Research Article

Simulating the Forming of Thermoplastic, Fibre Reinforced Plastics - Demonstrated for a Side Impact Protection Beam

Florian Althammer, Sebastian Iwan*, Sascha Mueller, Juergen Troeltzsch and Lothar Kroll
Department of Lightweight Structures and Polymer Technology, Faculty of Mechanical Engineering, Technical University of Chemnitz, Chemnitz, Germany

* Corresponding author. E-mail: sebastian.iwan@mb.tu-chemnitz.de DOI: 10.14416/j.ijast.2017.05.006
Received: 27 October 2016; Accepted: 16 March 2017; Published online: 29 May 2017

Abstract
The aim of this study is the derivation of optimal forming parameters for a realistic simulation of the forming processes using fibre reinforced thermoplastics. To do this, at first, existing solutions for the thermoplastic prepreg forming simulation are introduced and compared with the results obtained by the PAM-FORM software used for these studies. In the second step, modelling and simulation are demonstrated for a side impact protection beam. The derivation of the geometry variants from the available forming die is described, and the simulation modelling approach is defined. Additional simulation models are subjected to a sensitivity analysis, and the influence of individual parameters, such as the meshing type and the material properties, is determined. The results of the sensitivity analysis demonstrate that the simulation of the shear angle is very robust due to the variation of all parameters. So the accuracy of the simulated shear angle is not strongly affected by the choice of the forming parameters, whereby an adequate information about the formability of the blank onto the die geometry can be obtained. However, the type of die meshing and the choice of the friction coefficient has a huge influence on the stresses within the blank as well as the thickness of the blank.

Keywords: Simulation of forming thermoplastics, PAM-FORM, FRP, Crash structures

1 Introduction

Over the past decade, more and more metallic lightweight construction materials used in structural car body parts have been replaced by fibre-reinforced structural parts that are based on thermoset and thermoplastic matrix systems. One reason for the increased use of Fibre Reinforced Plastics (FRP) in the field of structural parts is the increased potential for lightweight construction of FRP in comparison with light metals. Another benefit of FRP is that both strength and stiffness inside the structure can be adjusted variably by using different reinforcement structures - made of glass, aramid or carbon fibres within the composite material [1]–[3].

Pressing and diaphragm forming are used to obtain FRP structural parts in series production. Both techniques employ deep-drawing technologies and use prepregs as blanks. Prepregs, in turn, are textile reinforcing structures that are preliminarily impregnated with a thermoset or thermoplastic matrix. Thermoplastic prepregs are particularly relevant for the forming simulation. Both manufacturing technologies make use of external preheating systems, in which the prepreg is heated without contact by means of an infrared heater or heating plates beyond the melting point of the matrix component so that the material can be processed and will flow. Figure 1 elucidates the process steps of the pressing and diaphragm forming techniques. [4]

Please cite this article as: F. Althammer, S. Iwan, S. Mueller, J. Troeltzsch, and L. Kroll, "Simulating the forming of thermoplastic, fibre reinforced plastics - demonstrated for a side impact protection beam," *KMUTNB Int J Appl Sci Technol*, vol. 10, no. 2, pp. 133–143, Apr.–Jun. 2017.

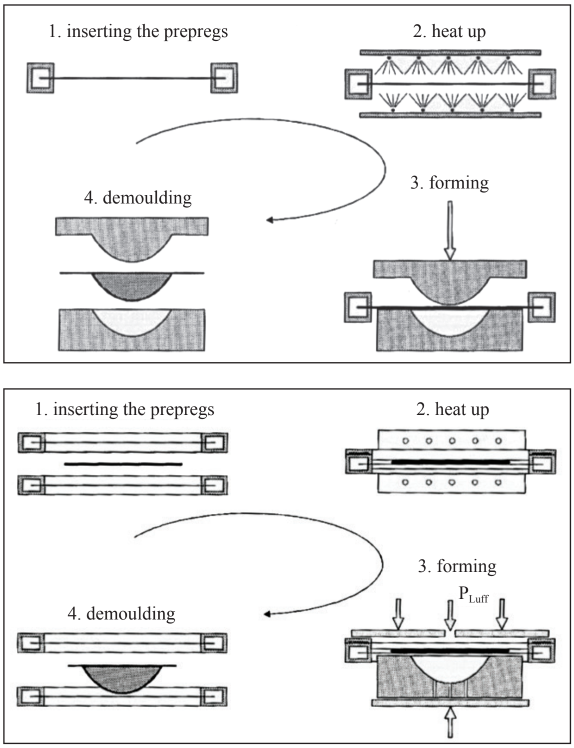

Figure 1: Process steps in pressing (top) and the diaphragm forming (bottom) [4].

