Healing Metals by Electrochemistry

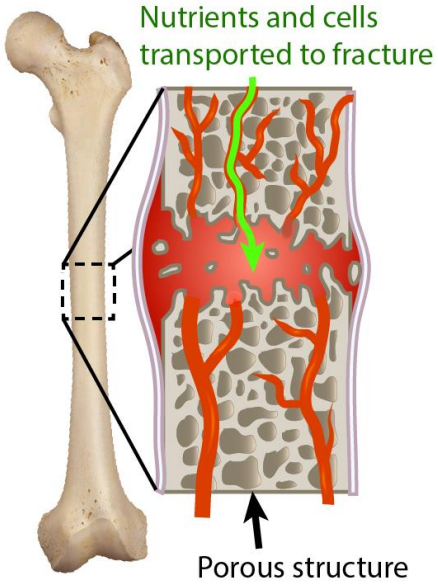
James H. Pikul, Assistant Professor
Zakaria Hsain, Ph.D. Candidate
Department of Mechanical Engineering and Applied Mechanics

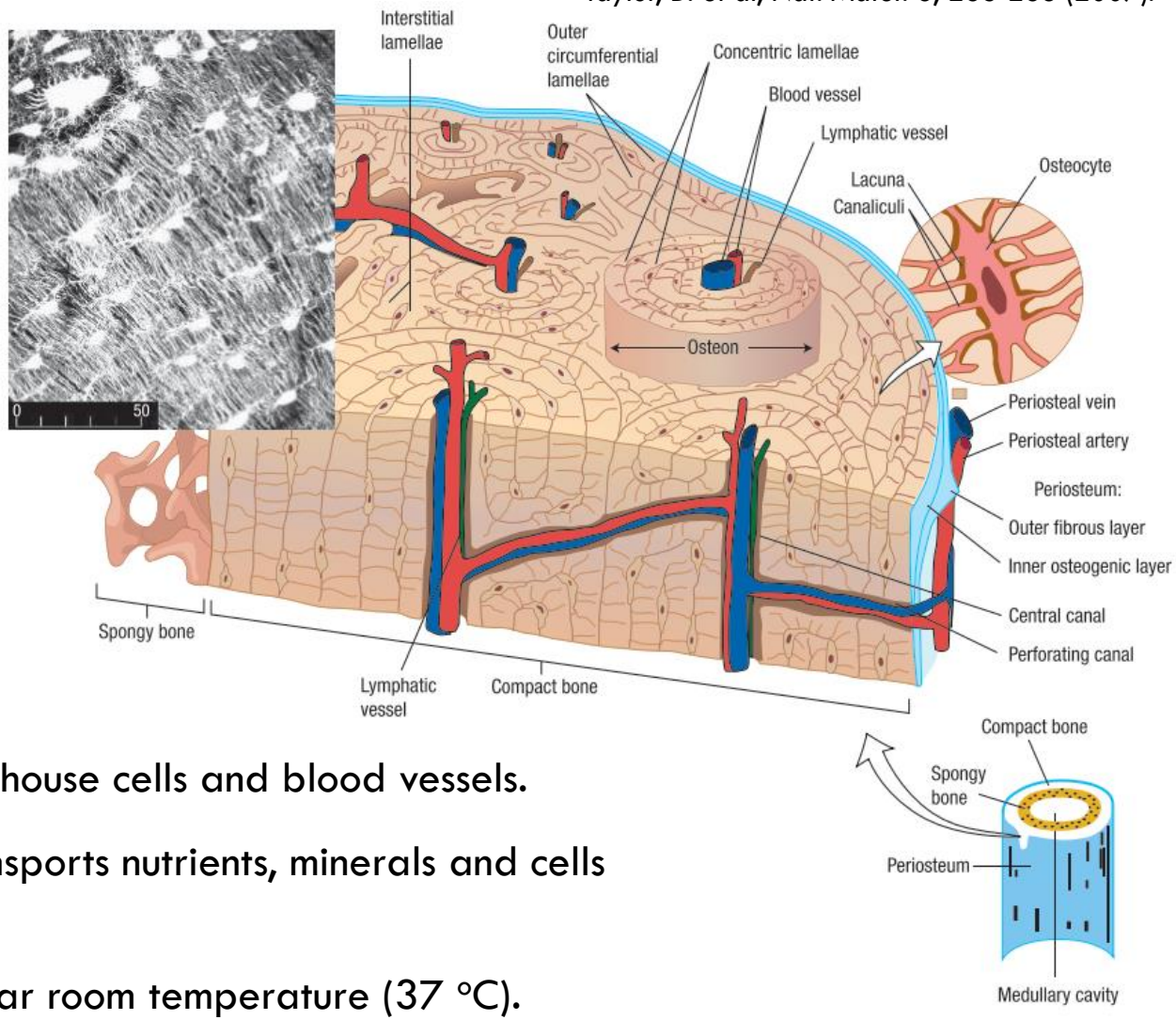
Penn
UNIVERSITY of PENNSYLVANIA

SINGH
Center for Nanotechnology

Transport-mediated healing in bone

