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Reprint of: Acoustic emission analysis for characterisation of damage mechanisms in fibre reinforced thermosetting polyurethane and epoxy ☆

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ABSTRACT

Acoustic emission analysis is used to investigate microscopic damage mechanisms and damage progress in unidirectional glass and carbon fibre reinforced composites. Under static loading the influence of fibre orientation on damage initiation and propagation is determined. A novel polyurethane matrix system significantly enhances material performance in terms of crack initiation load levels, crack growth, damage tolerance and off-axis tensile strength. Hysteresis measurements during stepwise increasing dynamic load tests highlight the effect of fibre–matrix-adhesion and resin fracture toughness in unidirectional 0° fibre reinforced composites. Acoustic detection of beginning fibre breakage correlates with a significant increase of loss work per cycle.

1. Introduction

In the last decades the use of fibre reinforced plastics (FRP) in engineering applications has increased dramatically. The biggest advantage of FRPs is their superior specific strength and stiffness. Starting in space and aeronautic industries, FRPs are nowadays used for lightweight structures in automotive, as well as marine and wind turbine industry. For the design of FRP structures knowledge about damage behaviour is essential to prevent failure during service life. Generally, mechanical testing methods are used to investigate the performance and failure characteristics of FRP. Unfortunately, most static testing methods only provide information about final failure without giving an insight in the initiation process and propagation of damage. To overcome this limitation, acoustic emission (AE) combined with frequency analysis and pattern recognition techniques is a promising approach. By the use of AE analysis crack initiation and propagation can be detected online during mechanical testing. Based on frequency composition of acoustic signals different damage mechanisms as matrix cracking, interphase failure and fibre breakage are distinguishable, even under dynamic loading.

First AE analysis in the field of fibre reinforced composites was done in the 1970s [1–4]. Activities were expanded in the 1980s but analysis was focused on the detection of damage onset, fracture activity and intensity. Correlations between acoustic signals and fracture mechanisms as matrix cracking, fibre breakage and interphase failure were not possible due to insufficient knowledge about physical backgrounds and inapplicable analysis techniques. The identification of different microscopic damage mechanisms succeeded in the mid 1990s by means of determination of the maximum in frequency spectra of AE signals. Matrix cracks show lowest, interphase failure a higher and fibre breakage highest peak frequencys [5,6]. But also sensor response, specimen geometry and sensor location are shown to have some influence on frequency composition of recorded AE signals [7,8]. Therefore, other features in addition to peak frequency are required in order to obtain reliable frequency based discriminations of failure mechanisms in composites.

Indeed, further investigations showed that the entire frequency composition of an AE signal is characteristic for the underlying failure mechanism. Characteristic frequency spectra can be attributed to density and stiffness of the materials involved [10,11]. Furthermore, the application of pattern recognition techniques [12] helps to improve the validity of AE analysis. It is useful to combine several frequency-based features for identification and classification of various failure mechanisms. Fig. 1 shows typical frequency spectra of the three basic microscopic damage mechanisms in fibre

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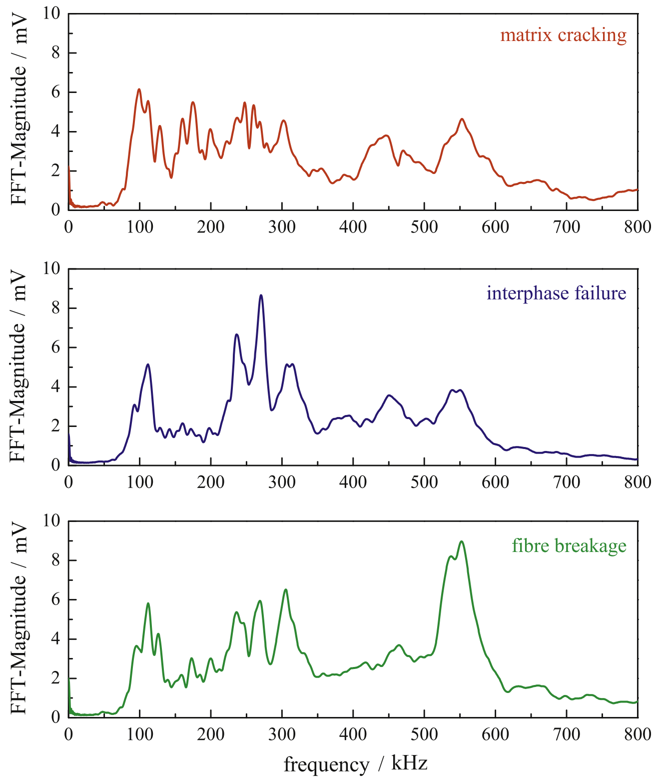

Fig. 1. Frequency spectra of matrix cracking, interphase failure and fibre breakage in glass fibre reinforced polyurethane. After classification of the acoustic signals recorded during testing, average FFTs are calculated from the respective waveforms by AWARE++ software [9]. Average frequency spectra shown here correspond to acoustic signals emitted from one tensile specimen during testing.

reinforced composites: fibre breakage, matrix cracking and interphase failure. Classification procedure itself is described more in detail in Section 2.5.

