Y Prize COMPETITION

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Healing and Morphogenesis of Cellular Metals by Electrochemistry

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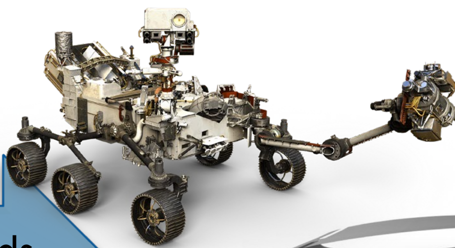
Designing with conventional vs. self-healing materials



With conventional materials

- ✓ Known properties, fabrication methods
- ✓ Well-established design methods (topology optimization, probabilistic design…)
- ○ Vulnerable to defects >> Maintenance
- ○ Limited service life

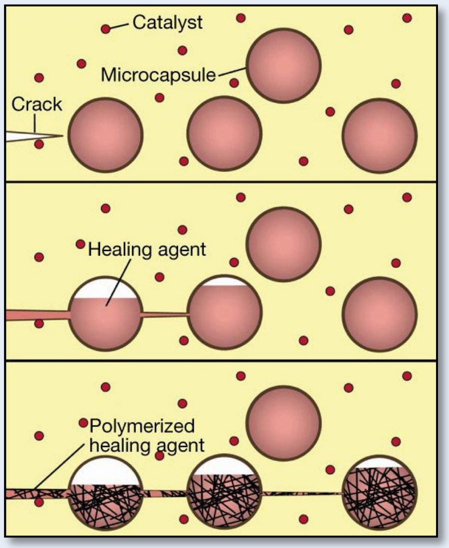
Aage, N. et al. Nature 550, 84–86 (2017).

With self-healing materials

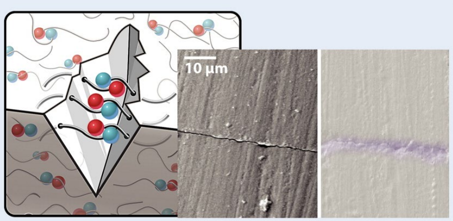
- ✓ Less constraints on design
- ✓ Tolerance for flaws, long service life
- ✓ Adaptability to environment
- ○ Difficult, too costly to fabricate at scale
- ○ Most are polymer-based materials

Healing in synthetic materials

Polymers heal using matter stored locally



White, S. R. et al. Nature 409, 794–797 (2001).

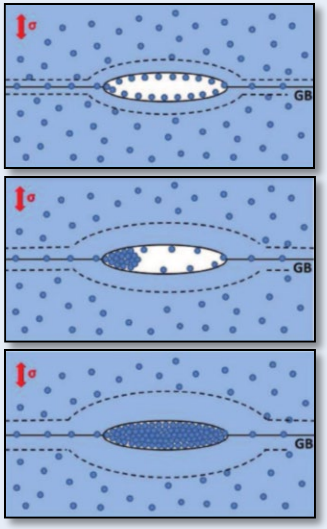


Blaiszik, B. J. et al. Annu. Rev. Mater. Res. 40, 179–211 (2010).

High-temperature energy-intensive healing in metals

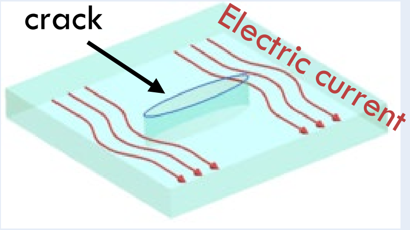
Low diffusivity at room temperature
10^{-45} to 10^{-35} m^2/s

Solute precipitation
(Up to 1200 °C)



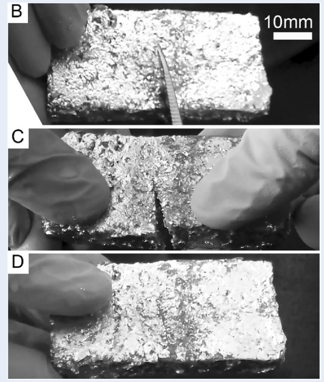
van Dijk, N. H. & van der Zwaag, S. Adv. Mater. Interfaces 1800226, 1–13 (2018).

Crack-localized joule heating
(Up to 600 °C at crack sites)



Song, H. et al. Sci. Rep. 7, 1–11 (2017).