Simulation of forming processes is crucial to reach accurate conclusions regarding the feasibility of effective strains. To simulate the forming process, a manufacturing technique similar to pressing is assumed, which permits that the prepreg can flow; so that wrinkling - mainly at the margins - is adjustable.

The Finite Element Method (FEM) is usually applied to the computer-aided analysis of forming procedures to discretise the real process for modelling and to allow the process to be described. In FEM, a functional is formed instead of a differential equation to be solved. This functional describes the node characteristics for the discrete elements formed by basic functions. It is possible to represent a virtual displacement of the nodes by additional consideration of the equilibrium conditions and kinematic behaviour, as well as the laws of deformation. [5]

The systems of equations to be solved are described in equation (1). They characterise the external forces F upon the stiffness matrix K and the displacement vectors x.

$$K \cdot x = F \qquad (1)$$

However, this elementary type of FEM does not consider internal system dynamics. As a result, in addition to this equation, other terms that take into account inertia and damping have to be included. Equation (2) depicts the extended form of the FEM's basic equation, including mass matrix M and damping matrix C, as well as the acceleration and speed vectors *x;* ¨, *x;* ˙.

$$M^{t+\Delta t}\ddot{x} + C^{t+\Delta t}\dot{x} + K^{t+\Delta t}x = F_{ext}^{t+\Delta t} \qquad (2)$$

Non-linearities are very important for modelling of forming processes, since they have a significant impact on the component characteristics. Material parameters have to be explored preliminarily in experiments. Based on these characteristics, the material non-linearities describing strain hardening inside the material due to large deformations can be taken into account. These material parameters, in turn, directly depend on effective strain, strain rate and temperature, and must comply with the forming process conditions in materials testing. [6]

2 Forming Simulation

2.1 *Forming simulation of FRP structural parts*

The forming behaviour of the thermoplastic prepregs is primarily influenced by the extent to which the textile reinforcing component can be draped and yields in the molten matrix component. Drapability means the capability of 2D textiles to adapt a three-dimensional geometry under the influence of external forces and is influenced by the material's mechanical parameters. The latter have to be investigated in experiments prior to simulation.

The shear angle represents the angle between the warp and weft threads in a woven fabric. After a deformation the shear angle is a significant indicator of the draping qualities of woven reinforced prepregs. To characterise the shearing properties, the shear modulus is investigated using a picture frame shear test (Figure 2).

The prepreg is clamped on all sides across four movable frame shear rails and pulled in a vertical direction. The shear angle between warp and weft threads

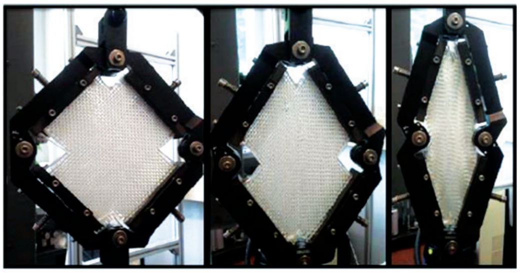

Figure 2: Picture frame shear test of glass fabric.

increases as a function of the shear force; initially, the shear force rises at a linear rate, but later, having reached a critical shear angle, it rises exponentially [7]. For the picture frame shear tests, the prepregs are heated to determine the shear char-acteristics and the draping qualities of the pre-impregnated textile prepregs. The prepregs are heated at a temperature near the matrix‘s melting point, so that the temperature-dependent shear forces and paths can be recorded. Based on the recorded force-path curves, it is possible to calculate the shear modulus G as a function of the shear angle; the shear modulus is of crucial importance for the simulation of the deformation process.

In addition to the prepregs' shear characteristics, other mechanical parameters are required: tensile strength, Young's modulus, flexural modulus and coefficient of friction. For the thermal characteristics of the prepregs, the material characteristics of thermal conductivity, specific thermal capacity and viscosity of the matrix are also required. These material parameters are usually investigated by means of the laser flash method [8], differential scanning calorimeter [8] and rotating rheometer [9].

Finally, forming process parameters, such as tempering of the forming dies, closing speeds and locking forces of the forming dies are required.

2.2 *FEA software*

Numerous software solutions were developed to map the deformation characteristics of textile and other prepregs. The applied programs differ with respect to the simulated material and the deformation calculation methods. Deformation can be represented by using a kinematic approach or by discretisation based on the FE method. If, in computer-aided deformation analysis, only the prepreg displacement and distortion have to be determined, then a kinematic approach using the Tschebyscheff mechanism is sufficient. The latter takes into account the shear effect of the textile structure, as well as the changing shear angles; in modelling, the points of intersection of the woven fabric are represented as joints, whereas the fibres are shown as bars. This method for prepreg modelling generates sufficiently accurate results in the representation of drapability and wrinkling. The mechanical parameters of the woven fabric, however, are not considered, so that it is impossible to predict potential stresses and distortions [10]. Programs like those are used for classic sheet metal or plastic film deep-drawing processes.

