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

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

- Catalyst
- Microcapsule
- Crack
- Healing agent
- Polymerized healing agent


High-temperature energy-intensive healing in metals

- Low diffusivity at room temperature
  \(10^{-45} \text{ to } 10^{-35} \text{ m}^2/\text{s}\)
- Crack-localized joule heating
  (Up to 600 °C at crack sites)
- Solute precipitation
  (Up to 1200 °C)


- Low melting point alloys
  (60 to 70 °C)

Transport-mediated healing in bone

- 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

- 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.

\[ \text{Ni}^{2+}_{(aq)} + 2e^- = \text{Ni}_{(s)} \]
Healing cellular nickel with 3 types of damage

Plastic deformation (P)

Tensile failure (F1)

Scission failure (F2)
Healing after scission failure (F2)

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)

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: $0.159 \pm 0.001 \, \Omega$

- Fully ruptured sample: Very high resistance

- Healed sample (1500 J): $0.163 \pm 0.032 \, \Omega$

Electrical resistance can be recovered to within 2.5% of its original value.
Our approach enables low-energy metal healing.
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!