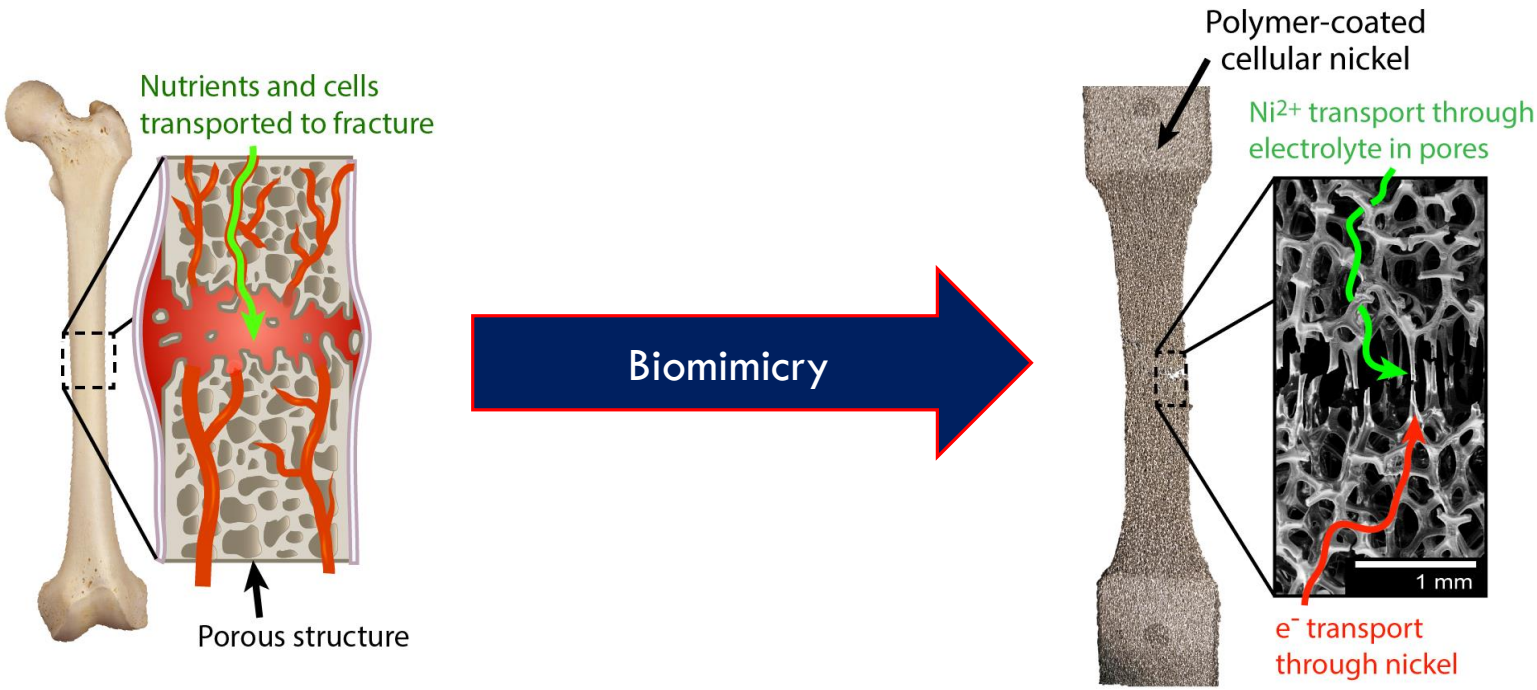
Taylor, D. et al, Nat. Mater. 6, 263-268 (2007).



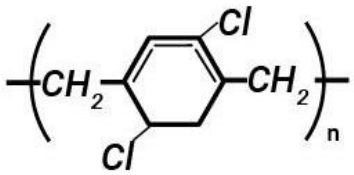


- Pores in cellular structure house cells and blood vessels.
- Blood vessel network transports nutrients, minerals and cells to the damage site.
- Bone heals effectively near room temperature (37 °C).

