DEFORMATION LIMITS OF POLYMER COATED METAL SHEETS

M.J. VAN DEN BOSCH[1,2], P.J.G. SCHREURS[2], M.G.D. GEERS[2]
[1] Netherlands Institute for Metals Research (NIMR), Delft, The Netherlands
[2] Eindhoven University of Technology, Eindhoven, The Netherlands

ABSTRACT

Polymer coated metals are increasingly used by the packaging and automotive industry. During industrial deformation processes (drawing, roll-forming, bending etc.) the polymer-metal laminate is highly deformed at high deformation rates. These forming conditions can affect the mechanical integrity e.g. the forming of cracks and delamination. The aim of this numerical-experimental project is to get an understanding of and develop predictive capabilities in the forming limits of polymer coated metal.

The numerical part consists of plain-strain deep-drawing and bending simulations of a metal substrate coated on two sides with a polymer layer. The material model used for the polymer and the metal is the general compressible Leonov model. A cohesive zone element is implemented into a finite element package to simulate delamination. It is inserted at the interface between the metal and the two polymer layers and describes a non-linear relation between the opening displacement and the corresponding stress. This relation highly depends on the polymer-metal system used and needs to be determined by experiments.

Experiments are performed to obtain cohesive zone parameters and verify the simulation results. The cohesive zone parameters are determined by several experiments. The surfaces, layers and interfaces are studied in-situ during deformation processes.

1 INTRODUCTION

Automotive industry has to answer increasing demands for more car models and more variety within a model. Besides that, car manufacturers want smaller cars plants and have more flexibility. To fulfill wishes of both consumers and manufacturers, the automotive industry can make use of the modular car concept, where a car is built from completely finished modules, with standardized interfaces, that are outsourced by the car manufacturer to supplier companies. These suppliers cannot afford to build a paint-shop to lacquer the exterior of a module and therefore want to use polymer coated metals that already have the right colors. Besides the automotive industry also the packaging industry (e.g. beverage cans) wants to make use of polymer coated metals. The advantages are lower production costs and reduction in environmental load because less painting and curing steps are required.

Polymer coated metals are already widely used in the domestic appliances and building industry. Using polymer coated metals in the automotive and packaging industry is, however, not as straightforward. In the automotive and packaging industry the forming processes induce large strains and sharp corners at high speeds and elevated temperatures. It has become evident that these conventional metal forming processes are not suitable for metals coated with a soft polymer layer. The industry wants to know how, when and why deformation mechanisms initiate, propagate and terminate.

This project aims to predict forming limits of polymer coated metal sheets in industrial forming processes. Therefore, the deformation behavior of polymer coated metals will be investigated numerically and experimentally. Issues to be addressed are the evolution of the microstructure of both the metal and the polymer layers, interaction at the interfaces and possible delamination, damaging and cracking of individual layers. In this abstract the focus is on the polymer coated metal as used by the packaging industry: electro-chemically coated steel (ECCS) with a layer of poly-ethylene terephthalate (PET).

2 SIMULATIONS

Numerically the complete polymer-metal system has to be modelled, where the proper description of the behavior of all layers and interfaces is crucial. The polymer coated metal system is simplified by assuming that there are only three layers: two PET layers, one at each side of the ECCS substrate. Between the coating and the substrate there is an interface. First, the finite element model geometry is discussed, whereafter the cohesive zone modelling is elaborated and finally a simulation result with delamination is shown.

2.1 Finite element model

As was mentioned in the introduction, industrial forming processes are to be modelled. For verification simulations of the experimental setup are made first. The experiments are deep-drawing tests (see figure 1) with polymer coated ECCS strips that are looked at from the side to observe the interface evolution. The deformation of the model can be assumed to be plain strain and the geometry is shown in figure 2.

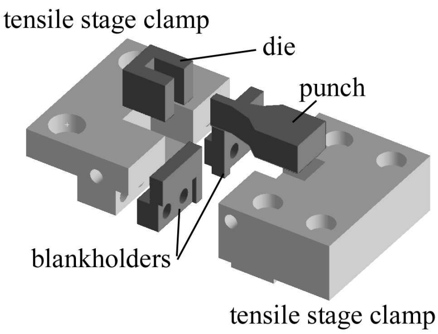

Figure 1: Exploded view of the experimental deep-draw setup.

