APPLICATION OF ACOUSTIC EMISSION ANALYSIS FOR DAMAGE INVESTIGATIONS IN FIBRE AND TEXTILE REINFORCED COMPOSITES

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ABSTRACT

For the verification of pertinent failure and damage models of fibre and textile reinforced composites a clear identification of the particular damage entities is an essential premise. In such fibrous composites, the characteristic failure mechanisms are initiated on the micro-scale and result in a spontaneous release of elastic energy in terms of mechanical stress waves, the so-called acoustic emissions. Therefore, the acoustic emission analysis represents an excellent potentiality for the online detection of the damage progression in fibre and textile reinforced composite structures. Differently structured multilayered symmetric cross-ply and angle-ply laminates, for whose manufacture different textile fabrics have been applied, were used for the analysis of the successive damage behaviour in thermosetting and thermoplastic fibrous composites. On the basis of extensive experimental preliminary investigations, a systematic optimisation of acoustic emission testing was accomplished. In this context, investigations were realised amongst others in regard to the minimisation of background noises, the effect of strain rate on the acoustic emission behaviour as well as the existence of the KAISER effect. Furthermore, the transfer behaviour of several components of the acoustic emission measurement chain was analysed via face-to-face technique. Due to the detected acoustic emissions, the gradual damage behaviour of the researched laminates could be classified regarding its acoustic activity and intensity into an elementary model with five characteristic damage phases.

KEYWORDS: acoustic emission testing, composites, damage behaviour, failure model, Kaiser effect, textile fabrics

INTRODUCTION

Against the background of worldwide increasing raw material costs and scanty natural resources the lightweight construction gains ever more significance. The constantly growing desire for individual mobility requires new structure concepts in particular for future applications in aeronautical and space technology as well as for automotive engineering. During the development of these lightweight structures, the components consisting of fibre and textile reinforced plastics are regarding their high freedom of design and their mechanical and thermal characteristics very meaningfully. System-compatible composites are currently employed intersectorally in countless industrial branches. This variety of applications will increase in the future due to the development of new high performance composite materials.
The systematic development of complexly stressed lightweight construction products requires certain dimensioning concepts which realistically comprehend in particular the extremely complex damage behaviour [1]. In addition, the dimensioning of composite components presupposes comprehensive knowledge of the different material variations as well as pertinent experiences with the modelling and construction of lightweight structures. For the minimisation of the development cycles of fibre reinforced components it requires spanning approaches and design concepts, which currently exist insufficiently for many composite materials [2]. There are different analytical and numerical procedures with sufficient accuracy for the computation of stress and strain fields available. The determined loads are evaluated afterwards by means of global and physically based failure criteria.

Failure and damage models which realistically detect the gradual damage behaviour as well as the degradation of the mechanical properties of the single layers must be compiled for the reliable dimensioning of fibre and textile reinforced composites [3]. However, due to the complexity of the damage and degradation mechanisms the structure based and composite spanning failure analysis of heterogeneous composites causes substantial difficulties. Within the damage research, the micro textural design as a function of the fibre type, the matrix material as well as the type of the textile reinforcement obtains a great relevance [4]. In this context, composite-suitable failure and degradation models developed at the Institute of Lightweight Structures and Polymer Technology are used for the description of the successive damage behaviour of fibrous composites [5]. These models distinguish on the one hand between the global fracture modes fibre failure (FF) and inter fibre failure (IFF) and consider on the other hand different sub-fracture modes for instance tensile fracture, compressive fracture and shear fracture.
A definite identification of the particular damage entities is a substantial condition for the verification of these failure models. These composite-typical damage mechanisms originate from microscale and initiate transient acoustic emissions which are generated by the release of elastic energy within a material or by a process. In this connection, for example fibre failure and delaminations produce very strong acoustic emissions [6]. Therefore, the acoustic emission analysis represents an excellent possibility for the online detection of the damage progression in fibre and textile reinforced composite structures [7]. Compared to other volume sensitive inspection methods like the microwave technique or the radiographic analysis this non-destructive evaluation which is applied for example for internal high pressure test with tubular specimens (*Fig. 1a and Fig. 1b*) as well as tensile tests with flat specimens (*Fig. 1c*) offers the advantage to correlate the chronological sequence of the damage phenomenology with acoustic activity and intensity parameters as well as mechanical properties [8]. Therewith, a test procedure is available which permits the experimental verification as well as the optimisation of the relevant mesomechanical computational models for the description of the gradual damage in fibrous composites. Furthermore, with the application of the acoustic emission analysis, a fundamental basis for the increase of the efficiency of existing material models is created.

