Nanoscale silver exhibits intrinsic self-healing abilities without external intervention

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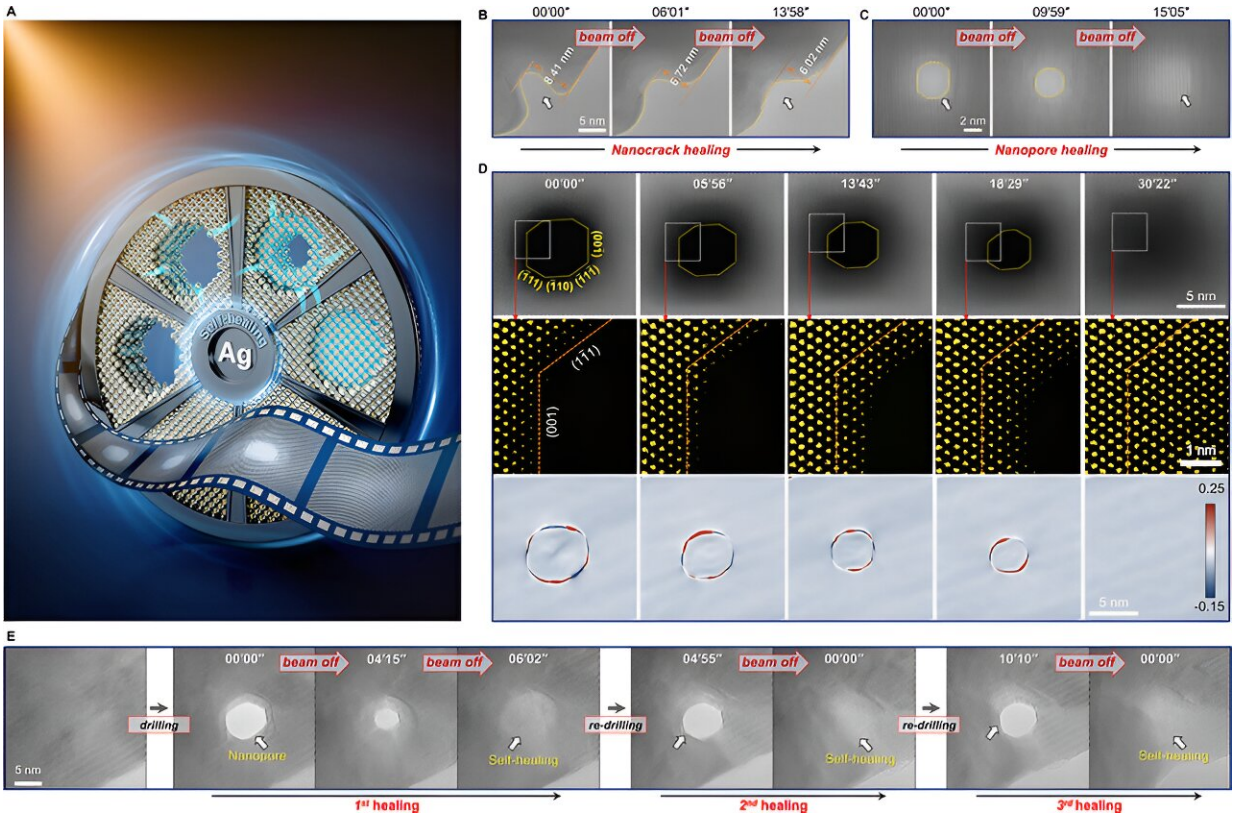

(A) An artistic poster depicting the autonomous self-healing phenomenon found in nanoscale Ag. (B, C) Sequential high-resolution TEM images showing the autonomous self-healing processes of a nanocrack (B) and nanopore (C) damage, respectively. (D) High-angle annular dark field (HAADF) images and the corresponding geometric phase analysis (GPA) of an overall self-healing process of nanopore. (E) Three runs of repeated reversible forming/healing cycles over the same region. Credit: IOP

As an innovative concept in materials science and engineering, the inspiration for self-healing materials comes from living organisms that have the innate ability to self-heal. Along this line, the search for self-healing materials has been generally focused on "soft" materials like polymers and hydrogels. For solid-state metals, one may intuitively imagine that any form of self-healing will be much more difficult to achieve.

While a few past studies have showcased the self-healing behavior in metals that more or less requires the assistance of external triggers (e.g., by heating, mechanical stimulus, or electron beam irradiation), whether the autonomous self-healing can occur in metal solids without any external intervention remains a scientific curiosity.

Now in a new study published in *Matter*, researchers from the Institute of Physics (IOP) of the Chinese Academy of Sciences have discovered that such an intrinsic and autonomous self-healing phenomenon can occur in nanoscale silver (Ag).

This study, which combines advanced in-situ transmission electron microscopy (TEM) with molecular dynamics (MD) simulations, reveals that nanoscale Ag can autonomously repair itself from structural damage, such as nanocracks and nanopores, without external intervention.

This remarkable ability is observed not only at room temperature but also at frigid temperatures as low as 173 K. Notably, over the same damaging area, the repeated reversible self-healing cycles can also be achieved with the same level of efficiency.

The experiments were performed inside an atomic-resolution TEM by utilizing single-crystalline Ag nanosheets as testing specimens. Both nanopores and nanocracks were purposefully fabricated through in-situ

drilling by TEM electron beam. To avoid any possible intervention to the healing process, the Ag nanosheet specimen was afterwards kept in a "beam-off" state until each moment for interval TEM imaging.

As an interesting and perhaps surprising result, the two representative kinds of structural damage were observed to undergo rapid self-healing autonomously within several to dozens of minutes, with the healed regions perfectly restoring the crystal lattice of Ag with atomically precise ordering.

Unlike Ag, gold (Au) did not show similar self-healing behavior at room temperature, despite the fact that Au is the most relevant element to Ag in the periodic table and they share many similarities in physical and chemical properties.

Further MD simulation results reproduced the experimental observations, especially regarding the difference in the healing behavior between Ag and Au. What sets Ag apart from Au is its high mobility of surface diffusion, a trait not commonly found in other metal solids.

By employing TEM, the researchers were able to in-situ track the trajectories of the healing process in Ag at the atomic level. With a combination of atomistic imaging and theoretical simulation results, the research highlights that self-healing is enabled by the surface-mediated self-diffusion of Ag atoms as driven by chemical potential imbalance due to the Gibbs-Thomson effect.

When a nascent damage structure (either nanopore or nanocrack) begins its existence in an Ag nanosheet, a concave site with negative local curvature is created. Due to the general curvature-dependence of chemical potential, the concave damage site will thereby have smaller chemical potential relative to the undamaged areas of the nanosheet. This built-in imbalance of chemical potential drives Ag atoms to migrate

and repair the damage autonomously, showcasing a sophisticated form of material self-maintenance.

The ability of Ag to autonomously self-heal nanoscale damage at room temperature and below shows a promising possibility for developing damage-tolerant components and devices at the sub-micrometer length scale.

Perhaps more importantly, in a broader sense, this unusual finding at a mechanistic level may provide a guiding framework for deeper understanding of the self-healing phenomena and concepts in metal solids in general.

More information: Jianlin Wang et al, Direct observation of autonomous self-healing in silver, *Matter* (2024). DOI: 10.1016/j.matt.2024.07.009

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