

NUMERICAL SIMULATION BASED PROCESS DEVELOPMENT OF THE NOVEL THERMOCLINCHING TECHNOLOGY FOR TEXTILE REINFORCED THERMOPLASTICS

Maik Gude, Andreas Freund*, Christian Vogel

Institute of Lightweight Engineering and Polymer Technology, TU Dresden
Holbeinstraße 3, 01307 Dresden, Germany

*Email: andreas.freund@tu-dresden.de, web page: <http://www.tu-dresden.de/mw/ilk>

Keywords: Thermoclinchng, Hybrid Structure, Thermoplastic Composite, Process Simulation, Meso Model

ABSTRACT

Hybrid structures in multi-material design offer a high potential for the use in lightweight applications, on condition that material specific manufacturing and joining technologies are provided. Therefore, the new joining technology "thermoclinchng" was developed at the ILK, which generates joining element free and form-locked joints with thermoplastic composites and metallic joining partners by means of plastic deformation. First studies have demonstrated the capability of the novel thermoclinchng technology by identifying process influencing parameters and developing a numerical process simulation concept. Thus, for an efficient and detailed development of a reliable thermoclinchng process, more detailed studies of the specific deformation phenomena in the joining zone are necessary.

This study shows the further development of the new joining technology concerning the accurate prediction of a defined and adjustable fabric structure in the head and neck area of the joint. To estimate the capacity of the novel joining technology, geometrical as well as process related parameter boundaries are determined. Furthermore, the influence of pre-cut orientations on the local material configuration is analyzed. Thereby occurring deformation characteristics are identified and described by performing a stepwise computertomography analysis for different deformation states during the thermoclinchng process.

Based on a developed process simulation concept a numerical parameter study is carried out to support the experimental studies of the specific deformation phenomena in the joining zone. Thus, the numerical studies sustain the high influence of geometrical and material specific parameters within the intermediate field of fluid and solid mechanics on the deformation characteristics and therefore the orientation of the fabric structure in the head and neck area of the thermoclinchng joint.

1 INTRODUCTION

The rising demand of lightweight constructions for an energy efficient and resource sustaining product development has led to a growing application of hybrid structures in areas such as aviation or automotive engineering. Thereby, hybrid structures made of continuous fiber reinforced thermoplastics and metallic components have proven to be very efficient due to their high-volume manufacturing ability and their adjustable highlevel mechanical properties. To fully exploit the specific structural and functional properties of the different materials, it is necessary to provide specific joining technologies. Therefore, the new joining technology "thermoclinchng" was introduced to join metallic components with fiber reinforced thermoplastic structures by means of plastic deformation [1].

An efficient development of a reliable thermoclinchng-process and the prediction of the joint quality require the application of numerical simulation tools. Despite the simulation of classical joining methods for metallic components, i.e. riveting or clinching, the here intended methods and simulations are not state of current research. To date exist only few approaches for the estimation of draping and forming behavior of dry and impregnated fabrics using kinematic algorithms [2] as well as finite elements based models [3]. The kinematic approach based on the flat projection of an arbitrary

equally spaced mesh onto a surface is implemented in commercial finite elements codes like MSC laminate Modeler, Composite Modeler or PAM Quickform for the rough estimation of fiber orientations and ply contours. Due to the absence of a physical description of constitutive material behavior the mentioned tools are not suited for the simulation of the forming process.

Numerical models offer a more realistic representation of forming phenomena using semi-discrete [4] or continuum based models [5, 6]. The well-known software PAM FORM [7] provides a macroscopic homogenized material model for dry textiles or textile composites with visco-elastic matrices including strain rate dependency for the relevant deformation modes but for shell elements only, i.e. massive forming with distinct and localized through-thickness effects cannot be reproduced. Due to the lack of existing models a new simulation concept has been developed, incorporating a multi-scale approach for the virtual material characterization and calibration of material laws as well as a fabric-related 3D finite elements model.

1 PROCESS DESCRIPTION

The development of the new joining technology “thermoclinching” is seized on process sequences from the metallic clinching process, which uses the principles of joining by plastic deformation. In regard to the metallic joining partner, the new joining technology is orientated on the single-staged clinching process with a pre-punched pilot hole to join metal sheets with differing sheet thickness and formability, also known as CONFIG-clinching [8]. Thereby, the non-ductile and die-sided material is pre-punched and interspersed from the ductile joining partner (cf. Figure 1).

