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Forming of carbon fiber reinforced thermoplastic composite tubes – Experimental and numerical approaches

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ABSTRACT

Continuous-reinforced thermoplastic composites are of growing importance for series production of lightweight components in manifold industrial areas. Novel manufacturing technologies allow the production of hollow semi-finished products that are post formed to enhance functionality. To maximize efficiency in the development process of such components it is necessary to evaluate the forming processes numerically using Finite Elements (FE)-methods. The aim is to perform feasibility studies at an early stage, reduce development time by virtual process optimization and to generate a detailed understanding of the post formed fiber architecture for further structural-mechanical analysis.

Introduction

Composite materials such as carbon fiber reinforced plastics exhibit outstanding mechanical performance at low material densities, thus offering the potential of significant weight reduction in structural lightweight components. In contrast to thermoset matrices thermoplastic matrices offer shorter processing times, a technically unlimited shelf life and direct recyclability [9]. Especially their thermoformability and weldability open up new processing options. One example is a production system based on economically manufactured semi-finished products, such as sheet material and cylindrical tubes, with subsequent forming processes analogous to metallic materials.

At the Institute of Lightweight Engineering and Polymer Technology (ILK), thermoplastic pre-consolidated tape material is braided, resulting in seamless tape preforms with load adapted multi-axis fiber orientations [5]. In a subsequent processing step pultrusion is used to manufacture consolidated composite tubes. These textile reinforced structures are well suited for post-forming processes such as flanging forming. During the forming process, the textile bindings prevent excessive fiber slipping and the formation of fiber-uncovered spots. However, the same effect may limit the degree of forming.

To assess the process limits for forming such textile reinforced thermoplastic composite tubes, adjusted process simulation methods are needed. Thus, process development time can be kept low and time consuming and therefore costly adjustment procedures can be avoided. Currently, most forming simulations of textile reinforced composites focus on draping flat fabric products into three-dimensional shapes [2,10]. To describe the textile deformation and the subsequent material forming behavior in detail, various testing methods have been established [1,3,8,11,13,14]. The potential of forming simulation for hollow textile reinforced thermoplastic-composites is investigated in this study. To determine the deformation behavior of the braided tubular structures testing methods have been adapted.

Composite tube application

Especially in mobility systems like automobiles, airplanes and ships, composite tubes can be used as driveshafts, frame structures or hydraulic system components. In most structural applications load introductions or functional elements are usually required of which most are made of metallic materials. The necessity of joining operations leads to an additional processing effort, such as precision drilling of holes for bolted connections or surface treatment and quality control for adhesively bonded connections. Thermoplastic composites offer additional possibilities to efficiently join separate components by utilizing welding or forming operations or a combination of both. Thus, significant cost savings

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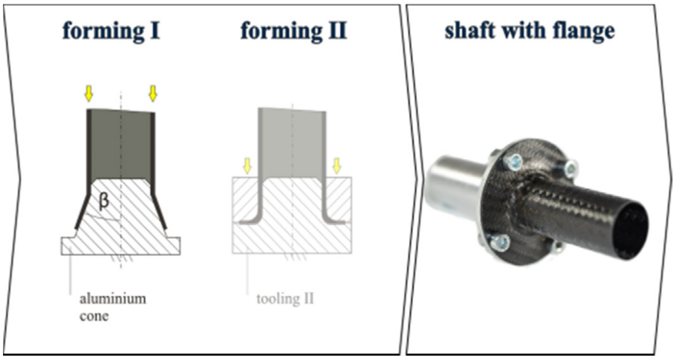

Fig. 1. Forming process of composite shafts with integrated flanges using thermoplastic semi-finished products: schematics of process step I and II and a resulting demonstrator part.

in the manufacturing and assembling process can be expected. The highest weight-saving potential can be found in all-composite designed components.

Thermoset matrices require a high preforming effort, thus increasing the component cost. With thermoformable thermoplastic semi-finished products, this drawback can be overcome. For this, the process limits have to be investigated. Especially for driveshafts, which are subjected to torque loads, flanges are commonly used for load introduction systems. This paper investigates the options and process limits for the forming of integrated flanges made of braided thermoplastic tubes (Fig. 1) and the corresponding simulation processes, focusing on forming process step I.

For thermoplastic tube forming experiments, a consolidated braided tube will be used. The layers are braided from pre-impregnated tapes with 50% fiber volume. For the 3 mm wide tapes unidirectional carbon fibers impregnated with a thermoplastic PA6 matrix are used. The braid angle is ±45°, with a balanced twill braid interlace. Fig. 2(b) shows the braided tube material. A pultrusion process is used to manufacture 3-ply semi-finished tubes. The wall thickness of the 3-layer tube is 0.75 mm.