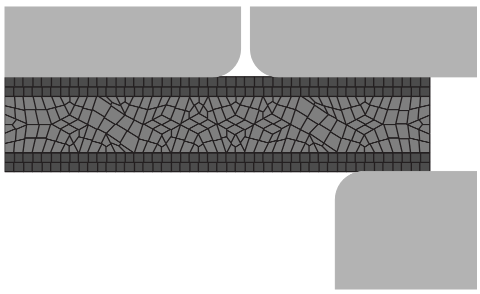

Figure 2: The plane strain model geometry of the experimental deep-draw setup with a polymer coated ECCS strip. Due to symmetry, only half the geometry is modelled.

The constitutive models for the metal and the polymer are given by the general compressible Leonov model. This constitutive model describes large strain, time dependent mechanical behavior of both PET and ECCS. The material parameters are taken from Van der Aa [1] since he used the same system.

2.2 Cohesive zones

In recent years cohesive zones have been widely used in the finite element method to simulate crack initiation and growth (Xu and Needleman [2], Xu and Needleman [3]). In more recent papers cohesive zones are used as interface model for laminates or adhesively bonded components (Abdul-Baqi [4], Ivankovic [5], Su [6]). The cohesive zones are introduced in the finite element package MSC.MARC by programming a user-element that obeys a non-linear traction-separation constitutive relation. This relation provides a phenomenological description of the microscopic processes that take place in a small area around the interface between two layers.

The interface traction-separation relation, or cohesive law, has a maximum strength and a work-of-separation. When the maximum strength and work-of-separation have been reached, delamination will take place and will propagate along the element boundaries. This implies an inherent mesh-dependency when making use of cohesive zones. However, in reality delamination can only occur at the interface between two layers. Therefore, cohesive zones are only placed between two layers and thus the mesh-dependency is not a topic of discussion for the direction in which the delamination propagates.

The cohesive law proposed by Xu and Needleman [3] is used. This cohesive law uses a potential ϕ (work-of-separation) and it is history-independent. This leads to a cohesive law that is reversible. The reversible uncoupled cohesive laws for both tangential and normal directions are given by:

$$\tau_t = 2\frac{\phi_n}{\delta_t}\left(\frac{\Delta_t}{\delta_t}\right)\exp\left(-\frac{\Delta_t^2}{\delta_t^2}\right), \tag{1}$$

$$\sigma_n = \frac{\phi_n}{\delta_n}\left(\frac{\Delta_n}{\delta_n}\right)\exp\left(-\frac{\Delta_n}{\delta_n}\right), \tag{2}$$

where τ_t is the shear stress, σ_n is the normal stress, ϕ_n is the normal work-of-separation, Δ_t and Δ_n are the openings in tangential and normal directions respectively, δ_t and δ_n are characteristic lengths. Equations (1) and (2) are graphically shown in figures 3a and 3b. An extension on this cohesive law is made to introduce irreversibility, which is shown in figure 3c.

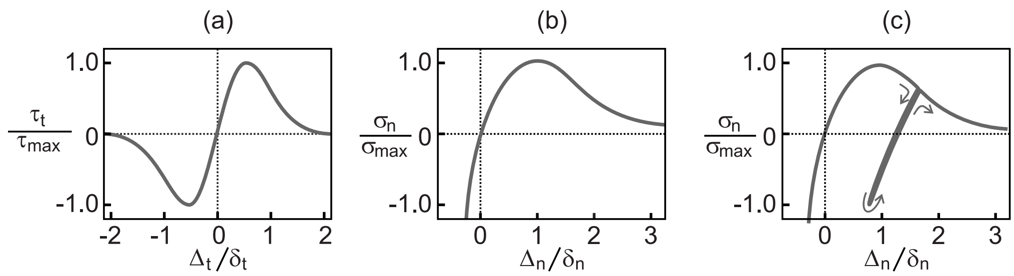

Figure 3: (a) The reversible cohesive law from eqn (1) in tangential direction and (b) from eqn (2) in normal direction, with τ_{max} as maximum shear stress and σ_{max} as the maximum normal stress. (c) The irreversible cohesive law in normal direction.

