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Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell

This article documents mechanochemical strain self-healing and use-positive aging, a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649, together with the boron doping of the carbon framework that strengthens the healed sites. Conventional rechargeable cells lose capacity as they are used: repeated lattice expansion and contraction during cycling produces mechanical fatigue that accumulates as monotonic, irreversible damage, so cycle life is bounded by how much strain the active material can absorb before capacity falls below a usable fraction of nominal. The hydrogen-aluminum surface-bond cell of the application discloses a mechanism that works in the opposite direction. The reversible morphological transformation of the metal nanoflakes creates strain at fold lines, edges, and dislocations, and those strained sites become the lowest-energy landing positions for mobile carbon species already present in the gel. The carbon migrates to the strained sites and incorporates into the flake structure, locally annealing the strain and progressively strengthening the flake over many cycles. The

> disclosure frames this as use-positive aging: a projected partial inversion of the conventional aging curve in which cumulative cycling maintains cell condition rather than degrading it.

The Fatigue Problem This Mechanism Solves

In established rechargeable chemistries, the same act of cycling a cell is what wears it out. The disclosure identifies mechanical fatigue from repeated lattice expansion and contraction during intercalation cycling as one of the use-driven degradation processes that limit cycle life, alongside electrolyte oxidation, plating, and dendrite formation. The result is a familiar curve: capacity decreases as cumulative cycling accumulates damage, and for commercially deployed lithium-ion chemistries cycle life falls in the range of approximately 500 to 3,000 deep-discharge cycles before capacity falls below 80 percent of nominal. The damage is monotonic. There is no path by which using the cell repairs it.

The hydrogen-aluminum cell faces a structurally similar source of strain, because its metal nanoflakes undergo a reversible morphological transformation between a contracted resting state and an expanded charged state on every cycle. The disclosed mechanochemical self-healing process turns that strain into the trigger for repair rather than the cause of decline.

Strain as the Healing Trigger

The mechanism begins with the dynamic flake expansion of the cell's principal chemistry. The disclosure states that the morphological transformation produces mechanical strain at the flake fold lines, edges, dislocations, and other geometrically active sites. These are described as locally activated lattice sites with elevated chemical reactivity, and they are identified as the targets for the healing process.

The framing matters: strain is not a side effect to be tolerated, it is the signal that locates where repair is needed. Every cycle that unfolds and refolds a flake regenerates exactly the activated sites the healing process acts on, so the trigger is renewed by the same use that creates the wear.

Why Mobile Carbon Lands at Strained Sites

The repair species is mobile carbon already resident in the gel. The disclosure draws it from two sources: the optional auxiliary carbon reservoir and the mobile fraction of the gel framework itself. The auxiliary reservoir is described as carbon species including small graphenic clusters of fewer than approximately 100 carbon atoms, soluble polycyclic aromatic species, fullerenes and fullerene fragments, and carbon nanoparticles in the size range of approximately 1 to 10 nanometers, present at a loading in the range of approximately 0.5 to 15 weight percent of gel mass.

According to the disclosure, mobile carbon species preferentially migrate to the strained flake sites because those sites present the lowest-energy landing positions for stray carbon. The migration is driven by the reduced bond-formation energy at strained sites relative to unstrained surface sites, in accordance with established mechanochemical and tribochemical principles. Once at the strained site, the carbon species incorporates into the flake structure, locally annealing the strain and restoring lattice integrity. The strained site, in other words, advertises itself energetically: it is where carbon binds most readily, so that is where carbon goes.

Strengthening Over Cumulative Cycling

Because each cycle regenerates strain and each strained site draws carbon, repeated cycling produces repeated strain-healing events. The disclosure states that the cumulative effect is to incorporate carbon into the flake fold lines, edges, and defect sites, progressively strengthening the flake structure. The flake becomes more cycle-stable as a function of cumulative cycling, up to a saturation set by the carbon delivery rate and the flake's ultimate carbon-incorporation capacity.

The disclosure addresses the obvious concern that filling strained sites with carbon might compromise the cell's storage chemistry. It states that the incorporation does not substantially degrade the flake's hydrogen-binding capacity, because the incorporated carbon localizes at strained sites that are not the principal hydrogen-binding sites. The principal binding sites are described as edge and dopant-adjacent positions on the metal lattice that remain accessible after carbon incorporation at strain sites. Repair and storage occupy different geometry on the flake.

Use-Positive Aging

The cumulative effect is what the disclosure names use-positive aging. It is presented as a projected partial inversion of the conventional aging curve. In a conventional cell, cumulative cycling damages the active material and capacity decreases monotonically. In the disclosed cell, the healing process is projected to compensate for cycling-induced strain, admitting a stabilized cycle-life regime in which cumulative cycling does not produce monotonic capacity loss until the auxiliary carbon reservoir is approaching exhaustion.

The disclosure is careful about the status of this claim. It states that the actual aging profile is to be determined empirically through prototype testing and is recited as projected based on the disclosed mechanism. If realized empirically, the projected behavior admits novel operating profiles in which cells are deliberately cycled to maintain their condition rather than preserved at rest. The reservoir-exhaustion boundary is the natural limit: healing continues as long as there is mobile carbon to deliver.

Calendar Stability at Rest

The mechanism is coupled to use, and the disclosure draws the corresponding consequence for cells at rest. In the absence of cycling, with no applied bias and no external load, the cell does not generate new strain and does not require healing. The bond-state population is stable, the gel does not undergo internal degradation in the absence of bias, and the flake morphology does not change in the absence of cycling-driven expansion.