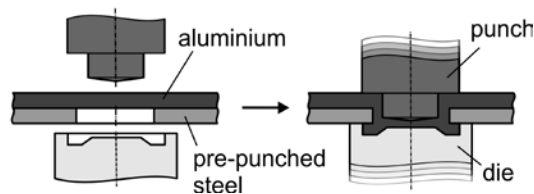


Figure 1: Schematic illustration of the single-staged clinching process with a pre-punched pilot hole

Similar to the CONFIG-clinching process, the developed joining technology “thermoclinching” intends a plastic deformation process to join metallic components with textile reinforced thermoplastic structures. Thereby, the thermoplastic composite is positioned with the metallic joining partner inside the mould and locally heated above melting temperature to increase the plastic deformation ability of the thermoplastic composite (Figure 2(a)).

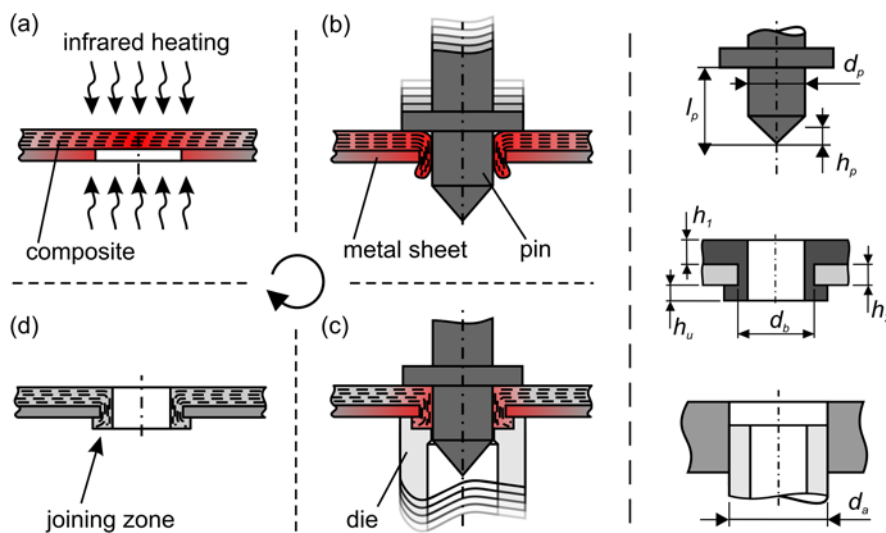


Figure 2: Schematic illustration of the novel joining process “thermoclinching” (left) and general tool dimensions (right)

After the heating process the mould is closed and the tapered pin is shifted forward, permeating the composite and shifting thermoplastic matrix and parts of the textile structure through the pre-punched hole of the metallic joining partner (Figure 2(b)). Subsequently, the passed-through material is compressed by a die to build a form-locked head of the joint (Figure 2(c)). The joining process is completed after cooling and solidification of the joining zone (Figure 2(d)).

To demonstrate the capability of the developed thermoclinching process, prototypic joints were manufactured using an experimental joining installation with defined mould, pin and die geometry (cf. Figure 2 (right)). The investigations on processing were performed on semi-finished parts such as pre-punched steel sheets in combination with both reinforced and unreinforced polypropylene (PP) sheets. According to the high deformation degree of the thermoplastic joining partner during the thermoclinching process, the glass fiber reinforced thermoplastic sheets (GF/PP) were locally cut crosswise in the space of the joining zone to improve the flexibility of the fibers. During the manufacturing trials it was shown that a reproducible manufacturing of thermoclinching joints with defined geometrical dimensions can be realized (cf. Table 1).

GF/PP fabric	TWINTEX TPP60 745
weave	twill 2/2
laminate structure	[(0°/90°)] ₄
fiber volume content	0.35
laminate thickness h_1	4 mm
PP material	Moplen HP501L
PP sheet thickness h_1	4 mm
steel sheet thickness h_2	1 mm
pilot hole diameter d_b	15 mm
pin length l_p	35 mm
pin diameter d_p	12 mm
die diameter d_a	22 mm
pin point length h_p	35 mm

Table 1: Semi-finished part properties.

