NUMERICAL MODELING OF SINGLE-STEP THERMOFORMING OF A HYBRID METAL/FRP LIGHTWEIGHT STRUCTURE

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Abstract
We present simulation results for the simultaneous forming process of metal and composites. A multi-scale modeling approach for the fiber-reinforced plastic (FRP) is proposed, starting from the thermo-mechanical properties of the polymer matrix and the anisotropic elastic response of the reinforcement to determine the anisotropic thermo-mechanical behavior of the composite. Based on thermo-mechanically coupled deep-drawing simulations, a parameter study is carried out using the commercial FE software LS-DYNA to determine correlations between process and material parameters and the occurrence of defects in the final workpiece.

1. Introduction

Numerical optimization of the production process of lightweight assemblies consisting of metal and fiber-reinforced components is of high importance [1]. It can reduce the time to market and can avoid the production of costly prototypes. The considered one-step thermoforming process consists of deep-drawing the metal sheet with a pre-heated fiber-reinforced-thermoplastic. The forming process and plastic flow of the matrix material induce local changes to the fiber orientation. During the following cooling phase, delamination may occur because of anisotropic properties of the FRP and different thermal expansion coefficients of metal and composite which will cause residual stresses. These processes strongly affect the shape and loading capacity of the final work piece [2].

2. Material modeling and parametrization

In the present paper the manufacturing of a hybrid structure consisting of a metal component and a semi-finished composite plate with a thermoplastic matrix and endless carbon fibers is considered. For numerical investigations of the forming process suitable material formulations and corresponding parameters must determine first. The aim is to model the FRP as a pre-consolidated non-flexible sheet at room temperature as well as a deformable textile coated by its melted matrix at process temperature.

2.1. Metal sheet

The numerical simulation of metal parts and structures is widely used in industrial applications. It is applied to predict the behavior of the workpiece especially in deep drawing processes regarding thickness development and wrinkling. The accuracy of the simulation depends on the material models for the plastic material behavior. Different yield criteria were developed in the last years whereas the number increases due to new materials involving complex material behavior [3]. Since the project is more focused on the precise prediction of the forming behavior of the FRP, a DC05 non-alloy steel is considered. For this kind of material, a temperature independent elastic-plastic material model with a Hill48-yield criterion [4] can adequately predict the forming behavior of the metal sheet.

2.2. Fiber-reinforced thermoplastic

For the thermo-mechanical modelling of the reinforcement, a pre-implemented material law "Fiber-Reinforced-Thermoplastic" (MAT249) [5] is used. The overall stress response $\boldsymbol{\sigma}$ consists of a superposition of the stresses in matrix $\boldsymbol{\sigma}^{\mathrm{m}}$ and textile $\boldsymbol{\sigma}^{\mathrm{f}}$ as

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^{\mathrm{m}} + \boldsymbol{\sigma}^{\mathrm{f}} \,. \tag{1}$$

The matrix is modeled with a simple thermal elastic-plastic constitutive law, that allows to include the mechanical parameters like stiffness, Poisson's ratio or flow rule as function of temperature.
Tension/compression and shear response of the reinforcement can be treated separately with up to three distinguished fiber directions. Orientation $\vec{m}_i$ and stretch state $|\vec{m}_i|$ of the textile are given as internal vectorial variables that can be calculated by

$$\vec{m}_i = \boldsymbol{F} \cdot \vec{m}_i^0 \tag{2}$$

using the deformation gradient $\boldsymbol{F}$. With this model, the support effect of the matrix material can be

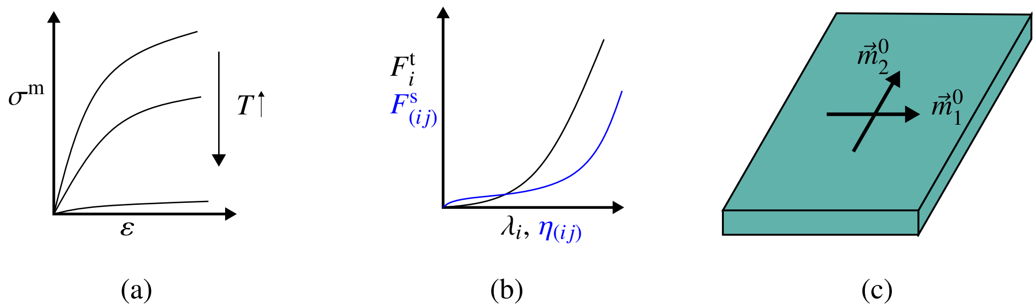


Figure 1. Modeling of thermo-mechanical behavior of FRP: (a) Qualitative stress-strain curves of matrix material at different temperatures; (b) Qualitative force-deformation curve of uniaxial tension test (black) and force-shear angle curve between fiber i and j of picture-frame test (blue) of the textile; (c) Schematic illustration of material model with two fiber directions

