Development of a springback prediction for a hybrid laminate with sensor functionality

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Abstract. Developing the idea of lightweight construction even further, we have considered the integration of additional functionalities directly into the semi-finished product. Enormous weight savings can be achieved through integration into a large-scale production process. However, these new material composites in the form of hybrid laminates are accompanied by new challenges in terms of forming properties. In particular, there is a need to investigate how the plastic layer with sensor functionality in a hybrid laminate impacts its springback properties. To this end we designed tests using the design of experiments (DOE) technique and identified the significant factors using analyses of variance (ANOVA). Due to the material combination we had to include additional factors such as temperature and punch holding time. Our research showed an adequate distinction between springback and spring-forward behaviour. Utilising FEM, the results were simulated and compared. Our biggest challenge lay in the exact description of the interface between metal and plastic in the FEM.

1. Introduction

The research and development of technologies for the manufacture of complex plastic/metal-based composite components has been the subject of intensive scientific and application-oriented efforts for many years. The development of hybrid laminates (fibre metal laminates - FML) is becoming a particular focus. They combine the contrasting properties of high strength and ductility in one material composite. In the aircraft industry, GLARE, a glass-fibre reinforced epoxy resin-aluminium foil laminate, has become well-known. Its predecessor was ARALL (aramid fibre-reinforced epoxy resin-aluminium foil laminate). Both laminates use a thermoset matrix in the fibre-reinforced plastic [1]. Although this allows for high stiffness and easier fibre impregnation, the long curing times render the manufacturing process rather cost-intensive. As a logical consequence, an FML with a thermoplastic matrix should be considered, as realised e.g. at the Chemnitz University of Technology. The two laminates CAPAAL© (carbon fibre-reinforced polyamide-aluminium laminate) and CAPET© (carbon fibre-reinforced polyetheretherketone-titanium laminate) are examples of this development [2]. Further developments to increase the degree of lightweight construction are aimed at direct functional integration. This prevents the need for complex assembly of functional elements at a later stage. A feasible approach can be found in the integration of a function into a sheet metal structure. For example, strain gauges can be printed on sheet metal and then shaped by sheet metal forming. Such a formed
tube can thus function as a force measuring ring [3]. Furthermore, it is possible to integrate a piezoceramic ring into a tube by means of swaging [4]. In [5] the authors present the integration of macro fibre composites (MFC) into a sheet metal structure. Another relevant aspect lies in the integration of functions into plastics. The options range from an increase in conductivity to an additional actuator-sensor functionality. According to the latest findings, the addition of PZT (lead zirconate titanate) particles to an epoxy resin matrix [6] should be another feasible option. A further development is described in [7], where the authors propose adding CNTs (carbon nanotubes) and PZTs to a thermoplastic (PP - polypropylene) for further processing in injection moulding. The CNT content ensures better electrical field coupling and thus increased sensor functionality. The combination of both topics (hybrid laminates and function integration) is the result of the overall idea of saving weight. The main goal was not only to develop a laminate with a sensor function, but also to enable a mass-production process for it. The sensorial hybrid laminate consists of three different layers: a metal sheet as the main structural component and carrier of the functional components, a functionalised foil for the generation of the sensorial properties and electrodes for recording the sensor signals and transmitting them to the evaluation electronics. The developed continuous manufacturing process of the sensorial hybrid laminate starts with the film extrusion of the piezoceramic thermoplastic compound. The aluminium surface is getting structured simultaneously. In the following rolling steps, the piezoceramic foil and the copper electrodes are continuously joined onto the sheet until a hybrid semi-finished product is created. Cut to size, it can be formed into components with functional properties. Finally, the formed composite is polarised. An embedded evaluation system processes the sensor signals generated in the component and classifies them on the basis of neural networks [8, 9, 10]. The following article deals with determining the forming properties of the hybrid composite during bending and in particular with the springback of an asymmetric composite. Springback generally refers to the upward bending of a sheet metal blank after the bending punch has retracted. This effect is caused by the superposition of elastic strains over the plastic strains. The true stress-strain curve of the material (hardening behaviour), E-modulus, sheet thickness, bending radius and forming temperature are known as influencing variables [11]. When bending in the die, an additional springback effect can occur. This is often referred to as negative springback or spring-forward behaviour. It is known that during the bending process, tensile stresses develop in the inner fibre of the sheet (die side) and compressive stresses occur in the inner fibre of the sheet (punch side) in the area of the bending radius. The reversible tensile stresses cause the springback behaviour. In spring-forward behaviour the tensile and compressive stresses occur in the transition from the bending zone (radius) to the legs on the workpiece, which are opposite to the stresses in the bending radius. This is known to happen with small bending radii in combination with a high bending impulse during die bending. While the workpiece in the radius is pressed into the die by the bending impulse, the workpiece gets in contact with the die, but the edges of the legs are only partially making contact with it. This causes an inverse stress distribution. If the tensile stresses on the inner fibre in the transition from the bending zone (radius) to the legs on the workpiece are greater than the tensile stresses on the outer fibre of the bending radius, spring-forward behaviour occurs [12]. Both phenomena (springback and spring-forward) will play a role in the following and we will discuss the relevant parameters and how they influence this behaviour. Furthermore, we attempt to recreate both phenomena with the help of FEM.

