Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 15, 2015, No. 1

EXPERIMENTAL CHARACTERIZATION AND NUMERICAL MODELING OF THE MECHANICAL BEHAVIOR OF HALF SANDWICH LAMINATE IN THE CONTEXT OF BLANKING

L. CHEN*, T. CLAUSMEYER, A. E. TEKKAYA

*Institute of Forming Technology and Lightweight Construction, TU Dortmund University,
Baroper Str. 303, 44227 Dortmund, Germany
Corresponding author: lin.chen@iul.tu-dortmund.de

Abstract

In this short paper the complex mechanical behavior of an aluminum/low density polyethylene (LDPE) half sandwich sheet in the context of blanking is investigated. Suitable mechanical tests for the polymer and metal layer as well as the delamination behavior of the adhesive between these two layers were conducted. The main focus of this study is to create a finite-element (FE) model for the blanking process of sandwich structures. Material parameters for a Lemaitre-type damage model, a Drucker-Prager and a cohesive zone model are identified for the metal, the polymer and the adhesive, respectively. The experimental force-displacement curves obtained in a blanking process of a half sandwich sheet are compared with the predicted results of the FE model. The qualitative agreement of the predicted force-displacement curves with the experimental results is good. Recommendations concerning the improvement of the FE model are given based on the obtained results.

Key words: sandwich plates, blanking, CDM, Drucker-Prager model, cohesive zone model

1. INTRODUCTION

Composite plates are increasingly used, e.g. in the automobile industry or structure applications because they offer advantages compared to solid metal sheets. These advantages include weight savings and noise-reduction. In manufacturing the forming behavior of these sandwich laminates is especially the focus of interest (Burchitz et al., 2005; Harhash et al., 2014). Composite plates exhibit unique failure modes during cold forming process compared to monolithic metal sheets. In the blanking process of two layer metal-polymer composites, the possible failure modes include the delamination of the two layers, the fracture of the surface metallic layer as well as the fracture of the polymer. Previous studies by Hambli (2001) and Steinbach et al. (2014) investigated the behavior of monolithic metal sheets during blanking with the help of simulations. However, to the best of the authors' knowledge, there is not yet any research giving the numerical analysis of metal/polymer/metal sandwich structure in blanking process. Although some experimental studies exist in this field (Liewald, 2013). In order to predict the formability of the LDPE/EN AW 5005A laminate in blanking process, in this paper a fully characterized FE model is constructed.

For this purpose half sandwich laminates manufactured from commercial Dibond sandwich material are investigated. For the mechanical characterization of the metallic layer uniaxial tensile tests and notched tensile tests with varying radii are conducted to obtain the ductile fracture properties. To characterize the polymer layer tensile tests and disk compression test are conducted. The interface behavior of the laminate is studied using delamination

 ISSN 1641-8581

tests under classical mode I and mode II failure modes. Material parameters of suitable material models for the polymer and the metallic layer are determined by inverse identification. The mechanical behavior of the metallic layers is described by an enhanced version of Lemaitre's damage finite strain elasto-plasticity model (Lemaitre, 1985). The validation of this model in the context of sheet metal blanking process was reported in a previous study (Steinbach et al., 2014). Since delamination in blanking is mainly governed by mode I and mode II failure, a corresponding cohesive zone model is chosen to consider this behavior in the finite-element simulations. Parameters for the cohesive zone model are successfully identified based on the experimental delamination tests. A FE-model of a blanking process is set-up in Abaqus to analyze the effect of blanking process using the identified material models for half sandwich laminate. The paper is structured as follows: The chosen methodology is explained. After that the results of mechanical tests, parameter identification and the blanking experiments are presented. Then the results of the blanking experiments are compared to the predictions of the FE model. The paper ends with a discussion and conclusion.