The simulation software PAM-FORM makes it possible to depict the process of forming thermoplastic FRPs, for which modelling is directly adapted to the forming procedure. In comparison with software aimed at FEM alone, the chosen methodology provides the process definition and the forming process calculation much more quickly.

Using the Composites module in PAM-FORM, one can simulate the organic sheet forming process and thus determine the fibre orientations, thickness distribution and formation of wrinkles, as well as stresses and strains in the membrane layers.

During CAD data import and meshing of the model geometries, PAM-FORM offers two meshing methods - feasibility and validation. The two methods are distinguished by the limitation of the element sizes, maximal distance between elements and the permitted interior angles of the elements.

The meshing characteristics of the used methods are listed in Table 1.

Table 1: Meshing methods for validation and feasibility [11]

Element Size	Feasibility	Validation
Minimum	0.3	0.2
Maximum	30	10
Chord Error	0.1	0.05
Angle Criteria	7.5°	15°

The meshed objects are subdivided into formable and non-formable parts. Blanks whose mesh elements consist of mid-surfaces with contact thickness, as a rule, are categorised as formable objects. The dies are, as a rule, assumed to be non-formable, so that their shell elements are modelled via their exteriors,

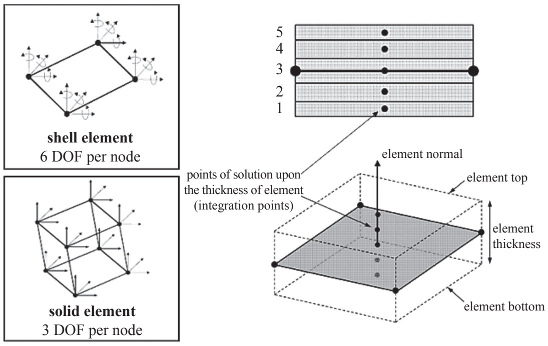

Figure 3: Element types and definition in PAM-FORM [11].

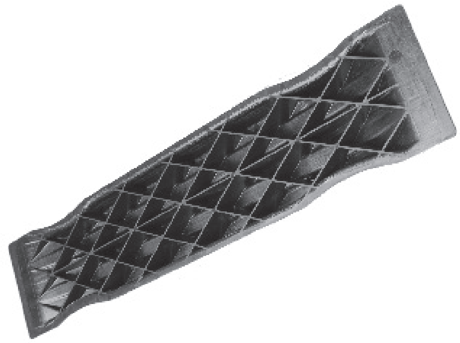

Figure 4: Side impact protection beam made of an organic sheet and a ribbed structure in an injection molding process [12].

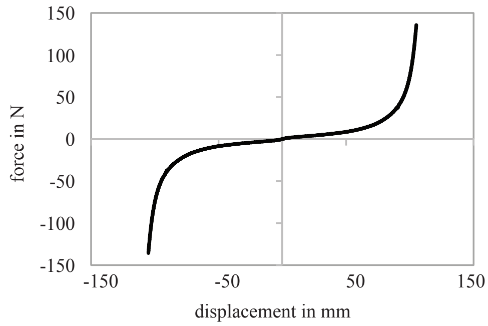

Figure 5: Force-displacement-curve of the picture frame shear test.

without contact thickness. In Figure 3, shell elements and solids, as well as the element structure and the distribution of the Gaussian points inside the element are depicted schematically.

3 Modelling Based on a Side Impact Protection Beam

3.1 *Model geometry*

The component has been developed in the research project "thermoPre" funded by the BMBF for demonstrating a structural health monitoring system used in automotive applications.

The abstracted side impact protection beam consisting of a formed organic sheet and a ribbed structure is manufactured by using an injection molding process (see Figure 4).

The CAD data record of the pressing die is used as the basis for the model geometries. First, from the available solid bodies, the die, the punch and the blank holders are derived as shell elements. The original formed part and thus the die are designed with a ribbing, which is only shaped in the follow-up injection moulding process, in order to inject backed the formed prepreg. In the press die, the ribbing is either incorporated in the die as a negative shape and is considered in the model geometry, in variation, as a recess, or as a closed surface, is no longer considered at all.

3.2 *Materials*

The TEPEX® dynalite 102-RG600 by the firm Lanxess, with a 47% fibre volume content of glass fibres and polyamide 6 was used as the thermoplastic pregreg. This organic sheet follows a laminar structure. Each layer has a thickness of 0.5 mm and a weight per unit area of 600 g/m^2.

