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Bending characterisation of a molten unidirectional carbon fibre reinforced thermoplastic composite using a Dynamic Mechanical Analysis system

A. Margossian [a], S. Bel [b], R. Hinterhoelzl [a,*]

[a] Institute for Carbon Composites, Technische Universität München, Faculty of Mechanical Engineering, Boltzmannstraße 15, D-85478 Garching b. München, Germany
[b] LGCIE Site Bohr, Université Lyon 1, 82 Blvd. Niels Bohr, Domaine Science DOUA, F-69622 Villeurbanne Cedex, France

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ABSTRACT

The quality of forming simulations based on Finite Element methods is mainly determined by the accuracy of the material properties. Out-of-plane bending is one of the deformation mechanisms that govern the appearance of wrinkles while forming composite reinforcements. This paper proposes a new test method using a Dynamic Mechanical Analysis (DMA) system for the characterisation of longitudinal out-of-plane bending properties of molten unidirectional thermoplastics. Investigations are presented for a unidirectional carbon fibre reinforced polyamide 6 composite. Several standard bending test fixtures are assessed quasistatically at three temperatures and three test speeds with specimens of different geometries. Additional tests are conducted at forming temperature with the selected test arrangement. The evaluation of different approaches for the calculation of the bending modulus shows the interlaminar shear to be negligible. Results highlight an important material strain rate dependency. The evolution of the bending modulus satisfies a linear fitting within the range of data.

1. Introduction

Because of new ecological challenges, the share of metallic parts in the transportation industry tends to decrease in favour of new material types such as Carbon Fibre Reinforced Polymers (CFRPs) [1]. CFRP components are particularly interesting since they offer higher specific mechanical properties than their metallic counterparts. Although thermoset composites have been more extensively considered so far, thermoplastics appear today to be very good candidates to address future challenges through their better recyclability potentials [1,2].

However, one of the main drawbacks of composites lies in their cost. Over the last decades, automatised processes which enable reduce labour time and thus cost savings, such as Automated Fibre Placement (AFP) and Automated Tape Laying (ATL) technologies, have shown good potential for the processing of unidirectional pre-impregnated composites [3]. These machines can be fed either with thermoset or thermoplastic tapes which are directly laid down onto a mould. The material is often locally softened by use of a laser or infrared heaters to ease the layup process. To prevent air entrapment between the layers, a compaction roller is used to compact the material. An exhausting review of the different existing methods is given by Lukaszewicz et al. [4]. The restriction of these automated equipment lies in their capability to lay up tapes on complex geometries, i.e. highly curved components with short radii. Moon et al. correlated the occurrence of defects to the smallest steering radius encountered during the process [5]. To overcome common defects induced by AFP and ATL technologies, e.g. tow buckling and bridging, and to use the main advantage of these machines, i.e. high layup rates, an alternative process has arisen. Instead of laying up tapes directly onto a mould, tapes are rather laid down onto a flat plane and formed in a subsequent step. Such blanks are called customised since they are composed of several layers of unidirectional pre-impregnated tapes oriented in different directions. The usage of customised blanks for forming purposes already showed good potential for cross-plied stacks of unidirectional pre-impregnated composites [6–8]. In the case of thermoplastics, customised blanks are subsequently consolidated before being processed, e.g. by means of a thermoforming process. Thermoforming is a manufacturing method that consists in forming consolidated customised thermoplastic blanks into complex 3D-geometries using a thermoforming unit [9–11]. The combination of pressure and temperature enables the material to deform.

* Corresponding author. Tel.: +49 89 289 15072; fax: +49 89 289 15097.
E-mail address: hinterhoelzl@lcc.mw.tum.de (R. Hinterhoelzl).

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As reported in the literature, automated forming methods such as thermoforming processes are also prone to defects. Among others, common flaws concern fibre re-orientations and wrinkles [12–15]. To avoid time and cost expensive trial-by-error approaches, simulations based on Finite Element (FE) methods have been developed [16–21]. These enable a better understanding of the forming process ahead of any trials by providing insights on the interactions existing between the different stakeholders (composites, tooling etc.). Depending on the level of details, i.e. macro- or meso-scale [16,17], simulations can predict the potential defects that could arise on part or tow level, respectively.

The quality of FE forming models is mainly governed by the accuracy of the input parameters [14,22]. Nowadays, experimental forming methods are modelled as isothermal processes. Therefore, if experimental forming processes occur under specific environmental conditions, material properties given as simulation inputs have to be determined accordingly. This is for example the case in the modelling of thermoforming processes in which thermoplastic composites have to be characterised in their molten states.