reduced with increasing temperature up to a vanishing stiffness at melting temperature T_{m}. This formulation is suitable to model the composite as a stiff pre-consolidated sheet at room temperature which will become more flexible at process temperature due to the melting matrix material.

2.2.1. Temperature dependent material parameters of the thermoplastic matrix

Polyamide 6.6 (PA6.6) was selected as matrix material. Stress-strain curves of PA6.6 in a temperature range from −40 °C to 150 °C and strains up to 4 % were taken from the
Campusplastics-Database [6]. Stiffnesses and initial yield stresses were determined according to Eherenstein [7]. Stiffnesses below the glass transition temperature T_{g} are fitted using an Arrhenius type equation and above T_{g} by a William-Landel-Ferry law. For temperatures above the melting point ($T_{\mathrm{m}} \approx 260\,°\mathrm{C}$) the stiffness is assumed to vanish. However, for numerical stability an artificial residual stiffness was included. Flow rules were empirically extrapolated according to [8] for temperatures

close to T_m. Finally, the curves that describe yield stress as function of strain were extrapolated for higher strains using the approach

$$\sigma_\mathrm{y} = A \cdot (\varepsilon_\mathrm{p} + B)^n - C \tag{3}$$

by Gosh. Figures 2a and 2b show the qualitative dependencies of stiffness and flow rule with respect to temperature. Those values are important to accurately predict the forming behavior as well as the occurring residual stresses while cooling down the components after forming.

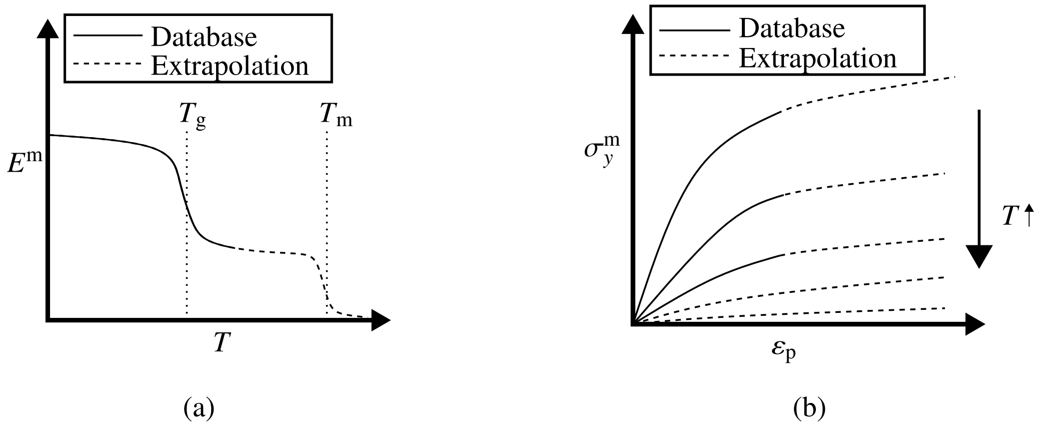


Figure 2. Extrapolation results for matrix material: (a) Stiffness vs. temperature; (b) Flow stress vs. plastic strain at different temperatures