A transported-mediated approach to heal metals

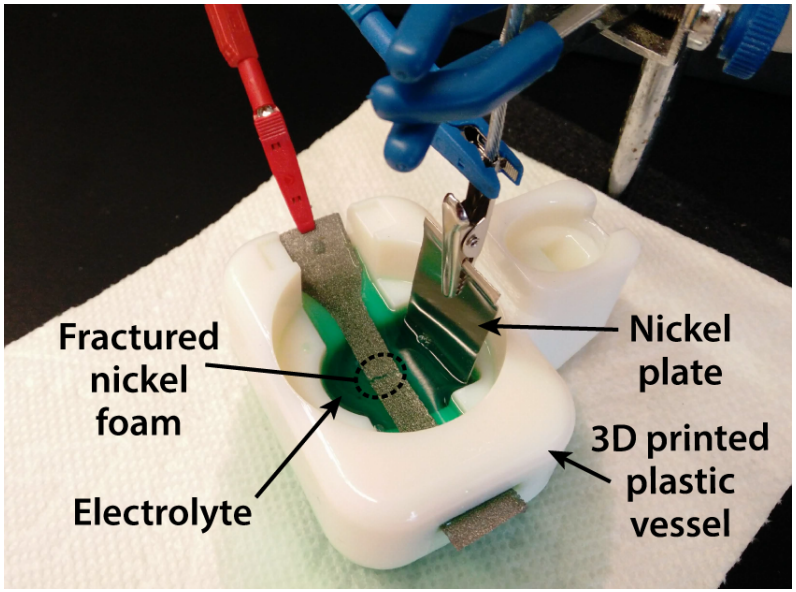


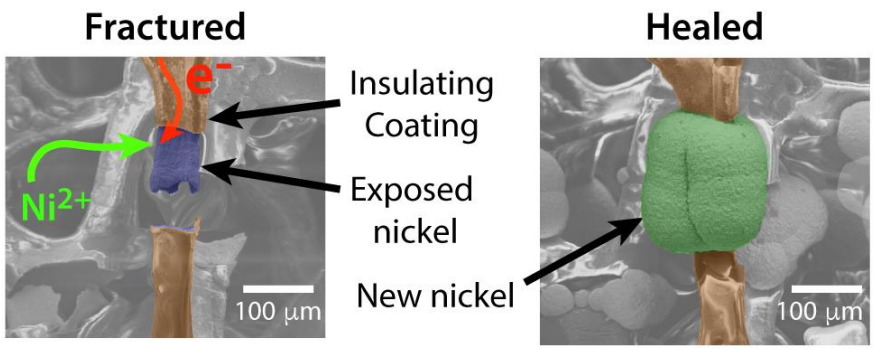
- Parylene D is an electrically-insulating polymer with excellent chemical stability.
- Parylene D is deposited on cellular nickel via a vapor-based process.



PARYLENE D

A transported-mediated approach to heal metals

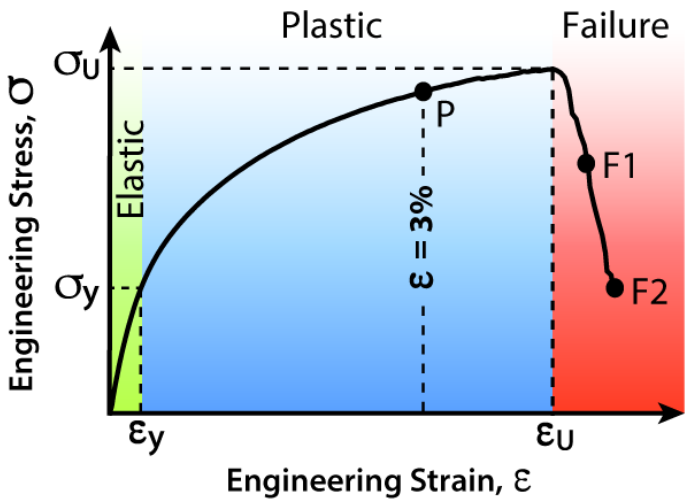




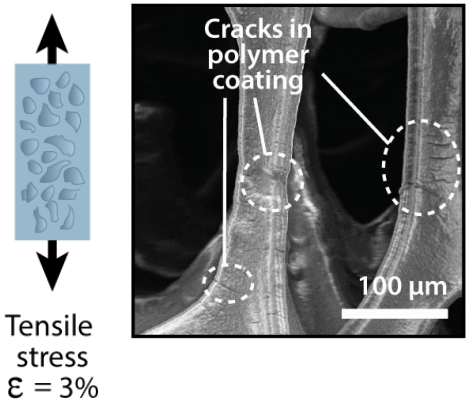
$Ni^{2+}_{(aq)} + 2e^- = Ni_{(s)}$

- Electrodeposition at -1.8 V vs. nickel counter electrode.
- Polymer coating allows selective nickel deposition in fracture locations.

