Thermo-Mechanical Modeling of Pre-Consolidated Fiber-Reinforced Plastics for the Simulation of Thermoforming Processes

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Multi-material design aims at the targeted combination of materials with different characteristics in order to meet technical requirements. Especially the combination of metals and fiber-reinforced plastics (FRP) has led to innovative lightweight structures with high loading capacity and ductility in recent years. The process chain required to produce such structures is characterized by a variety of process parameters which have a significant influence on the quality of the manufactured workpiece. In order to treat the thermoforming process numerically, we present constitutive models for the metal and composite part to simulate the deformation behavior of these components. In addition, experimental setups are described to identify the required material parameters. Simulations of the manufacturing process will indicate correlations between material as well as process parameters and possible defects of the final structure that may occur during manufacturing.

1 Introduction

In recent years, innovative lightweight structures in multi-material design have been generated by the targeted combination of materials with different property profiles. Especially the combination of metals and FRP has opened new potentials for the generation of structural components with high load-bearing capacity, high ductility and minimum mass [1]. The development process of such structure’s places high demands on the engineer due to the complex interactions between design, dimensioning and manufacturing [2]. Numerical optimization of the production process of such lightweight assemblies is therefore of high importance [3]. 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 [4].

2 Constitutive models and parameter identification

In the present paper the manufacturing of a hybrid structure consisting of a metal component and a bi-axial reinforced composite plate with a thermoplastic matrix and carbon fibers is considered. For numerical investigations of the forming process suitable material formulations and corresponding parameters must be determined first.

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 changes and wrinkling. The accuracy of the simulation depends on the material models for the plastic material behavior. The stress update is based on a rate formulation using the JAUFLANN yield condition to calculate the stress increment. To determine the plastic strain increment, the HILL yield condition

\[ \mathcal{F} \leq \sigma_1^2 - \frac{2r_0}{1 + r_0} \sigma_1 \sigma_2 + \frac{r_0 (1 + r_{90})}{r_{90} (1 + r_0)} \sigma_2^2 - \sigma_y^2 (\epsilon_{pl}) \]  

(1)

is used to consider the orthotropic deformation behavior of the rolled metal sheet. In (1) \( \sigma_1 \) and \( \sigma_2 \) are the in-plane principal stresses and the LANKFORD parameter \( r_0 \) and \( r_{90} \) describe the shape of the yield surface. In order to identify the mechanical parameters, uniaxial tensile tests of samples with different orientation with respect to the rolling direction have to be performed.

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### 2.2 Fiber-reinforced Thermoplastic

The material model employed to describe the behavior of the composite assumes an additive superposition of textile and matrix contribution

\[ \sigma_{\text{FRP}} = \sigma_{\text{textile}} + \sigma_{\text{matrix}}. \]  

(2)

The latter one is modeled by an hypoelastic-plastic constitutive law similar the model used for the metal part. An associated flow rule combined with the VON-MISES yield criterion describes the evolution of plastic deformation. The mechanical properties can be defined as temperature dependent. Fibers are described as an anisotropic hyperelastic material with orientation vectors stored at the integration points. Their tension/compression and shear behavior are decoupled and can be defined by means of stress-strain curves and shear response as a function of shear angles of the fibers. A modified integration rule in the thickness direction of the shell elements can account for the typical low bending stiffness at temperatures above the melting point while still having a high in-plane tension stiffness. A more detailed description of the material model is shown in [5].

Experimental data for the parametrization are the force-displacement curves under tensile loads as well as the shear force vs. shear angle curve. The characteristic behavior for in-plane tension is determined from tensile tests on strip specimens. The typically non-linear shear force vs. shear angle curves are recorded using the picture-frame test. Gravimetric cantilever tests may be used to determine the temperature dependent bending stiffness. The mentioned material tests are performed at different process-related temperatures. The temperature dependent material parameters of the polymer matrix were identified based on stress-strain curves at varying temperatures of polyamide 6.6 from the campusplastic database [6].

### 3 Numerical results

Simulations were performed using the finite element software LS-DYNA. A metal sheet and FRP sheet are formed simultaneously with varying process and material parameters. Fig. 1 shows the correlation between process temperature and the formation of wrinkles. Lower temperatures lead to higher compressive stresses in the matrix which induce more wrinkles.

![Wrinkle formation of the FRP after thermoforming at different process temperatures.](image)

Fig. 1: Wrinkle formation of the FRP after thermoforming at different process temperatures.

Further parameter studies were performed to show more correlations between process parameters like forming temperature and binder force on the deformation behavior of the FRP and metal components and its tendency of the occurrence of defects like the formation of wrinkles.

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