2. Materials and Methods

2.1. Materials and Specimen Preparation

The dimensions and structure of the specimens for the V-bend test are shown in Figure 1. The asymmetric laminate consists of an aluminium sheet (EN AW-6082 T4) and the piezoceramic compound with a composition of PP + 70 wt.% PZT + 0.5 wt.% CNT. The composition of the
piezoceramic foil results from a series of preliminary studies investigating the influence of the filler on the rheology [13], the electrical properties [7] and the adhesion strength [14]. The second electrode (copper electrode) was neglected for this series of tests, but the influence on the bending result can be found in [14].

Figure 1. Prepared samples (a) drawing of the sensorial hybrid laminate; (b) front and back view; (c) structure of the heatable V-bending tool.

2.2. Experimental Procedure
In all tests, we use a heated V-bending tool with changeable bending radii (Figure 1 c). The tool is mounted in a universal testing machine (Hegewald & Peschke, type: inspekt 150 kN; with Load cell 5 kN), which allows for recording of the traverse path and the force during the bending process. A DIC (digital image correlation) system (GOM ARAMIS 4M) was used to accurately determine the bending path. Due to the placement of point components on the punch and die the movement of the active tool elements can be tracked in relation to each other. The heating of the specimen in the bending die before and during the test had been measured in advance using thermocouples. Our constant parameters for the test were the punch speed with 1 mm/s and the maximum calibration force with 1 kN. We measured the angle of the formed specimens with a goniometer. The springback is described by springback factor k:

\[
k = \frac{\alpha_2}{\alpha_1} = \frac{r_{i1} + 0.5 \cdot s}{r_{i2} + 0.5 \cdot s}
\]

where \(\alpha_1\) is the tool angle and \(\alpha_2\) is the angle of the workpiece after forming. In the following examination, the angle on the tool \(\alpha_1\) is 90°. Another way of calculating this would be via the tool’s inner radius \(r_{i1}\) and the inner radius on the workpiece \(r_{i2}\), with half the sheet thickness \(s\) (all dimensions are shown in Figure 1 c). If the k-factor takes on a value smaller than 1 (\(\alpha_2 < \alpha_1\)), this is referred to as springback. However, if the value is greater than 1 (\(\alpha_2 > \alpha_1\)), this equals the previously described spring-forward behaviour [11].
2.3. Design of Experiment

In order to create and evaluate the DOE, we used the software R that allowed us to create a 2-level factorial experimental design. It is a well-known fact that the spring-forward behaviour depends on small bending radii. Therefore, we created two experimental designs for the springback and spring-forward effects. These are our response variables. Additionally, the effects were subdivided further in order to first investigate the monolithic aluminium sheet and subsequently the sensorial hybrid laminate. For the test plans of the monolithic aluminium we selected the parameters bending temperature, holding time at bottom dead centre and alignment of the bending axis to the rolling direction. The parameter bending radius, which was aliased with the other parameters, results from the product of the three parameters \( D = ABC \). This leads to \( 2^{4-1} = 8 \) experiments. In the test plan of the spring-forward behaviour we omitted the factor bending radius and instead decided on aliasing the factor alignment of the bending axis to the rolling direction with the other two factors \( C = AB \). The number of experiments can be calculated with \( 2^{3-1} = 4 \). An example of a factorial experimental design can be found in Table 1, displaying the parameters for the springback behaviour of the sensorial laminate. For comparison to the monolithic aluminium, we added the position of the plastic in relation to the active tool element as an additional parameter. When setting up the test plan for the springback (Table 1), the factors position of the plastic to the active tool element \( D = ABC \) and bending radius \( E = AB \) are set in relation to the other factors. This results in \( 2^{5-2} = 8 \) experiments. In the experimental design of the spring-forward behaviour only the factor position of the plastic to the active tool element \( D = ABC \) is aliased with the other factors, resulting in a total number of trials of \( 2^{4-1} = 8 \). All experiments are repeated twice. Our selection of the levels of the respective parameters is mainly based on literature and preliminary tests. For example, the selection of the holding time at bottom dead centre was based on [15]. The bending temperature is taken from preliminary tests which can be found in [14].

