# Bringing Ultrasonic Fatigue to Light

## High Frequency Stress and Strain Measurements During Ultrasonic Fatigue Testing with 3-D Scanning Vibrometry

**In recent years piezoelectric ultrasonic facilities have been used more and more to investigate the fatigue behavior of high performance metals, e.g. titanium alloys or metal matrix composites (MMC) in the very high cycle fatigue regime. This innovative testing technique requires adequate tools for calibration and measurement such as 3-D scanning vibrometry, which offers a lot of advantages.**


**Fig. 1: Experimental setup for ultrasonic fatigue testing.**

### Motivation

Many modern engineered systems, such as heavily stressed motor parts or offshore structures, have to resist more than 10 million cycles due to either high frequency loading or a lifetime of up to more than 30 years. This cycle range is named the Very High Cycle Fatigue (VHCF) regime. For a reliable application of these high performance components, a detailed knowledge of the fatigue behavior of materials used in the VHCF regime becomes more and more important. Conventional testing facilities can only perform long duration tests at frequencies of up to 200 Hz.

### The Ultrasonic Testing Facility

In order to realize for example $10^{10}$ cycles in short time periods, an innovative ultrasonic testing facility for tension-compression experiments was developed at the Institute of Materials Science and Engineering (WKK) at the University of Kaiserslautern in Germany. The loading principle of the testing system is based on a piezoelectric converter, which is designed to resonate fatigue specimens at a frequency of 20 kHz with a standing longitudinal wave that causes fatigue in the material. An eigenfrequency of 20 kHz is therefore an essential property of the specimen. Finite element analysis is used during the design process in order to ensure an adequate specimen design.

The 3-D scanning laser vibrometer promised to be an effective instrument to measure the eigenfrequencies and eigenmodes and verify our finite element model. Stress and strain evaluation using conventional techniques such as strain gages is quite difficult due to their tactile nature during high frequency oscillation. Therefore the potential of 3-D scanning laser vibrometry for high resolution non-contact stress and strain measurement during ultrasonic fatigue was evaluated.

### Experimental Setup

A PSV-400-3D Scanning Vibrometer from Polytec was used for the experiments at the WKK. The positioning of the three laser heads, shown in fig. 1, was chosen to ensure accessibility to the tapered region of the fatigue specimen. Very low displacement amplitudes of 30 nm were selected for determining the eigenfrequency and eigenmodes, and to prevent unwanted fatigue damage of the material. The strain measurements were focused

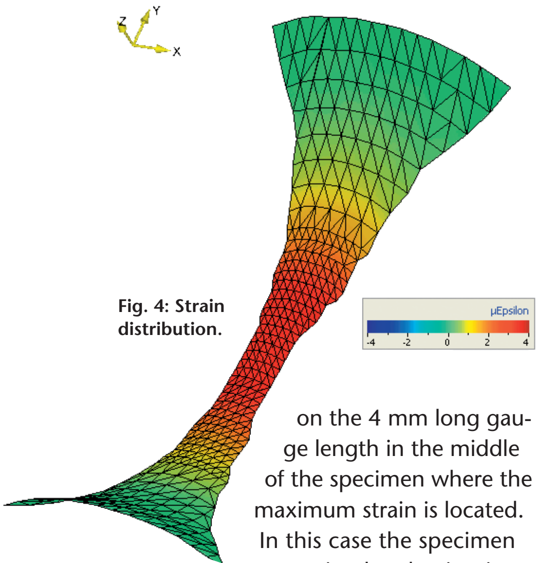


**Fig. 4: Strain distribution.**

on the 4 mm long gauge length in the middle of the specimen where the maximum strain is located. In this case the specimen was stimulated at its eigenfrequencies with high displacement amplitudes of up to 42 µm.

## Selected Results

Correlation with the FE model was performed with specimens in their initial state (prior to fatigue). The frequency response (in fig. 2a) indicates an eigenfrequency of 20.06 kHz and the eigenmode at this frequency (top of fig. 3) shows the expected longitudinal oscillation. Both results fit very well to the calculated FE results. Furthermore, the detailed visualization of the high frequency oscillation confirms that the specimens are oscillating correctly for this investigation.