The disclosure concludes that calendar life at rest is not limited by the same processes that limit cycle life and is not coupled to the use-driven healing process. This separates the two regimes cleanly: a cell sitting idle is not waiting to be repaired, because nothing is wearing. Healing is a response to use, not a maintenance load that runs continuously.

Boron-Doped Carbon at Healed Sites

The disclosure describes an embodiment in which the auxiliary carbon reservoir includes a fraction of boron-doped mobile carbon in addition to undoped mobile carbon. During healing, the boron-doped carbon migrates to mechanically strained sites alongside the undoped carbon. Upon incorporation, the boron-doped carbon forms boron-carbon bonds that exhibit higher bond strength and higher mechanical stiffness than carbon-carbon bonds, a property the disclosure attributes to published research on boron-carbon composite mechanics.

This is expected to admit modest extension of cycle life relative to undoped-embodiment cycling, attributable to the stronger boron-carbon bond character at healed sites, with the actual quantitative extension to be determined empirically. The disclosure gives estimated cycle-life ranges for boron-doped embodiments before first gel-replacement service in the range of approximately 8,000 to 40,000 deep-discharge cycles, compared to approximately 5,000 to 30,000 cycles for analogous undoped embodiments. The disclosure also notes that this healing-related effect is one of multiple operating effects of boron doping and is not the principal source of the boron-doped capacity benefit.

Shared Geometry with Controlled Peak-Power Failure

The same strained-site geometry serves a second disclosed function. Under peak current draw, an embodiment with a boron-doped carbon framework admits controlled local failure at strained sites, in which carbon-carbon and boron-carbon bonds break and release bonding electrons into the gel's conduction band to supply additional current. The disclosure states that this controlled failure is preferentially localized to the regions of highest strain, which are the same regions to which the auxiliary carbon reservoir migrates during subsequent healing.

After such a peak event, the cell undergoes a recovery period during which the auxiliary carbon migrates to the failed sites and reforms the framework via the same mechanochemical healing mechanism. The disclosure gives this recovery period as in the range of approximately 30 seconds to 60 minutes per peak power event, depending on the extent of failure and the reservoir loading. The healing mechanism therefore both anneals cycling fatigue and restores framework integrity after deliberate peak-power discharge, drawing on the same mobile-carbon reservoir for both.

Disclosure Scope

This article describes subject matter disclosed in U.S. Provisional Application No. 64/055,649. The mechanochemical self-healing process and the use-positive aging behavior are disclosed as concepts and mechanisms. The aging profile is recited in the application as projected from the disclosed mechanism and to be determined empirically through prototype testing; cycle-life ranges and other numerical values stated here are reproduced as they appear in the application. No mechanism, threshold, material, or numerical value beyond those in the application is asserted.

Hydrogen-Aluminum Energy Cell (/h-al-battery)

All 40 steps → (/inventive-steps)

Sealed electrochemical cell storing energy as reversible covalent hydrogen bonds on carbon electrodes.

Provisional application

PRIMARY TECHNICAL DISCLOSURE

- A Hydrogen-Aluminum Surface-Bond Storage Cell with Bulk-Equipotential Charge Retention (/articles/a-hydrogen-aluminum-surface-bond-storage-cell-with-bulk-equipotential-charge-retention)

SECONDARY TECHNICAL

- Charge Retention by Bulk-Equipotential Saturation Without an Internal Separator (/articles/h-al-battery/bulk-equipotential-charge-retention)
- Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer (/articles/h-al-battery/hydrogen-metal-surface-bond-storage)
- Electron-Mediated Bond Stability: The Kinetically Trapped Idle State Behind Indefinite Calendar Life (/articles/h-al-battery/electron-mediated-bond-stability)
- Hot-Proton Charging Versus Cold-Proton Discharge: The Bias-Gated Asymmetry That Blocks Self-Charge and Self-Discharge (/articles/h-al-battery/hot-cold-proton-asymmetry)
- Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel (/articles/h-al-battery/asymmetric-dual-domain-paths)
- Hydrophobic Gating: Rejecting Neutral and Molecular Hydrogen While Admitting Only Biased Protons (/articles/h-al-battery/hydrophobic-gating)
- The Storage Gel as a Polarized Electrochemical Switch: Coherent Alignment, Equipotential Locking, and Load-Proportional Discharge (/articles/h-al-battery/gel-polarized-switch)
- Flake-Flake Electrostatic Isolation: DLVO Repulsion as a Self-Discharge Barrier in a Separator-Free Hydrogen-Aluminum Cell (/articles/h-al-battery/flake-electrostatic-isolation)
- Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias (/articles/h-al-battery/dynamic-flake-expansion)
- Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism (/articles/h-al-battery/hydrogen-locked-expanded-state)
- Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon (/articles/h-al-battery/secondary-carbon-hydrogen-storage)

- **Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell (/articles/h-al-battery/mechanochemical-self-healing)**
- Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier (/articles/h-al-battery/boron-doping-precision-multiplier)
- The Floating Aluminum Equipotential Extension Layer: A Multifunctional Inner Case for the Bulk-Equipotential Cell (/articles/h-al-battery/aluminum-equipotential-extension-layer)

Hydrogen-Aluminum Energy Cell overview → (/h-al-battery)