State of the art mechanical testing of composites has only limited explanatory power regarding damage evolution until final failure. In particular, it is not possible to determine the load levels at which first microcracking occurs within the material. Furthermore, it is not clear which components are getting damaged and how crack propagation develops. Therefore, this study focuses on microscopic failure mechanisms of glass and carbon fibre reinforced composites under quasi-static as well as under dynamic loading. The investigation of different fibre and matrix combinations by means of acoustic emission analysis during mechanical testing allows to reveal basic structure-properties-relationships concerning fibre–matrix interaction in composite materials. Combining AE analysis with static and dynamic testing of fibre reinforced composites helps to establish a fundamental understanding of their failure behaviour by detailed analysis of microscopic damage mechanisms.

2. Experimental

2.1. Materials

Matrix systems used were a two part standard epoxy/amine infusion resin EPR L 1100 + EPH 294 (EP) from MOMENTIVE and a novel thermosetting polyurethane formulation (PU) provided by Henkel AG & Co. KGaA. Glass fibre (GF) reinforced laminates were made of unidirectional SAERTEX noncrimp fabric (E-Glass) with an areal weight of 701 g/m^2. Carbon fibre (CF) laminates were reinforced by a 244 g/m^2 SAERTEX unidirectional HTS noncrimp fabric.

2.2. Processing and sample preparation

Unidirectional glass and carbon fibre reinforced laminates were manufactured by VARTM-process. Laminate thickness of 2 mm corresponds in both cases – GFRP and CFRP laminates – to fibre volume contents of about 54%. Pre-cut dry textiles were placed in an aluminium RTM-tool, which is afterwards clamped together and heated in a hydraulic hot press. Before injection, the two-part resin systems were stirred in a laboratory mixer and degassed after being homogenously mixed. A curing cycle of four hours at 90 °C was chosen for complete curing of both resin systems. Quality assurance was done by visual inspection for the GFRP laminates and with ultrasonic C-scans for the CFRP laminates. Tensile testing samples were prepared with end tabs according to ISO 527-5 [13] and cut out from the laminates with a circular diamond saw. Deviant to ISO standard a sample width of 20 mm was chosen for proper attachment of the piezo AE sensors. Specimens were prepared from unidirectional reinforced laminates with distinct fibre orientations between 0° and 90° to the direction of load applied to the specimen during testing.

2.3. Static testing

Static tensile tests were conducted in a Zwick 1475 universal testing machine with hydraulic clamping fixtures. Crosshead speed of 0.5 mm/min was chosen for a better differentiation of the single AE signals. Strain measurement was done with an extensometer (Fig. 2). Each series consists of five tested valid specimens. For collecting acoustic signals during testing two AE sensors were clamped onto the specimens with silicon grease as coupling medium. Testing conditions were 23°C and 50% relative humidity.

2.4. Dynamic testing

Dynamic testing was carried out in an Instron Schenk IPLH50K servo-hydraulic testing machine under laboratory conditions (23 °C and 50% r.h.). Tension–tension fatigue tests were performed as stepwise increasing load tests at 1 Hz testing frequency with stress controlled sinusoidal loading and a stress ratio of $R = 0.1$. Strain was measured by means of piston displacement of the servo

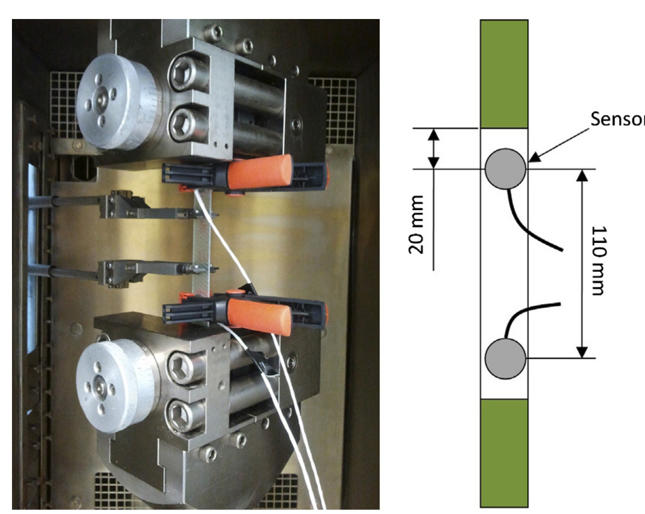

Fig. 2. Static testing setup. Strain is measured by an extensometer (left). Two AE sensors are clamped to the sample at defined positions (right).