This paper proposes an innovative test method using a Dynamic Mechanical Analysis (DMA) system for the characterisation of longitudinal out-of-plane bending properties of molten unidirectional thermoplastic composites. The need of a new approach is motivated through a review of current characterisation test methods. Subsequently, the capabilities of the DMA system are assessed at three temperatures and three test speeds for four different standard test fixtures and two different specimen geometries. Once the most suitable test configuration is defined, the characterisation of a unidirectional carbon fibre reinforced polyamide 6 (PA6) composite is performed at forming temperature for different test speeds. Finally, different approaches for the calculation of the bending modulus are compared. The strain rate dependency of the bending modulus is subsequently evaluated with the selected theory.

2. Bending in FE forming simulations

Forming simulations based on FE methods are developed in order to anticipate the occurrence of potential flaws during experimental forming. Defects such as fibre re-orientations and wrinkles (both in-plane and out-of-plane) are typically sought since they alter the mechanical performances of the final components [23]. Besides, out-of-plane wrinkles, also referred to as out-of-plane buckles, also affect the shape of the component [24,25]. The occurrence of out-of-plane wrinkles is complex and has been studied by several researchers. For a given material, experimental studies reported that, amongst other factors, stress conditions induced by manufacturing boundary conditions, forming speeds, original blank dimensions and strain gradients play a role in their development [9,25–28]. Considering simulation, Boisse et al. also showed that the appearance of out-of-plane wrinkles is a global phenomenon which depends on boundary conditions and all types of strains and stiffness [14]. Sensitivity analyses particularly showed that the material bending stiffness mainly determines the shape of the wrinkles. In a latter study, Haanappel et al. indicated that an increasing bending stiffness leads to a reduction of the number of wrinkles [20]. Correlations between the material bending stiffness and the shape, the size and the quantity of wrinkles have also been recently made by Liang et al. [29].

The determination of accurate out-of-plane bending properties is essential for the precision with which out-of-plane wrinkles are computed by FE forming simulations. In the following, the main test methods used to investigate out-of-plane bending properties are presented. The capabilities as well as the limits of each test method towards pre-impregnated composites are detailed.

3. Review of existing test methods

Although some test methods developed at room temperature can easily be accommodated within environmental thermal chambers, e.g. picture frame/bias-extension tests [30–32], the adaptation of conventional bending test setups is more complicated. An overview of the main test methods developed to determine out-of-plane bending properties of dry reinforcement and pre-impregnated composites is presented in Table 1.

Although various types of setups have been developed throughout the years, most of them are adapted from the cantilever test developed by Peirce [33]. In this test setup, a rectangular piece of material is laid on a support. The specimen is gradually pushed over an inclined plane. The test is over when the tip of the material comes into contact with the incline plane. Thanks to mechanical relationships, as well as the inherent properties of the specimen, the bending stiffness can be calculated. A variant of this test was proposed by Bilbao et al. in 2008 [34]. The device introduced by Bilbao et al. offers the main advantage to vary the load to which the specimen is subjected. To do so, the specimen is placed on top of a support composed of laths. By their removal, the overhang length of the specimen is subjected to gravity and thus bent under its own weight. As described by the authors, the test is a succession of quasistatic experiments with different load cases. The displacements of the specimen are successively recorded by a digital camera which enables to report the shape of the specimen. Until recently, all variants of cantilever tests were only suitable for tests performed at room temperature. In 2014, Liang et al. proposed an adaptation within an environmental thermal chamber [29]. Investigations proved the method to be applicable to the characterisation of thermoplastic composites through a control of the testing temperature. However, the usage of defined strain rates was not made possible since specimens were only subjected to gravity.

Soteropoulos et al. [23,35] identified that the tips of the specimens tested with a cantilever setup are often twisted while bending due to non-linear loading effects. To evacuate this issue, Soteropoulos et al. designed a test in which specimens are hung vertically and thus aligned with gravity. In this setup, a load is attached to a string linked to the tip of the specimen. By using a digital camera and attaching different type of loads, the displacement of the specimen can be recorded and the bending stiffness determined. To the author's best knowledge, this method has not been applied under regulated environmental conditions yet. Other test setups such as the Kawabata test, which are appropriate for the characterisation of out-of-plane bending properties at room temperature, have also never been used under regulated conditions [36]. In the middle of 1990s, Martin et al. proposed an innovative test method composed of a Vee-bending fixture mounted on a tensile testing machine and enclosed in a thermal chamber [37]. In a latter study, Dykes et al. proposed an enhanced version of this test setup. The new design of the fixture ensured constant shear deformation rates at the supports [38,39]. However, the Vee-bending technique cannot be considered as a method used to characterise out-of-plane bending properties. In fact, the main goal of these analyses was to investigate the longitudinal and transverse viscosities of molten unidirectional thermoplastics. Therefore, bending tests were performed such that inter-ply shear becomes the main deformation mode.

For the analysis of the bending behaviour of thermoplastic composites, a novel approach using a rheometre and a dedicated environmental chamber was suggested at the University of Twente [22,40–42]. The rheometre is an oscillating rotational testing machine which offers a close temperature control and the application of different rotational velocities. The idea of the setup can be assimilated to a variant of the Kawabata test enclosed in a thermal