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RESEARCH NEWS STORY

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Can Smoother Surfaces Prevent Hydrogen Embrittlement?

Research reveals surface features affect the formation of hydrogen-induced defects in iron, providing guidelines for the design of hydrogen-resistant materials

Hydrogen is a promising fuel for developing sustainable industrial processes, but its use is hindered by hydrogen embrittlement—a phenomenon that weakens metals and can cause sudden failure. Now, researchers from Japan have provided the first experimental evidence linking surface roughness to atomic-scale defects caused by hydrogen in iron. Using positron annihilation lifetime spectroscopy, they showed that rougher surfaces result in greater accumulation of defects, offering new insights into designing hydrogen-resistant materials through precision surface engineering.

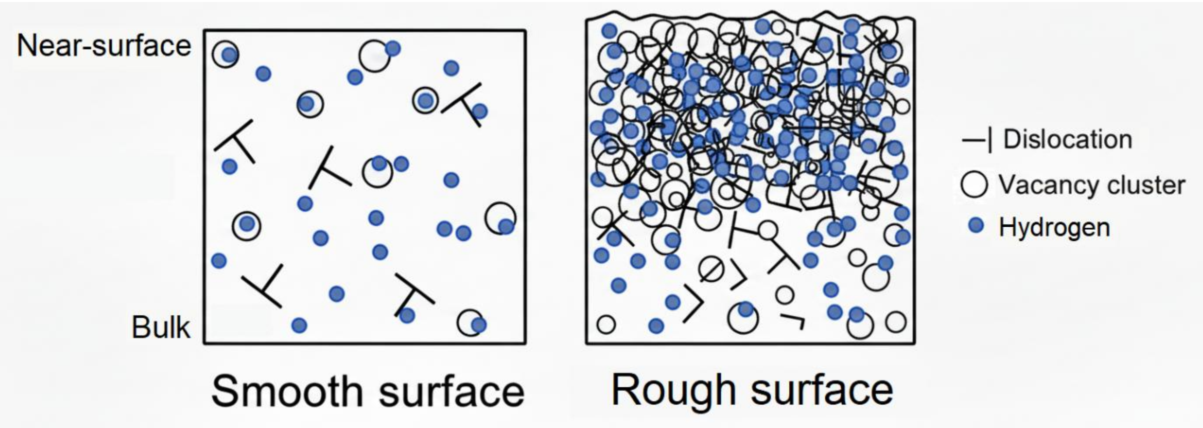

Image title: Surface roughness and its effect on hydrogen embrittlement
Image caption: This diagram depicts how metals with a smoother surface are less prone to the accumulation of hydrogen-induced defects, namely dislocations and vacancy clusters.
Image credit: Assistant Professor Luca Chiari from Chiba University, Japan
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As the world strives to achieve carbon neutrality and slow down climate change, hydrogen has emerged as a promising fuel and energy carrier. Producing only water when consumed, hydrogen could help decarbonize industrial processes, power generation, and transportation. However, fulfilling this vision requires massive infrastructure—from high-pressure storage tanks to dedicated pipelines—that must withstand constant material stress due to the nature of hydrogen.

One of the biggest obstacles is hydrogen embrittlement. This is a complex phenomenon where metals, including high-strength steels used to transport hydrogen, suffer severe deterioration of their mechanical properties that can lead to sudden failure. Over the past few decades, scientists have identified key factors contributing to hydrogen embrittlement. Hydrogen interacts with the metal's structure, promoting the movement of existing defects called dislocations. In turn, this leads to missing atoms (or 'vacancies') in the material's crystalline structure. While the general mechanisms behind hydrogen embrittlement have been studied extensively in the bulk of materials, less is known about how this phenomenon occurs at the material's surface. Specifically, it is unclear how common metal manufacturing steps like polishing or grinding influence the atomic-level factors that ultimately lead to material failure.

Now, in a recent study, a research team led by Assistant Professor Luca Chiari from the Graduate School of Engineering, Chiba University, Japan, has provided the first experimental evidence needed to bridge this knowledge gap. Their findings, made available online on September 2, 2025, and published in Volume 171 of the *International Journal of Hydrogen Energy* on September 24, 2025, clarify how varying surface conditions affect the atomic structure of hydrogen-charged pure iron. The study was co-authored by Kansei Yamamoto, also from Chiba University, and Dr. Koji Michishio from the National Institute of Advanced Industrial Science and Technology (AIST), Japan.

The researchers systematically investigated how surface roughness influences the formation and size of various hydrogen-related defects. To this end, they prepared high-purity iron sheets with four different levels of surface roughness using standard mechanical polishing techniques. They then subjected the samples to mechanical tension while simultaneously charging them with hydrogen by exposure to an electrolytic solution and an electrical current, leading to the formation of hydrogen-induced defects.

One of the study's key innovations was the measurement technique used to analyze surface defects: positron annihilation lifetime spectroscopy (PALS). This highly sensitive, non-destructive method uses the antimatter particles of the electrons, called positrons, as atomic-scale probes to precisely locate and measure the size of defects, such as dislocations and vacancy clusters, within the material. By using a slow positron beam, the team was able to probe defects specifically in the shallow near-surface layers of the iron samples, isolating them from those in the bulk of the material.

The results of the experiments revealed that the size of the hydrogen-induced vacancy clusters grew larger as surface roughness increased. Simply put, clusters in the roughest samples were estimated to contain more missing atoms than those in the smoother samples. Interestingly, this proved to be a localized effect, with the size of the vacancy clusters in the bulk of the material remaining constant regardless of how the surface was polished. Thus, the researchers found that dense networks of dislocations caused by mechanical processing near the surface can create super-concentrated traps for hydrogen, leading to the accumulation of atomic vacancies into larger clusters right where crack initiation often occurs.

These findings provide the first experimental proof that a macroscopic feature such as surface coarseness can directly dictate the size of atomic defects that ultimately lead to cracks in a hydrogen environment. The study could thus lead to an entirely new approach to material design and manufacturing based on precision surface engineering to combat hydrogen embrittlement. By accurately controlling surface roughness, engineers may be able to prevent the formation of these large vacancy clusters, leading to naturally hydrogen-resistant metals. "*The results provide a fundamental understanding of the hydrogen embrittlement mechanisms and could help reduce the overall life-cycle cost of materials used in hydrogen technologies,*" remarks Dr. Chiari.

Furthermore, the successful application of PALS holds wider implications for materials science and engineering. "*Our work could position this technique as a new standard for material certification and in-service inspection, offering a new paradigm to ensure the integrity of the hydrogen infrastructure,*" says Dr. Chiari.

Overall, this work is a major step towards fundamental guidelines for the design of safe and reliable materials, which are urgently needed for the transition to a hydrogen economy.

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About Assistant Professor Luca Chiari from Chiba University, Japan
Dr. Luca Chiari is an Assistant Professor at the Graduate School of Engineering, Chiba University, Japan. He specializes in materials science, particularly in defect analysis, positron annihilation spectroscopy, positron and positronium physics and chemistry, and hydrogen embrittlement. He has published over 70 research articles on these topics. He is also a member of the Japanese Positron Science Society and the Iron and Steel Institute of Japan.

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Reference:
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