2. MATERIAL MODELS

For the analysis of the mechanical behavior of the composite sheets with the help of FE method it is essential to describe the material behavior of the polymer and metal layer as well as the interfacing adhesive. The selected models for the three layers are briefly presented in the following. The metal and the polymer are subjected to large inelastic deformation before rupture. Consequently the chosen constitutive models fall into the context of elasto-plasticity and damage at large deformation. For both materials the elastic behavior is modelled as isotropic. Assuming an additive split of the symmetric part $\mathbf{d} = \mathrm{sym}(\mathbf{l})$ of the velocity gradient $\mathbf{l}=\dot{\mathbf{F}}\cdot\mathbf{F}^{-1}$ into an elastic part ($\mathbf{d}^e$) and a plastic part ($\mathbf{d}^p$) $\mathbf{d}=\mathbf{d}^e+\mathbf{d}^p$, one obtains the Jaumann-type stress update

$$\dot{T}^J = (1-D)\left[\frac{E\nu}{(1+\nu)(1-2\nu)}\mathrm{tr}(\mathbf{d}^e)\mathbf{1}+\frac{E\nu}{(1+\nu)}\mathbf{d}^e\right] \tag{1}$$

for the general case of fully-coupled elasto-plasticity, with $\mathbf{F}$ the deformation gradient, D the damage variable as well as E the Young's modulus and ν the Poisson's ratio. $\mathrm{tr}(\bullet)$ denotes the trace operator. The general form of the yield condition for coupled damage and plasticity with isotropic hardening is

$$\Phi = \frac{1}{(1-D)}\sigma_{eqv} - \sigma_y(\alpha) \le 0 \tag{2}$$

where σ_y and α represent the deformation-dependent yield stress and the equivalent plastic strain, respectively. For the metal $\sigma_{eqv} = \sigma_{eqv}^{vM} := \sqrt{3/2}\,\|\mathrm{dev}(\mathbf{T})\|$ the pressure-independent v. Mises equivalent stress is chosen in terms of the norm $\|\bullet\|$. For the polymer the pressure-dependent equivalent Drucker-Prager (Drucker et al., 1952) stress

$$\sigma_{eqv} = \sigma_{eqv}^{DP} := \sigma_{eqv}^{vM} + 1/3\,\mathrm{tr}(\mathbf{T})\tan(\beta) \tag{3}$$

with material-specific friction angle β, which considers the pressure-dependency of plastic yielding, is selected. The rate of plastic deformation $\mathbf{d}^p = \lambda\,(\partial\Phi/\partial\mathbf{T})$ is determined by an associated flow rule in terms of the plastic multiplicator λ. The evolution of damage is given by

$$\dot{D} = \lambda\left\langle\frac{Y-Y_0}{S}\right\rangle^{\kappa}\frac{1}{(1-D)^{\beta}} \tag{4}$$

where Y_0 β, S and κ are required damage material parameters.

The driving force for damage Y which is here stated in terms of the principal stresses T_i, considers the pressure-dependence of the propagation of damage by the material parameter h and was previously used by Soyarslan et al. (2008)

$$Y = \frac{1}{2E(1-D)^2}\Big(-(1+\nu)\textstyle\sum_{i=1}^{3}\big(\langle T_i\rangle^2 - h\langle T_i\rangle^2\big) +$$
$$\nu\Big(\langle\mathrm{tr}(\mathbf{T})\rangle^2 - h\langle-\mathrm{tr}(\mathbf{T})\rangle^2\Big)\Big) \tag{5}$$

All FE-simulations are carried out in Abaqus using a VUMAT routine of the implemented Lemaitre coupled damage model. For the polymer the Abaqus implementation of Drucker-Prager plasticity is used. The contribution of a material point to the total element stiffness is set to zero as soon as the damage variable D reaches the critical value D_{cr} in the metal. For the polymer a linear relation between the damage variable D and the equivalent plastic strain α is used, after the α has reached the critical value α_f.

In this research, the mixed mode delamination of the half sandwich is simulated by the commercial software ABAQUS built-in cohesive zone model.

The constitutive behavior of this model is formulated as a traction-separation law (TSL), which relates the traction, T, to the separation, δ. The elastic behavior is given by

$$\mathbf{T} = \begin{Bmatrix} T_n \\ T_s \\ T_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & 0 & 0 \\ 0 & K_{ss} & 0 \\ 0 & 0 & K_{tt} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{Bmatrix} = \mathbf{K\varepsilon}, \quad (6)$$

where the nominal strain ε is defined as the corresponding displacement δ divided by the original thickness of the cohesive element. K_{nn} corresponds to the stiffness in the normal direction while K_{ss} and K_{tt}, correspond to the two shear stiffness in the 3D case. T_n, T_s and T_t are the corresponding cohesive tractions. For the damage initiation, the maximum separation criterion is used and is given by

$$MAX = \left\{ \frac{\langle \delta_n \rangle}{\delta_{n\max}}, \frac{\delta_t}{\delta_{s\max}}, \frac{\delta_s}{\delta_{t\max}} \right\} = 1, \quad (7)$$

where δ_n, δ_t and δ_s are the separation in normal, first shear and second shear direction. $\delta_{n\max}$, $\delta_{s\max}$ and $\delta_{t\max}$ are the critical separation values for the three strain components. The damage evolution is using the table data from the delamination tests as shown in table 2.