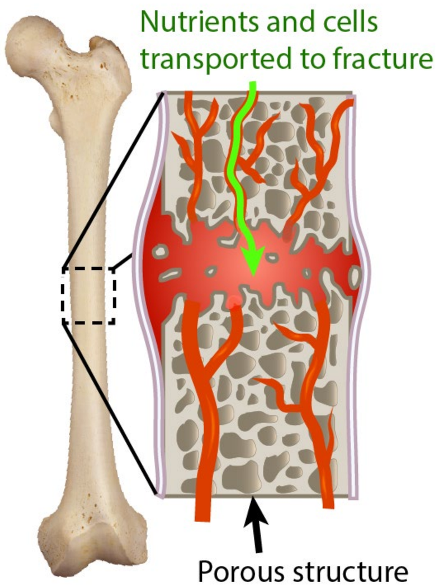
Low melting point alloys
(60 to 70 °C)

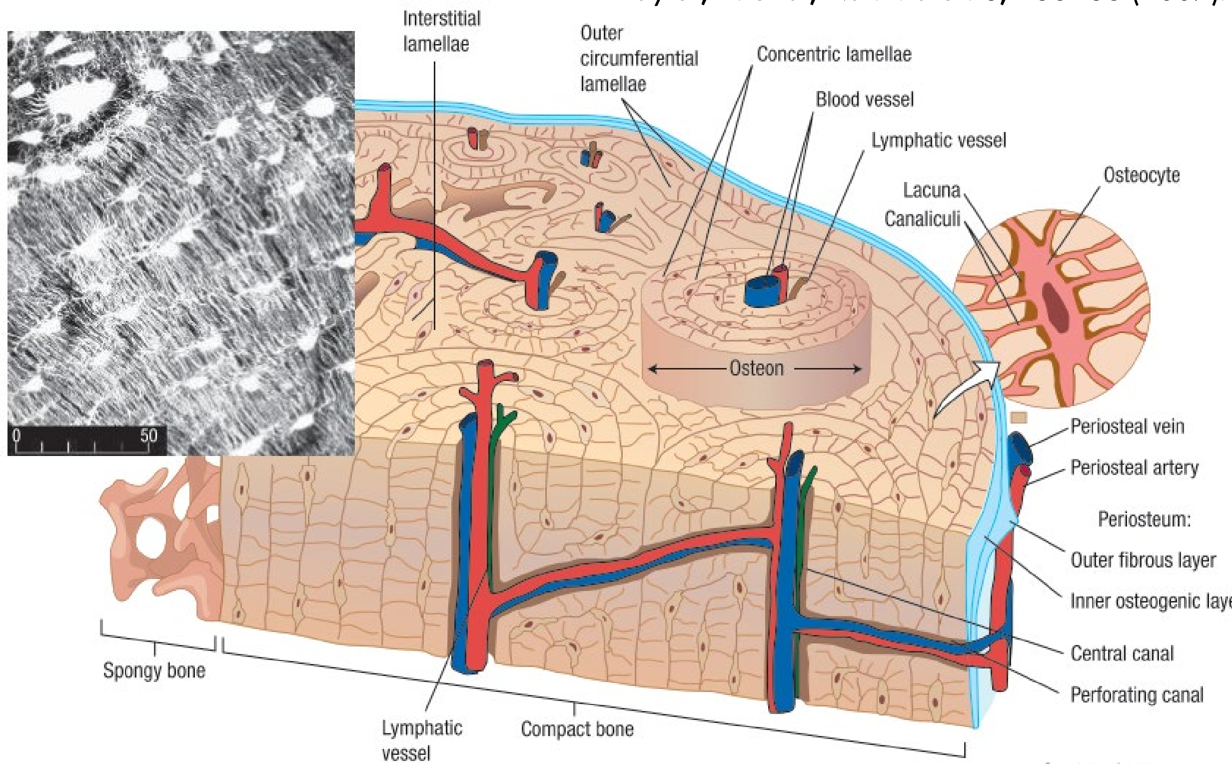


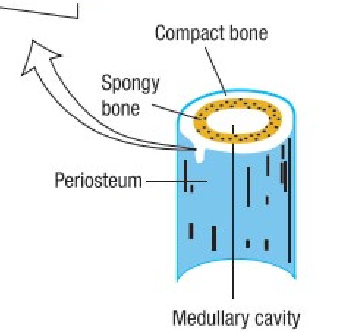
Van Meerbeek, I. M. et al. Adv. Mater. 28, 2801–2806 (2016).

Transport-mediated healing in bone

Taylor, D. et al, Nat. Mater. 6, 263-268 (2007).