| Position of the Plastic to Active Tool Element (D=ABC) | Bending Temperature (A) | Holding Time at Bottom Dead Centre (B) | Bending Axis to Rolling Direction (C) | Bending Radius (E=AB) |
|-------------------------------------------------------|-------------------------|---------------------------------------|--------------------------------------|-----------------------|
| A 20 °C                                               | 1 + + + + +              | +                                     | +                                    | 5 mm                  |
| B 60 s                                               | 2 + + - - +              | -                                     | -                                    | 10 mm                 |
| C 90°                                                | 3 + - + - -              | +                                     | -                                    |                       |
| D Towards Punch                                       | 4 + - - + -              |                                       | +                                    |                       |
| E Towards Die                                        | 5 - + - - -              |                                       |                                       |                       |
| F 15 mm                                              | 6 - + - - -              |                                       |                                       |                       |
| G 10 mm                                              | 7 - - + - -              |                                       |                                       |                       |
| H 5 mm                                               | 8 - - - - +              |                                       |                                       |                       |

2.4. Modelling with the finite element method

We based our FE model on the experiments and derived its basic structure from the available CAD data. The complete structure in the FE programme Abaqus is shown in Figure 2. To save computing time, we utilised the given symmetry and had to map only a quarter of the process. The boundary conditions were attached to the corresponding planes of symmetry. The active tool element punch and die are modelled as rigid bodies, whereas the aluminium sheet and the piezoceramic foil are modelled using Continuum Shell Elements (SC8R). During meshing, we took care to generate a finer mesh in the area of the bending radius than in the bending leg. In addition to its high impact on the accuracy, it also reduces computation time. The material model for both layers comprises their elastic and plastic properties. The elastic
properties are defined as isotropic with the modulus of elasticity and lateral contraction. The hardening behaviour is defined by the true stress-strain curve with an isotropic hardening. It was determined using the uniaxial tensile test for both the aluminium alloy and the piezoceramic foil. We extrapolated the true stress-strain curve for both materials. Regarding the piezoceramic plastic, no viscous modelling was used. Instead, Hill'48 criteria were used to model the anisotropy in the sheet material. The failure behaviour of the aluminium sheet is represented by a forming limit curve. We defined no failure criterion for the piezoceramic foil. In the simulations with increased forming temperature, the material parameters are provided for the corresponding temperatures. The behaviour is modelled as isothermal, i.e. the composite is given a constant temperature and there is no heat transfer to the tool or to the surrounding air. The modelling of the interface played a major role in our investigation, for which we used the following approaches:
- Tie constrain - fixed nodal connection between aluminium and piezoceramic foil
- Cohesive elements - definition of an element layer between aluminium and piezoceramic foil with failure criterion
- Cohesive surface - definition of a surface between aluminium and piezoceramic foil with failure criterion.

For the cohesive elements and the surface, failure is defined by a limit stress. The limit stresses within the plane and orthogonally to it had been determined in advance by means of interlaminar shear strength tests and a tensile shear test. The development of damage is described by the law of damage evolution. Using Coulomb’s law of friction, we modelled the interaction of the deformable components aluminium and sensorial composite. The frictional behaviour between the aluminium and the tool as well as between the piezoceramic foil and the tool had previously been determined as a function of pressure and temperature using a modified test according to DIN EN ISO 8295 [16]. We used the explicit solver for the forming simulation. The springback is calculated by transferring the model into an implicit simulation relieving the stresses. Finally, the angle at the legs is measured once more and compared to the results from the experiment.