Table 1. Material parameters of Al layer in Lemaitre damage model.

E, GPa	ν	σ_0, MPa	β	S, MPa	κ	Y_o, MPa	D_{cr}	h
65	0.29	116	0.15	10.2	0.25	0.3	0.18	0

Table 2. Parameters in cohesive zone model.

K_{nn}, MPa mm^{-2}	δ_{nmax}, mm	K_{ss}=K_{tt}, MPa mm^{-2}	δ_{smax}= δ_{tmax}, mm
297.7	0.053	17.9	0.21

3. METHODS

3.1. Testing methods

A commercial Dibond sandwich laminate (EN AW 5005A/LDPE/ EN AW 5005A) is decomposed by means of pliers after moderate heating of the adhesive in order to study the mechanical behavior of each component separately. The thickness of a single aluminum layer is 0.3 mm, while the thickness of the polymer core is 2.4 mm. Uniaxial tension tests (DIN 50125) and notched tensile tests with notch radii 5mm and 10 mm are conducted to obtain the flow curve and the material parameters for the elasto-plastic damage model chosen for the Al layer. Disk compression tests and uniaxial tension tests (DIN EN ISO 527) are performed for characterization of the mechanical behavior of LDPE. The disk compression test sample is composed of four layers of circular (12 mm) LDPE sheet. The height of the disk sample is around 9.23 mm. The amount of glue between each layer is kept to minimum to limit the influence of the glue on the mechanical test. The cross head speed of the universal testing machine Zwick 250 is set to 5 mm/s for all mechanical tests.

The mechanical behavior of the interfacing adhesive between the aluminum and LDPE layer is studied with the help of two delamination tests. The traction separation relationship of the aluminum layer and LDPE layer under tensile mode (mode I) are tested with the help of specially-designed sample holder as shown in figure 1. For the investigation of delamination under tensile mode, the top and bottom free sides of Al/LDPE half sandwich plate are glued onto two square columns made of steel. The area of the interface between Al and LDPE is reduced to around 1/9 of the half sandwich plate´s area, such that the delamination occurs under mode I during the separation of the Al layer and LDPE layer. Shear mode delamination (mode II) is realized with the help of an additionally designed device as shown in figure 1. Two grooves are cut on both sides of the sample. The distance between two parallel grooves is 5 mm. This sample is mounted in the universal testing machine such that fracture occurs along a shear delamination path when the crosshead is moving.

The blanking tool is also mounted in the universal test machine Zwick 250. The commercially available punch is manufactured of hard alloy. For the presented experiments the diameter is set to 8 mm and the clearance is 0.08 mm. All the blanking tests are conducted at a constant speed of 5 mm/s such that the strain rate in the blanking experiment is of the same order of magnitude as in the mechanical tests.

3.2. Simulation methods

FE-models for the mechanical tests are set-up. 8 node trilinear elements with reduced integration (C3D8R) are employed in the 3D FE-model of the notched tensile tests and in the separation tests for Al. The minimum mesh size is set to 0.02 mm in the center of the minimum cross section of the notched tensile test samples; the same mesh size is used in the blanking simulation in the area between the punch and die of the sandwich sheet. The delamination test is simulated using a traction separation law. The polymer side is considered as elastic body for simplicity, while the Lemaitre model is used for Al. The same mesh size is used at both sides of the interface. For the simulation of the blanking process an axisymmetric finite element model using CAX4R elements for the half sandwich laminate is set up. Punch and die are simulated as rigid body.

4. RESULTS OF MECHANICAL TESTS AND PARAMETER IDENTIFICATION

4.1. Mechanical tests and parameter identification of Al layer

In this section the experimental results of the notched tensile tests for the Al layer, the delamination tests as well the results of the tension and disk compression tests of for LDPE are presented. These results provide the basis for the identification of material parameters.

