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Mechanical behaviour and damage mechanisms analysis of a flax-fibre reinforced composite by acoustic emission

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ABSTRACT

This article presents the mechanical characterization of an eco composite consisting of a thermoplastic matrix reinforced by flax fibres. Different configurations of specimens were tested with uniaxial tensile loading and their mechanical behaviours were discussed. Moreover, the acoustic emission technique was used to detect the appearance of damage mechanisms and to follow their evolution. In addition, a list of these mechanisms was established by means of macroscopic and microscopic observations. The acoustic emission records were post processed by the k-means unsupervised pattern recognition algorithm. Depending on the specimen configuration, three or four classes of events were obtained. The acoustic characteristics of these classes were compared. Then, a correlation between these AE events classes and the damage mechanisms observed was proposed. Their effects on the mechanical behaviour of the material were investigated by means of a variable called the Sentry Function.

1. Introduction

The use of eco composites has increased during the last decade [1]. To face recent ecological challenges, engineers are looking for lighter and greener materials for numerous applications, for example in transportation or sport and leisure industries. Composites reinforced with plant fibres are particularly interesting, especially flax fibres reinforced polymers (FFRP) [2]. Flax fibres exhibit specific properties sometimes better than those of synthetic glass fibres [3]. Their microstructure composed of coaxial layers reinforced by oriented micro fibrils gives them high mechanical strength and stiffness [4]. However, despite these advantages, FFRP tend to be still limited to non structural applications. Several technological limitations still have to be broken. Among them, the understanding and anticipation of micro damage mechanisms leading to the failure of the material. Moreover, the use of thermosetting matrices makes eco composites hard to recycle, reducing their environmental performances. In addition, thermoplastic matrices often depend upon manufacturing processes, such as thermo compression, which can damage the fibres due to the temperature required to melt the polymers. Moreover, thermoplastics are often incompatible with the manufacturing of large structures at small scales using processes such as resin transfer moulding (RTM) or resin liquid infusion (LRI).

Acoustic emission (AE) technique has been often used for the identification and characterization of micro failure mechanisms in composites [5,6]. Micro structural changes in materials release strain energy, resulting in the propagation of acoustic waves. These signals are recorded by sensors fixed on the material. Then, features are deduced from these acoustic bursts. Among them, temporal features are often used, such as amplitudes, energies and rise times [7,8]. Moreover, acoustic emission works performed on glass or carbon fibre reinforced composites often involve mixed time-frequency analyses [9–12]. AE technique has also been used for several natural fibre composites with different reinforcements and matrices [13–16] and at different observation scales. Rhomany et al. [17] used it during a tensile test performed on a flax fibre bundle to isolate the damage mechanisms related to technical fibres. They noticed three damage mechanisms. The lowest amplitudes were caused by the longitudinal separation of the elementary fibres inside the bundle. Then, events produced by fibre micro-cracking were recorded, followed by the complete failure of elementary fibres leading to the breakage of the entire bundle. Some authors also performed AE monitored tests on pure resin specimens. Several phenomena can be distinguished, such as matrix cracking and matrix/matrix friction [18]. At the composite scale, amplitudes between 40 and 60 dB are usually attributed to

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Table 1
AE characteristics of the main damage mechanisms in eco composites according to the literature.

Failure mechanism	Material	Characteristics	Ref.
Matrix cracking	Flax/LPET	Amplitude [40–50] dB	[19]
	Birch/Polyethylene	Amplitude [35–45] dB, duration [1–80] ms	[18]
	PP/Hemp and Chenovene	Amplitude [40–60] dB	[15]
	Flax/Epoxy	Amplitude [42–60] dB	[14]
Matrix-Matrix friction	Flax/LPET	Amplitude [40–55] dB, duration [20–120] ms	[19]
Fibre-matrix debonding	Flax/LPET	Amplitude [45–60] dB	[19]
		Amplitude [45–60] dB, duration [50–200] ms	
	PP/Hemp and Chenovene	Amplitude [60–65] dB	[15]
	Flax/Epoxy	Amplitude [60–70] dB	[14]
Fibre-matrix friction	Flax/LPET	Amplitude [55–85] dB, duration [100–600] ms	[19]
Fibre pull-out	Flax/LPET	Amplitude [60–80] dB	[19]
Fibre cracking	Flax fibre bundle	Amplitude [35–60] dB	[17]
Fibre breakage	Flax fibre bundle	Amplitude > 60 dB	[17]
	Flax/LPET	Amplitude [80–96] dB	[19]
	PP/Hemp and Chenovene	Amplitude [85–95] dB	[15]
	Flax/Epoxy	Amplitude [70–100] dB	[14]