In the tensile test at room temperature, the prepreg has a tensile strength of 404 MPa and a Young's modulus of 22.4 GPa in 0° orientation and 390 MPa and 21.5 GPa in 90° orientation [13].

To obtain near real forming results for the mechanical parameters of the material, results were used from experiments in which the organic sheet was heated up to the applicable forming temperature. The shear modulus, which is important for the deformation modelling as a function of the shear angle, is calculated via an imported force-displacement measuring curve in the material card. For this purpose, the picture frame shear test shown in Figure 2 was performed. Figure 5 illustrates the resulting force-displacement curve, which records the shear modulus according to point symmetry to the origin over the negative and positive shear angle values.

3.3 *Modelling*

To create an initial or basic simulation model, the shell elements of the punch, the blankholder and the die are imported into PAM-FORM. For the first simulation step, the validation meshing method is chosen (see also Table 1). The meshed dies are shown in Figure 6.

3.4 *Definition of the forming procedure*

For forming process modelling, the procedure is subdivided into two steps - “closing” and “drawing”. During the closing step, the blankholders traverse vertically downward at a speed of 0.5 m/s and press the inserted organic sheet against the die. Step 2, drawing, includes the forming of the organic sheet by traversing the punch against the die. The punch traverses at a speed of 0.7 m/s. During this motion, the blankholders fix the organic sheet by means of a locking force of 2 kN or 200 kg.

The generated die meshes and the blank mesh are already in their final positions following the forming process. The sequence and the motion of the used objects are defined via the geometric boundary conditions, as well as the traverse speed values. For closing, the blank is shifted along the vertical axis until it contacts the die. For the drawing step, the punch is traversed vertically until it contacts the blank.

The dies are assumed to be non-deformable elements for both process steps. The contact between the dies and the blank is characterised by a coefficient of friction of 0.12.

3.5 *Simulation variants and variables for analysis*

The simulation variants are designed to establish a sensitivity analysis, thereby varying numerous parameters that can be used to determine an optimal blank size. Figure 7 summarises all variations and analysis parameters.

Starting with the basic version, the optimal blank size of the organic sheets in the planar state is first determined. The derived blank size is used as the reference for the comparison of the simulation variants. Mesh size of the blank, die meshing, thermal impacts, the consideration of ribbing contours and the coefficients of friction for the contact characterisation are defined as relevant influencing factors for a sensitivity analysis.

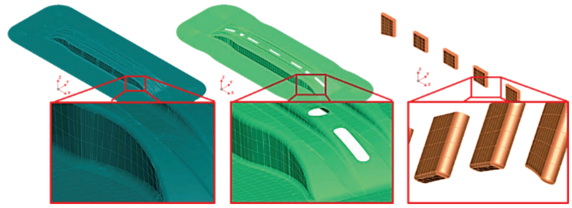

Figure 6: Meshing of the dies with validation tool (left: die, middle: punch, right: blankholder).

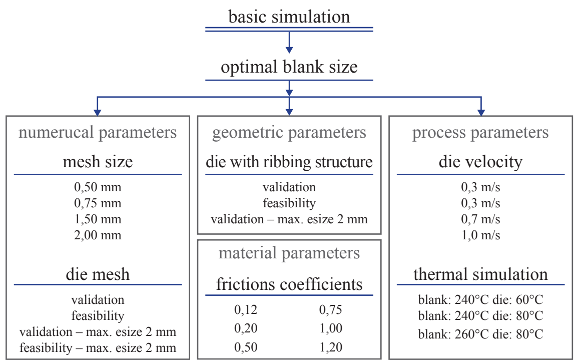

Figure 7: Significant simulation parameters and variants.

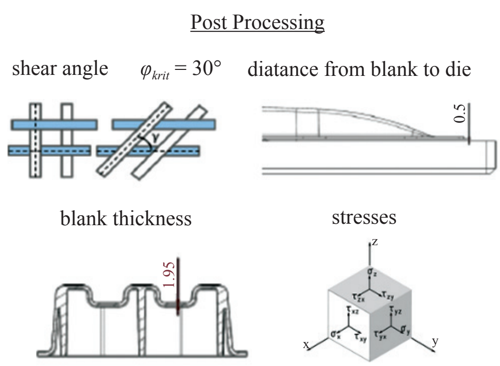

Figure 8: Evaluation criteria in Post Processing.

The shear angle, the distance from blank to die, blank thickness and the stresses appearing in the thermoplastic prepreg (Figure 8) are used as evaluation criteria and for the assessment of the various simulation variants.

The shear angle is the most essential evaluation parameter. In the experiments performed in the picture frame shear test, a critical shear angle of 30° was determined. Smaller shear angles in the organic sheet negatively affect draping and the moulding of the die contour. The distance from blank to die is a criterion for the moulding of the die contour; greater distance values result in wrinkling. The thickness over the cross section should be distributed as homogeneously as possible so that it is possible to detect pinching and linear compression, as well as any hindering of the flow.