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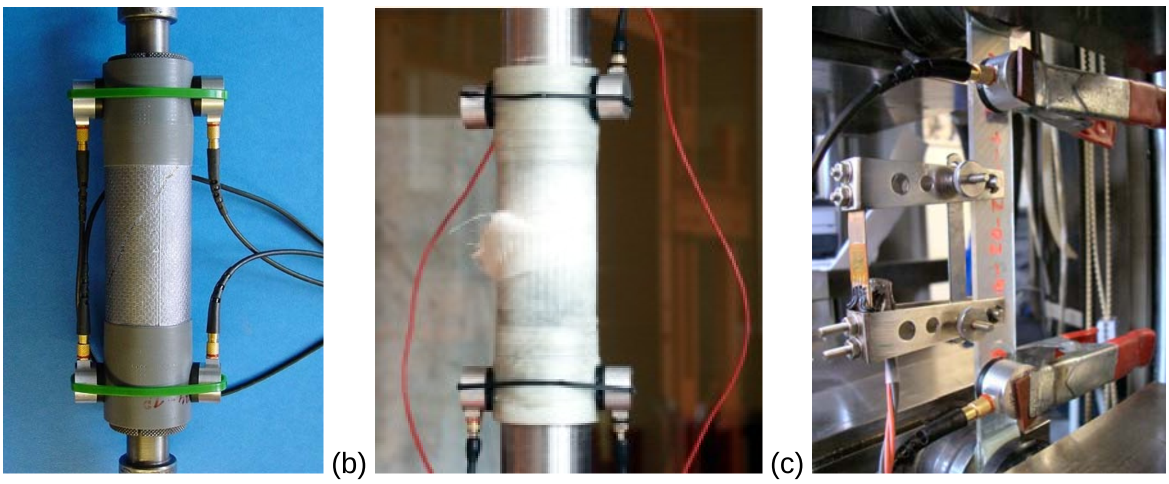


Fig. 1 Acoustic emission examinations associated with internal high pressure tests at CMC (a) and GF/EP (b) tube specimens as well as tensile tests at GFRP flat specimens (c)

Via acoustic emission testing, different multiaxially reinforced polymers were analysed under quasi-static loading and their failure processes were simultaneously detected. On the basis of the experimental results, an evaluation of the acoustic activity and intensity behaviour occurs in correlation with hypothetically predicted fracture characteristic values. During the successive damage process, crack initiation points were objectively identified. Afterwards, sub- and ultracritical loads (*Fig. 2*) could be investigated with intensive phases of increased acoustic activity.

PROCESS DESCRIPTION AND EXPERIMENTAL SETUP

The acoustic emission testing is a passive acoustic volume-sensitive test procedure for the integral non-destructive diagnostics of materials and components under an external applied mechanical or thermal load. This non-destructive evaluation covers a wide field of applications beginning from the detection of smallest material defects on micro level up to the continuous monitoring of assemblies and systems. The philosophy of the described test method contains the detection of transient surface waves generated by the spontaneous release of elastically stored energy within a material or by process for the identification of substance processes and material conditions. According to the different size of acoustic emission sources, the frequency domain of acoustic emission phenomena varies over many decimal powers from the infrasonic range to the ultrasonic region. The most intensive acoustic emission events as for example earthquakes are to be found at the lower end of the frequency scale (*Fig. 3a*).

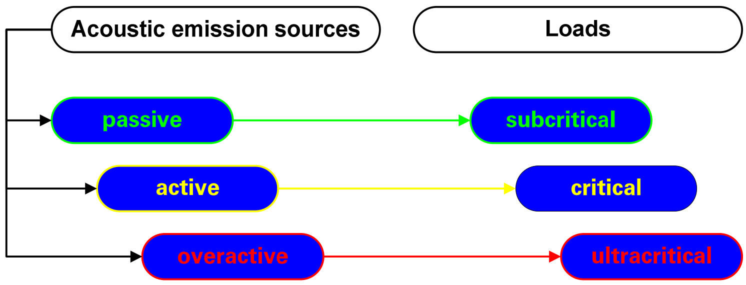


Fig. 2 Guidelines for acoustic emission sources

In *Fig. 3b*, the complex acoustic emission measurement chain consisting of many separate measuring components is schematically represented. The emitted elastic wave propagating through the material is detected using acoustic emission sensors, which are fixed on the specimen via a coupling agent. The converted acoustic emission signal is transmitted to a preamplifier which intensifies the electrical signal. The amplified signal is supplied to the acoustic emission analyser. The downstream frequency filters undertake the task of eliminating background noises. The acoustic emission exerciser processes the detected signals, converts the detected bursts into feature data sets, determines the source location, calculates statistics and displays them graphically and numerically in real time.

