

Press Release

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Simulation model for reliable prediction of the low cycle fatigue lifetime for highly stressed components in contact with hydrogen

The fatigue life of highly stressed components in a hydrogen atmosphere has so far only been estimated with large uncertainties. Classical fracture mechanics calculations are often too conservative and yield significantly shorter service lives than occur. Researchers at Fraunhofer IWM have now developed, for the first time, a crack initiation-based prediction model that allows the Low Cycle Fatigue (LCF) lifetime under the influence of hydrogen to be calculated on a physically sound basis. This makes it possible to reliably predict the service life of components in hydrogen turbines and engines at an early stage of development, reduce costly testing, and design safety factors more realistically. This is an important step towards safe and environmentally friendly hydrogen operation of turbines.

The demand for gas turbines is enormous. In the power plant sector, gas turbines compensate for fluctuations in renewable electricity generation. The AI boom urgently requires turbines for power generation. And in aircraft construction, more efficient engines are being developed. Many manufacturers are increasingly relying on hydrogen-powered turbines, since this can drastically reduce CO₂ emissions.

Development and qualification processes are time-consuming and costly, since the stresses on components and the materials used change when hydrogen is combusted, and both efficiency and service life must already be ensured during the development phase.

The challenge: lifetime prediction for hydrogen technologies

Valid lifetime predictions must take many influencing factors into account: hydrogen pressure, gas purity, temperature, material and surface conditions, and mechanical loading. However, their interaction cannot be captured experimentally in a single test, which contributes to the high development effort, as many tests are required. In addition, different degradation and damage processes occur simultaneously in the material, and not least induced by hydrogen, leading to material fatigue and reducing service life. The better and, above all, the more completely these processes can be described and simulated, the better the performance limits of the materials can be exploited, and component safety can be calibrated.

The initiation and growth of short cracks of about 20 µm up to the technical crack initiation length of about 1 mm account for up to 90% of the actual component service life. This is referred to as Low Cycle Fatigue (LCF). Hydrogen can increase crack growth by a factor of 100 or more. However, this effect of hydrogen on short cracks has not yet been mathematically modeled based on fundamental physical principles. As a result, components must be designed very conservatively, with high safety factors.

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Fatigue under the influence of hydrogen simulated for the first time

Scientists at Fraunhofer IWM have now developed a simulation model that, for the first time, represents the influence of hydrogen on low cycle fatigue behavior on the basis of physical relationships. This enables the model to account for a wide range of influencing factors such as temperature, hydrogen pressure, loading frequency and mechanical load range, and to predict the service life of highly stressed components in, for example, gas turbines and jet engines.

The model describes hydrogen-influenced short crack growth from approximately 20 µm to 1 mm based on elastic-plastic fracture mechanics. The HELP effect (hydrogen-enhanced localized plasticity) is considered the central damage mechanism: hydrogen reaching the crack tip occupies dislocations in the metal lattice, increasing local plasticity and thereby accelerating crack growth. At temperatures above 400 °C, oxygen diffusion along grain boundaries is additionally considered as a further contributing damage mechanism.

»Components used in hydrogen atmospheres are exposed to a wide variety of operating conditions, resulting from combinations of hydrogen pressure, temperature, and varying load cycles. It is generally not feasible to cover every possible scenario experimentally. Our simulation model is capable of mathematically capturing this complexity and reliably estimating service life even under extreme operating conditions,« explains Fabien Ebling, project leader at Fraunhofer IWM.

The model is not based on empirical values but explains the physical cause of the damage, i.e. hydrogen atoms that mobilize dislocations in the metal lattice and thereby accelerate crack growth. This is intended to drastically reduce the elaborate and costly testing of components in hydrogen test rigs.

The model is particularly valuable in early development phases, when component geometries and operating concepts have not yet been finalized. This allows parameter studies to be carried out, pressure limits to be defined, or the influence of test frequency on damage to be assessed even before the first prototype is built.

Funding

The research results were obtained within the projects AdHyBau (20M1904E), *Hybrid construction methods with generative metal structures and fiber composites for high-performance electric motors*, and AdHyBau2 (20M2202C), *Development of an approvable hydrogen-electric propulsion system for aircraft and testing of the cryogenically cooled electric motor*, both funded by the German Federal Ministry for Economic Affairs and Energy (BMWE).



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Experimental investigation of the fatigue life of hollow specimens at temperatures of up to 1000 °C and internal hydrogen pressures of up to 250 bar. The test results serve to validate the LCF lifetime model developed at Fraunhofer IWM for highly stressed components in contact with hydrogen.

The **Fraunhofer-Gesellschaft**, headquartered in Germany, is one of the world's leading organizations for applied research. It plays a major role in innovation by prioritizing research on cutting-edge technologies and the transfer of results to industry to strengthen Germany's industrial base and for the benefit of society as a whole. Founded in 1949, the Fraunhofer-Gesellschaft currently operates 74 institutes and research units throughout Germany. Its roughly 30,000 employees, predominantly scientists and engineers, work with an annual business volume of 3.6 billion euros; 3.2 billion euros of this stems from contract research.

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