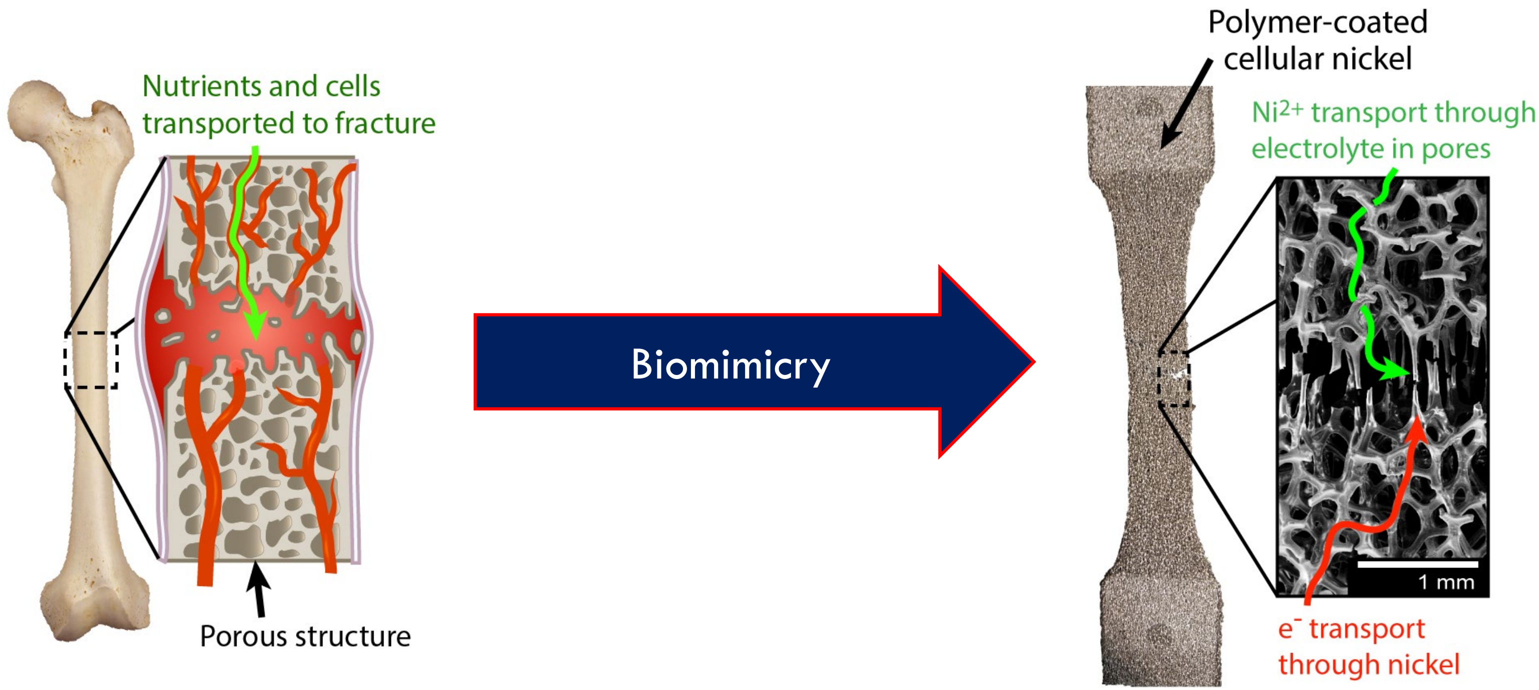


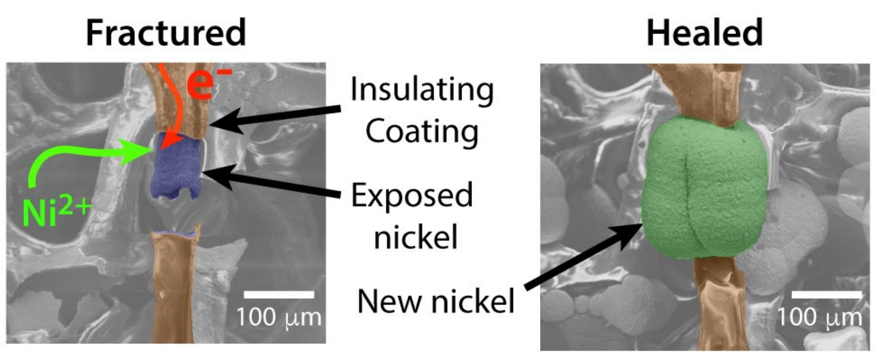




- Pores in cellular structure house cells and blood vessels.
- Blood vessel network transports nutrients, minerals and cells to the damage site.
- Bone heals effectively near room temperature (37 °C).

