Fall 2019 Joint Colloquium
Materials Department, Mechanical Engineering & Materials Research Laboratory

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Hydrogen Induced Fast Fracture in Ferritic Steels

One of the recurring anomalies in the hydrogen induced fracture of high strength steels is the apparent disconnect between the toughness and tensile strength. For example, the toughness of a high strength steel is typically reduced from approximately $100\ \mathrm{MPa}\sqrt{\mathrm{m}}$ to about $20\ \mathrm{MPa}\sqrt{\mathrm{m}}$ in the presence of hydrogen while concurrently the strength reduces from 2 GPa to about 400 MPa. Traditional fracture mechanics then suggests that quasi-brittle fracture under uniaxial tension occurred by the growth of a pre-existing flaw of size $\approx 1600\ \mu\mathrm{m}$. There is no evidence of the presence of such large pre-existing flaws in high quality steels. This raises the question as to what is the hydrogen-mediated fracture process that reduces the strength of such steels?

Here we propose, supported by detailed atomistic and continuum calculations, that unlike macroscopic toughness, hydrogen-mediated tensile failure is a result of a fast-fracture mechanism. Specifically, we show that failure originates from the fast propagation of cleavage cracks that initiate from cavities that form around inclusions such as carbide particles. The failure process occurs in two stages. In stage-A, hydrides rapidly form around the roots of stressed notches on the cavity surfaces with hydrogen fed from the hydrogen gas within the cavity. These hydrides promote cleavage fracture with the cracks propagating at $> 100\ \mathrm{ms}^{-1}$ until the hydrogen gas in the cavity is exhausted. Predictions of this hydrogen-assisted crack growth mechanism are supported by atomistic calculations of binding energies, mobility barriers and molecular dynamics calculations of the fracture process. Typically, cracks grow by less than 1 μm via this hydrogen-assisted mechanism and thus insufficient to cause macroscopic fracture of the specimen. However, this stage is then followed by a stage-B process where these fast propagating cracks can continue to grow, now in the absence of hydrogen supply, given an appropriate level of remote tensile stress. This is surprising because the fracture energy is now that of Fe in the absence of H and cleavage fracture requires opening tractions on the order of 15 GPa to be generated. Thus, fracture is usually precluded due to plasticity around the crack-tip. Here we show via macroscopic continuum crack growth calculations in a rate dependent elastic-plastic solid with fracture modelled using a cohesive zone that cleavage is possible if the crack propagates fast enough. This is because strain-rates at the tips of fast propagating cracks are sufficiently high for the drag on the motion of dislocations resulting from phonon scattering to limit plasticity. This combined atomistic/continuum model is used to explain a host of well-established experimental observations including (but not limited to): (i) insensitivity of the strength to the concentration of trapped hydrogen; (ii) the extensive microcracking in addition to the final cleavage fracture event and (iii) the higher susceptibility of high strength steels to hydrogen embrittlement.

Bio

Prof. Vikram Deshpande joined the faculty of Engineering at the University of Cambridge as a lecturer in October 2001 and was promoted to a professorship in Materials Engineering in 2010. He has written in excess of 200 journal articles in the experimental and theoretical mechanics solid mechanics with an h-index of 65. He serves on the editorial boards of a number of journals in mechanics and biomechanics including Proceedings of the Royal Society, London A, Journal of the Mechanics and Physics of Solids, Molecular and Cellular Biomechanics and Modelling and Simulation in Materials Science and Engineering.

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