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Versatile ultrasonic fatigue testing method with variable load ratio for small scaled samples

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Abstract – A high frequency testing system for investigation of fatigue behavior of small scaled samples has been developed. The concept is utilizing the fast vibrational displacements of an ultrasonic transducer and a tensile machine, in order to conduct highly accelerated fatigue tests with a variable load ratio. Variation of the load ratio enables to obtain realistic fatigue data by simulating the actual loading conditions of the materials during the operation or to avoid problems such as buckling of thin samples. Another additional feature of this experimental set-up is that static as well as high frequency dynamic measurements can be performed in one setup, for example to conduct a preload profile before or while high cycle fatigue testing. Particular challenges for such a concept are the sensors to detect and control the forces, displacements and temperatures during ultrasonic fatigue testing. A combination of different non-contact displacement, rigid and low profile force sensors and hot / cold air and water circulation setup for controlled environmental testing is proposed in this testing ensemble.

Keywords – ultrasonic fatigue testing, Al-wire fatigue, tensile test, laser speckle extensometer, piezoelectric force sensor

I. INTRODUCTION

In recent years, knowledge of the fatigue response of the structural materials up to the very high cycle regime (VHCF) has gained a considerable attention [1]. For this purpose, ultrasonic resonance fatigue test systems working at a frequency of ~20 kHz are used to obtain lifetime data of bulk metallic materials in the ranges of 1e6 up to 1e10 cycles in a reasonably short time. The resonance system consists of a driving system, a piezoelectric transducer, an acoustic sonotrode and the sample. The mechanical part which consists of several half wavelength pieces, is excited to longitudinal push-pull vibrations at a resonance frequency of about 20 kHz. Distribution of displacement and strain varies in a sinusoidal manner along the mechanical parts of the system, with the maximum strain occurring in the mid-section and maximum displacement at the end of each part [2]. Thus the bulk sample is subjected to symmetrical cyclic loads with a zero mean stress $\sigma_m = \frac{\sigma_{\text{min}} + \sigma_{\text{max}}}{2}$ and a load ratio of $R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = -1$, with $\sigma_{\text{min}}$ and $\sigma_{\text{max}}$ being the minimum to maximum stresses in the fatigue cycle. Contrary to bulk materials, investigation of mechanical properties of small scaled materials with overall dimensions of a few millimeters and thicknesses in the micron range require special measurement techniques which can be very challenging to perform [3]. Thus, in this study, an ultrasonic fatigue testing system has been specially adapted for fatigue testing of small scaled samples up to very high cycle regime. In order to avoid buckling of the samples with a high aspect ratio, fatigue tests are conducted under cyclic tensile loading with a positive mean stress ($\sigma_m > 0$). In the following the developed experimental set-up is described and the applicability of the testing system for investigation of small scaled materials is demonstrated on Aluminum bond wires.

II. EXPERIMENTAL METHOD

A. Description of the setup

The principle of the proposed setup is the combination of a tensile machine and an ultrasonic (US) transducer. With this combination it is possible to utilize large displacements with small speeds and small cyclic oscillations at high velocities. Figure 1 shows the two steps, preloading (green) and high frequency oscillation (red) schematically. The setup consists of a heavy mobile crosshead, which can be moved up and down efficiently via a worm gear and a stepper motor, on which an ultrasonic transducer is fixed. The US transducer by TELSONIC operates at a constant frequency of around 20 kHz. The upper sample fixture is built in the sonotrode at the free movable end where the displacement reaches its maximum.

The lower sample fixture is mounted with a force sensor onto an x-y-stage which after positioning can be bolted to the baseplate. The force sensor is a piezoelectric force transducer by HBM, which has the benefits not to reduce the rigidity of the system and can detect highly dynamic loads close to the fixture due to its structural design. The sensor is bolted between the lower sample fixture and the stage with a preload of 5 kN. This piezoelectric charge measurement is prone to thermal and time dependent drift, nevertheless dynamic load differences can be measured regardless since the drift is slow under controlled temperature conditions.
The movement of the crosshead during a test is measured by differential capacitive displacement sensors (CDS) by μEpsilon which are placed at the lower sample fixture and due to clearance issues at the middle of the sonotrode respectively. They provide very precise total displacement values with a resolution below 1 nm. This is then compared to the differential displacement using a laser speckle extensometer (LSE) by MessPhysik, which measures the differential displacement of the sample using digital image correlation [4]. The LSE measures directly the displacement/strain of the sample in a contactless manner and provides exact results by avoiding the influence of the fixtures and stiffness of the set-up. The LSE and the capacitive measurements are conducted during the crosshead movement for the preload and calibration tests, since the sampling rate of the LSE sensor is limited to 100 Hz. The US fatigue tests are conducted without those sensors after the desired preload is reached.