Similar investigations were carried out on a specimen that had been loaded with a stress amplitude of only 50% of the yield strength. In spite of this, fatigue failure occurred after 1.2 * $10^9$ cycles due to interior fatigue damage. In comparison to the initial state, the eigenfrequencies reduced because of this subsurface fatigue damage. The eigenmodes in the range of 20 kHz also show clear differences (lower half of fig. 3). An asymmetric velocity distribution along the specimen and a considerable inhomogeneity in the area of the fatigue failure were observed.

Fig. 4 shows the strain distribution during the high frequency oscillation with a maximum in the middle of the specimen. The correlation between stress amplitude in the gauge length measured with the 3-D scanning system and displacement amplitude at the free end measured by Polytec´s CLV-2534-2 single-spot vibrometer shows an increase of stress amplitude with an increasing displacement amplitude. A comparison with the correlation based on the FE model shows a high degree of congruence (fig. 5).

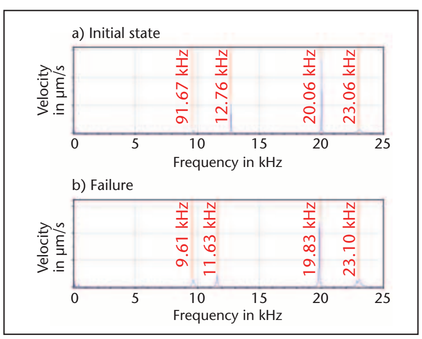


**Fig. 2: Frequency response.**
**a) initial; b) after fatigue damage.**

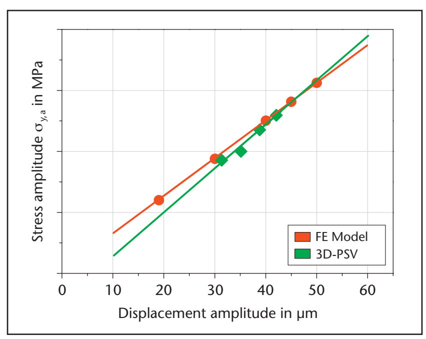


**Fig. 5: Comparison of FE model and measurement.**

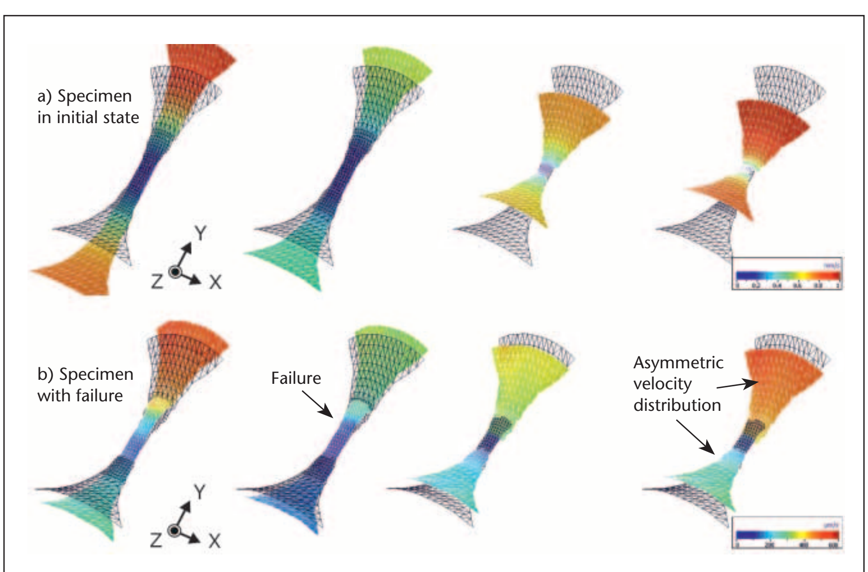


**Fig. 3: Deflection shape; above: initial; below: after fatigue damage.**

## Conclusion

The work presented here illustrates possible applications of 3-D scanning vibrometry in the field of ultrasonic fatigue testing of metals. The results of investigations of the eigenmodes of specimens with different fatigue states indicate the potential to characterize the current fatigue status and to locate fatigue failure. 3-D scanning vibrometry is capable of non-contact local strain measurement with a high spatial resolution and offers an alternative to strain gages for evaluation of high mechanical stresses along the gauge length during ultrasonic fatigue testing.


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