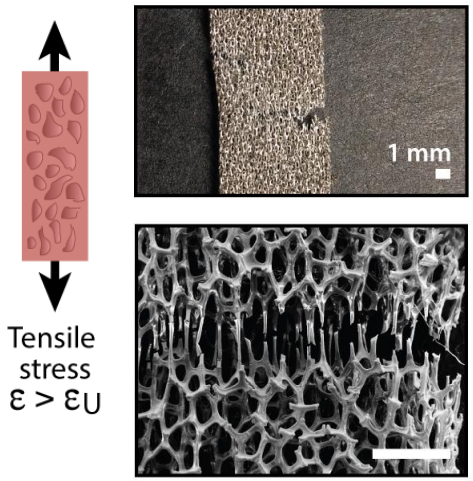
Healing cellular nickel with 3 types of damage



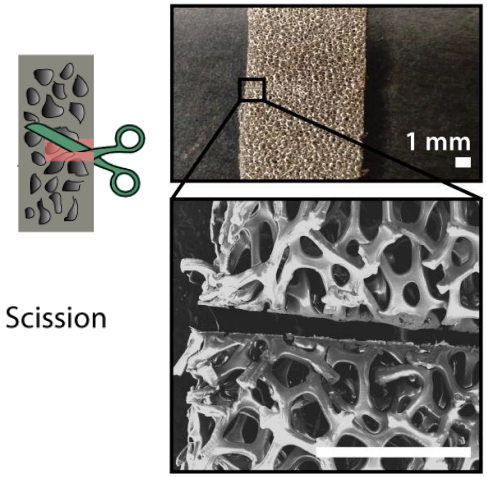
Plastic deformation (P)



Tensile failure (F1)

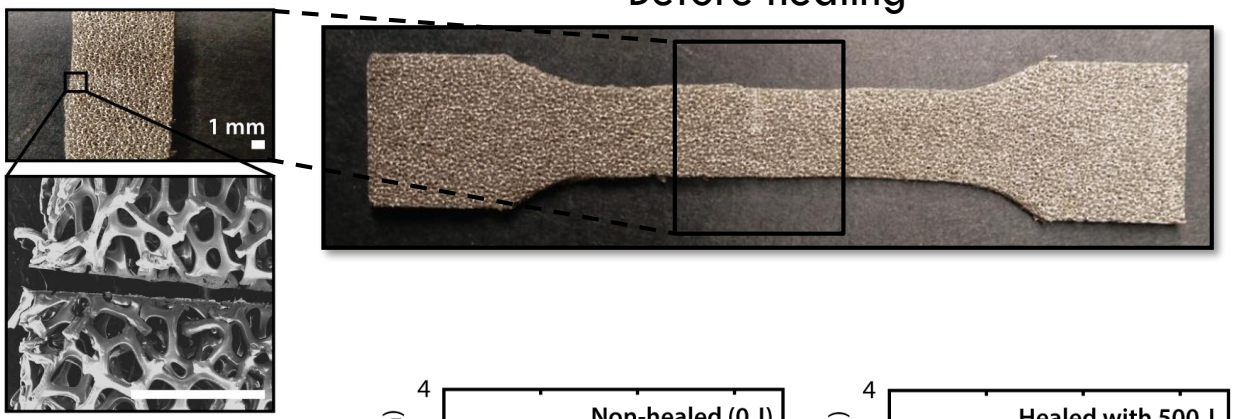


Scission failure (F2)

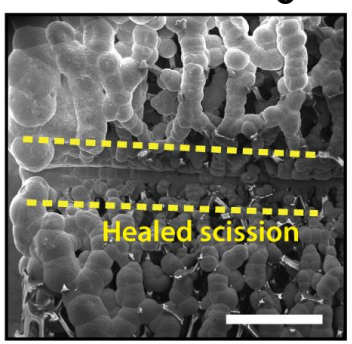


Healing after scission failure (F2)

