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Ultrasonic fatigue and microstructural characterization of carbon fiber fabric reinforced polyphenylene sulfide in the very high cycle fatigue regime

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ABSTRACT

Carbon fiber reinforced polymers (CFRP) are increasingly used for high performance applications, especially for aircraft structures. These structural components are subjected higher than 10^8 loading cycles during their operation time of more than 20 years. To utilize the full mechanical performance of CFRP for lightweight applications, the very high cycle fatigue (VHCF) behavior has to be well understood. Therefore the VHCF behavior of a carbon fiber twill 2/2 fabric reinforced polyphenylene sulfide (CF-PPS) was analyzed systematically up to 10^9 loading cycles. To realize these investigations in an economic reasonable time period a novel ultrasonic fatigue testing facility for CFRP was used. This facility works with cyclic three-point bending at a frequency of 20 kHz. Lifetime-oriented investigations at stress ratios between $R = 0.21$ and 0.51 showed an exponential decrease of the bearable stress amplitudes in the range between 10^6 and 10^9 cycles. Interrupted constant amplitude tests were performed for the characterization of the fatigue damage development. Based on light optical as well as SEM investigations the fatigue damage mechanisms in the VHCF regime were characterized in detail. The surface crack density was determined for several load amplitudes and in different fatigue states by analyzing merged light optical micrographs. Furthermore the stiffness degradation was measured ex-situ during interruptions of the constant amplitude tests, which shows a good correlation with the surface crack density of ultrasonically fatigued CF-PPS.

1. Introduction and motivation for VHCF testing of CFRP

Carbon fiber reinforced polymers (CFRP) are one of the state of the art materials for highly loaded lightweight structures and are of growing importance especially in the aircraft industry. During their operation time of partially more than 20 years structural CFRP parts are often loaded with more than 10^8 cycles [1]. This range of more than 10^7 cycles is known as Very High Cycle Fatigue (VHCF) regime [2]. To utilize the full mechanical performance of CFRP for lightweight applications, the fatigue behavior and the failure mechanisms have to be well understood. However, the VHCF behavior of CFRP is insufficiently characterized so far due to very long test periods of VHCF experiments. For example a single VHCF experiment up to 10^9 cycles with a testing frequency of about 5 Hz would take at least 6.3 years. The few data available about very high cycle fatigue of CFRP were obtained by long-term experiments with testing frequencies of 0.1–157 Hz [3]. Investigations up to 3×10^8 cycles on a CF-EP laminate have been carried out by Hosoi et al. using testing frequencies between 5 and 100 Hz [4–7]. Fatigue results of CF-PEEK up to 10^9 cycles were presented in 2006 by Michel et al. using different loading conditions and frequencies of 0.1–157 Hz [3]. Further results of CFRP in the VHCF regime were presented from Gude et al. and Yoshi et al. [8,9]. However especially the increase of testing frequencies to reach the VHCF area is always discussed with the strong argument of critical overheating of the polymer matrix [7]. The concerns of overcritical heating and the excessively high requirements to the specimen geometry were the main reasons why the efficient ultrasonic testing facilities for metals operate at a frequency of 20 kHz [10,11] could not be easily adapted to CFRP. Nonetheless first VCHF investigations of composites concerning the fatigue crack growth of glass-fiber-aluminum laminate material (GLARE) have been carried out up to 10^8 cycles by the use of an ultrasonic resonance device working

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with a frequency of 21 kHz and a load ratio of R = −1 [12].

In the presented work the VHCF behavior of a C-fiber twill 2/2 fabric reinforced polyphenylene sulfide (CF-PPS) was investigated systematically up to 10^9 loading cycles for the first time. To perform the VHCF experiments in an economical reasonable time period a novel ultrasonic fatigue testing facility (UTF) for cyclic three-point bending was developed at the Institute of Materials Science and Engineering (WKK), University of Kaiserslautern (Germany). The ultrasonic fatigue testing system, called “UltraFAST-WKK-Kaiserslautern”, works with a frequency of 20 kHz and a permanent online monitoring via infrared thermography and Laser Doppler vibrometry among others. Further details to the used ultrasonic fatigue testing facility for CFRP are given in Ref. [13]. Constant amplitude tests were performed to describe the VHCF behavior up to 10^9 cycles in detail. The failure mechanisms as well as the fatigue damage development were characterized and correlated with the ex-situ measured stiffness degradation of the CF-PPS-specimens.

