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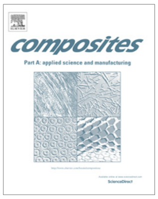

A thermo-viscoelastic approach for the characterization and modeling of the bending behavior of thermoplastic composites – Part II

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ABSTRACT

A proper description of the bending behavior is crucial to obtain accurate forming simulations, especially for continuous fiber-reinforced thermoplastic composites. These materials exhibit a highly temperature and bending-curvature dependent bending stiffness. These dependencies make the property challenging to characterize with conventional characterization methods, and therefore require novel techniques. The first part of the study has shown how Dynamic Mechanical Analysis and a rheometer-based method can be used to examine viscoelastic bending behavior. This subsequent part focuses on combining their advantages in a universal characterization method, which provides an accurate description of the bending behavior over a broad temperature range, including the phase transition of recrystallization. Dynamic isothermal experiments as well as dynamic experiments over defined temperature ranges were conducted. The aforementioned experiments were reconstructed in simulations, employing the non-linear viscoelastic material model from the first part of the study, to evaluate the characterization method and to further validate the model.

1. Introduction

Continuous fiber-reinforced plastics (CFRP) offer excellent mechanical properties, especially with respect to their density, and thus, are potentially capable of replacing metals in structural automotive and aerospace applications. However, while many non- and semi-structural parts are already being made of lighter materials such as light weight metals and unreinforced or fiber-reinforced plastics, the relatively high costs of CFRP and their complex material behavior oppose their widespread application in the significantly more cost-sensitive automotive industry [1].

The aerospace industry has been employing CFRP materials for decades, but mostly with thermoset resin matrices. The demand for short cycle times and recyclability [2], as well as reductions of emissions [3–5] in the automotive sector renders thermoplastic CFRPs more attractive, due to their re-melting capability and their processability via thermoforming. The thermoforming process is the most commonly used manufacturing technique to form thermoplastic prepreg sheets. Fig. 1 schematically depicts the process with its single steps. It is governed by the temperature change of the thermoplastic prepreg, as most of the mechanical properties of the prepreg are heavily temperature dependent. Due to the complex material behavior of CFRP, virtual prototyping is a crucial part of any industrial development process. Simulating the temperature governed thermoforming process requires the coupling of thermal and mechanical analyses [6,7]. Simulation results heavily depend on the quality of material properties taken into account, as proven by several studies [6,8–10]. Thus, the thorough characterization of such properties, including the examination of their temperature and other dependencies, is crucial in order to be able to conduct forming simulations with reasonable outcomes. The inherent temperature dependency makes such properties challenging to characterize [11], as most conventional characterization methods are designed for isothermal experiments or even at room temperature. Furthermore, since thermoplastics exhibit a viscoelastic behavior, dynamic measurement methods are essential for the characterization of their properties.

The characterization of the material's out-of-plane bending stiffness is important, as it determines the size and shape of wrinkles, while their formation also depends on further material properties [6,7,12,9,8,13,14]. Wrinkles, thereby, are one of the most common defects in parts made of CFRPs. However, currently there

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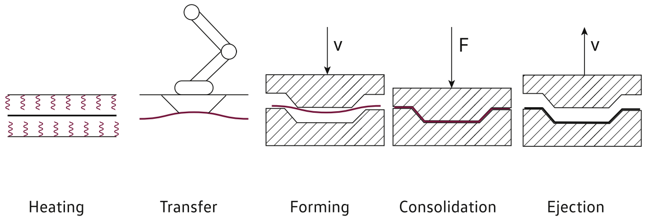

Fig. 1. Schematic of the thermoforming process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is no established method for the efficient characterization of the bending behavior. In some research publications, the cantilever test, usually used for the determination of the bending behavior of textile materials, is modified for high temperatures [14,15]. Nevertheless, it is limited to static experiments, delivering the long-term behavior. Dynamic mechanical analysis equipment was used in [9] for transient testing, but only at distinct temperatures, instead of a wide temperature range, as it occurs in thermoforming. Also, only a scalar value for the bending stiffness was retrieved, neglecting a curvature-dependency.