The force-displacement curves of the notched tensile tests (notch radii 5 and 10 mm) are shown in figure 2. Necking happens after considerable plastic deformation and partially leads to an obvious force decrease following the point of maximum force in EN AW 5005A aluminum sheet. The elastic and Swift-type hardening parameters are directly determined from the tensile test. The material parameters are given in table 1. The parameter h governing the pressure-dependency of damage evolution was set to 0.

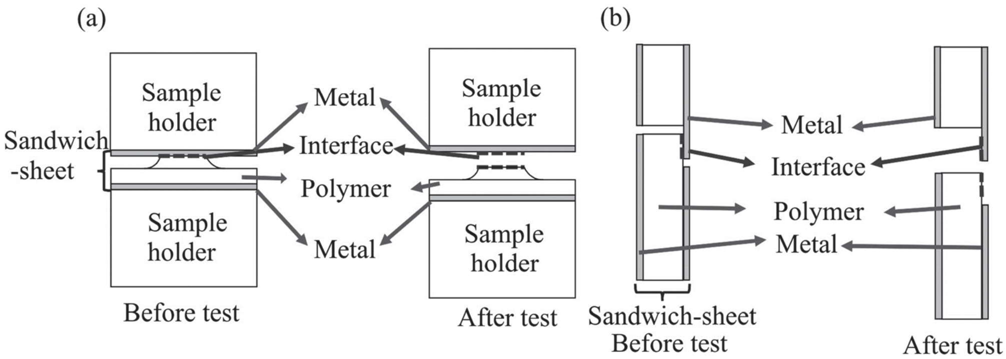

Fig. 1. Designed tensile test devices (a) and shear tensile test devices (b).

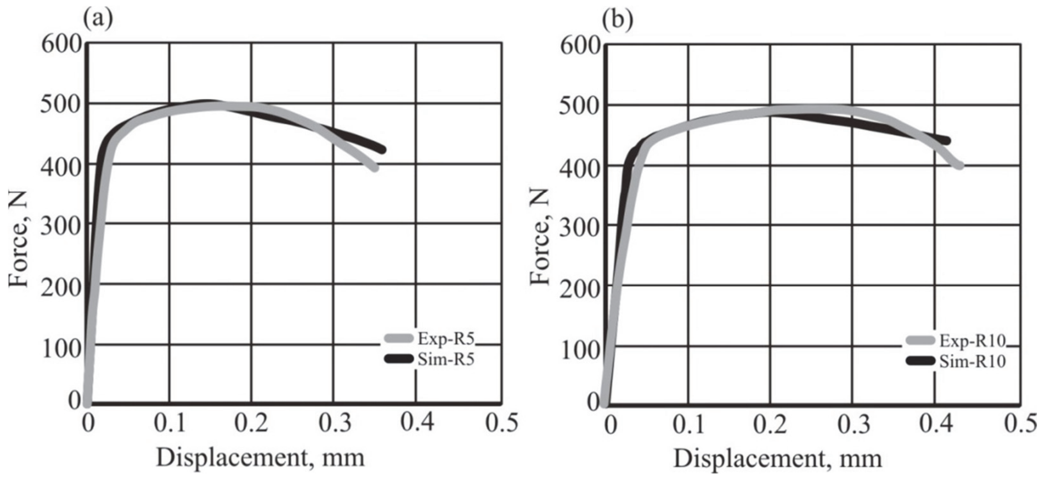

Fig. 2. Comparison of simulation and experiment for notch radius 5 (a) and 10 mm (b).

The damage parameters in the Lemaitre model are obtained by fitting the simulated force-displacement curves of notched tensile tests to the experimental ones. The identified model accounts for the softening and fracture observed in the experiments. Since damage is fully coupled with elasticity and plasticity, the decrease of the force is affected by the plastic softening due to damage as well as necking. The end point of the force-displacement curve is determined by the deletion of the critical element at the center of the minimum cross section in the notched specimen. From there fracture initiates and rapidly propagates through the cross section of the sample. It shows that the predicted force-displacement curves for the tensile test with radius 5 mm and radius 10 mm, and in particular the onset of fracture agrees well with the experimentally determined ones.

4.2. Mechanical tests and parameter identification of interface

The traction separation behavior of the interface is specified by determining the stiffness K_{nm} and K_{ss} which equals to K_{tt}, the damage initiation criterion and the damage evolution. The stiffness of the interface is achieved from the initial linear part of the traction-separation curve from tensile and shear-mode delamination tests. From this curve the critical displacement and the following damage evolution behavior are also used in simulation.

