Hydrogen embrittlement

One dislocation at a time

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Direct observation of enhanced dislocation mobility in iron by in-situ electron microscopy offers a key insight and adds more fuel to the ongoing debate on mechanisms of hydrogen embrittlement.

Tiniest atom in Nature, hydrogen is pervasive and sneaky. When they come in contact with a metal, hydrogen atoms, either from gas or liquid sources, rush into the solid and squeeze through the narrow spaces between the host atoms. Being chemically active, atomic hydrogen can potentially bind to either host or impurity atoms, forming hydrides and hence changing material properties. Metals, well known and widely used in industry for their strength and ductility, can become dangerously brittle when exposed to hydrogen. This is known as hydrogen embrittlement, and can lead to catastrophic failure of a load-bearing part. For example, hydrogen produced when water molecules break apart in coolants in a nuclear reactor can result in sudden failure of its pressure vessel. In another example, while blending hydrogen in natural gas pipelines provides a promising pathway for transitioning into the hydrogen economy [1], it could also lower fatigue resistance of the pipeline steel, making it more susceptible to crack growth due to cyclic loading induced by pressure fluctuations in the pipeline. Remarkably, perhaps owing to a multitude of recognized failure mechanisms in which hydrogen can potentially participate, it still remains unknown exactly why hydrogen makes a metal brittle. Now writing in Nature Materials, Longchao Huang and colleagues present unambiguous experimental observations of hydrogen enhanced dislocation mobility in iron, offering key insight into the hydrogen embrittlement mechanisms [2].

Theories and models, often conflicting and highly debated, have developed over many decades of hydrogen research [3]. Perhaps something hydrogen researchers could agree on is that loss of ductility in many metals is related with how hydrogen interacts with dislocations. Dislocations are ubiquitous line-shaped crystal defects, and it is the motion of dislocations that causes a crystal to slide along its atomic planes resulting in an irreversible change of the material's shape, that is, crystal plasticity. Dislocations are known to be mobile in ductile/plastic crystals and less mobile or even immobile in brittle crystals. Thus, one could expect that hydrogen embrittles metals by somehow reducing dislocation mobility. Yet, controversially, a well-known model of hydrogen-assisted local plasticity (HELP) relates loss of ductility precisely to an enhancement in dislocation mobility due to the presence of hydrogen [4]. The key idea of HELP is that, by making dislocation motion easier, hydrogen promotes slip localization resulting in accumulation of local atomic misfit and potentially dangerous stress concentrations. Such local stress accumulation can at times lead to initiation of a crack threatening material's integrity. However, governed by weak link statistics, evolution of an initial stress concentrator into a catastrophic failure is notoriously difficult to predict and control. In addition to HELP model not being universally accepted, debates continue as to the nature of atomic scale mechanisms by which hydrogen assists dislocation motion. Or even if any such assistance is real [5]. Indeed, theoretical arguments and, indirectly, experimental observations have been presented both for an enhancing and inhibiting role of hydrogen in dislocation motion.

In their work [2] Huang and colleagues used in-situ mechanical testing in environmental transmission electron microscope to study the impact of hydrogen exposure on the motion of individual dislocations and observed unambiguously that hydrogen enhances dislocation mobility in α- iron. Being the majority element in industrial steels, iron in its elemental form arranges its atoms in a body-centered cubic (BCC) lattice. In BCC metals, the screw dislocations (with line direction parallel to the Burgers vector) are known to control the plastic deformation behavior of the material and are the focus of the authors' attention. Taking abundant precaution, the authors painstakingly harvest screw dislocations in configurations most conducive to direct in-situ observations in an electron microscope. Magnified almost millionfold, they measure, observe and photograph – in real time – how much mechanical force it takes to start a dislocation moving and how far it moves when the metal is charged (supplied) with atomic hydrogen and when it is hydrogen-free. In their experiments Huang and colleagues establish an unprecedented level of control over the motion of individual dislocations. Perhaps the most interesting and convincing result is their observation that the effect of hydrogen on dislocation mobility is reversible: high mobility in the presence of hydrogen recovers back to the reference state of low dislocation mobility once hydrogen is removed. The recovery is not immediate and is facilitated by forcing a dislocation to move back and forth under oscillating loads, thus suggesting that hydrogen binds to the dislocation and is reluctant to let it escape.

Consistent with previous suggestions [6], the authors present a theoretical model for the mechanism by which hydrogen interacts with a screw dislocation and makes its motion easier by lowering the energy barrier for kink-pair nucleation (Figure 1). Further theoretical studies are clearly needed to fully explain the observed phenomenon, such as going beyond the empirical potential model employed in this study and possibly using a more accurate quantum mechanical method [7]. The question of whether the HELP mechanism is responsible for hydrogen embrittlement remains open. Nevertheless, Huang and colleagues make an important and definitive step towards solving the overall puzzle by providing clear evidence that hydrogen can and does indeed enhance dislocation mobility in BCC metals such as iron.

Competing interests
The author declares no competing interests.

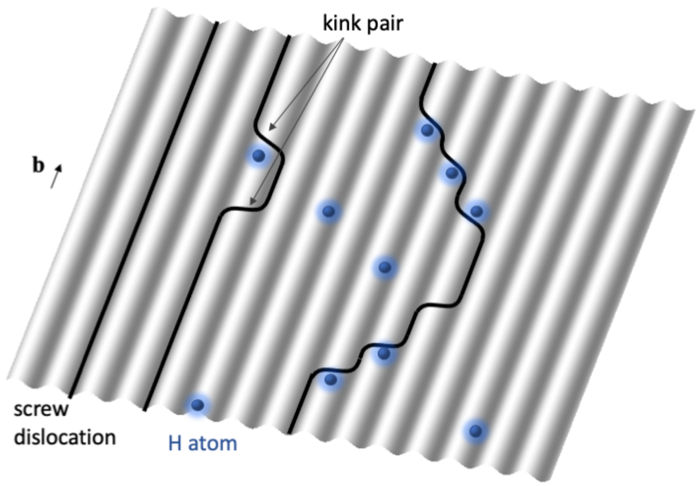

Figure 1. Schematic of dislocation motion in a crystal. The washboard surface represents energy barriers resisting dislocation motion through a crystal lattice. A screw dislocation (thick black line) is initially parallel to the Burgers vector **b**. Presence of hydrogen atoms can facilitate nucleation of kink pairs by which the dislocation can begin to move forward.

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