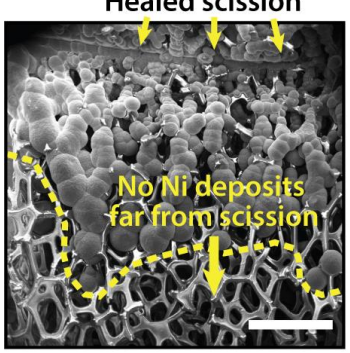
Before healing

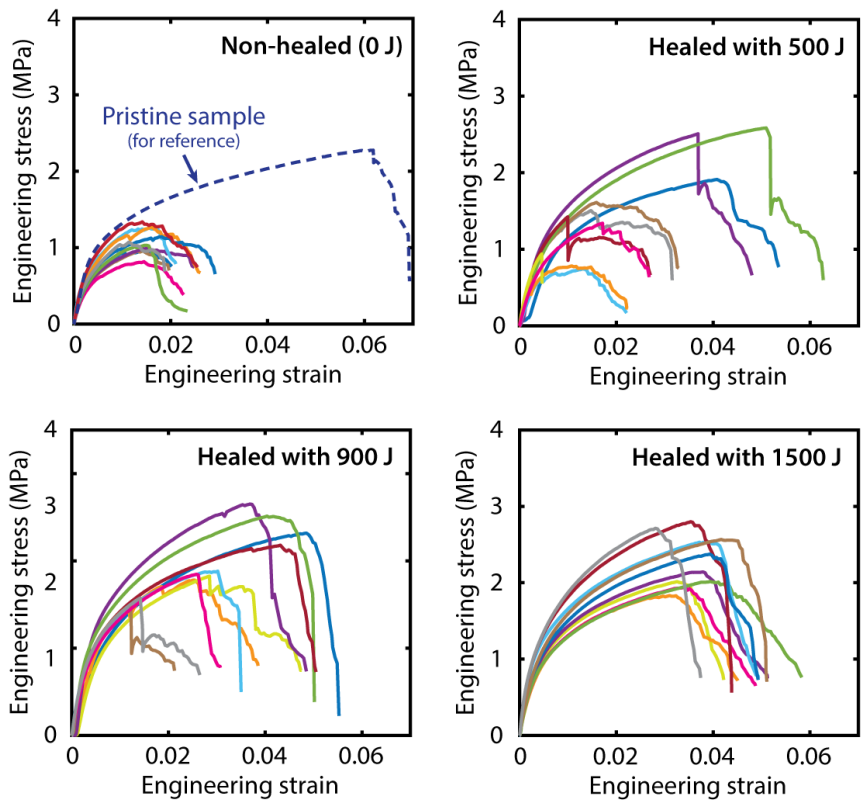


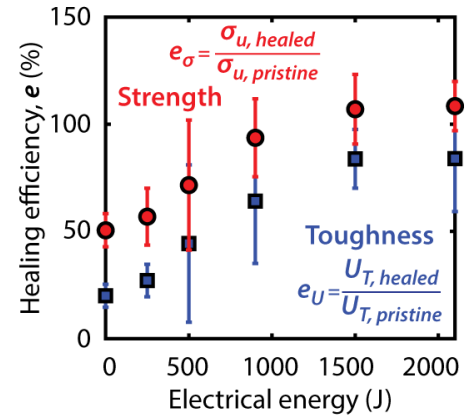
After healing



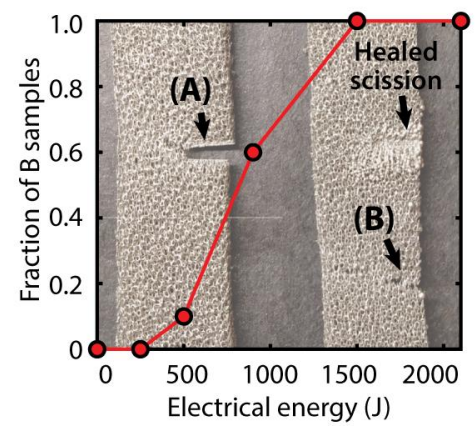
Healed scission





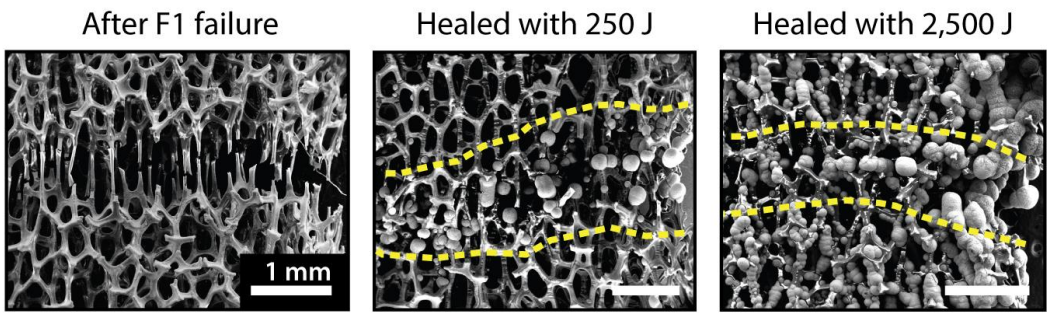


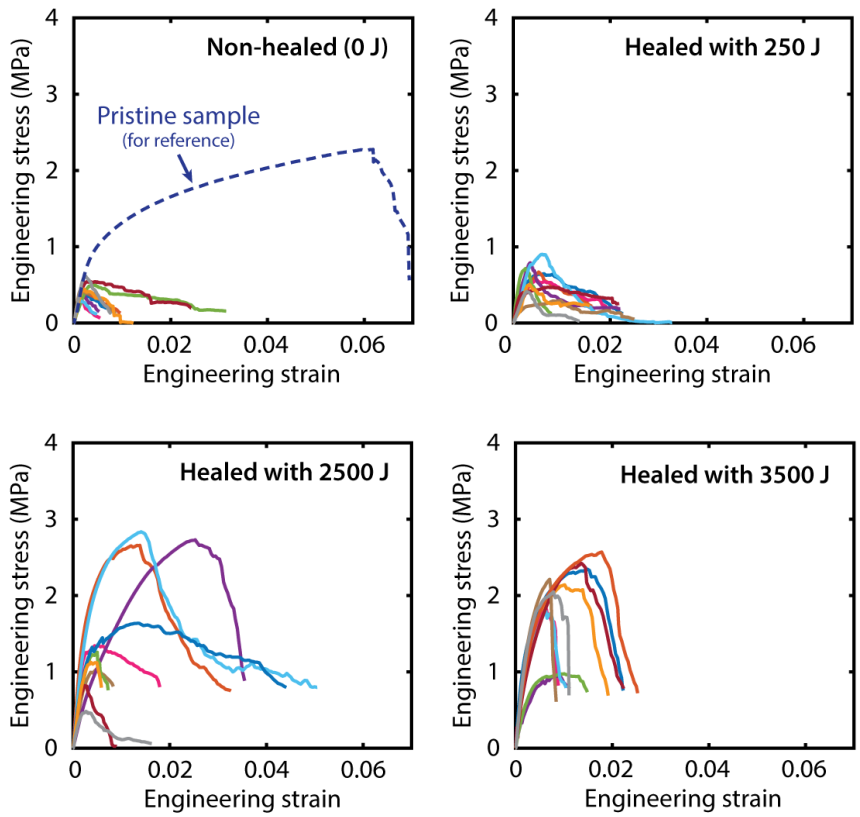
Strength healing efficiency plateaus at 100% after 1,500 J.



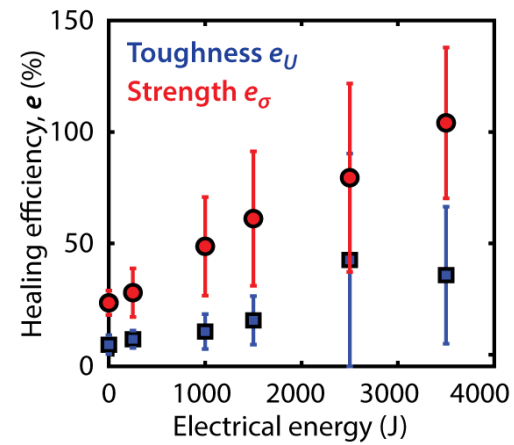