As the fiber reinforcement in the joining zone has such a significant influence on the load carrying capacity of the thermoclinching joints, the microstructure of the joining zone has to be analyzed. Accordingly, non-destructive and destructive analyses such as computed tomography scans and micrograph analyses were performed on the thermoclinching joints, indicating a relocation of the deformed textile reinforcement structure into the neck and head area of the joints (Figure 4).

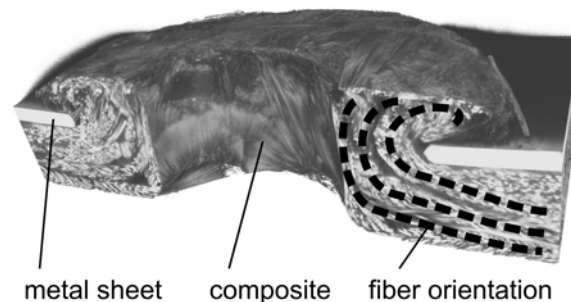


Figure 4: Micro structure analysis of the thermoclinching joining zone by computed tomography

Although the relocation of the textile reinforcement considerably contributes to the load carrying capacity of the joints, the received analyses also show that the composite fiber orientation is largely

undefined and not yet reproducible. For the understanding of the local material configuration and to achieve a defined and adjustable fabric structure in the head area of the joint, further experiments with regard to the deformation behavior during the thermoclinching process are necessary. Therefore, the usage of numerical simulation offers the opportunity to reduce accruing test efforts during the process development.

3 DEVELOPMENT OF A SIMULATION CONCEPT

The efficient development of the novel thermoclinching process regarding a defined and adjustable fabric structure of the joint requires the development of adapted numerical simulation tools. With a process temperature level above melting temperature of the thermoplastic matrix the simulation problem is located in the transition between solid continuum mechanics and fluid dynamics making the estimation of material data in the viscous state a challenging mission. Simple tension or bending tests on textile reinforced coupon specimen are not possible as the polymer migrates from the clamping area. Thus, the material data are estimated from the behavior of its constituents using a multi-scale approach. For numerical pre-studies available and proven material data of previous research activities at the ILK have been taken into account. Temperature levels above 80 °C require an extrapolation with usage of the Ramberg/Osgood-approximation [9].

At microscopic level a unit cell based simulation is inappropriate as the matrix migration problem is persistent. Previous studies on homogenization methods revealed the high quality prediction of the mechanical properties of two-phase composite materials using the micromechanical model of Huang [10]. In contrast to well-known rules of mixture (Chamis [11] or Puck [12]) a complete set of direction-dependent stress-strain-curves can be generated. Early virtual forming studies of un-reinforced PP-sheets have been run with ABAQUS/Explicit assuming a small anisotropy from the injection molding process. The results showed a proper reproduction of experimental results (Figure 5) validating the method of material data generation.

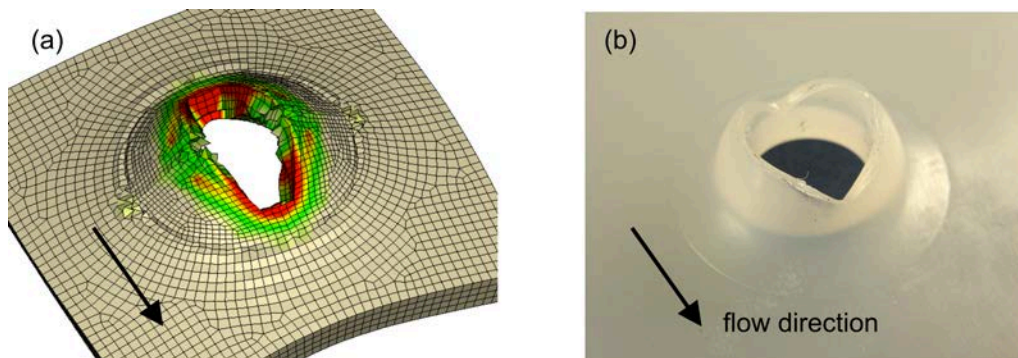


Figure 5: Effects of pure matrix material's anisotropy after indentation by the pin, demonstrated (a) in a numerical analysis and (b) in experimental validation

The principal anisotropic directions, i.e. the pure material's texture, contain the information about the probable fiber orientation with special focus onto the neck area and allow studies of the relation between the joint size and the local orientation field. The observed high deformation grades led to element deletion as well as highly distorted elements and thus require special methods to maintain a high-quality mesh throughout an analysis. The finite elements software ABAQUS provides the adaptive remeshing based on the Arbitrary Lagrangian-Eulerian (ALE). The drawback of this powerful method is the loss of detailed texture information and the poor representation of effects of large deformations as folding or interlaminar slip.