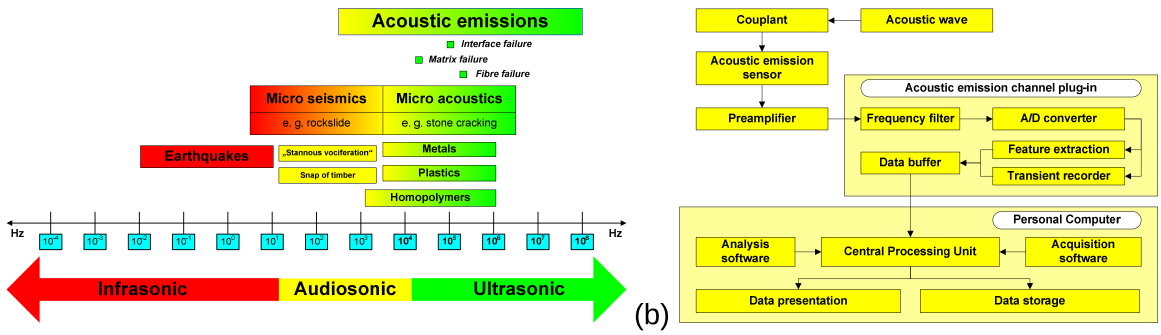


Fig. 3 (a) Frequency domain of acoustic emissions, (b) Acoustic emission process chain [9]

A modular four-channel acoustic emission exerciser VALLEN AMSY-5 is available at the INSTITUTE OF LIGHTWEIGHT ENGINEERING AND POLYMER TECHNOLOGY for the realisation of the acoustic emission examinations. For the detection of acoustic emissions, supersensitive piezoelectric resonance sensors of the type VS-150M and PAC-R15 are applied, whose detected signals are intensified by amplifiers of the type VS-AEP4 and PAC-1220A. The acoustic coupling of the piezoelectric acoustic transducers which are attached with fixating clamps on the specimen surface takes place via common silicone grease (*Fig. 4*). During the examination, the longitudinal and transversal deformation behaviour is recorded by means of external extensometers whose data are registered directly both by the acoustic emission exerciser and by a separate multi-channel analyser.

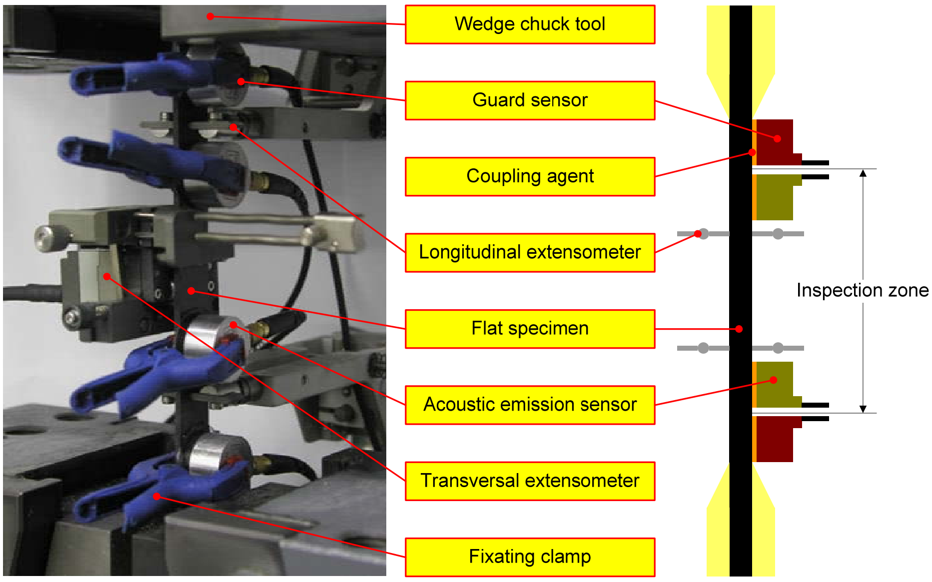


Fig. 4 Experimental setup and guard sensor principle

For the examination of the sensitivity of acoustic emission sensors as well as for the calibration of the complete measurement chain it is necessary to produce defined reference signals at the test specimen. These test signals are adapted to the type of acoustic transducer and approximately reproduce the sound propagation characteristics in a realistic way. For the generation of these reference sources, different methods are available (*Fig. 5*). Due to the uncomplicated and fast practicability, the technique of pencil lead break became generally accepted predominantly [10]. For example, the anisotropy of the acoustic velocity on the surface of composite materials can be verified via this method.

