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Original Research Article

Thermoplastic fibre metal laminates: Stiffness properties and forming behaviour by means of deep drawing

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ABSTRACT

Hybrid materials provide a high potential for lighter structures and an improved crash performance. The investigated hybrid sandwich laminate consists of steel cover sheets and a carbon fibre-reinforced thermoplastic core. The first part of this investigation is focusing on an analytical prediction as well as on a comparison of numerical and experimental results for the evaluation of the laminate properties to get a general understanding for the material. Within the second part the forming behaviour of this material is investigated experimentally, analytically and numerically by means of cup deep drawing. These results indicate that cup deep drawing of thermoplastic fibre metal laminates is possible but limited. The limits in terms of achievable drawing depths are found to be defined by cracking and wrinkling of the cover sheets as well as fibre failure in the composite material.

1. Introduction

Among other advances such as the technical improvement of the propulsion system, lightweight engineering plays a major role in the development of electric vehicles [1]. Ultimately, the cost reduction due to the reduced battery capacity that results from the weight reduction outweighs the additional cost for an innovative lightweight design.

Function-integrative system lightweight engineering in multi-material-design therefore presents a great opportunity for the development of resource-efficient products [2]. Nevertheless,

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significant challenges have to be overcome to compensate for the additional weight and cost associated with a battery powered electric propulsion system. This can be achieved with new material combinations, load-adapted constructions and a high degree of function integration in mass production.

Lightweight engineering with sandwich materials such as LITECOR® from thyssenkrupp is the state of the art. Furthermore, an improvement of the sandwich properties can be achieved by adding fibre-reinforcement into the core. The excellent properties of comparable steel hybrid composites are already known from investigations within the InEco®-Project [3]. Also fibre metal laminates (FMLs) which are made up of metal (mainly aluminium) sheet layers bonded to composite material layers combine advantageous properties from both metals and composites. These include impact and corrosion resistance, decreased metal fatigue, fire resistance and lower weight [4,5].

Fibre metal laminates have shown their advantages for aerospace applications concerning damage tolerance and their potential for lightweight design [6]. For these constructions a thermoset matrix composite is used which results in a long processing cycle to cure the polymer matrix [4]. The processing time and associated costs can be reduced when using a thermoplastic matrix [7]. Furthermore, the damping properties, damage tolerances and properties in terms of impact and fatigue strength as well as the recyclability can be improved when using a thermoplastic rather than a thermoset matrix for fibre metal laminates [8].

For the application in the automotive industry, short production times are necessary. This can therefore be achieved by using thermoplastic materials, which can be formed several times by melting before and solidifying after the forming process. For the channel forming of a fibre metal laminate with a glass-fibre reinforced polypropylene core and 0.5 mm aluminium thick cover sheets, [9] already found that a certain preheat temperature, a heated press tooling and a rapid transfer to the tool press should be ensured to properly form such sandwich laminates. This can be attributed to the limited temperature process window of the thermoplastic core. As a consequence thereof, increasing the feed rate is also beneficial for the forming process [10]. In this context, the analytical or numerical modelling of the forming process is very important. Approaches from literature are presented subsequently.

Mosse et al. [11] suggested a three-layer approach with elastic–plastic shell elements for the metal covers and a textile element formulation for the core layer allowing for large in-plane shear deformations without bending stiffness. They tried friction coefficients in the range between 0 and 100 to explore the contact interaction between the layers and concluded that rather low values lead to a more accurate representation of the corresponding experiment. A testing procedure to measure the frictional behaviour was presented by ten Thije et al. [12] and provided friction coefficients between 0.05 and 0.4 depending on the testing conditions. DharMalingam et al. [13] also used a three-layer approach in LS-Dyna with shell elements to simulate the forming of an aluminium/Twintex/aluminium FML through deriving the material parameters of the core at thermoforming temperature from test data of the solid state. They stated that the elastic constants at thermoforming temperature only differ from those at room temperature in that the Poisson's ratio as well as the in-plane shear modulus (almost) vanish when the matrix reaches its melting point. Abbassi et al. [14] confirmed this fibre-dominated core behaviour by determining orthotropic elastic constants through different tests. Dong et al. [15] deployed the Abaqus code to describe the draping of composites with an updated material law since the angle between the warp and weft directions of the fibres usually change during forming. Behrens et al. [16], in turn, utilised LS-Dyna to mimic a steel/glass fibre-PA6/steel FML by treating the fibres and the matrix mechanically separately. Their work showed that the squeezing and intake behaviour of a unidirectional reinforced core can be predicted properly with this modelling approach.

A core of carbon fibre-reinforced thermoplastic material, so-called organo sheets, in combination with cover sheets of steel is investigated within this work. The core is used to increase the tension as well as the compression stiffness in the fibre direction and the steel cover sheets are used to build the laminate with increased bending stiffness orthogonal to the fibre-reinforcement. The first part of this investigation is focusing on an analytical prediction as well as on a comparison of numerical and experimental results for the evaluation of the laminate properties to get a general understanding for the material. Within the second part the forming behaviour of this material by means of cup deep drawing is investigated experimentally, analytically, and numerically. Semi-finished products with different composite layups were investigated during this work. Nevertheless, all materials consisted of two 0.25 mm thick HC220Y steel cover sheets and carbon fibre-reinforced polyamide 6 (PA6) with a fibre volume content of around 45%. The steel cover sheet thickness of 0.25 mm was set due to the fact that this was the thinnest galvanised steel sheet type with a larger width commercially available through project partners. The sandwich material was merged in a fully automated production process, as described in [17].

2. Properties of carbon fibre-reinforced metal laminates

This first part includes an analytical prediction of the laminate properties for a comparison with a reference material as well as a comparison of numerical and experimental results for the evaluation of the laminate stiffness to get a general understanding for the material. The analytical prediction of the laminate properties therefore shows that the properties of those laminates are predictable and can precisely be compared with traditional materials. The comparison of the experimentally determined and numerically predicted spring stiffness shows a simple approach of evaluating different laminate layups and demonstrates the influence of the forming on the mechanical properties.

2.1. *Analytical prediction of laminate properties*

For an analytical evaluation of the material combinations as shown in Fig. 1, an analytical method has been developed [18]. For a given cover sheet thickness t_D, the analytical method