A transported-mediated approach to heal metals

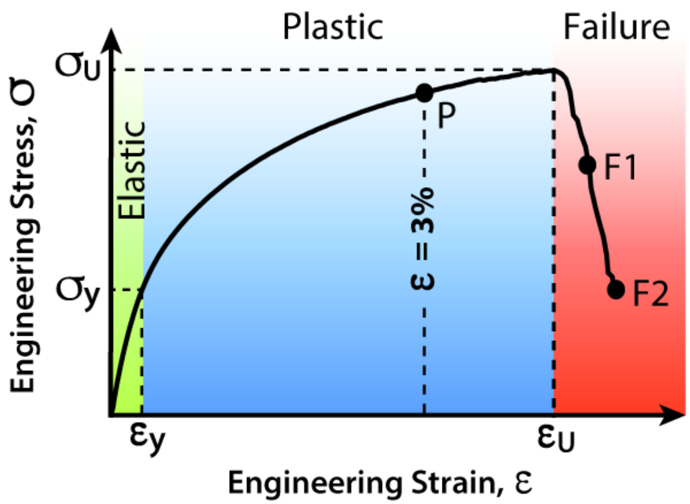




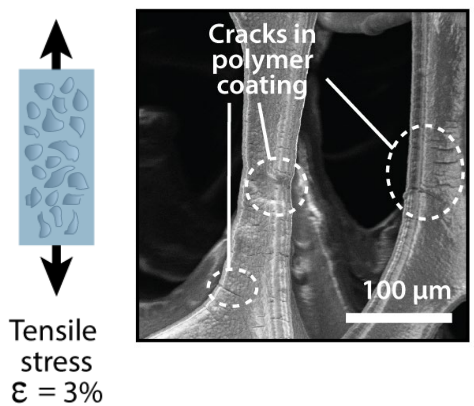
$Ni^{2+}_{(aq)} + 2e^{-} = Ni_{(s)}$

- Electrodeposition at -1.8 V vs. nickel counter electrode.
- Polymer coating has lower failure strain than metal.
- Polymer coating allows control over the location and onset of healing.

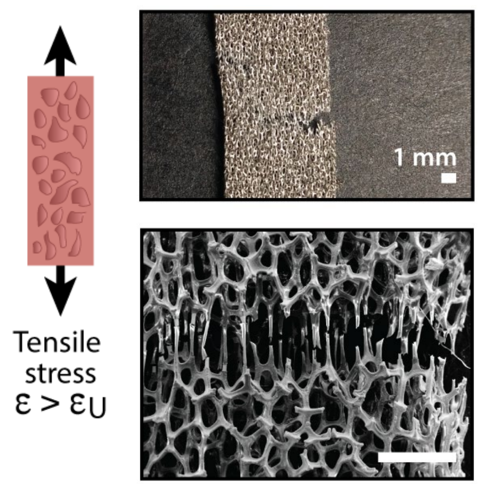
Healing cellular nickel with 3 types of damage



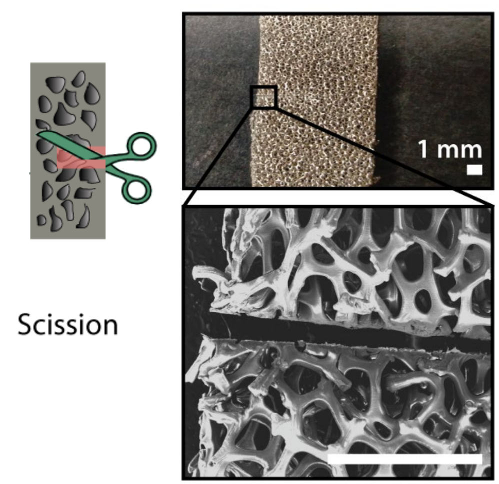
Plastic deformation (P)



Tensile failure (F1)

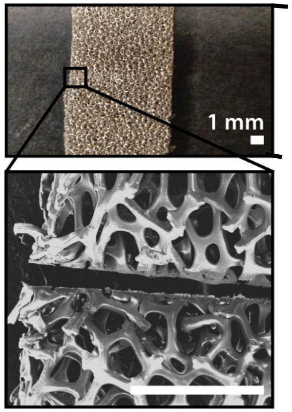


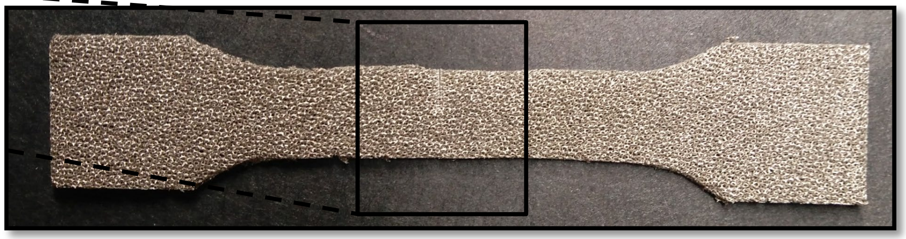
Scission failure (F2)

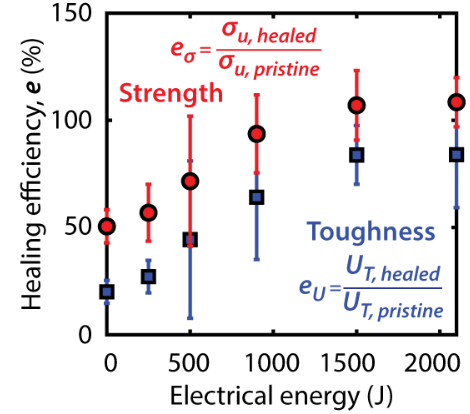


Healing after scission failure (F2)