Braided material testing for forming simulation

To determine realistic parameters for "as manufactured" conditions, braided hoses were used to manufacture flat specimens. The plates were consolidated in the autoclave at 240 °C and a pressure of 5 bar. The main deformation mode is occurring during textile forming is the intra-ply shear mode. Textile shear is also known as the trellis effect and is generally referred to as rotation of the yarns about the textile's crossing points [16]. Typically, this deformation behavior results in a progressively increasing nonlinear shear resistance. For an experimental determination of this shear resistance different test methods and test devices have been developed [4,8,13,14]. The Bias-Extension-Test (BET) is a very straightforward methodology, especially with regard to specimen preparation and test procedure [3]. Compared to other test methods, the BET offers the advantage of testing the flattened tube material which is limited in width. The specimen with a defined height-to-width ratio and a fiber orientation of ±45° is clamped and pulled similar to conventional tensile tests within a conventional testing machine. During tensile deformation three characteristic zones A, B, and C form. Fig. 2(a) illustrates this kinematics of shear deformation. As proposed in [12], the shear angle in zone C can be calculated from the kinematic relationship by using of crosshead displacement. In contrast to other test procedures, the interpretation of BET's is significantly more complex due to the occurrence of the mentioned different shear zones.

Launey et al. derived an implicit formula to determine a normalized shear force, taking the shear zone B and C into account [11]. The shear force behavior was examined at different temperatures and quasi-static displacement velocities. Temperatures at the beginning of melting at 220 °C, at the maximum forming temperature of 240 °C, as well as intermediate values of 225 °C and 230 °C were chosen. Tests at the beginning of softening at 180 °C are not useful, due to the occurrence of preliminary specimen failure without significant shear deformations. Fig. 2(c) shows the results with a logarithmic scaled force axis. The experiments indicate that at temperatures near the melting point shear appears only at high resistance forces. At 220 °C the specimen failed at a rather early stage. The measured forces decrease further with increasing temperature. Above melting temperature the specimens are stretched significantly over the displacement point. According to the kinematic equation, the maximum shear angle is reached at this point. This is a sign of early fiber slippage and has already been observed and studied e.g. by Zhu et al. [17].

For a numerical identification of possible out of plane wrinkling, the characterization of the materials specific bending stiffness is required. An experimental setup based on cantilever bending method according to DIN 53362 is used (Fig. 3a). To capture the occurring viscous effects with this quasi-static test method, the experiments were carried out at 240 °C. It is known that the flexural properties of bidirectional reinforced composites are dependent on the direction. The bending tests were carried out in ±45° fiber direction. The experimental results are illustrated in Fig. 3(b).

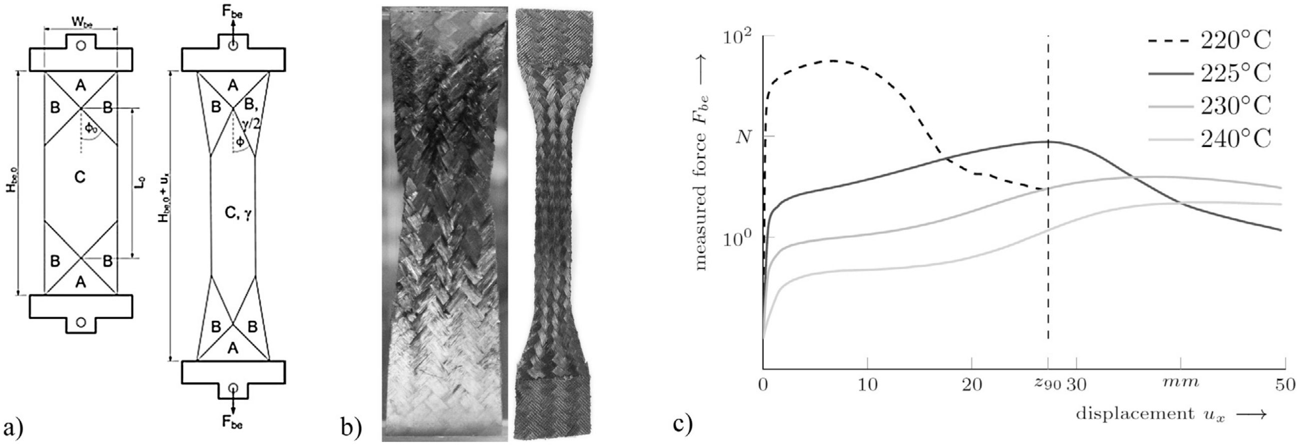

Fig. 2. Bias-Extension-Test: (a) Characteristic shear zones, (b) deformed test specimen for different test temperatures and (c) results for 220 °C, 225 °C, 230 °C and 240 °C.

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