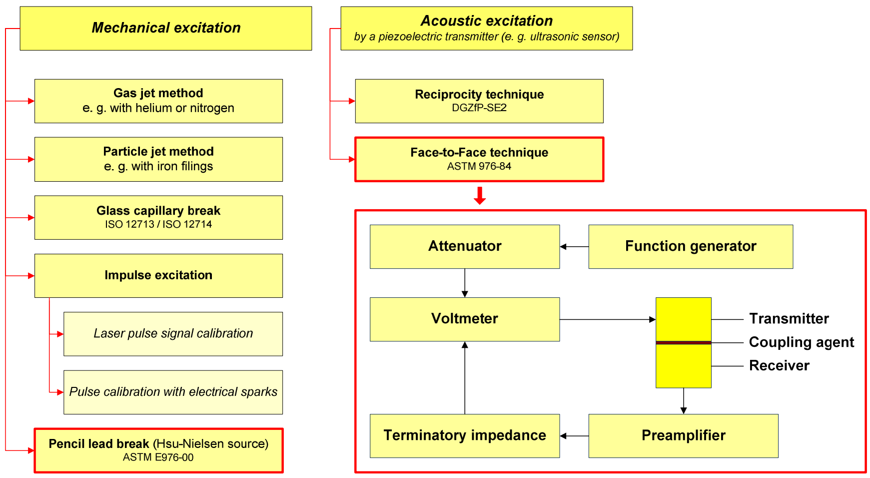


Fig. 5 Methods for the calibration of acoustic emission mensural modules

In the context of the suppression of interfering background noises, coming from the clamping of the universal testing machine, the so-called guard sensor principle (*Fig. 4*) is applied during acoustic emission examination. This inspection method is based on the application of guard sensors in the close-up range of clamping or load transmissions. A guard sensor is an acoustic emission transducer used to discriminate from sources originating outside the area of interest [11]. The guard sensors are directly fixated on the specimen close to the load transmission. A multiplicity of acoustic emission signals which have their source in the clamping zone is recorded at first by one of the both guard sensors fixed in the exterior zone of the test specimen. The acoustic emission signals detected by the guard sensors are extracted via software filters of the electronic measuring equipment. A bigger part of acoustic emission signals which have their origin in the real inspection zone is measured via the both acoustic transducers in the test range. The experimental investigations show that the eliminated acoustic emission signals constitute in some cases nearly ninety percent of all emitted acoustic emission events of the entire specimen. Consequently, the number of detected datasets can be drastically reduced by the application of guard sensors whereby only damage-relevant acoustic emissions incorporate into the evaluation of the experimental results.

MATERIAL CHARACTERISATION

Variably designed thermoplastic and thermosetting fibrous composites with a multiaxial fibre reinforcement, for whose fabrication different textile structures (*Fig. 6*) have been employed, were utilised for studies of the gradual damage behaviour. On the one hand carbon fibre reinforced polyether ether ketones (CF/PEEK) are tested and otherwise carbon and glass fibre reinforced epoxy resins (CF/EP and GF/EP) are analysed experimentally. For a load-compatible design of the fibre architecture the symmetric layer constructions, specified in *Tab. 1*, are selected.
The impregnation and consolidation of the textile preforms took place on the one hand under effect of pressure and temperature in autoclave and contrariwise in resin transfer moulding whereby the infiltration of the multilayer weft-knitted fabrics (*Fig. 6*) occurs in an evacuated moulding tool with an industrial epoxy resin. Via water jet cutting, standardised specimens in different directions were cut out from the manufactured composites. Following, the gradual damage behaviour of selected flat specimens are analysed experimentally with uniaxial quasi-static tensile tests and simultaneously accomplished acoustic emission examinations.

Tab. 1 Specific laminate configurations

Material	Textile structure	Layer sequence
CF/PEEK	Stitch bonded triaxial layer fabric	$[(90°/+60°/0°)/(90°/-60°/0°)]_S$
	Stitch bonded biaxial layer fabric	$[(0°/90°)/(0°/90°)/(0°/90°)]_S$
	Satin weave fabric	$[(0°/90°)_3]_S$
CF/EP	Plain weave fabric	$[(0°/90°)_4]_S$
GF/EP	Unidirectional warp cloths	$[0°]_{16}$
	Plain weave fabric	$[(0°/90°)_4]_S$
	Multilayer weft-knitted fabric	$[90°/0°]_S$