3. Results
3.1. Results from the ANOVA
To understand the significative parameters that affects the springback behaviour, ANOVA test is carried out. The underlying assumptions should be examined, i.e. verifying that all groups follow a normal distribution and the variability of the groups is uniform (hypothesis of homoscedasticity). We checked the normal distribution of the residuals using the Shapiro-Wilk test and the probability plot, as well as the uniformity of the inter-group variability using Bartlett’s test. The underlying assumptions of the ANOVA could be verified for all factorial planes, the only exception being the investigation of the spring-forward behaviour in the sensorial hybrid laminate. Judging from the results we could conclude that temperature is a significant
factor for springback in monolithic aluminium. But in this case the hot bending process reduces the springback and the null hypothesis has to be rejected for the radius as well, seeing that by using a smaller bending radius it is actually possible to reduce the springback (Figure 3 a). The ANOVA developed to investigate the spring-forward behaviour in monolithic aluminium defines the temperature and the punch holding time as significant factors. At a significance level of the test of 95 %, the p-value is smaller than the area of the rejection zone of 0.05, so that the null hypothesis of the ineffectiveness of the factors is rejected. Adapting the punch holding time, it is possible to reduce the spring-forward behaviour, but forming the sheet at room temperature does have a positive impact on the spring-forward behaviour (Figure 3 b) as well. The ANOVA developed for the springback in the sensorial hybrid laminate defines the radius as the only significant factor. As with monolithic aluminium, a smaller radius has a positive effect (Figure 3 c). In order to obtain accurate data from the fourth plane developed for the study of spring-forward behaviour in the sensorial hybrid laminate, the first-order interaction has to be defined as well. When examining the main effects without interaction, the normal probability plot clearly shows that the assumption is not verified (Figure 4 a): the points show two subgroups that one straight line does not fit well. Taking the interactions into account, the probability plot (Figure 4 b) show that the residuals are well approximated by a straight line model so the normal assumptions cannot be rejected. In this way, interaction effect is discovered. In this case, the analysis of variance yields completely different results than in the other three iterations. The factors that reject the null hypothesis are the position of the plastic, which is the least important factor for springback in the sensorial hybrid laminate, and the interaction between temperature and punch holding time. Figure 3 d shows the layer that influences springback positively.

Figure 3. Determined parameter influences in V-bending on a) EN AW-6082 T4 - springback behaviour, b) EN AW-6082 T4 - spring-forward behaviour c) sensorial hybrid laminate - springback behaviour d) sensorial hybrid laminate - spring-forward behaviour.
3.2. Results from the FEM-calculations

In order to be able to compare the FEM to the experiments, we had to set exactly the same force and displacement. The DIC system provides exact displacement values during bending. Our comparison of the measured angles after springback yields a percentage deviation of 0.03 % for the modelled monolithic aluminium when using a fine mesh in the bending zone. In order to describe the spring-forward behaviour for the monolithic aluminium, a fine mesh will be necessary in transition from the bending zone (radius) to the legs as well, as the reverse stress distribution occurs in this zone. By using a constant mesh size in the bending zone and a linear increase of the mesh size in the bending leg, the deviation from the experiment could be reduced from 3.9 % to 0.9 %. Simulating the sensorial hybrid laminate, the importance of the interface model becomes apparent. Figure 5 shows this relationship for the spring-forward behaviour as an example. Compared to the experiment, the model with the tie constrain shows a deviation of 1.83 %. The models with cohesive elements overestimate the spring-forward behaviour even more clearly, showing a deviation of 2.11 % from the experiment. This can be attributed to the additional layer and its relatively stiff behaviour. Due to the high accuracy, a deviation of 0.33 % from the experiment, and the significantly shorter computing time, the approach with the cohesive surface is preferable to the others.

Figure 5. Comparison of modelling approaches for the interface using spring-forward behaviour as an example (bending radius of 1 mm, room temperature, position of plastic to die).

4. Conclusions and Future Work

We were able to show that the influencing factors on the springback behaviour and the spring-forward behaviour can be determined for monolithic aluminium, but in particular for sensorial hybrid laminates, using the tool of DOE and ANOVA. To reduce springback in monolithic aluminium, the bending temperature can be increased and the bending radius reduced. The
spring-forward behaviour of monolithic aluminium can be reduced by using a holding time and by bending at room temperature. The greatest influencing factor on the springback behaviour of the sensorial hybrid laminates is the bending radius. Similar to the bending of monolithic aluminium, a small bending radius has a positive effect on the springback. On the other hand, the position of the plastic in relation to the active tool element strongly influences the spring-forward behaviour of the sensorial laminate. The positioning of the plastic to the die improves the behaviour. Likewise, the interaction of bending temperature and holding time has an effect on the spring-forward behaviour. These relationships have also been confirmed by modelling the bending process. However, the meshing in the FE model plays an important role and considering the sensorial laminate, the right choice of interface modelling is of pivotal importance. We have shown that the cohesive surface model produces the most accurate results with acceptable computing times. In future studies, we will conduct research on the use of a kinematic hardening model and the influence of the punch holding time in simulations.

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