The delamination tests under tensile mode and shear mode are successfully conducted by means of the designed device on uniaxial tensile test machine. The traction separation curve of tensile delamination is shown in figure 3a. The traction increases linearly at the first. The maximum traction is 26.0 MPa. Figure 3a depicts the contour plot of polymer layer in tensile mode delamination test when the traction is close to the peak value. The color of the contour represents the level of damage of the interface. The interface only extends at the center square of the polymer sheet, therefore the rest margin of the polymer sheet remains undamaged during the whole test. It could be deduced from the contour plot that the delamination initiates from the four corners of the square and propagates towards the center.

Figure 3b shows the traction separation curve of delamination test under mode II. The contour plot of the FE model shown in figure 3b illustrates the shear model delamination. The maximum traction 7.2 MPa under shear mode is smaller than that of tensile model. The separation of the two surfaces happens within a longer path until the maximum traction achieves compared with that under tensile mode. The energy per area needed for the total separation is 8.5 kJm^{-2}, which is larger than that of tensile mode (2.8 kJm^{-2}).

4.3. Mechanical tests and parameter identification of LDPE layer

Parameters for the Drucker-Prager model described in section 3.1 are identified for LDPE. The strain rate dependency and temperature dependency are not taken into consideration. The pressure sensitivity parameter β is calculated to be 32° from equation (3) using the experimentally determined yield strength in tension and compression. Figure 4a shows the stress strain curve from tensile test and compression test in terms of the engineering strain and the nominal stress. The yield strength σ_t = 12.2 MPa in tension and σ_c = 20.1 MPa in compression are determined according to DIN EN ISO 527. It means that plastic yielding depends on the pres-

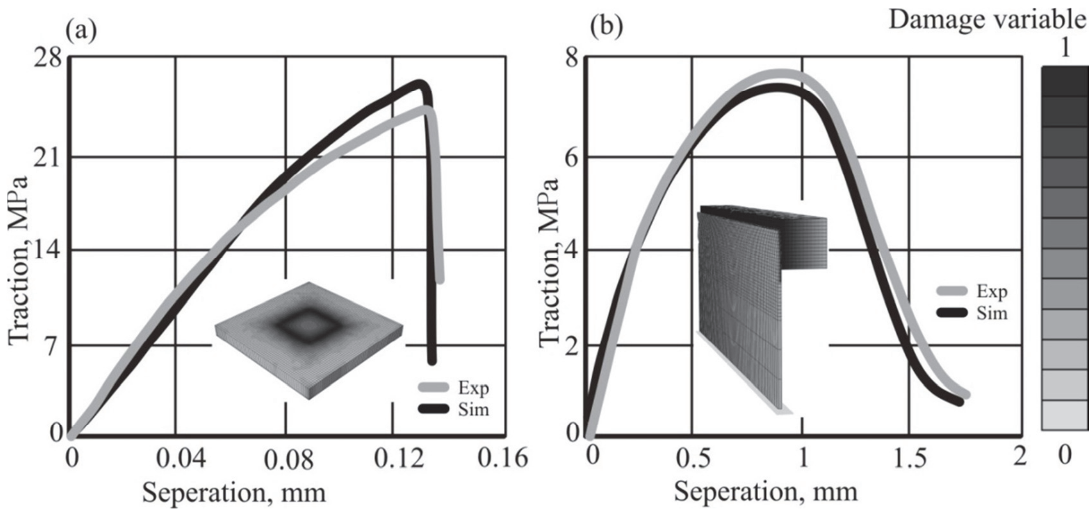

Fig. 3. Comparison of traction separation curve from delamination test and simulation under tensile mode (a) and shear mode (b).

sure. The isotropic hardening behavior for LDPE is determined from the disk compression test. Assuming an isochoric motion, the obtained true stress-true strain curve is input as tabulated hardening data for the polymer model.

monolithic sheets. Partial delamination occurs between the polymer and the metal. Furthermore, the rollover is larger due to the low stiffness of LDPE. In a top view of the circular workpiece the area affected by rollover appears as a ring. In this ring the aluminum layer bends towards the polymer layer. The workpiece on top of the die is studied while the removed part under punch is considered as scrap.