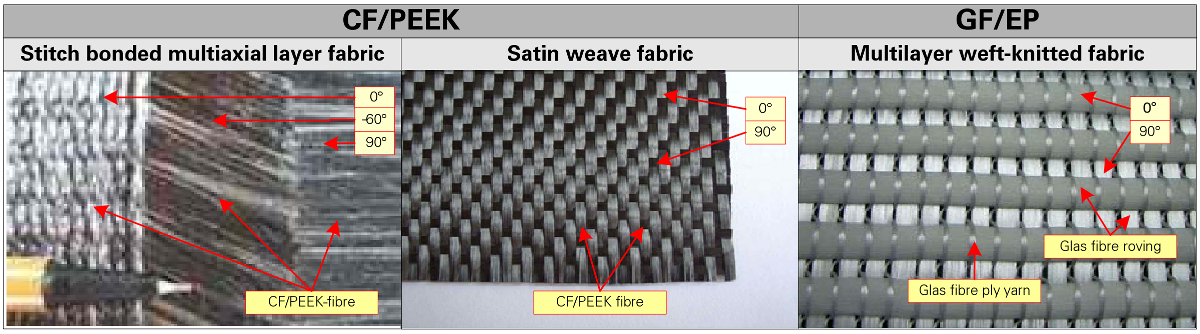


Fig. 6 Selected textile fabrics

PRELIMINARY INVESTIGATIONS

Background noises from the direct peripherals of the gauging represent a serious problem in the context of acoustic emission examinations. With uniaxial tensile tests, a multiplicity of sliding and relaxation noises coming from the load transmission (*Fig. 7a*) are generated which interfere during the acoustic emission testing with the real wanted signals out of the inspection zone. In particular, the junction between the cap strip material and the specimen originates permanently unmeant background noises as a result of the inherent damage during the load tests due to the conventional utilisation of brittle adhesives (e. g. epoxy resin). Therefore, primary preliminary investigations tend to the analysis of suitable combinations consisting of cap strip material and adhesive which must feature as high as possible acoustic emission passivity. Hence, common adhesives and cap strip materials were selected and jointly combined in a multitude of tests. As a result of the accomplished investigations on different material configurations it could be noted that a combination of polyvinyl chloride cap strips and a two-component polyurethane adhesive offers high acoustic emission passivity (*Fig. 7b*) and is therewith predestined for acoustic emission measurements.

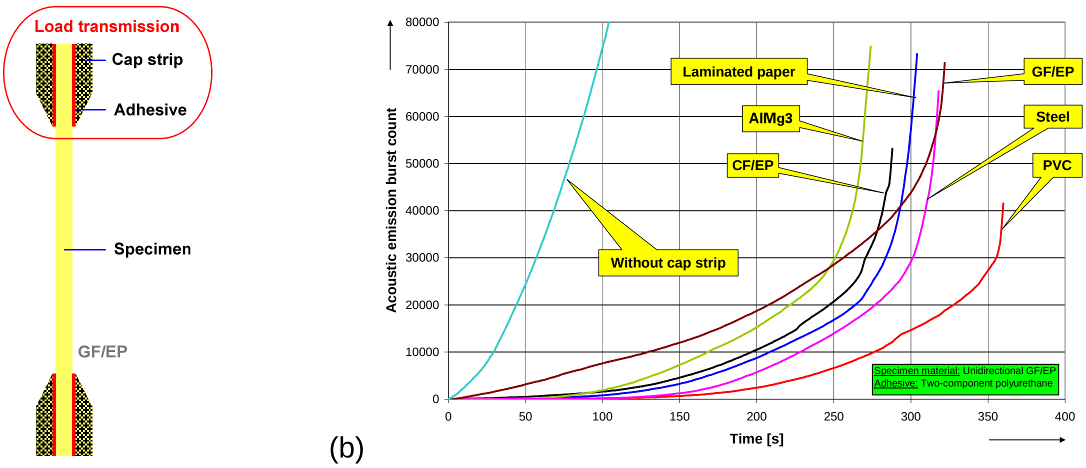


Fig. 7 (a) Load transmission, (b) Acoustic emission activity of different cap strip materials

In further studies, the influence of strain rate on the acoustic emission behaviour of CF/EP and GF/EP laminates was analysed. In the context of these investigations, the strain rate was increased in three steps within the range of two decimal powers. *Fig. 8a* shows, that the strain rate has a negligible small influence of the acoustic emission burst count in GF/EP composites. By contrast, the acoustic emission activity falls quasi linear with a rising strain rate in CF/EP laminates. This effect is based upon the phenomenon that evolving material-immanent damages only have insufficient time with increasing strain rate to release the elastically stored energy in terms of mechanical stress waves to the environment.