Beside the ALE method ABAQUS provides a Combined Eulerian-Lagrangian (CEL) analysis with different mesh domains. Since anisotropic materials are not supported by the CEL the model has been separated into two domains with Lagrangian elements for the solid-like areas and Eulerian meshes for the fluid-like sections. Both domains interact via contact conditions. The embedment of Lagrangian (roving) elements into the Eulerian (matrix) elements led to promising deformation states but serious convergence problems with increasing pin indentation depths (cf. Figure 6).

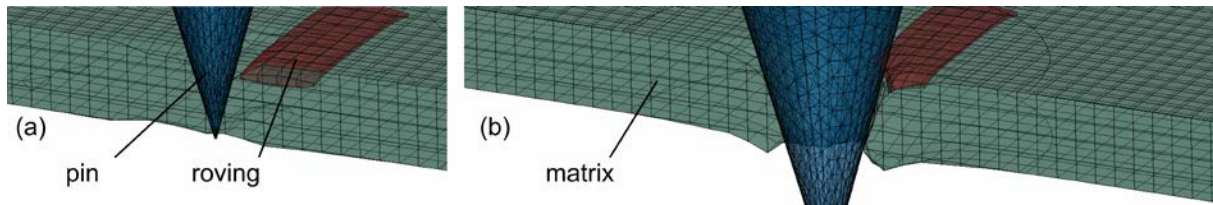


Figure 6: Generated CEL-analysis of matrix and roving deformation at onset of pin-indentation (a) and with deformed roving (b)

But the observed small deformations and deformation speeds imply the neglect of matrix for further simulations and consequently the consideration of isolated rovings. Beside, as a minor benefit high-quality meshes of the rovings can be generated by simple extrusion. The usage of an anisotropic elasto-plastic material law and contact conditions with friction allow a realistic representation of cross-section distortion and interlaminar slip, i.e. relative tangential motion between rovings or fabrics. In early studies a representative model size of appr. 90 x 90 mm with 144 isolated rovings and cuts perpendicular to the fiber direction (Figure 7) has been considered. A bell-shaped temperature field with melting temperature in the center and room temperature at the boundary represents the temperature distribution from local heating. Consecutively the conical pin indents the model and shifts the rovings creating a local buckling instability of the upper-most rovings due to the radial force components during the indentation process. In the end of the process the lower die pushes the rovings back and creates the undercut.

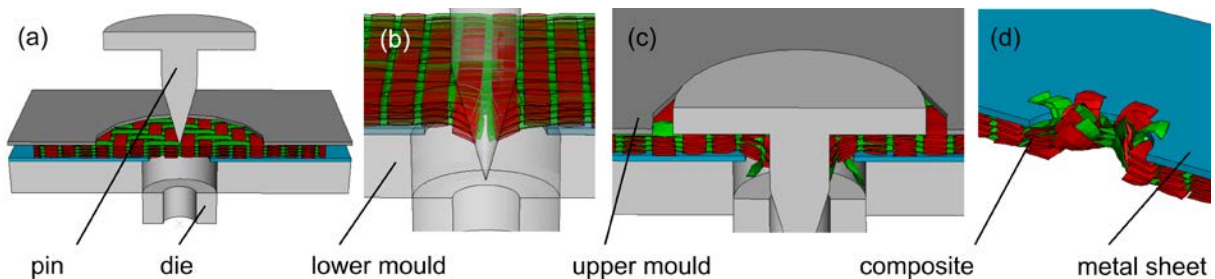


Figure 7: Deformation analysis with extracted rovings and simplified test rig (a), roving deflection during indentation (b) and at its end (c), folding during die movement (d)