The concept provides two different fatigue measuring options, under hot or cold air flow or water circulating bath, displayed in Figure 2. For both options the sensors for the crosshead movement and tensile measurements are removed. In the former case, a differential laser Doppler vibrometer (LDV) can be used with a deflection mirror in order to detect the dynamic displacement of the fixtures under ultrasonic vibration. The second measurement possibility, which is shown in Figure 2b is designed to carry out tests at a defined sample temperature (±1°C). For this purpose, the lower sample fixture is enclosed by a sealed acrylic glass tube. A pump circulates water from a tank, where it is regulated to the desired temperature, and ensures a complete rinsing of the sample. A temperature sensor measures the water temperature near the sample. This is preferred especially when the ultrasonic displacement loads are high enough to produce heat due to friction of the sample fixtures or damping of the sample itself. The realized setup is shown in Figure 3.

Fig. 2: Schematic overview of the test assembly with a LSE sensor a) and under water cooling conditions without LSE b).

Fig. 3: Realized setup showing a LSE and CDS a) and piezoelectric sensor setup b) and the hot air and water cooled assembly c).

The preloaded piezoelectric sensor was calibrated using a 100 N load cell placed in between the sonotrode joints and tested in tension and compression of a large rigid steel rod. As shown in Figure 4 the both sensors have a good compliance at lower load levels. With increasing the tensile load level, the piezoelectric sensor shows a higher force than the load cell and vice versa in the case of compression.
Wire fatigue under tensile loading

The described setup was used to measure the high cycle fatigue behavior of 400 μm Al wires, which are used as bonding wires in high power semiconductor devices. Prior to clamping the wires in the upper and lower fixtures, they were glued in a paper frame in order to achieve a sufficient clamping force without severely deforming the ductile Al wire. This provided also an electrical insulation layer and allowed to determine the time to fracture by resistance surveillance.

In order to determine the fatigue testing conditions including the pre-load and the stress amplitude level, tensile tests with a constant strain rate of 1.2e-3 s⁻¹ were performed by using this set-up. The displacement of the wires were determined by using both CDS and LSE based on a gauge length of 18 mm. In Figure 5 the tensile results are plotted in a stress strain diagram showing an ultimate tensile strength of 43 MPa.

The fatigue tests were conducted at several displacement amplitudes from 6 μm up to 11 μm (~0.18% and 0.33% max. strain), which were measured using the LDV at the faces of the sample fixtures. For each loading amplitude, seven wires were tested. In order to remain in the tensile range the wire was pre-strained up to +12 μm (~0.12% strain), resulting in a pre-stress value of 12 MPa and load ratio of R=0.1. The wire length between the fixtures was 10 mm.

Figure 6 shows the results of the dynamic fatigue tests in terms of maximum stress amplitude against cycles to failure. The fit curves show the calculated fracture probability for 0%, 5%, 50% and 90%. At the highest amplitude of 11 μm and 22.5 MPa the average loading cycles to failure reach 8e4 Nbars. The loading cycles to failure was detected by a 20 Hz sampling rate of the wire resistance which results in an accuracy of ±1000 cycles for a test conducted at 20 kHz. The endurance limit and the threshold lifetime are calculated to be at 19 MPa and 300 cycles respectively.

Figure 7 shows the cumulative distribution function where the normalization of the S-N field is plotted as a unique cumulative distribution function with a normalizing variable \( V = (\log N - B) (\log \sigma - C) \). The constant B is 5.79 and represents the threshold lifetime at 300 cycles and the constant C is 2.94 equals to the endurance limit at 19 MPa. The statistical calculations were conducted with the help of the ProFatigue software program [5].
force and displacement conditions at small samples under the combined very low and very high strain rates without influencing one another. It emphasizes the importance of choosing the suitable types of sensors such as non-contact CDS and LSE displacement measurements and highly dynamic piezoelectric force sensors. A setup for testing under hot/cold air flow as well as under water cooling conditions was shown. Finally, the system was applied for determination of the fatigue behavior of 400 μm thick Al wires in the HCF regime under cyclic tensile loading.

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V. REFERENCES


VI. VITA

Christoph Gasser studied Electronics Engineering at the Technical University in Vienna and graduated with a BSc degree in autumn 2018. Since then, he currently works as a scientific assistant for the Christian Doppler Laboratory for Lifetime and Reliability of Interfaces in Complex Multi-Material Electronics and studies Embedded Systems at the TU Vienna.