The simulation variants were analysed with respect to local stress peaks, as well as the total stress that appears in the organic sheet.

The temperature distribution in the organic sheet is also taken into account. For a simplified thermal analysis, the following parameters are assumed to be independent of temperature: density, viscosity, thermal conductivity and heat absorption. The die and prepreg temperatures are also defined using a constant initial temperature. Thermal transmission only occurs in the form of thermal conduction in the material, as well as heat transfer between the organic sheet and die, which is defined at 2000 W/(m^{2}K). The value is derived from the injection moulding process [3].

For the evaluation of the sensitivity analysis results, six geometric discontinuity points are defined along the side impact protection beam (Figure 10).

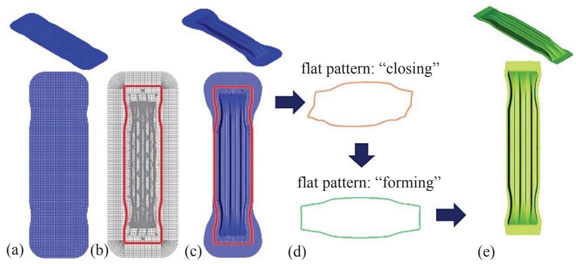

Figure 9: Determination of the optimal blank size.

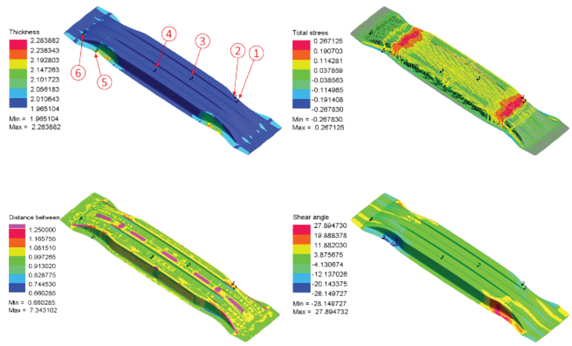

Figure 10: Basic simulation results, with 1 mm mesh size: blank thickness (top left), stress distribution (top right), distance from blank to punch (bottom left) and the adjusting shear angles (bottom right).

4 Presentation and Discussion of the Results

4.1 *Determination of the optimal blank size*

The optimal blank size for the organic sheet is determined by projecting mesh lines of the near-net-shape blank on the undefined initial size of the formed organic sheet [Figure 9 (a)–(c)]. In a development step performed in both the closing and drawing processes, the blank size curve is applied to the organic sheet in reverse [Figure 9 (d)], so that it is possible to derive the optimal blank geometry. In Figure 9 (e), the near-net-shape formed side impact protection beam and the derived organic sheet derived are illustrated.

4.2 *Results and discussion of the basic simulation*

For the process parameters of the basic simulation defined in Section 3.5, the following analysis parameter values are adjusted, as shown in Figure 10.

The blank thickness distribution adjusting in the formed side impact protection beam is almost homogeneous and amounts to 2 mm. Material build-ups resulting from the bending of the organic sheet are only found around the points 1, 2 and 5. Wrinkles are probably formed. In general, the organic sheet is only upset by a few tenths or hundredths of a millimetre.

As a result of the appearance of displacements and distortions in the organic sheet due to the anisotropy of the reinforcing fibres, stresses that depend on the orientation appear in 0°- and 90°- direction. The highest tensile stresses were investigated in the beads and in the neighbourhood of point 2, where they achieve maximum values of 267 MPa. Apart from stretching in a few locations, compacting also appears, and these compacted zones are characterised by compression stresses of -268 MPa. In 0°- direction, stresses from 10 MPa to 115 MPa appear in the component, distributed widely across the component. According to manufacturer data [13], the tensile strength of the organic sheet is approximately 400 MPa. Consequently, the appearing stresses can be estimated as non-critical.

With regard to the distances from organic sheet to punch, most values are approximately 1 mm for the element surface distance, calculated according to 2.2 or Figure 3. At the radiuses of the side impact protection beam, higher distance values can be noticed occasionally. At these positions, the material is compressed and flow is hindered, effects which are triggered by the forming punch. In general, the punch geometry is properly represented in the forming process.

In the basic simulation, the critical shear angle of 30° is not achieved. In the material, there appear only low shear angles of approximately ±3° in 0°- orientation. As already observed in the thickness distribution, problems arise from the external joining or component surfaces, where minimal and maximal shear angles of ± 28° appear. As a result of the high shear effects in the material, wrinkles and poor drapability have to be expected to an increasing degree.