4 COMPARISON WITH EXPERIMENTAL RESULTS

Since the thermoclinching process itself takes less than two seconds, the process has been stopped at several levels of pin-indentation depths, allowing a computertomography of the current deformation states. The following Figure 8 compares three stages during the thermoclinching process, starting with the onset of piercing up to the completely extended pin and the onset of the die. Thereby, beside a vertical fiber deformation a horizontal deformation of the textile reinforcement was observed. This raises the surface-near fibers in the joining zone uncontrollably, pulling them out of the joints neck area. In the final phase of the joining process the deformed reinforcement structure is compressed by the die. Thereby, the ends of the fibers show an unwanted splitting both in pin facing and pin averted direction. These studies show that the developed simulation concept is able to represent the obvious principle deformation characteristics in the joining area during the thermoclinching process.

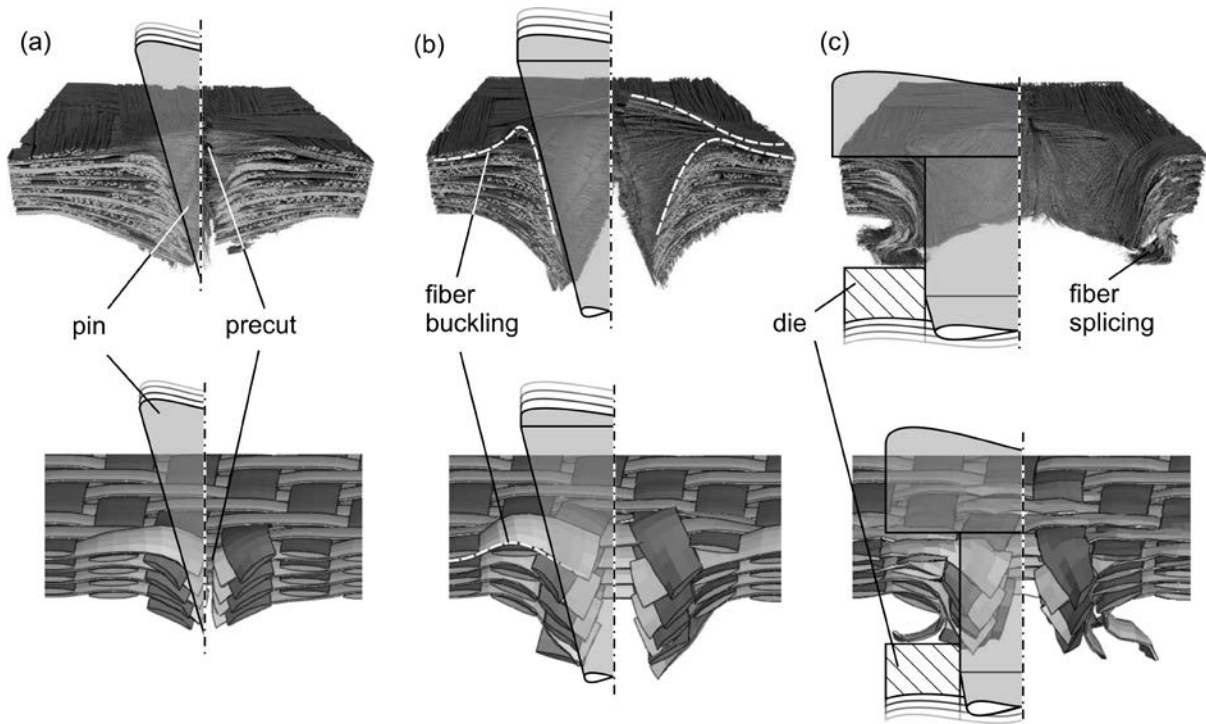


Figure 8: Numerical simulations and experimental results of the deformation analysis during the thermo-clinching process with different process stages at (a) 10 mm and (b) 20 mm pin indentation and (c) full indentation of the pin with onset of the die

5 INFLUENCE OF PRE-CUT CHARACTERISTICS

Beside the investigated and obvious geometric parameters like hole and pin diameter, the exact location of the pre-cut with respect to the textile pattern as well as its orientation have big influence on the fiber alignment in the joining area. The later ones are of particular importance, since their individual values are not controllable in future manufacturing application. In addition an exact alignment of the single fabric layers in the stack is hardly realizable. In consequence, the influence of pre-cut location and orientation has been investigated with the developed simulation concept. In a first step the pre-cut location relative to the textile pattern has been varied with an orientation perpendicular to the fiber direction. Figure 9 shows that the investigated pre-cut locations have specific influence on the roving position in the neck and head area of the joint. Here, the interstice location, i.e. the gap between the encircling rovings, provides the best fiber alignment (Figure 9a) compared to the mid-roving (Figure 9b) and crossing-point (Figure 9c) indentation position.