matrix cracking. Fibre/matrix debonding is often attributed to amplitudes between 45 and 70 dB. Of course, the values of these intervals depend on the kind of fibres and matrix used. Friction phenomena (matrix/matrix or matrix/fibre) are sometimes ignored or included in the previous categories. Aslan [19] distinguished these events in the case of flax/LPET composites. Fibre failures are attributed to the events exhibiting the highest amplitudes and energies. They generally occur just before complete failure of the specimen. Data concerning fibre pull-out or fibre cracking is scarcer. In fact, these mechanisms are harder to isolate from the others. However, they are often attributed to amplitudes between fibre/matrix debonding and fibre breakage. In particular cases, especially for crossed-ply composites, the AE technique can be used to detect delamination [20]. However, this global phenomenon contains several damage mechanisms such as fibre pull-out and cracking, or fibre/matrix friction. Despite an increasing number of multi parametric studies, it is worth emphasizing that amplitude remains the classification feature the most often discussed in literature for natural fibre composites. Data concerning features such as duration and energy are scarcer [18,19]. Table 1 summarizes the values obtained by five different sources for different kinds of eco composites.

The present paper reports the production and the mechanical characterization of an eco composite made of a thermoplastic matrix reinforced by flax fibres. The matrix is a recent liquid thermoplastic resin initially developed for RTM processes, allowing the use of the liquid resin infusion technique. The composite obtained was subjected to quasi static tensile loading to investigate its mechanical behaviour. Moreover, the tensile tests were monitored by acoustic emission. The main objective was to identify the failure mechanisms occurring under the load, and to correlate their effects with the tensile behaviour of the material.

2. Material and experimental procedure

2.1. Materials and manufacturing

The reinforcement used in this work is a layer of unidirectional fibres held together without any twist. For this product (FlaxTape©) manufactured by LINEO [21], the fibres are sprayed with a mist of water that reactivates their external layer of pectin cement. This ensures the cohesion of the parallel fibres, and allows the handling of the layer without misaligning or separating them. For this study, the surface mass of the Flax Tape was 200 g·m^{-2}. The matrix is a thermoplastic liquid resin (Elium RT 150©) manufactured by ARKEMA. This acrylic resin is activated by peroxide (CH50x). It can be processed by RTM or LRI as a thermosetting resin, whereas the composite obtained after polymerization is thermoplastic.

Composite plates are processed by liquid resin infusion. A flat mould is initially prepared with a release agent. Unidirectional flax fibre sheets are manually cut from the reinforcement roll. The flax sheets are dried at 110 °C for one hour in a ventilated oven. The temperature and cycle have been determined to remove enough water without degrading too much the mechanical properties of the fibres [22]. After drying, the layers of flax are superposed on the mould in the desired stacking sequence. They are then covered with a peel ply and an infusion mesh made of a perforated film and a grid which increases the permeability of the medium. This stack of dry material is then covered by an impermeable flexible film, fixed to the mould by an adhesive sealer. This sealed bag contains a resin inlet, initially closed, and a flexible pipe connected to a vacuum pump. Maximum vacuum is applied and maintained for one hour at least to allow the degassing of the stacked plies. Then, the pressure is set to −0.5 bars, and the resin inlet is opened. The resin is distributed through the infusion mesh and impregnates the fibres. When the layers are totally impregnated, the resin inlet is closed and the vacuum is maintained until the end of polymerization.

Three types of unidirectional specimens composed of five flax plies were prepared for the tensile tests, with fibre directions of 90°, 45° and 0°. They were labelled UD-90, UD-45 and UD-0. Moreover, two kinds of crossed-ply specimens labelled CR-(0/90) and CR-(+45/−45) were manufactured with stacking sequences of [0/90/0/90/0] and [+45/−45/+45/−45/+45]. These specimens were chosen to favour damage mechanisms in particular configurations. UD-90 specimens were assumed to favour matrix cracking and fibre-matrix interface failure. UD-45 specimens were assumed to show a higher number of fibre-matrix debonding, due to a shear loading configuration. Fibre cracks were assumed to be detected just before the failure of specimens UD-0. Due to inter-laminar shear stress, delamination was expected to occur for CR-(0/90) specimen, a failure mechanism emphasized in CR-(+45/−45) configuration. Several samples were extracted from these different composite plates to determine their density. Their masses were measured with a weigh scale to the nearest 10^{-4} g. Their volumes were measured by weighing the samples immerged on water at room temperature based on the Archimedes principle.