Before healing

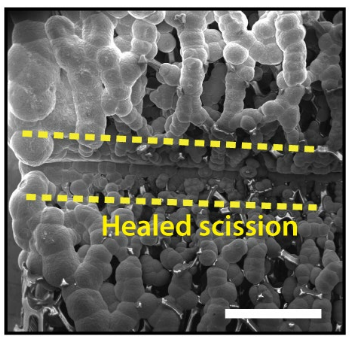




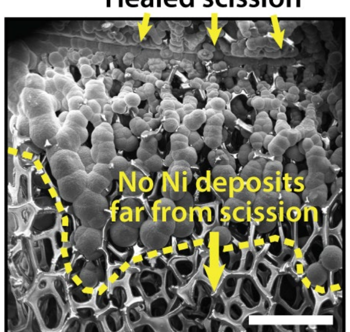


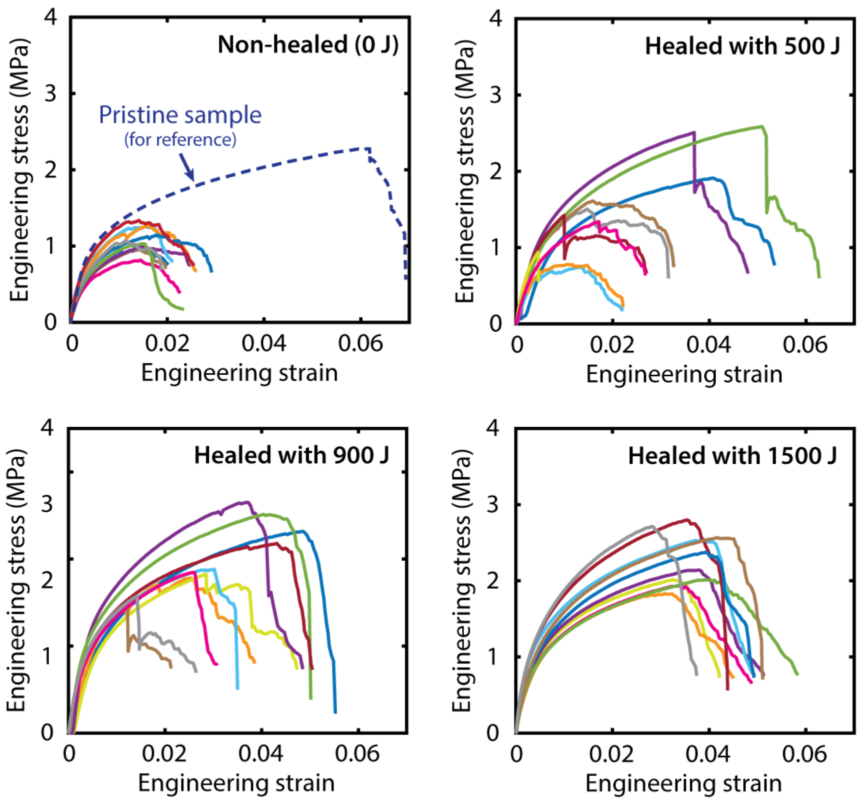
Strength healing efficiency plateaus at 100% after 1,500 J.