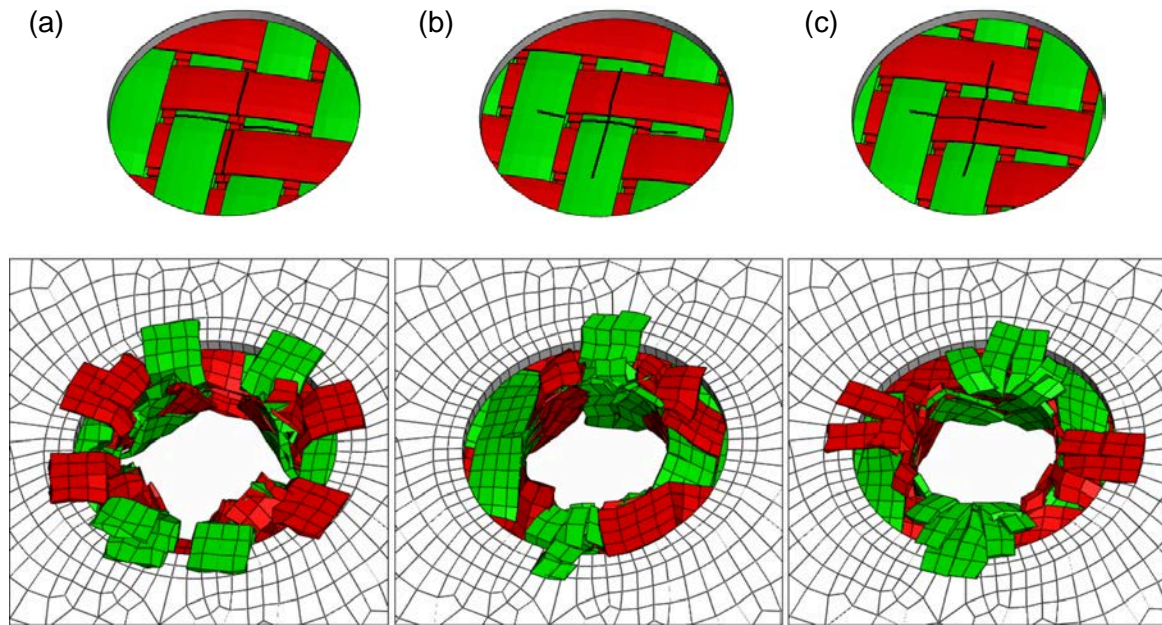


Figure 9: Numerical simulation of characteristic fiber alignment depending on the pre-cut location relative to the textile pattern: interstice (a), mid roving (b) and crossing point (c)

In a subsequent step and based on the crossing point position, the orientation of the pre-cut has been rotated by 45° (Figure 10b). Both pre-cut orientations show a similar roving alignment (cross shaped) in the head area with a primarily assemble of fibers in the neck area.