4.3 *Results and discussion of the sensitivity analysis*

Starting at Figure 8, the results of the other simulation variants are considered and discussed in the following. In a first step, the element size in the blank mesh is regarded as a significant numerical parameter for modelling.

In Figure 11, as well as in the figures following, diagrams on the top show the shear angle and the distance from organic sheet to punch, whereas the diagrams on the bottom elucidate the blank thickness and the stresses in the composite material in comparison with the simulation variants. For each simulation variant, in vertical direction, the values of the preliminarily six defined points on the side impact protection beam are shown (see Figure 10), as well as both peak values. Starting with the shear angles, when using a coarsened element chord mesh, one can detect a reduction in the minimally and maximally appearing shear angles. The lower resolution in the representation of the mesh causes the distortions to be mapped less clearly. A refinement of the element chord mesh, however, only results in a marginal amplification of the shear angle. In the points defined on the side impact protection beam, no relevant influence of the mesh increment size on the shear angle may be detected.

When examining the element distances, an increase in the distances as a function of mesh coarsening can be observed. The maximal distances are not mapped in the diagram, since, in PAM-FORM, the distances between the blank elements and the recesses in the punch are taken into account for the blankholders, and values of approximately seven millimetres occur. These values

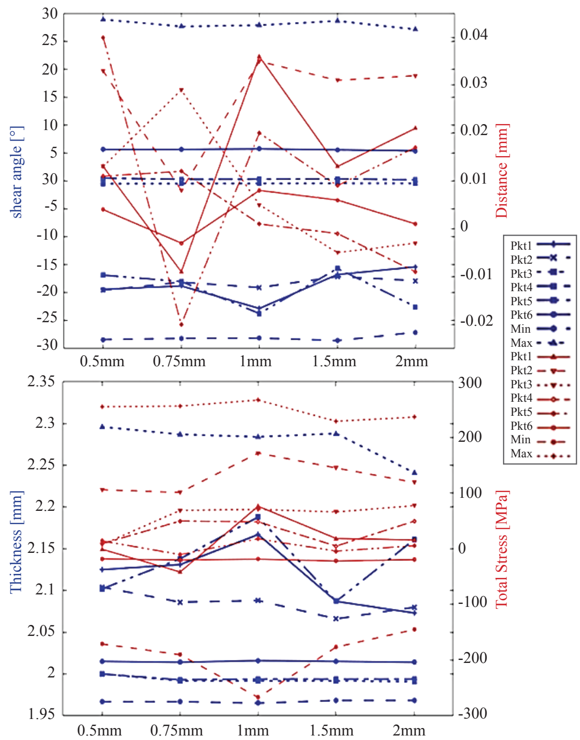

Figure 11: Mesh increment size affecting shear angle, die distance to blank and punch (top), blank thickness and stress in the fibres (bottom).

are not considered in the evaluation. The increase in the element size and the fact that they can only be mapped at a lower resolution can also be noticed in the blank thickness distribution. For the majority of measured values, it can be determined that blank thickness slightly decreases with an increase in the blank mesh increment. The range of values comprises a few hundredths of a millimetre.

With respect to the stresses in the composite material, the tensile and compressive stresses slightly decrease as a function of increasing mesh size increments. The influence of the mesh size increments on the stress distribution is, however, not significant, despite the deviations in the “1 mm”-variant.

After the variation of the blank mesh increments, the methods and variants of die meshing are compared in Figure 12. Starting with the standard meshing methods (variants 1 and 2) of PAM-FORM according to Table 1, simulation variants are illustrated with decreased maximal element size for validation and

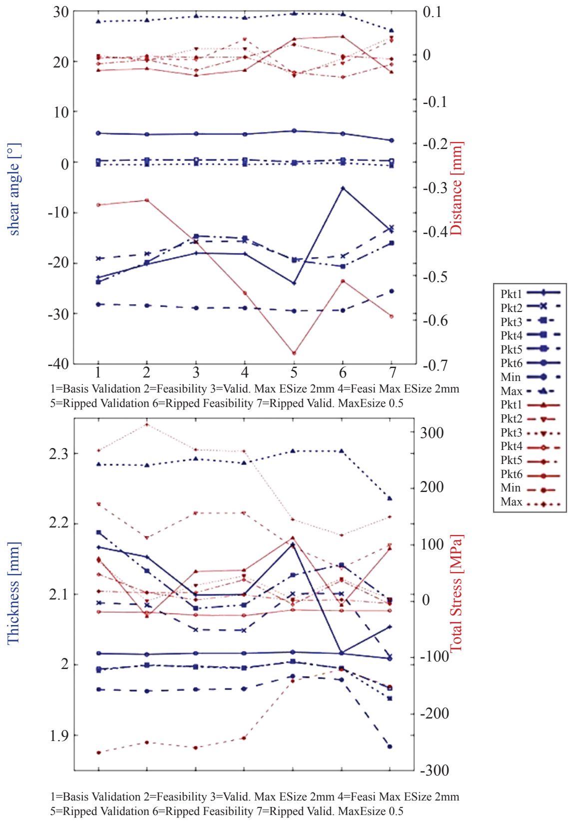

Figure 12: Die mesh sizes acting on the shear angle, die distance to blank and punch (top) blank thickness and stress in the fibres (bottom).

feasibility (variants 3 and 4), as well as with die with ribbing (variants 5 and 6) and die with ribbing in combination with a refined blank mesh (variant 7).