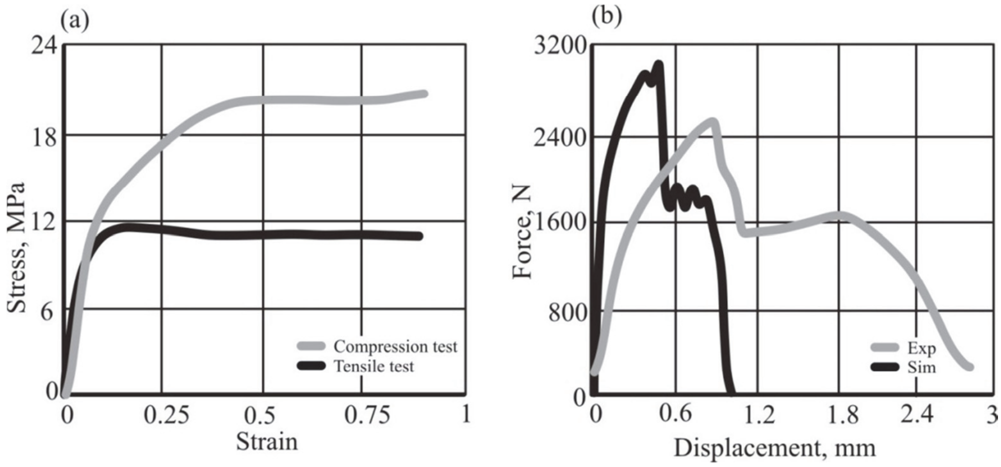

Fig. 4. Stress strain curve of LDPE tension and compression test (a) and force-displacement curve of half sandwich blanking (b).

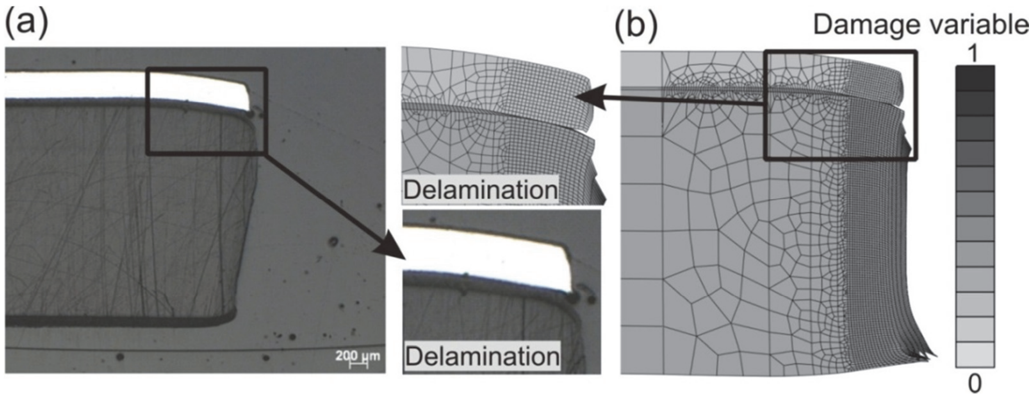

Fig. 5. Experimental (a) and simulated cutting edge from half sandwich sheet (b).

5. APPLICATION

Finally, the experimental results of the blanking process of the half sandwich sheet are presented. With the identified models at hand, the blanking process is simulated and the predictions of the simulation are compared to the experimental results. Figure 4b shows the force-displacement curve of blanking process. The first peak refers to the blanking of the aluminum layer, the following peak is corresponding to the cutting of the polymer layer. The maximum force is overestimated by the simulation by about 20%, while the level of the force related to separation of the polymer agree well in simulation and experiment. Rupture occurs at a smaller displacement according to the simulation than in the experiment for the Al layer and the polymer.

The cutting edge of half sandwich sheets show different characteristics compared to blanking of

Figure 5 shows the cutting edge of the workpiece. Then along with the penetration of the punch the aluminum layer is cut and exhibits typical roll over and burnish area. After the scrap of the aluminum layer separates the workpiece, it is pushed by the punch towards the polymer layer. The polymer layer is then pushed by the aluminum scrap towards the die. At this time the interface close to the punch is under the combination of large tension and shear load. This leads to the partial delamination of the workpiece. Finally the polymer layer is cut by the decreasing distance of the punch and die. The fully characterized FE model for half sandwich plate is applied in blanking process.

The damage variable contour of the cohesive element and the polymer layer is shown in figure 5b.

