Experimental and Numerical Analysis of Deep Drawing and Failure Characteristics for Sheet Metal/Polymer Hybrid Structure

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Micro Abstract

Lightweight component design is an everlasting matter in the automotive industry. To face challenges concerning lightweight like damping effects or increasing the load-bearing capacity, one approach is the development of new hybrid materials, e.g. sandwich materials. For these layered structures an extensive material characterization including failure analysis with regard to the influence on deep drawing process is carried out and the results are used as input for the numerical modelling.

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Introduction

Concerning the lightweight potential these layered structures combine varying material characteristics with the aim to achieve an appropriate stiffness apart from less weight. One approach is the development of sandwich structures, realized as combination of different materials. In contrast to a monolithic sheet metal material, sandwich structures show a complex behaviour in case of deep drawing loading conditions.



Figure 1. Schematic illustration of layered sandwich material

In figure 1 an exemplary layup for a sandwich structure consisting of two sheet metal outer layers and a polymer core is shown. An extensive material characterization for the layers is carried out along with investigations concerning the deep drawing capacity. The layers show different characteristics while loading the structure, which influence not only the deep drawing behaviour of the whole sandwich structure, but also the component quality. Due to various deep drawing process parameters, instabilities such as interlaminar failures, ruptures or wrinkling of the structural component arise. Therefore, the failure behaviour and the influence on the deep drawing process are considered in experimental investigations. For this purpose, experimental characterization tests for the interlaminar failure as well as for the material failure are performed. Finally, the experimental results are used as input for the numerical modelling and FE simulation of a deep drawing process with layered sandwich material. The FE simulation also takes into account the variable material behaviour of the layers, layer interactions and failure capabilities. Based on the obtained results it is possible to achieve an advancement of the prediction accuracy in the numerical simulation.

1 Experimental material characterization

For the characterization of the layered structure different test approaches were executed separately for the sheet metal outer layer with thickness of 0.25 mm and the polymer core with 0.7 mm. To obtain anisotropic parameters and the flow behaviour quasi-static tensile tests with cut-out specimen configurations (0°, 45° and 90°) according to EN ISO 6892-1 were investigated. With regard to an accurate description of the material hardening behaviour, high strains are taken into account. State of the art for the description and evaluation of material flow behaviour is the use of an extrapolation beyond the point of the uniform elongation, true stress - true plastic strain curve determined in the uniaxial tensile test is needed. Using an inadequate extrapolation method an inaccurate description of the material behaviour at high strain can occur, which leads to invalid numerical results in the FE simulation. To ensure a realistic description of the flow behaviour at high strains, the hydraulic bulge test (DIN ISO 16808) is applied and the sheet blank deformation is measured with an optical system continuously [1] [2]. The Transformation of the determined biaxial data to the uniaxial stress state is performed with a mathematical approach based on the principle of the equivalence of plastic work [3].

In general the behaviour of polymers is effected by strain rate. Related to this strain rate dependency experiments for the polymer and the sheet metal by tensile test with varying strain rate values are executed with a deformation dilatometer DIL 805A/D+T from TA Instruments, formerly Bähr GmbH.



Figure 2. True stress - true (plastic) strain curves for sheet metal layer (left) with thickness 0.25 mm and polymer layer (right) with thickness 0.7 mm

Figure 2 shows the true stress - true plastic strain behaviour for the sheet metal layer (thickness s = 0.25 mm) and the polymeric core (s = 0.7 mm) for different strain rates. For more detailed information regarding the investigations for the flow behaviour see [4]. Figure 2 indicates that tensile strength of the polymer layer increases with an increasing strain rate. The stress values for polymer and sheet metal are considerably differing. The influence of increasing strain rate on the stress values of the sheet metal layer is unincisive. The material flow behaviour of the polymer is more sensitive to strain rate value.