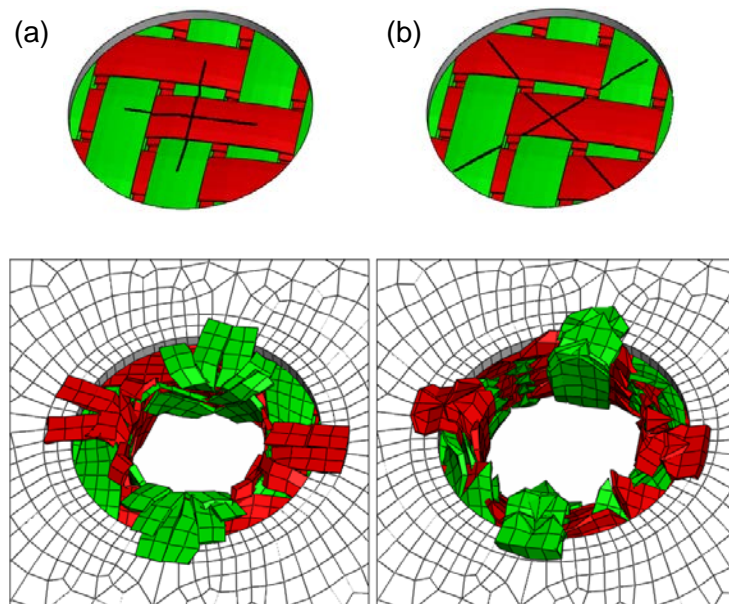


Figure 10: Numerical simulation of characteristic fiber alignment depending on the pre-cut orientation: perpendicular (a) and diagonal (b) to the fiber directions

More detailed studies of the specific deformation phenomena considering the accurate prediction of the separation of fiber bundles due to transverse matrix flow and the pressure-forming in the neck area as well as the future strength analysis require a further development of the simulation model.

6 CONCLUSIONS

The developed numerical process simulation method is able to successfully predict the locally material structure with inhomogeneous three-dimensional fiber orientation incorporating an anisotropic elastic/plastic material model for the rovings from a preceding multi-scale approach. The locally varying fiber content in the joining zone during the thermoclinching process is represented by compressed and closely packed rovings whereas matrix migration is still not taken into account. The comparison with experimental results showed a good representation of principal deformation characteristics. The developed process simulation concept supports the systematic thermoclinching process development by a material and process understanding and is an efficient basis for subsequent virtual joint strength tests.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude towards the Deutsche Forschungsgemeinschaft (DFG) for funding the subproject C2 within the scope of DFG priority programme 1640.

REFERENCES

- [1] M. Gude, W. Hufenbach, C. Vogel, A. Freund, R. Kupfer, Thermoclinching – a novel joining process for lightweight structures in multi-material design, *Composites Theory and Practice*, **14**, 2014, pp. 128-133.
- [2] F. Van der Weeën, Algorithms for draping fabrics on doubly curved surfaces, *International Journal for Numerical Methods in Engineering*, **31**, No. 7, pp. 1414-1426 (1991).
- [3] M.J. Clifford, A.C. Long, P. de Luca, Forming of Engineered Prepregs and Reinforced Thermoplastics, *Second Global Symposium on Innovations in Materials Processing and Manufacturing: Sheet Materials, New Orleans (2001)*, LA USA, pp. 303-316.
- [4] N. Hamila, P. Boisse, Simulations of textile composite reinforcement draping using a new semi-discrete three node finite element, *Composites Part B*, **39**, pp. 999–1010 (2008).
- [5] M.A. Khan, M.A. Mabrouki, E. Vidal-Sallé, E. Boisse, Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark, *Journal of Materials Processing Technology*, **210**, pp. 378-388 (2010).
- [6] A. Willems, S.V. Lomov, D. Vandepitte, I. Verpoest, Double dome forming simulations of woven textile composites, in: *Juster N, Rosochowski A, editors. The ninth international conference on material forming ESAFORM (2006)*, Glasgow, pp. 747-750.
- [7] ESI Group, PAM-FORM 2G 2009 - User's Guide (2009).
- [8] J. Wößner, Selbst nicht umformbare Bleche werden geclincht – Confix-Fügen bewältigt extreme Dickenunterschiede, *Industrieanzeiger* **43** (1998).
- [9] W. Ramberg, W.R. Osgood, Description of stress-strain curves by three parameters, Technical Note 902, National Advisory Committee for Aeronautics (1943).
- [10] Z.-M. Huang, A unified Micromechanical Model for the Mechanical Properties of Two Constituent Composite Materials, Part II: Plastic Behavior, *Journal of Thermoplastic Composite Materials* **13**, pp. 344-362 (2000).
- [11] C. Chamis, Mechanics of composite materials: Past, present and future, *Journal of Composites Technology and Research* **11**, pp. 3-14 (1989).
- [12] VDI Guideline 2014 Part 3, Development of FRP components (fibre-reinforced plastics) – Analysis, (2006).