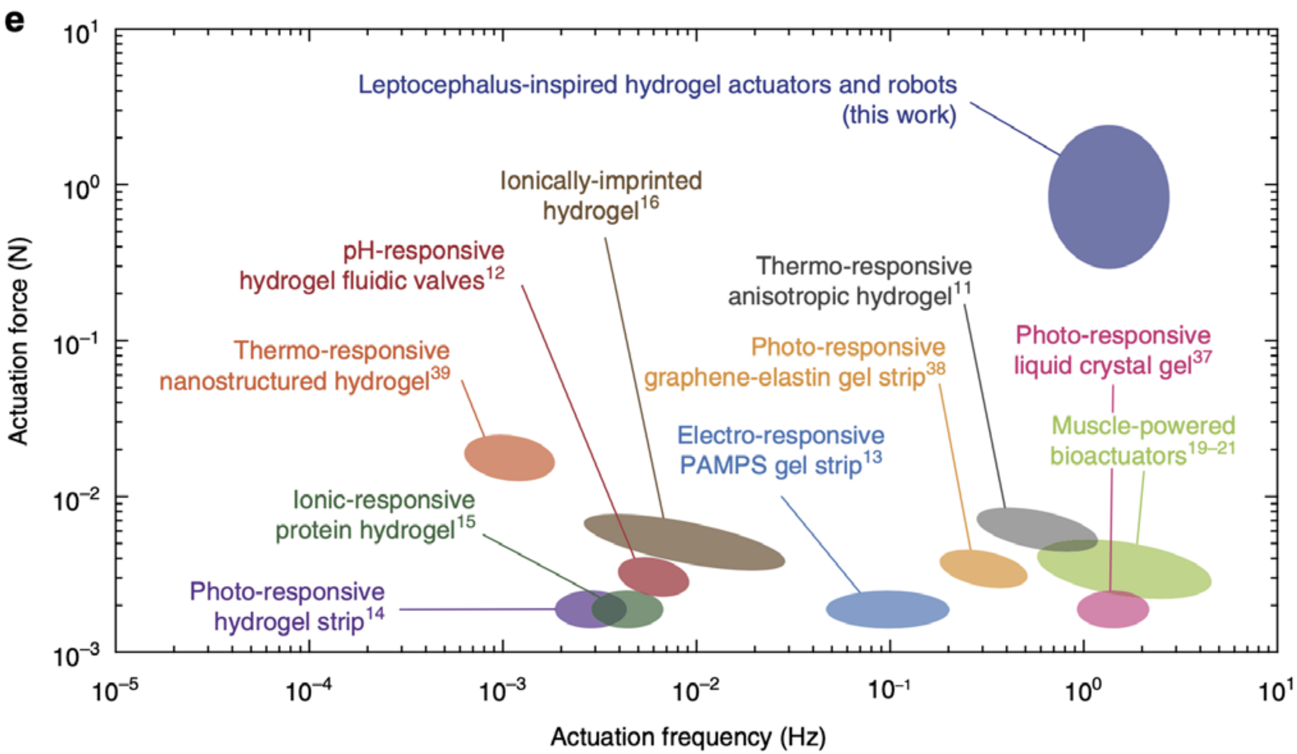


Fig. 12. Plot of ϵ_{tw} as a function of ϵ_p for different training procedures.

A1, B1, B2 → High permanent strain



Yuk, H., et al. (2017). "Hydraulic hydrogel actuators and robots optically and sonically camouflaged in water." Nat Commun 8: 14230.
 stresses. We further demonstrate that the agile and transparent hydrogel actuators and robots perform extraordinary functions including swimming, kicking rubber-balls and