2.3 Numerical results

In figure 4 the result of a delamination simulation is shown. It can be seen clearly that the polymer layer has delaminated from the ECCS substrate. Besides that, the polymer layer undergoes severe deformation that would have led to a distorted mesh and premature ending of the analysis, when no remeshing was used. The Operator Split Arbitrary Lagrangian Eulerian (OS-ALE) is used, which is a r-method re-meshing algorithm. It reallocates the nodes of the elements, improves the quality of the mesh and thus tries to prevent element distortion. When the OS-ALE re-meshing algorithm cannot ensure a reasonable mesh quality anymore, an adaptive re-meshing step is required. An adaptive re-meshing method refines the mesh in areas with high gradients in the state variables and coarsens the mesh in areas where these gradients are small.

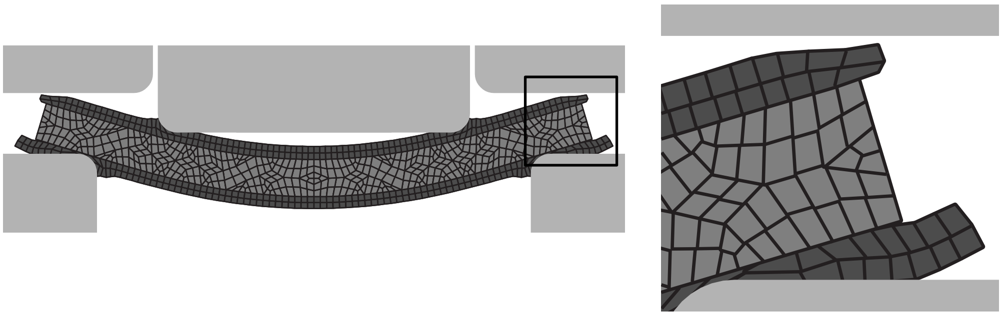

Figure 4: Result of a simulation (left) where the delaminated areas are clearly visible (right).

3 EXPERIMENTS

The simulation, from the last section, has been done with arbitrary cohesive law parameters. In order to obtain realistic simulation results, the cohesive law and its parameters must be determined by experiments for the specific system used.

In the literature a variety of experiments are suggested to characterize a cohesive law. The most straightforward way to determine the normal traction-seperation curve, is to perform a tensile test with two butt-jointed specimens (Su [6]) or a notched specimen (Ivankovic [5]). Although in the latter publication only the normal traction-seperation curve was measured, it is also required to measure the tangential traction-seperation curve. That curve can be determined by a shear experiment (Su [6]). In tensile/shear tests the elastic energy that is being stored in the testing equipment may cause a problem. At the moment the interface starts to soften, this energy is released instantaneously causing complete fracture of the interface. To measure the softening behavior of the interface, other, more complicated experiments are required, for example: the wedge-peel test as used by Ferracin [9] or peel-tests proposed by Su [6] and Cui [7].

The cohesive law depends on the adhesion of the PET layer to the ECCS substrate. The adhesion depends on the pre-treatment and surface properties of the ECCS, the application method of the PET layer and its crystallinity (Rastogi [8]). This inherent dependency on the system used, dictates that the cohesive law and its parameters only can be measured on the system itself, thus restricting the variety of experiments that can be performed.

Experiments are also required to verify the simulation results as soon as the experimentally determined cohesive law has been implemented. Deep-drawing tests are performed with polymer coated ECCS strip of 30$\times$3.5 [mm] with a thickness range of 0.1-0.3 [mm]. A sample preparation procedure has been developed to ensure that the deformation can be observed in-situ from the side of the sample by a light microscope or in a scanning electron microscope (SEM).

4 CONCLUSIONS

A plain strain finite element model has been used to analyse the deformation of polymer coated metal. The constitutive behavior of both the polymer and metal is described by the large strain, time dependent general compressible Leonov model. Delamination can be simulated by the implementation of a cohesive zone element into the finite element program. The cohesive law has been determined by several experiments, for instance a peel-off test.

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