2.2.2. Deformation behavior of textile

During the forming of a textile into a three-dimensional shape, the three basic deformation mechanisms shear, tension and bending can be observed. The main parameters for textile characterization are the force-deformation curves under tensile and bending loads as well as the shear force vs. shear angle curve. In-plane shear deformation is the main deformation mechanism during the forming of typical technical textiles. To model this mechanism, shear force vs. shear angle curves are required, which can be determined using a picture frame test as illustrated in fig. 3a. The recorded shear force vs. shear angle curves are typically strongly non-linear (cf. Fig. 1b), since the shear force increases due to the increasing contact of adjacent fibers. This behavior finally ends up in a so-called locking angle, from which no further deformation without wrinkling is possible.
The characteristic force-deformation relationship for the in-plane tension can be determined according to DIN EN ISO 13934-1 in a basic tensile test on strip specimens (see Fig. 3b). The out-of-plane bending behavior of textiles strongly affects the development of wrinkles and is therefore an important mechanism in textile forming. Compared to many other methods used, the gravimetric cantilever bending test (cf. Fig. 3c) according to DIN 53362 is characterized by its simplicity, the good reproducibility and the applicability even at process temperatures. Experimental data of biaxial reinforced weft-knitted fabrics made of carbon and polyamide 6.6 hybrid yarns are available and used for parametrization of the textile contribution of the material model.

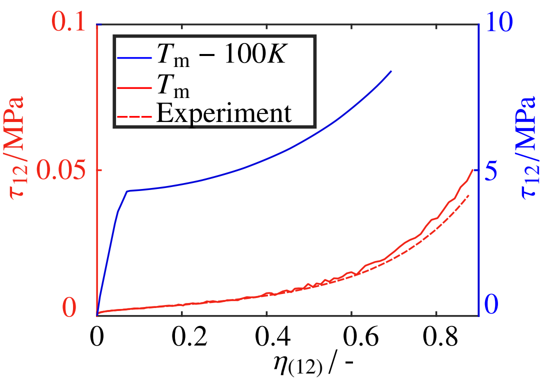
2.3. Validation of thermo-mechanical modelling approach

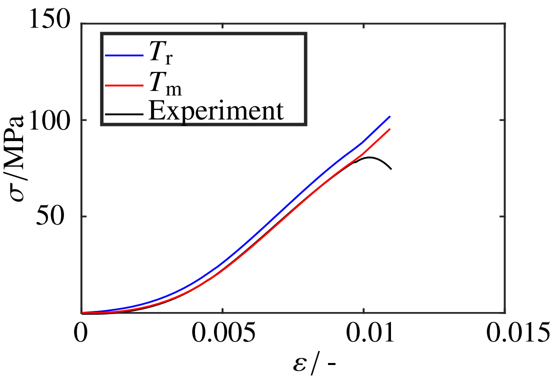
Numerical simulation of the experiments described earlier were performed at different temperatures to examine the capability of the modeling approach for the composite explained in Section 2.2. For in-plane deformation modes, a uniaxial tensile and a picture frame test were modeled. Gravity-loaded specimens with selected fixed boundary nodes were investigated to test the out-of-plane behavior. Figures 4a and 4b show that the in-plane deformation of the fibers coated by the melted thermoplastic behaves like

(a) (b) (c)

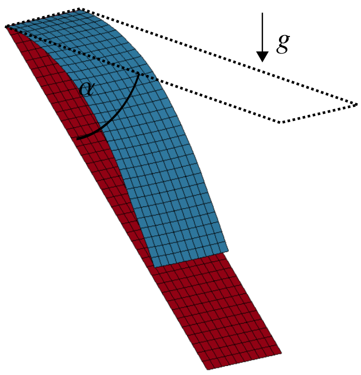
Figure 3. Experimental setup: (a) Picture frame test; (b) Tensile test; (c) Cantilever test, TU Dresden, ITM

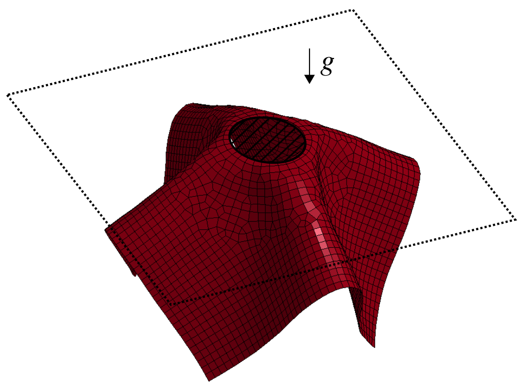
the experimental investigated dry fabric. At lower temperatures, the matrix contribution becomes more relevant which will cause a significant increase of the shear stiffness. Figures 4c and 4d show that the FRP sheet above T_m bends like the flexible textile examined with the cantilever test. The multiaxial bending deformation of the square specimen is also in good agreement with numerical results depicted in [10]. At lower temperatures the bending stiffness increases due to higher support of the matrix material.