Beginning with the shear angles' analysis, only a slight decrease or increase may be seen. A die variant with refined meshing or the use of a die with ribbing provides only slight shear angle differences in the range of ± 5°.

The distances from blank to punch also follow a similar distribution over the variants, with only small differences in the measured values. We can observe an increase in the distance when using die meshes of higher resolution or when using dies with ribbing only at point 6 on the side impact protection beam.

When investigating the blank thickness, a decrease may be observed between the variants 5 to 7. Among the standard methods, taking the die without ribbing, we can detect a significant thickness reduction with a die mesh of higher resolution. When applying the die with ribbing, the blank thickness values are the same as those of the variant without ribbing.

A similar diminishing trend can be recognised for the variants 5 to 7 also in the stresses that appear in the organic sheet. In the dies with ribbing, clearly lower stresses in the organic sheet can be seen. In this case, the minimal and maximal stresses amount to almost 50% of the values gained for the variant without ribbing. With respect to the stresses, the difference between the validation and feasibility method is apparent in general. Since the feasibility method is characterised by lower resolution in principle in the die meshing, the appearing local stresses are mapped less precisely. As has already been seen in the basis simulation, even in die meshing, higher stress peaks do not appear in the forming procedure, so that - with respect to strength analysis - the process has to be assessed as non-critical in the simulation.

In Figure 13, the calculation results for the varied material parameter of the coefficient of friction between the dies and the blank are recorded. The results cover a coefficient of friction range from 0.12 to 1.2. The increase in the coefficient of friction results in a slight reduction of the shear angles by a few degrees over the whole side impact protection beam.

The alterations of the die distance as a function of an increasing coefficient of friction are also only marginal. Die distance diminishes only locally, and, at a coefficient of friction of 1.2, it amounts to a minimal value of 0.4 millimetres distance among the mesh elements. In this case, the blank material is strongly compacted due to high friction and shear effects. Blank thickness decreases in a distributed manner across the side impact protection beam as a function of an increasing coefficient of friction due to increased friction between the blank and the die surface. More than 1/10th millimetre differences in thickness can be recognised locally. Furthermore, stresses in the composite material increase in the opposite direction as a function of increasing coefficient of friction. At a coefficient of friction of 0.75 and higher, a strong increase in stresses can be identified locally.

Finally the results of the varied punch speeds and the die and blank tempering are listed in Figure 14. The die closing speeds particularly affect the extreme shear angles in the organic sheet - the extremes are amplified: as a result of decreasing speed, the maximum

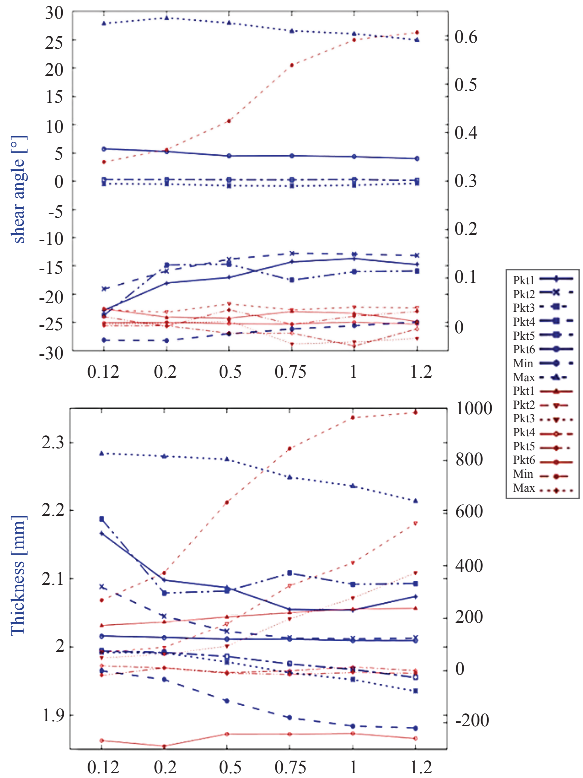

Figure 13: How the coefficient of friction affects shear angle, die distance to blank and punch (top), blank thickness and stress in the fibres (bottom).

