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Foreseeing Failure

Take a wire paperclip. Now, bend it back and forth in the same spot 15, maybe 20 times. Chances are the paperclip will have broken before you finish. This is due to what's called metal fatigue, which occurs when a metal component is cyclically stressed until it fails.

While the broken paperclip is a trivial example of metal fatigue, the phenomenon is a huge problem in the wider world. "Most unexpected failures — bridges, airplanes, oil rigs, heart valves — fail by that process," said UC Santa Barbara materials science professor Tresa Pollock, who specializes in the mechanical and and environmental performance of materials in extreme environments. Virtually any structural metal that is subjected to cyclic stress — deformations, vibrations, extreme temperatures, impacts and the like — is vulnerable, with results that can cost hundreds of billions of dollars each year.

To forsee and avoid such catastrophic fates, Pollock and fellow researchers at UCSB, University of Illinois at Urbana-Champaign and Université de Poitiers in France have developed a theory that predicts the limits to which metals can be subjected to cyclic stress before failing. And they can predict failure from the first cycle.

Their research is published in the journal Science.

Being able to predict when a metal component is likely to fail from cyclic stress has long been a priority when designing an engineered system, whether it's an artificial heart valve or a nuclear power plant. However, according to Pollock, who also serves

as the interim dean of the College of Engineering at UC Santa Barbara, the process of making this determination hasn’t changed much in almost two centuries.

“They take something, cycle it and measure the cycles to failure,” she said.

But these empirically-driven results often come without the deeper, quantitative insights that would enable predictions across a broad range of metals under various conditions. Further complicating the matter is that failures can often occur after millions or billions of cycles. “And if you have to test something for a year or 10 years before it fails, then it’s a little difficult to generate enough test results to design against that failure,” Pollock said.

Advanced Techniques Provide New Insights

From the moment a solid metal is subjected to its first cycle of stress — typically first in tension, followed by compression and then back to zero — it is set on a trajectory to failure. But often, the damage isn’t immediately visible to the naked eye. On the nanometer scale, however, the damage is there: Atoms in the metal’s stressed zone slip against one another, creating patterns of wear called “slip bands.” As the material experiences more cycles, more of these slip bands emerge, and eventually a microcrack forms. Further loading cycles cause the crack to grow until it becomes a macroscopic crack and the metal fails.

“Fatigue strength” is stress that can be tolerated for a high number of cycles before failing, often between a million and a billion. Testing a large collection of engineering metals and alloys with a suite of new techniques enabled the researchers to connect the measurements from the first cycle of slip localization to the metal’s fatigue strength in a surprisingly straightforward way.

“We never expected that this correlation would be so linear across so many different materials,” she continued. “The set of materials examined are very, very different from one another and they all fall on the same curve.”

At the core of the team’s discovery is the UCSB-developed TriBeam microscope, which allows for new high-resolution approaches to studying slip bands, along with new ultrasonic fatigue testing and multimodal data analysis techniques. “The ability to develop and maintain these advanced instruments and combine them with machine-learning assisted analysis within the UCSB infrastructure was critically important,” Pollock said.

The site and the intensity of the first slip localization events are, according to the study, predictive of when the material will fail and where the crack will start to form. Key to these predictions is the metal's "yield strength" — known as the point of no return where the metal is irreversibly deformed during loading.

"The surprising observation is that some slip bands that appear during the first half-cycle of tension completely disappear by the end of the cycle," Pollock explained. "However, a small fraction of the bands do not disappear or 'reverse' during the first cycle; these were found to be the sites where failure occurred a billion cycles later."

The researchers' high-resolution studies also provide insights into factors that influence the fatigue strength of a metal, including processing methods and crystal structure — the three-dimensional arrangement of the metals' atoms. How the atoms slip against one another differs by how they are stacked. Body-centered cubic arrangements (atoms at each corner and at the center of the cube) experience more dispersed slip events, while face-centered cubic (atoms at each corner and on each face of the cube) and hexagonal-closed pack metals exhibit more localized slips and larger variation in their intensity. These parameters can account for differences in the fatigue life of metals with different crystalline structures, and factor into the research team's theory.

These newly discovered correlations and quantitative insights advance the understanding of metal fatigue, with the implication that they can be used to more optimally design engineered systems and more definitively predict when and how a metal component will fail.

"If you can predict how the metal is going to perform from the first cycle, you wouldn't have to undergo all these expensive and time-consuming testing approaches," Pollock said, "and we can make better materials and protect ourselves against disasters."

Pollock's research for this study was supported by the U.S. Department of Defense's Vannevar Bush Faculty Fellowship (VBFF), which is awarded to approximately 10 faculty members across all fields each year. VBFF supports new, out-of-the box ideas where researcher creativity intersects with the unknown.

About UC Santa Barbara

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