(a) (b)





(c) (d)

Figure 4. Numerical results and comparison to experimental data of (a) picture frame test (b) uniaxial tension test (c) cantilever test and (d) multiaxial bending test

3. Modeling thermoform process of S-Rail structure and numerical results

The simultaneous forming process of metal and pre-heated fiber-reinforced thermoplastic is considered in this section. The simulation was performed using the finite element software LS-DYNA. A S-Rail geometry as illustrated in Figure 5 was chosen which has become a standard benchmark for testing finite element simulation codes in stamping operations. The tools are modeled as rigid bodies. Due to a lack

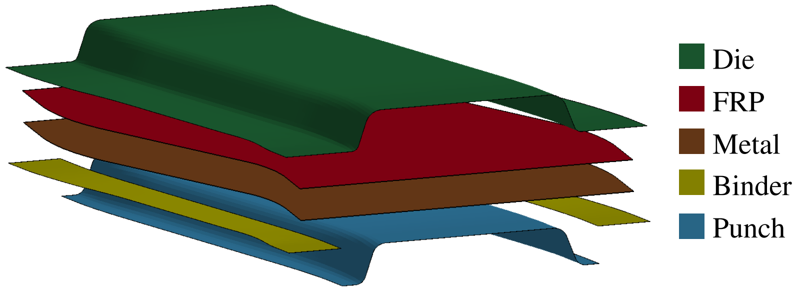


Figure 5. Tool geometry and components of forming process

of experimental values, a constant friction coefficient ($\mu_0 = 0.1$) between tool and metal/FRP as well as between metal and FRP was used. Simulations are performed to investigate the influence of process parameter, e.g. blank-holder force, as well as material parameters like fiber directions on the formation of wrinkles and other defects.
Figure 6a shows the distribution of thickness reduction after forming. Negative values indicate an accumulation of material which causes wrinkling. This this is caused by missing tensile forces in x-direction. By applying additional loads, the formation of wrinkles can be reduced as shown in figure 6b.

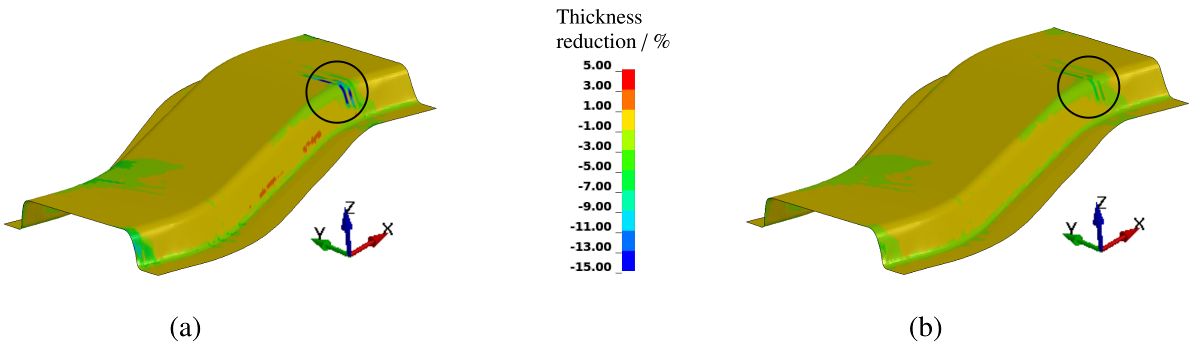


Figure 6. Contribution of thickness reduction of the fiber-reinforced thermoplastic after forming (a) without additional loads in x-direction and (b) including forces in x-direction

4. Conclusion

A thermo-mechanical modelling approach to predict the temperature dependent deformation behavior of fiber-reinforced thermoplastics was described. For this purpose, an anisotropic thermo-mechanical material model was parametrized. The temperature dependent parameters of the thermoplastic matrix were fitted and extrapolated using values taken by an open-source database. The deformation behavior of the textile structure was determined using experimental results of a biaxially reinforced weft-knitted fabric. An anisotropic constitutive law with a Hill48-yield criterion was used to describe the forming behavior of the metal sheet. Forming simulations at process temperature with varying process parameters were performed to examine which parameters may influence the occurrence of defects and how to prevent them.

5. Acknowledgement

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