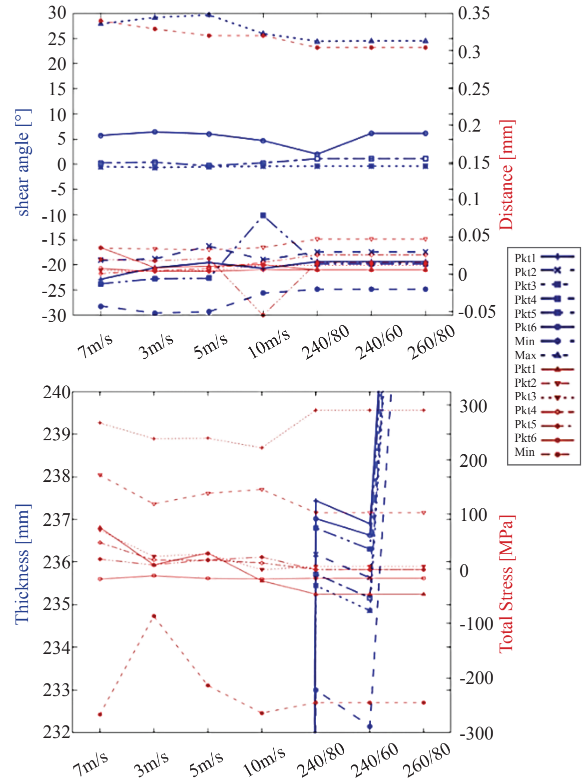

Figure 14: Influences of punch speeds and die tempering to shear angle and distance (top) plus temperature and stresses (bottom).

values of shear angle become higher, whereas the minimum shear angle values become lower. A decrease of the shear angle is to be identified at punch speeds of 10 m/s. The shear angles of the speeds 3 m/s and 5 m/s range close to the critical shear angle of 30°.

For this reason, the selection of punch speed values below those in the basis simulation is to be assessed critically. With regard to the distances from blank to the punch (as in the upper die), no significant influences of the traversing speed values can be identified. At higher speed values, the blank is compressed slightly more. For the thermal variants, no relevant differences in shear angle and measured element distances can be seen.

Concerning the blank temperatures, when reducing die tempering from 80°C down to 60°C, only slight temperature differences amounting max. two degrees Celsius appear.

A greater influence of the variants can be seen in the stress distribution. At lower punch speeds, clearly lower maximal and higher minimal stresses appear. A consideration of the thermal impacts during the simulation does not indicate a measurable influence on the stress distribution in the organic sheet.

5 Conclusions

In the presentation and discussion of the results, at first, the determination of the optimal blank size and the results of the basic simulation for the analysis parameters are introduced. With the initial configuration selected, no critical parameters for the shear angle and the stresses were found in the forming process. With respect to the blank thickness distribution and the die distance between the blank and the punch, local compressions and thickenings were identified, which may result in wrinkling and material heterogeneities.

The sensitivity analysis provides smaller shear angles for meshing of the organic sheet, fewer local variations in the blank thickness distribution and lower stresses in the composite material with meshes of lower resolution.

For die meshing, we observe lower resolution in the meshing of the feasibility method; the die contour can only be mapped less accurately, and the method provides low minimum shear angles. For the optimised meshing methods with maximal element sizes of greater than two millimetres, only a slight influence on the analysis parameters can be identified. In the case of the dies with ribbing, significantly fewer stresses emerge in the composite material. The shear angles that appear in the organic sheet are only slightly influenced by the die with ribbing. The combination of an organic sheet mesh of higher resolution with the die with ribbing only affects the shear angles and the blank thickness.

Increasing the coefficients of friction provides smaller maximum and greater minimum shear angles, reducing blank thickness values, diminishing die-blank distances and increasing stresses in the FRP.

The punch speeds that approximate to the critical shear angle only at very low speeds only slightly influence the shear angles in the side impact protection beam. The thermal analysis of the forming process does not provide any significant influences of the die and blank tempering on the analysis parameters. Due to the speedy running process, temperature cannot be adapted by thermal conduction across large surfaces.

For further refinement of modelling and simulation results, the calculated values have to be compared with experiments on the local shear angles and the blank thicknesses inside the organic sheet; additional temperature-dependent material characteristics have to be determined. The evaluation of the stresses that appear has to be consolidated by the execution of forming tests with measuring elements that can contribute to the verification and validation of the calculated stress values. The anisotropic cooling down characteristics of the organic sheets, which induces internal stresses and may cause a "springback" effect, are not considered in forming simulation. Another approach might be able to add an additional process step that would also take into account the cooling down characteristics and the drafting. From this step, structural-mechanical characteristics could be exported in order to evaluate the strength in the manufactured part in additional calculations.

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