As discussed in the first part of the study [16], dynamic mechanical analysis (DMA) can be used to investigate both the temperature and deformation rate dependency of materials. It is a very versatile analysis method that allows for measurements over broad temperature and deformation rate ranges. However, DMA usually implements minuscule deformations, therefore phenomena based on inter-fiber and inter-roving movement will not be accounted for. Generally, when it comes to the characterization of the bending behavior. a bending curvature dependency cannot be thoroughly examined by DMA.

Experiments in a modified rheometer [17,16] allowed for a large deformation and a subsequent relaxation of the specimen, while the bending moment was measured by means of the rheometer setup. The experiments consisted of a single deformation and the specimens were subsequently held at maximum deflection. Hence, viscoelastic effects, e.g., relaxation, could be examined. Based on these results, a non-linear viscoelastic (NLVE) material model implemented in the parallel rheological framework (PRF) of Abaqus was fitted to the experimental data by an iterative optimization of the model parameters. This NLVE material model was deemed to be capable of representing the experimentally measured course of the bending moment with respect to the bending angle or time, respectively.

The promising findings have shown that the investigated test methods are capable of delivering detailed information about the materials bending behavior; however, a universal test method would be desirable that allows for both large deformations and dynamic testing over a broad continuous temperature range instead of isothermal experiments. Thus, building on these previous findings, the same rheometer bending setup was modified to perform various dynamic experiments. The results of those dynamic experiments are, on one hand, used to further validate the NLVE material model, and, on the other hand, to further develop the method towards the characterization of the bending behavior of thermoplastic composites over a continuous, broad temperature range.

In Section 2 the tested material as well as the experimental setup will be specified. Section 3 gives a brief review of the material model, used in the simulations, as well of previous experimental and simulative results in [16]. New iso-thermal dynamic experiments with oscillatory constant rate deformation as well as oscillatory sine deformation are presented in Sections 4 and 6, while corresponding simulation results are presented in 5 and 7. The results of experiments with oscillatory constant rate deformation and simultaneous cooling are finally presented in Section 8 along with a procedure to generate a material model which is capable of describing the bending behavior of a broad temperature range in Section 9.

2. Material and experimental setup

All experiments described in the scope of this work were performed on the same woven textile reinforced thermoplastic prepreg as in [16], Tepex 102 dynalite RG 600(x)/47% supplied by Bond-Laminates. The prepreg consists of a polyamide 6 (PA6) matrix enclosing a 2/2 twill glass fiber weave [18]. Main material properties are listed in Table 1. Fig. 2 depicts a specimen of the examined material, where the matrix material was etched off at the left side in order to expose the glass weave. The specimens were cut in such a fashion, that the fiber directions are aligned with the edges of the specimen, in order to avoid an influence of varying fiber orientations.

All experiments were performed on a modified rheometer setup developed at the University of Twente [17]. The device is similar to the bending test of the Kawabata Evaluation System (KES) but allows for experiments at elevated temperatures, as being equipped with a thermal chamber. The fixture, see Fig. 3, was specifically designed and consists of a rotating and a fixed part. The specimen is not clamped but resting loosely on support pins in the fixture in order to avoid the application of tensional or compressional strains and, thus, to ensure pure bending. This loose mounting allows the specimen to move, which introduces a frictional component into the experiments. A sticking of the matrix material to the fixtures and a high friction between them is avoided by covering the contact surface of the specimens with a polyimide tape. Aside from the precise temperature control by means of the thermal chamber, the rheometer also allows for the application of different rotational velocities to deform the specimen in order to identify for a strain rate dependency of the bending behavior. In order to avoid degradation by oxidation at elevated temperatures, the chamber is flooded with nitrogen gas.

The specimens are 35 mm long and 25 mm wide, while the thickness is determined by the material. The area of the specimen which is bent in between the two fixtures is 15 × 25 mm^2.

In *Euler-Bernoulli* beam theory, also known as classical beam theory, the product of *Young*'s modulus E and moment of inertia I is referred to as flexural rigidity. In order to account for the fact,

Table 1
Main material properties [18].

Trade name	Tepex dynalite 102-RG600(x)/47%
Matrix	PA6
Fibers	Glass
Reinforcement type	Twill weave 2/2
Fiber volume (%)	47
Density (gm/cm^3)	1.8
Thickness (mm)	0.5
Melting Temperature (°C)	220

Fig. 2. Tepex material; matrix removed on left side, exposing the glass weave. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)