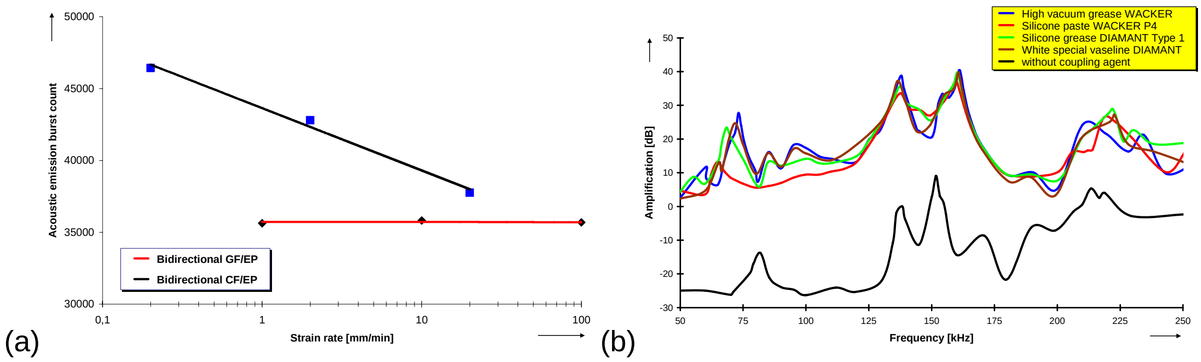
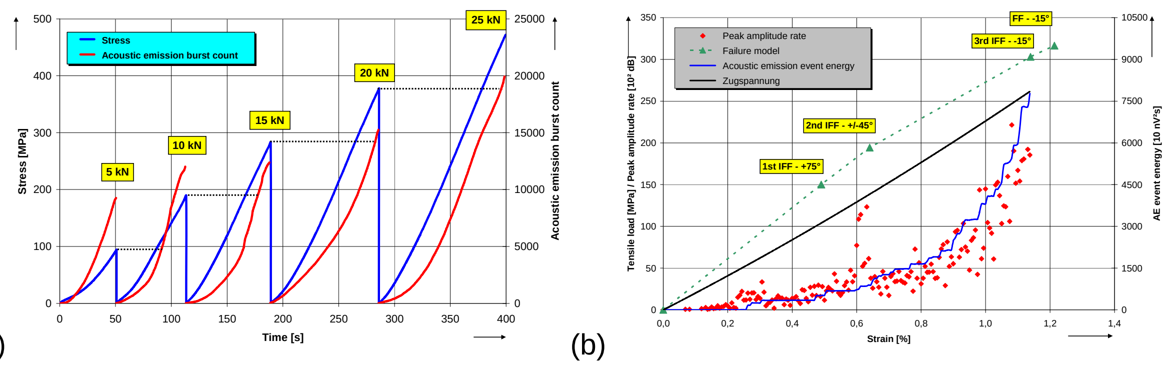


Fig. 8 (a) Effect of strain rate on the acoustic emission burst count, (b) Frequency response of the acoustic emission sensor PAC-R15 depending on the coupling agent

In concluding preliminary investigations, the influence of the coupling agent on the transfer characteristics of the acoustic emission sensors was analysed. In addition, different common couplants for example high vacuum grease, silicone paste and silicone grease were available. As a reference, the transfer behaviour of the acoustic transducers was recorded without the application of a couplant. For the evaluation of the frequency response curve of the senors, the so-called face-to-face-technique was applied. The corresponding experimental setup is specifically illustrated in *Fig. 5*. The synthetic sinusoidal test signal which is simulates a continuous acoustic emission and that is utilised for the examination of the measured frequency-dependent root mean square value of the acoustic emission signal is generated via a function generator and is inducted using an attenuator into the transmitter. Simultaneously, both the test signal and the received signal are detected by means of a calibrated oscilloscope and a voltmeter, respectively. The investigations show that there is a significant dependence of the sensor sensitivity on the used couplant. According to *Fig. 8b*, the highest sensitivity is realised with the application of the coupling agent WACKER HIGH VACUUM GREASE. Further, it can be observed that a displacement of the resonance points is effected as a function of the coupling agent.

DAMAGE ANALYSIS

An interesting acoustic emission phenomenon is the so-called KAISER effect which is based on the irreversibility of the acoustic emission behaviour of materials. The KAISER effect is characterised by the absence of detectable acoustic emissions until the previous maximum applied load level has been exceeded [11]. If a material is loaded very strongly for the first time, then the process-related residual stresses and external loads summate themselves. Thereby, irreversible transients can occur which stabilize the material and produce acoustic emissions. If the material is afterwards unloaded and stressed again after a short period, then the specified material processes proceed again only if the previous maximum load is exceeded. While the existence of the KAISER effect is undisputed for a multiplicity of metallic materials, the appearance of this reversible phenomenon in fibre and textile reinforced plastics is controversially discussed in numerous scientific publications [12-16].
In the context of the mechanical loading of composite materials contrary to the KAISER effect, the so-called felicity effect is often detected which describes the appearance of significant acoustic emissions at a load level below the previous maximum applied level [11]. Within the range of high stress levels, the KAISER effect is not definitely observed in thermosetting and thermoplastic fibrous composites. This fact is to be interpreted with the visco-elastic characteristics of the matrix material [17]. Due to the different damage entities and their complex interactions, a clear KAISER effect could not be verified on the basis of investigations on CF/EP laminates (*Fig. 9a*). But experimental observations suggest that the measured acoustic emission activity continuously decreases with repeated loading and unloading cycles. In pertinent literature this phenomenon is called acoustic emission shakedown [18]. Furthermore, the analysis of the acoustic emission behaviour clarifies the appearance of the so-called felicity effect in the researched case.