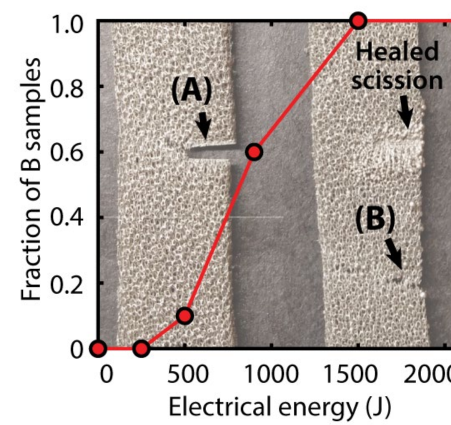
After healing



Healed scission

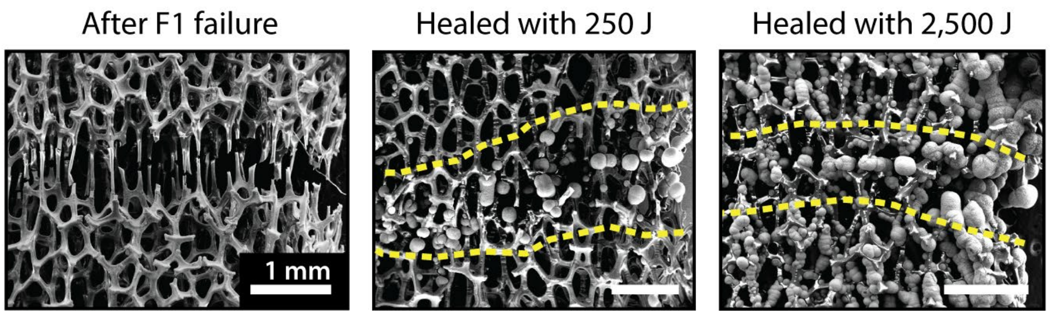


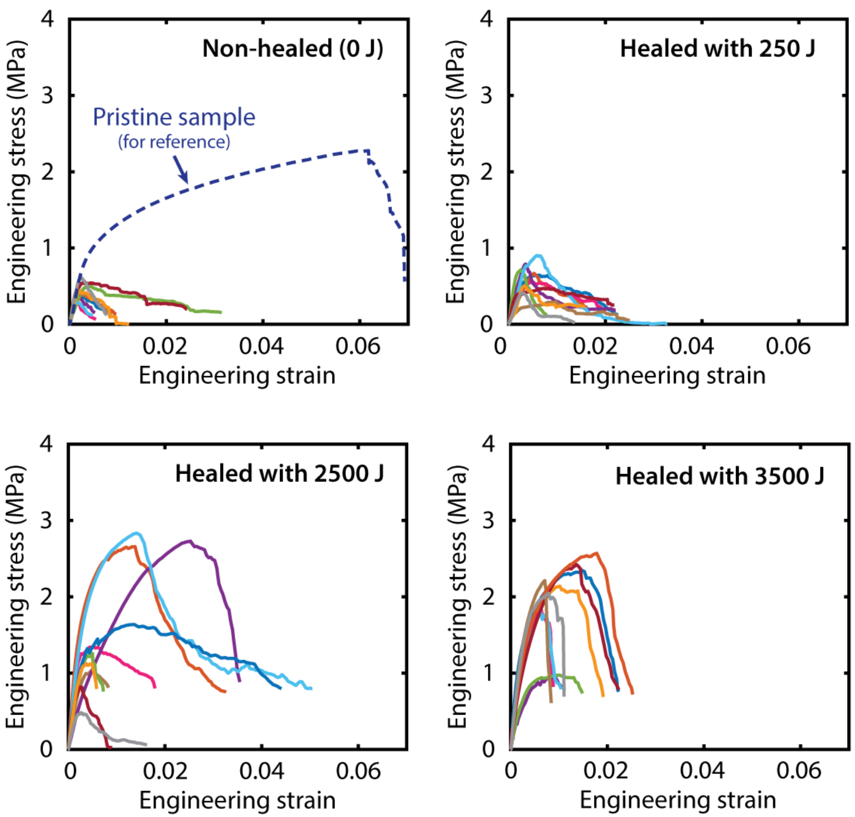




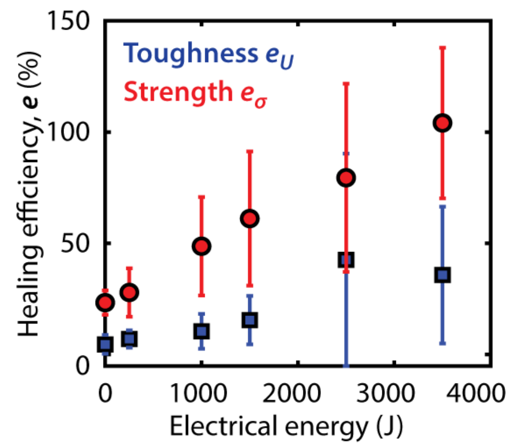
Strength of healed scission exceeds material strength in B samples.

Healing after tensile failure (F1)



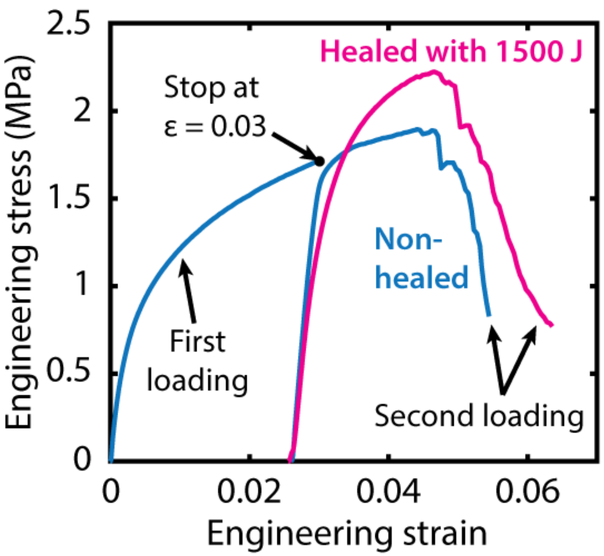


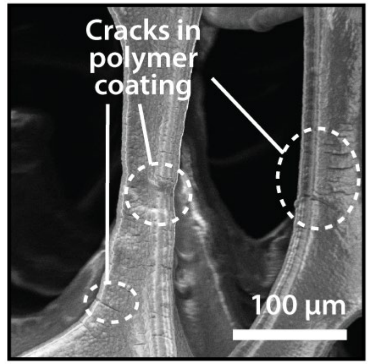
- Poor segregation of nickel deposits due to distributed strain.