From this figure it could be seen that the simulated cutting edge is similar to that of the experimental one, in particular for Al and the upper part of LDPE. The roll over behavior of the half sandwich sheet is qualitatively captured by the simulation. The applied cohesive zone model gives a good prediction of the position and the length of delamination in the region close to the cutting edge. On the other hand the simulation results shed light to the other possible failure of delamination which could not be directly revealed from experiment. In figure 5b the elements are highlighted in terms of the interface far away from the cutting edge but under the position where aluminum layer starts to bend towards the polymer layer. The interface at this region is under large tension stress due to the lack of blank holder force. If the interface strength of the sandwich product is not strong or homogeneous enough, delamination could also happen at this region.

6. DISCUSSION AND CONCLUSION

This study is probably one of the first to compare a FE-model with experimental data for the blanking of half sandwich sheet. The complex mechanical behavior involving elasto-plasticity and damage of a composite sheet was described in a comprehensive, yet efficient approach. The results indicate that the simulation model can be modified to improve the agreement between simulation and experiment. It is expected that more elaborate consideration of the strain rate sensitivity of the polymer will improve the prediction quality of the simulation. A better agreement of the predicted maximum force in blanking may be obtained by identifying the parameter *h* with a suitable experiment. However, the presented method of setting up a simulation model for the blanking of sandwich presents an important contribution to establishing proper simulation methods for this industrial application.

ACKNOWLEDGEMENTS

Funding of Lin Chen by German Academic Exchange Service (DAAD) is appreciated.

REFERENCES

Burchitz, I., Boesenkool, R., Zwaag, Svd., Tassoul, M., 2005, Highlights of designing with Hylite – a new material concept, *Mater Design*, 26, 271-279.

Harhash, M., Sokolova, O., Carradó, A., Palkowski, H., 2014, Mechanical properties and forming behaviour of laminated steel/polymer sandwich systems with local inlays – Part 1, *Compos Struct*, 118, 112-120.

Lemaitre, J., 1985, A continuum damage mechanics model for ductile fracture, *J Eng Mater-T ASME*, 107, 83-89.

Steinbach, F., Chen, L., Güner, A., Tekkaya, A., E., 2014, Experiment and numerical analysis of dry shearing of aluminum 6082, *Adv Mat Res*, 1018, 261-268.

Hambli, R., 2001, Comparison between Lemaitre and Gurson damage models in crack growth simulation during blanking process, *Int J Mech Sci,* 43, 2769-2790.

Liewald, M., Bolay, C., Thullner, S., 2013, Shear cutting and counter shear cutting of sandwich materials, *Journal of Manufacturing Processes*, 15, 364-373.

Drucker, D. C., Prager, W., Greenberg, H. J., 1952, Extended limit design theorems for continuous media, *Q Appl Math*, 9, 381-389.

Soyarslan, C., Tekkaya, A. E., Akyüz, U., 2008, Application of continuum damage mechanics in discontinuous crack formation: forward extrusion chevron predictions, *Z Angew Math Mech,* 88, 436-453.

CHARAKTERYSTYKA DOŚWIADCZALNA I NUMERYCZNE MODELOWANIE MECHANICZNEGO ZACHOWANIA STRUKTUR KOMPOZYTOWYCH TYPU SANDWICH W PROCESIE WYKRAWANIA

Streszczenie

W pracy badano złożone, mechaniczne zachowanie blach o strukturze kompozytowej typu sandwich zbudowanych z aluminium i polietylenu o niskiej gęstości (LDPE) w procesie wykrawania. Przeprowadzono testy mechaniczne dla warstwy polimeru i metalu a także badano proces delaminacji warstwy adhezyjnej. Głównym celem pracy było opracowanie modelu elementów skończonych (MES) zachowania się struktur kompozytowych typu sandwich w procesie wykrawania. W ramach zadania zidentyfikowano parametry modelu Lemaitre'a dla warstwy metalu, Druckera-Pragera dla polimeru oraz kohezji dla warstwy adhezyjnej. Zarejestrowane w trakcie procesu wykrawania materiału kompozytowego siły porównano z siłami obliczonymi modelem MES. Otrzymano dobrą jakościowo zgodność wyników. Na podstawie przeprowadzonych badań sformułowano wytyczne pozwalające na poprawę opracowanego modelu numerycznego.

Received: October 16, 2014
Received in a revised form: November 18, 2014
Accepted: November 26, 2014