(a) (b)

Fig. 9 (a) Felicity effect on a fabric reinforced CF/EP composite, (b) Acoustic emission behaviour of a multiaxially reinforced CF/PEEK laminate in 45° direction

Allowing for the scientific expertise of the preliminary investigations, the gradual damage behaviour of different fibre and textile reinforced plastics was analysed experimentally. Due to the multiplicity of the researched laminates, a selected significant example is presented in this article. In the following, the successive damage is characterised regarding the acoustic emission activity and intensity behaviour on the basis of a CF/PEEK composite. The particular processes of the micro, meso and macro failure in different fibrous composites feature an individual acoustic emission characteristic. Thereby, for example significant alterations like jumps or knee points in the progression of the acoustic emission burst count or event energy indicate a damage progression, the achievement of instable damage phases or the occurrence of novel failure mechanisms. Out of the numerous studies, the cognition could be obtained that the time- and strain-dependent totalised descriptive information parameters, especially the acoustic emission burst count and the acoustic emission event energy, are suitable for the characterisation of the acoustic emission activity and intensity behaviour in textile reinforced plastics.

The initially leisurely and continuously running and later strongly progressively increasing activity and intensity progression indicates a very complex damage phenomenology. Due to the detected acoustic emissions, the gradual damage behaviour of the researched CF/PEEK composite can be classified regarding its acoustic activity and intensity into five characteristic damage phases which are represented in *Fig. 10* by the example of a specimen in 30° direction. The first period is associated with the occurrence of sporadic acoustic emission events with low energy, which indicate manufacture-induced inhomogeneities in the composite. Technically relevant damages are not anticipated here. In the second phase, acoustic emission events with middle amplitudes and a discontinuous energy release rate are detected which suggest primary crack initiations. With the crossing of this crack formation limit, the damage process begins which is associated with a slight cracking rate. The third phase is characterised from a continuous release of acoustic energy. The acoustic emission events increase linearly which can be interpreted with the formation of novel inter fibre failures. At the beginning of the fourth section, an increased release of acoustic emission energy is observed, consequently an exponential growth of the acoustic emission events with constantly increasing intensities is measured. The multiplicity of the detected acoustic emission events with high amplitudes characterise an inspection zone with innumerable material damages. The more inter fibre failures exist and degrade the cross section during a similar load, the faster further damages follow. In this phase, in the cracked single layers the crack saturation begins, whereby a characteristic damage state is obtained. In the last damage phase, a sudden progressive increase of the acoustic emission behaviour signalises the catastrophic final failure. This is characterised by an abrupt jump in the activity progress as well as by a narrow high energy intensity band (*Fig. 9b*). The increase may be regarded approximately as infinite and confirms the hypothesis that the final failure of fibre reinforced plastics result from the simultaneous tearing of several fibre bundles. This actuality could be verified on all tested laminates. Therefore, it is appropriate to define a critical point of the composite damage close to the transition from the quasi linear to the progressive acoustic emission behaviour (*Fig. 11*). After crossing this critical point the total failure of the composite is inevitable during a progressive load.

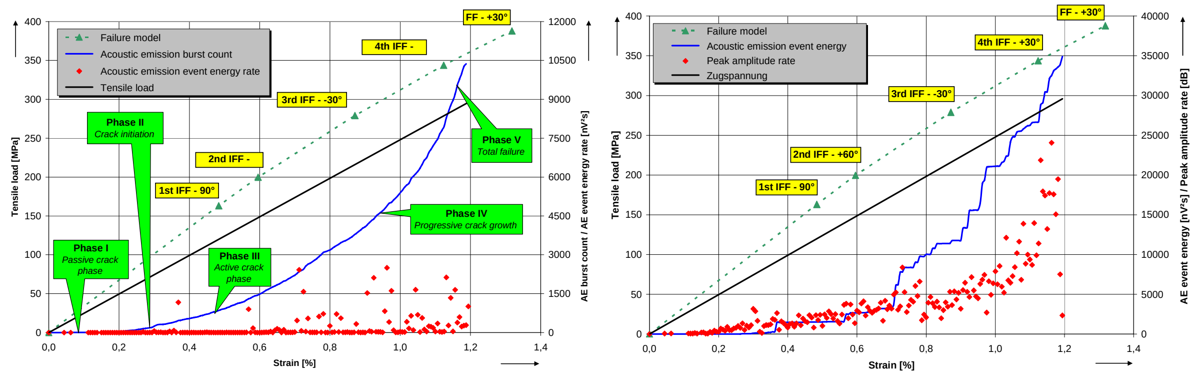


Fig. 10 Acoustic emission and deformation behaviour of a CF/PEEK laminate in 30° direction