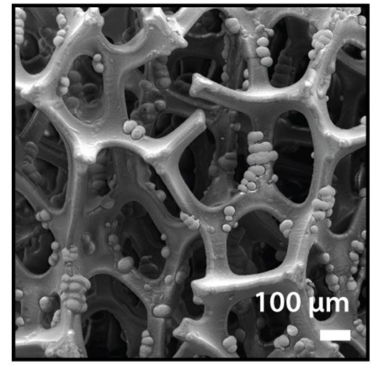
- Strength healing efficiency reaches 104% at 3,500 J.
- Limited recovery of toughness due to low ductility of electrodeposited nickel (27 nm grain size, by XRD).

Healing after plastic deformation (P)

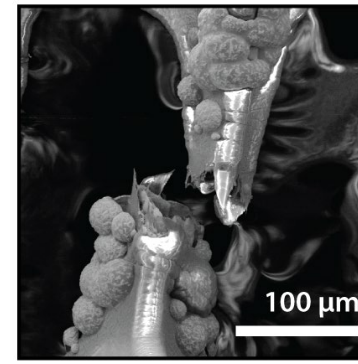




After first loading



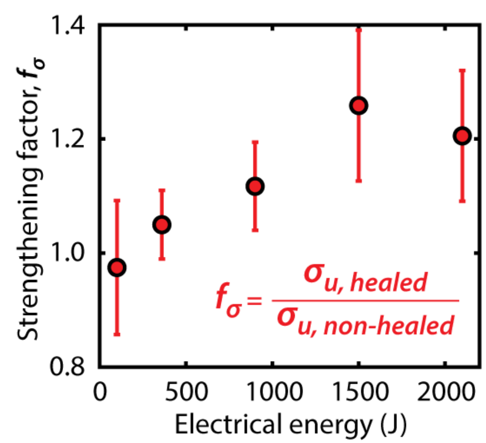
After healing



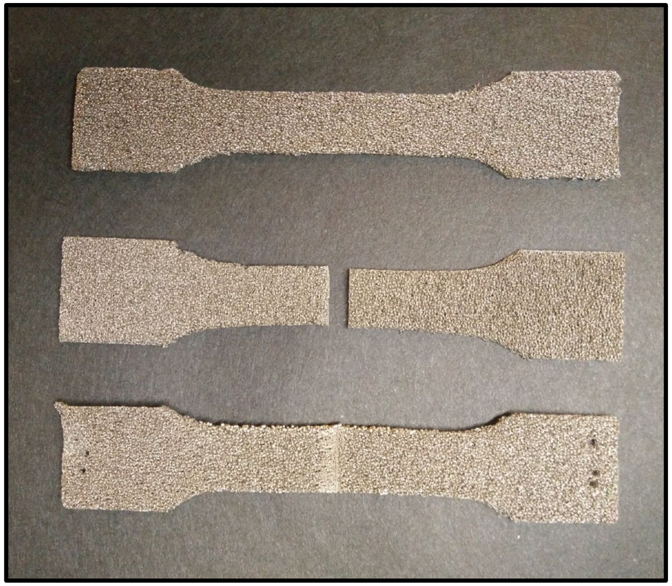
After second loading

1) Loading in tension until 3% strain
2) Electrochemical healing
3) Loading in tension until failure