Strength of healed scission exceeds material strength in B samples.

Healing after tensile failure (F1)



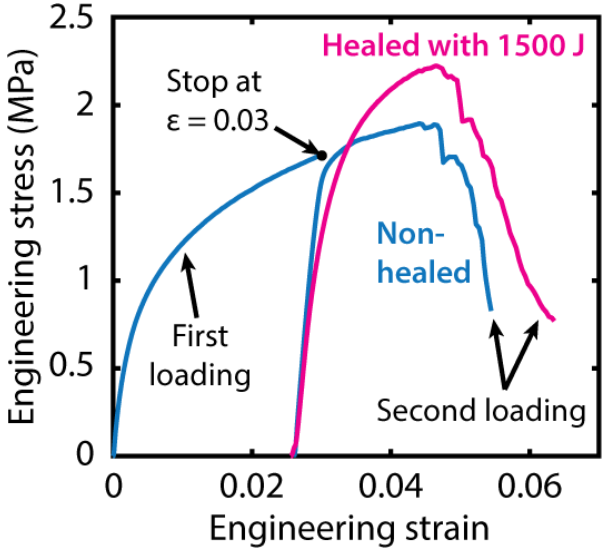


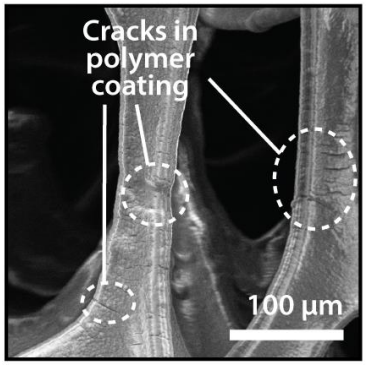
- Poor segregation of nickel deposits due to distributed strain.



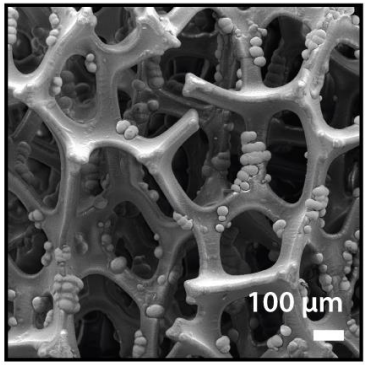
- Strength healing efficiency reaches 104% at 3,500 J.
- Limited recovery of toughness due to low ductility of electrodeposited nickel (27 nm grain size, by XRD).