2 Material failure behaviour

To ensure a good prediction of the material behaviour in the FE simulation the description of the failure behaviour for the chosen material is needed. Especially for new hybrid materials this is an important aspect. To describe the deep drawability of monolithic sheet material the forming limit curve (FLC) is often used in FE simulation [5]. The FLC is valid for plane stress states from uniaxial to equibiaxial tension and linear strain paths. An additional alternative to the FLC for the failure description of sheet metal materials are stressbased fracture models. These approach is related to a relationship between stress state- and the fracture strain. The fracture strain can be described with stress triaxiality η and the the normalized Lode angle $\overline{\theta}$ [5] [6].

A exemplary fracture model illustration for aluminum 6061 material is shown in figure 3 left hand side [6]. Beese, Bai and Wierzbicki [6] worked on a fracture model for aluminum materials. With regard to their study investigations for the fracture behaviour are performed for the sheet



Figure 3. 3D fracture locus [6] (left) and plastic strain plots from optical measurement and FE simulation of tensile test witch notched sample (right)

metal outer layer. Right hand side of figure 3 the plastic strain value from optical measurement and numerical simulation are shown for a waisted sample configuration. For the estimation, several sample geometries and experimental investigations (tensile test, tensile test with waisted sample geometry and shear test) are used to generate different stress states, which enable a determination of the fracture curve. With this curve the failure characteristics of the blank sheet material are described. Besides the use of an optical measurement system (Aramis, GOM mbH) for the experimental investigations, FE simulations for the named specimens and configurations are needed to provide local strains by Digital Image Correlation (DIC). Stress states are identified indirectly through FE simulation [6]. With these steps the failure characteristics for the blank sheet material are described. Within the numerical modelling the failure is described with

$$D = \sum \frac{\overline{\epsilon}_{pl}}{\overline{\epsilon}_{pl}^f(\eta, \overline{\theta})} \tag{1}$$

Formula (1) describes the damage variable D, at each increment the equivalent plastic strain $\overline{\epsilon}_{pl}$ is divided by the fracture strain $\overline{\epsilon}_{pl}^{f}$ [5]. For D \geq 1 there is a damage effect.

3 Interface behaviour

The failure behaviour of hybrid material structures is different in comparison to monolithic steels. A substantial failure for fiber reinforced plastics is delamination. This effect can occur in sandwich materials at the interface of the layers as well.



Figure 4. Overview of load-dependent failure modes [7]

In figure 4 the failure modes for hybrid materials are shown. The loads within deep drawing processes are overlapping, as a result a material failure can occur. Based on the involved loads the failure can be classified as mode I, II and III [7]. To investigate the characteristics of the interface only a few experimental methods exist: e.g. T-Peel test [8], Double Cantilever Beam (DCB) test [9] or End-Notch Flexure (ENF) test [10]. DCB set-up depicts interlaminar fracture toughness for mode I and ENF test analyses mode II.

4 Numerical modelling

With the estimated data based on the experimental results a FE model for a conventional deep drawing process of a spherical cup geometry has been built up. The results from the material characterization tests are used as input data for the material modelling. In a first approach polymer core and sheet metal layer are modelled as solid elements. For the interface cohesive elements with a thickness of 0.01 mm are used. The specific attributes of these elements are described with a traction separation relationship, which is estimated from the mechanical testing.



Figure 5. FE modelling approach for sandwich material, experimental and numerical results

In figure 5 the chosen approach for the FE modelling of a deep drawing process for sandwich material is shown. All layers are modelled with the data from the experimental characterization. The damage prediction corresponds well with the experimental deep drawing results. For more detailed information see [4].

Conclusions

With the presented results the deep drawing behaviour of a hybrid sandwich structure can be predicted by numerical simulation. All necessary effects like material flow behaviour of polymer and sheet metal layer as well as the failure behaviour of the structure and the interface are taken into account. With the presented FE approach the deep drawing process of a spherical cup can be modelled and the prediction of failure states is possible.

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