Up to 1.5x improvement in strength compared to non-healed samples



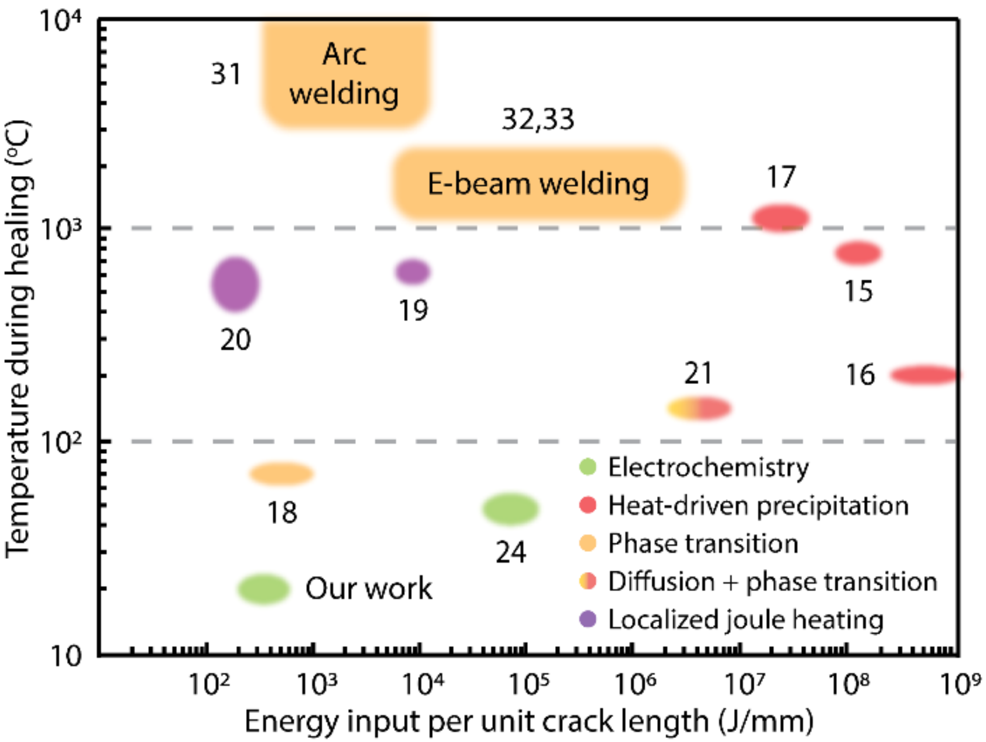
Healing electrical conductivity

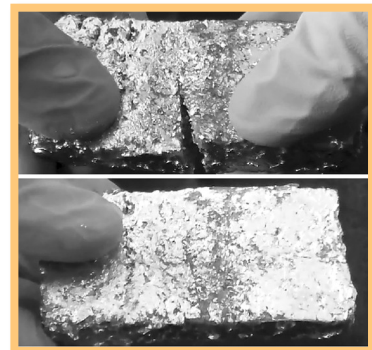


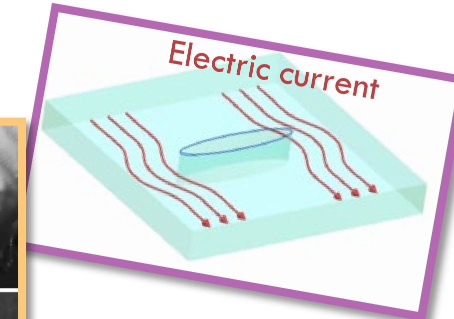
- Pristine sample: 0.159 ± 0.001 Ω
- Fully ruptured sample: Very high resistance
- Healed sample (1500 J): 0.163 ± 0.032 Ω

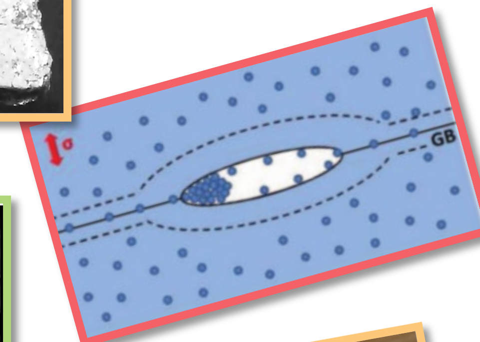
Electrical resistance can be recovered to within 2.5% of its original value.

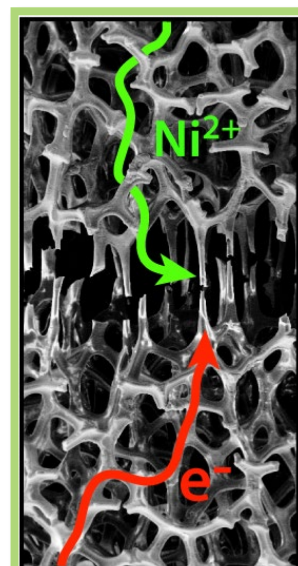
Our approach enables low-energy metal healing











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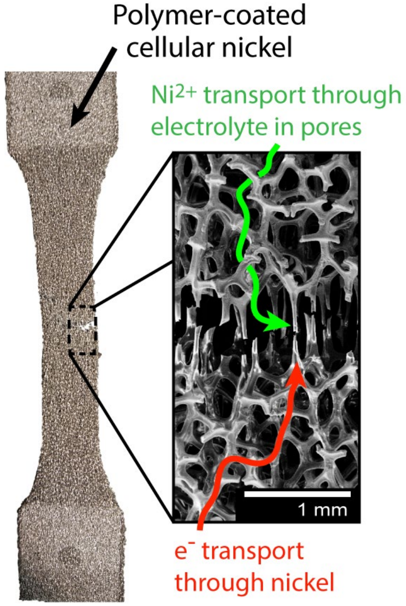
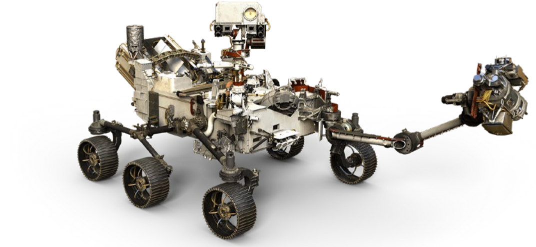
Summary

- Electrochemistry enables **transport-mediated healing** in cellular metals.
- We enable **rapid**, **effective**, **low-energy**, **room-temperature** healing of cellular metals.



- 100% recovery of strength after scission failure and tensile failure.
- Up to 1.5x strengthening of plastically-deformed cellular nickel.
- Low-energy healing: a cleaved sample can be healed up to **162** times with a smartphone battery.
- Full recovery of electrical conductivity after fracture.

- Further developments (e.g. autonomous healing) can revolutionize how we design metal parts in aerospace vehicles and robots.



Potential Applications

Surprise us with your creativity!