Healing after plastic deformation (P)

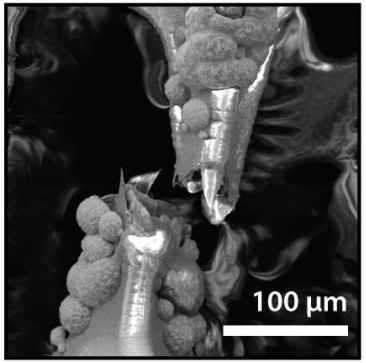




After first loading



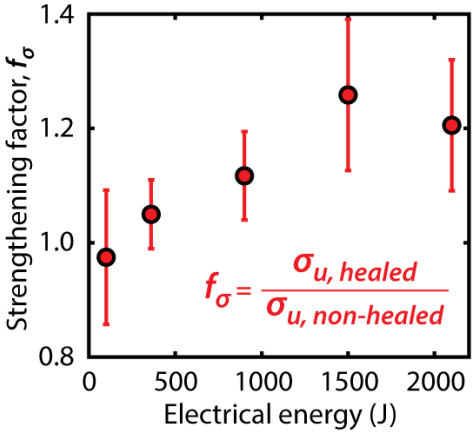
After healing



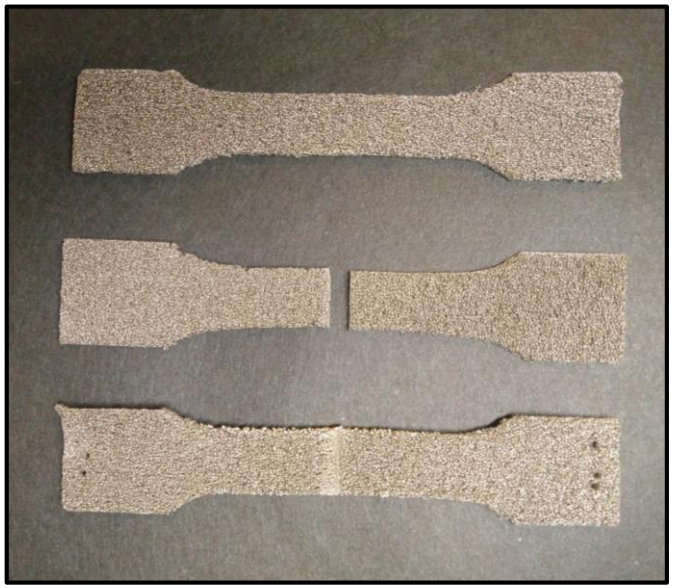
After second loading

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



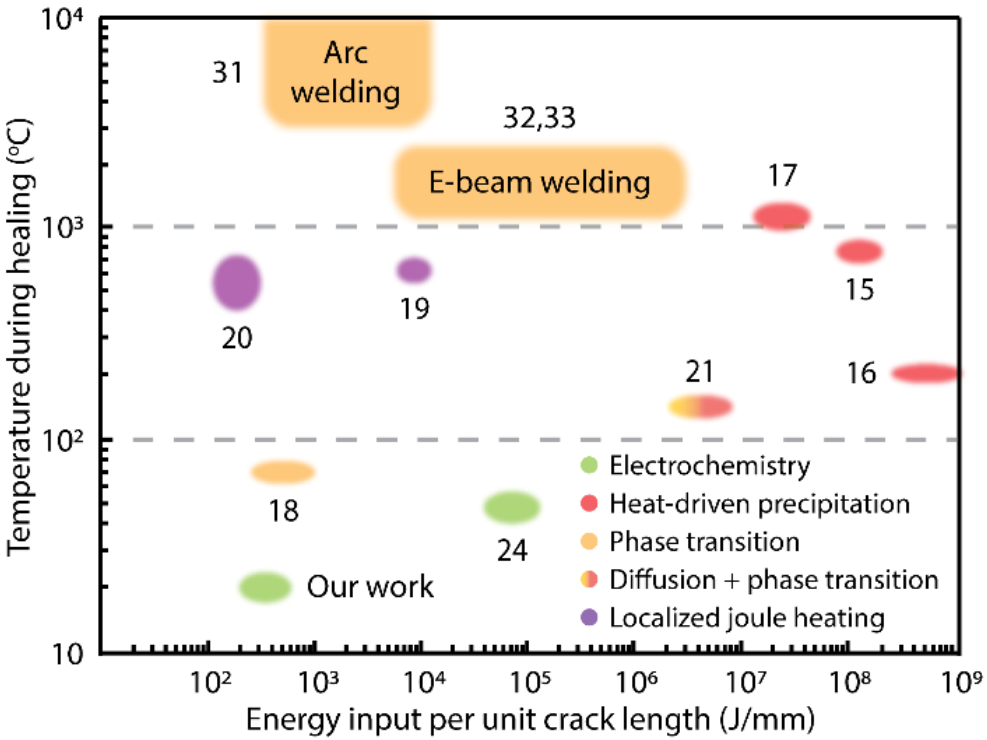
Healing electrical conductivity

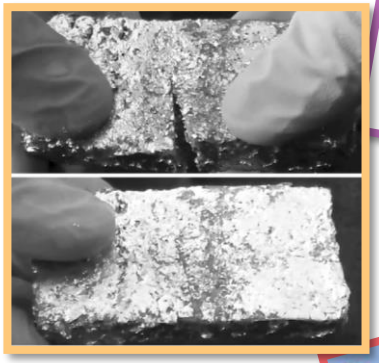


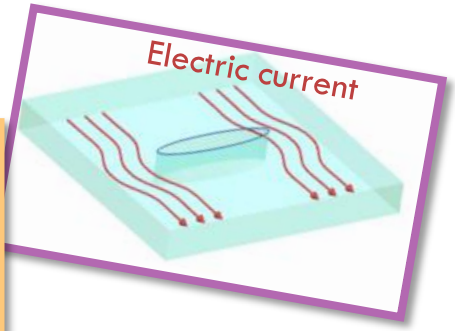
- Pristine sample: 0.159 ± 0.001 Ω
- Fully ruptured sample: Very high resistance
- Healed sample (1500 J): 0.163 ± 0.032 Ω

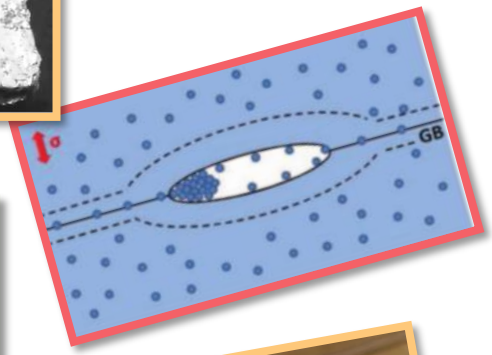
Electrical resistance can be recovered to within 2.5% of its original value.

Our approach enables low-energy metal healing





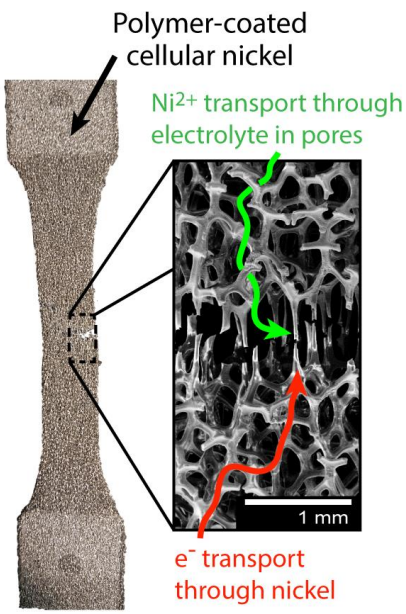




[15] K. W. Gao et al., Scr. Mater. **2001**, 44, 1055.
[16] C. Chen et al., Appl. Phys. Lett. **2016**, 109, 093503.
[17] H. Yu et al., Metall. Mater. Trans. A **2014**, 45, 1001.
[18] I. M. Van Meerbeek et al., Adv. Mater. **2016**, 28, 2801.
[19] H. Song et al., Sci. Rep. **2017**, 7, 1.
[20] A. Hosoi et al., Mater. Sci. Eng., A **2012**, 533, 38.
[21] J. T. Kim et al., Sci. Rep. **2018**, 8, 2.
[24] X. G. Zheng et al., Mater. Sci. Eng., A **2013**, 561, 52.
[31] L. Jeffus, Welding: Principles and Applications, Cengage Learning, 2017.
[32] H. Shultz, Electron Beam Welding, Abington Publishing, 1993.
[33] D. A. Schauer et al., Electron Beam Welding Cavity Temperature Distributions in Pure Metals and Alloys, AWS Annual Meeting, New Orleans, LA, USA 1978.

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.

CONSULT OUR PUBLISHED PAPER!

FULL PAPER

Metal Healing

ADVANCED FUNCTIONAL MATERIALS

www.afm-journal.de

Low-Energy Room-Temperature Healing of Cellular Metals

*Zakaria Hsain and James H. Pikul**

DOI: 10.1002/adfm.201905631