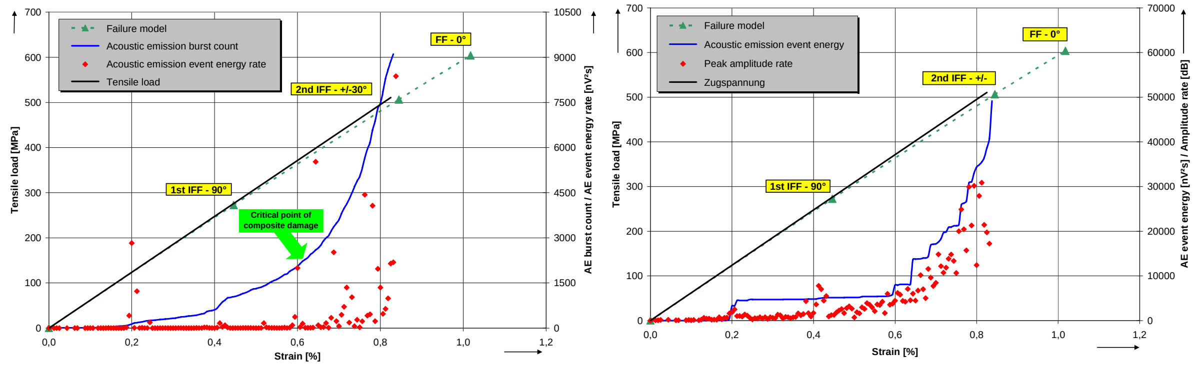


Fig. 11 Acoustic emission and deformation behaviour of a CF/PEEK laminate in 90° direction

CONCLUSIONS

The successive damage behaviour of textile reinforced composites was studied in uniaxial tensile tests and their time- and load-dependent failure processes was recorded and analysed via acoustic emission examinations. In systematic preliminary investigations this non-destructive evaluation could be optimised in regard to the elimination of background noises using the guard sensor principle. Referring to this, a load transmission consisting of polyvinyl chloride cap strips and two-component polyurethane adhesive with a very low acoustic activity could be developed. In the course of the numerous preliminary investigations, the transfer behaviour of the used acoustic emission sensor could be advanced by means of a suitable coupling agent. A further object of investigation was the reversible phenomenon of the KAISER effect which is deemed to be disputed at polymeric fibrous composites. The existence of the KAISER effect could not be verified in the researched laminates. In contrast, the felicity effect as well as the so-called acoustic emission shakedown phenomenon could be definitely detected.

The substantial studies show that the acoustic emission testing is suitable for objective determination of crack initiation points. Further, this non-destructive evaluation qualifies for the acquisition of the failure progression and documents a critical damage phase during the transition from the continuous to progressive acoustic activity and intensity behaviour. In addition, the catastrophic final failure of a thermosetting and thermoplastic fibrous composite can be forecasted already far before the real total failure by a strongly exponential increase of the acoustic emission activity accompanied by a narrow high energy intensity band. Due to the detected acoustic emissions, the gradual damage behaviour of the researched textile reinforced composites could be classified regarding its acoustic activity and intensity in an elementary failure model with five characteristic damages phases. Particularly, it could be shown, that significant alterations in the acoustic emission activity and intensity as a function of time or mechanical parameters are suitable for the identification of acoustic emissions sources and for the evaluation of damage phases in polymeric composites.

For the experimental analysis of different damage mechanisms via acoustic emission testing, the question of the most effective procedure arises in the future. It must be the ultimate ambition to differentiate the discriminative damage phenomena, to characterise the different failure types by one or more descriptive acoustic emission parameters and to assure and classify the obtained results in an acoustic emission material database. In principle, it is possible to provide a definite verification of each sonic-induced event via the acoustic emission analysis. Only if different recorded wave forms can be clearly assigned to certain damage phenomena, the possibility of an automatic categorisation of detected acoustic emissions via suitable pattern recognition methods exists. In this context, ultimate strengths and strains could be exactly determined. At this point, future investigations should start.

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