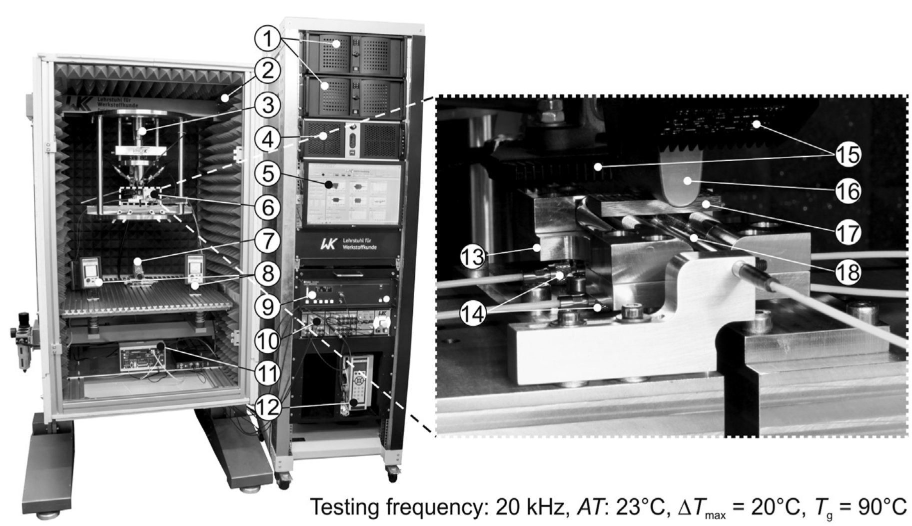
2. Test procedure and investigated composite material

All the fatigue experiments in the presented work have been carried out using a novel ultrasonic fatigue testing facility for cyclic three-point bending. The developed UTF uses the reverse piezoelectrical effect to transform a high frequency alternating voltage of 20 kHz into a mechanical oscillation of the same frequency. Compared to well-known ultrasonic testing facilities for metals the specimen in this facility is not a positively locked part of the ultrasonic resonance system. Hence, an additional monotonic deflection was applied to the CF-PPS specimen to ensure a permanent contact between specimen and the loading device during ultrasonic cycling. Thus, the total load of the specimen consists of a monotonic three-point bending load with a superimposed cyclic oscillation at a frequency of 20 kHz. To avoid a critical increase in temperature of the specimen of $\Delta T > 20$ °C the entire fatigue experiment was split up in pulse-pause sequences and the specimen is permanently cooled with dry air. The effective test frequency of all experiments performed within this work was about 965 Hz. This enabled fatigue experiments up to 1×10^9 cycles in only 12 days. The high testing frequency as well as the data acquisition with a recording rate of 500 kHz and the online data processing required a stable process control ensured by a real time environment and a specifically developed LabVIEW program. The non-contact online characterization of the fatigue behavior of the CF-PPS specimens was realized by the permanent use of Laser vibrometry, IR-thermography, confocal chromatic distance control and piezoelectrical force sensors. In Fig. 1 the developed UTF is presented. Further description of the UTF and the underlying testing principle is given in Ref. [13].

The material investigated within this work is a commercial C-fiber twill 2/2 fabric reinforced polyphenylene sulfide (CF-PPS) manufactured by Bond-Laminates (Brilon, Germany). The aircraft qualified material has a glass transition temperature (T_g) of about 90 °C and a melting point (T_{pm}) of around 290 °C [14]. The used laminate has a thickness of 4 mm according to 19 layers of twill 2/2 fabric with an orthotropic layup, a fiber volume content of 54.8% and a total density of 1.54 g/cm^3. The used fabric of HT-carbon fibers has a surface weight of 200 g/m^2.

The operating principle of this ultrasonic testing facility requires a specific specimen design ensuring the same frequency of the first transversal bending eigenmode of the specimen and of the ultrasonic resonance system. For the development of a suitable specimen geometry an orthotropic elastic material model was used. To enable FEM-simulations using ABAQUS CAE based on this orthotropic material model, nine elastic constants were determined in a comprehensive material characterization. Furthermore the mechanical properties were identified in tensile and bending tests according to DIN EN ISO 527-4, DIN EN ISO 14125, DIN EN ISO 14129 and DIN 65148. All the determined values and are summarized in Table 1. Further details to the investigated material are also published in Ref. [13].

The simulated CF-PPS specimen is shown in Fig. 2a. As a result, the distance between the nodal points L_{NP} (blue color) during



1: Real-Time-systems	7: LDV-sensor	13: Shoulders
2: Convection chamber	8: Charge amplifier	14: Piezoel. force sensors
3: Ultrasonic resonance system	9: LDV-controler	15: Specimen cooling
4: Windows-system (Host)	10: Junction box	16: Loading device
5: User interface	11: Controler conf. sensor	17: CF-PPS-specimen
6: IR-thermocamera	12: Digital US-generator	18: Confocal sensor

Fig. 1. Novel in-house developed ultrasonic testing facility for cyclic 3-point bending of CFRP at a frequency of 20 kHz.