Prediction models for paper processing and usage behavior based on material properties

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INTRODUCTION:

In recent years, several methods have been increasingly used to analyze natural fiber-based materials with regard to their processing properties and behavior in use. These include the finite element method as well as methods based on automated machine learning using artificial neural networks. All of these methods make it possible to investigate the loads acting on the materials and draw conclusions from them in order to develop improved processes and products. Time-consuming and cost-intensive tests at prototype level can be reduced and developments can be implemented more efficiently. The following three examples of recent research work at PTS will explain application oriented opportunities in more detail:

Flexibilization of Hexagonal Honeycomb Cores and Production of Double-Curved Honeycomb Moulded Parts

The use of lightweight construction principles in the mobility sector enables resources to be conserved during production and use. A distinction must be made between the use of materials and energy to generate the structures and the use of energy for movement during use and recycling, in the sense of the circular economy. Due to their low density, flat, closed lightweight components usually also have low thermal conductivity, which enables thermal insulation in addition to the enveloping and supporting function. The combination of shell and honeycomb construction is a possibility for realizing advantageous lightweight structures, but requires a curvature capacity of the component elements. Thus the subject of a ZIM R&D cooperation project “2k WaFo” was the realization of multi-curved lightweight construction elements based on the innovative FlexCore process.

Honeycomb core panels are a widespread lightweight construction application, but until now only flat geometries have been available in the medium and lower price segments. This is due to the fact that specially mouldable honeycomb cores are required to generate curved components, which are considerably more complex and therefore more cost-intensive in production than conventional hexagonal honeycomb cores, for example. Based on this situation, a process for producing mouldable honeycomb cores from virtually endless honeycomb cores was developed at TU Dresden. Several challenges were identified and cooperatively solved within the research project in order to achieve the operational maturity of novel honeycomb moulded parts based on hexagonal honeycomb cores. The various project objectives, such as reproducible flexibilization, material conservation, efficient joining process, process prediction and process monitoring, were distributed among the project partners SmartPac Verpackungsmaschinen GmbH (SmartPac, machine manufacturer), Deutsche Werkstätten Hellerau GmbH (DWH, first user) as well as the Chair of Wood Technology and Fibre Materials Engineering at TU Dresden (HFT, project coordination and process development) and the Papiertechnische Stiftung (PTS, process prediction and optimization).

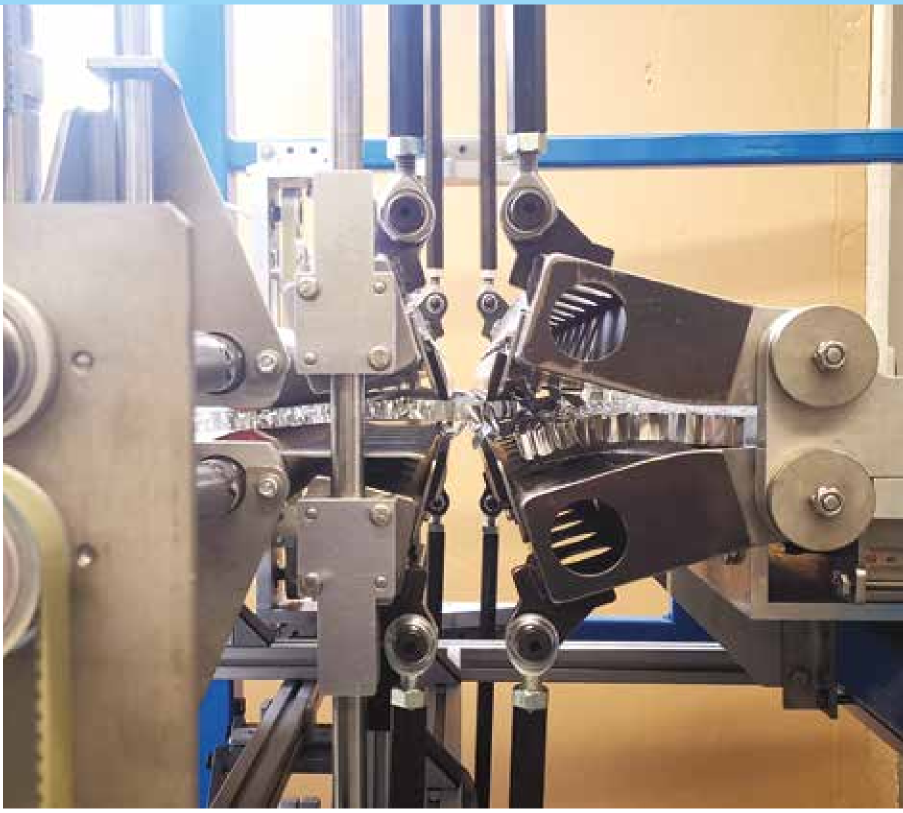


Figure 1: Flexibilizing element with aluminium honeycomb core.

The existing FlexCore process for the production of mouldable honeycomb cores was improved in several details by HFT, expanded to include block processing and implemented in the form of a format-flexible forming unit by the project partner SmartPac (detail in Fig. 1). An efficient manufacturing process for single and double-curved honeycomb moulded parts was developed and successfully implemented by HFT and DWH for the honeycomb cores flexibilized in this way (see Fig. 2 overleaf). Alongside the process development, various prediction models were developed at PTS.

Figure 2: Single and double curved honeycomb moulded part.

These were used to carry out simulation-based preliminary investigations and variant studies and to derive design information for process development and mechanical engineering.

An important issue was the assessment of the influence of imperfections in the semi-finished product on the process stability of the forming processes. Among other things, it was shown that when the honeycomb cores are over-expanded, uneven bonding is compensated for by partial, local material failure. The resulting feedback effect on the working element can be used for active process control. Another important aspect was the geometric design and control of the gripper elements, which have to grip the honeycomb core securely over the narrow web edges. The length of the gripper contact surfaces in the web direction should not be less than half the cell length in the event of over-expansion.

As a particular challenge, a prediction tool for determining the 3D forming limits as a function of the degree of pre-compaction of the hexagonal honeycomb cores was developed (Fig. 3) and experimentally compared, and a simplified geometric prediction approach was tested. A key finding is that even with ideally frictionless mould surfaces, the curvature is not symmetrical around the central axis. This can be explained by the volume-specific material accumulation and thus stiffening on the pressure side.

A flexibilization device for hexagonal honeycomb cores made of paper and aluminum and a joining process for multi-curved lightweight moulded parts are now available for potential users. A key reason for the successful implementation of the project was the excellent cooperation and expertise of the project partners, which will be continued in future joint projects.

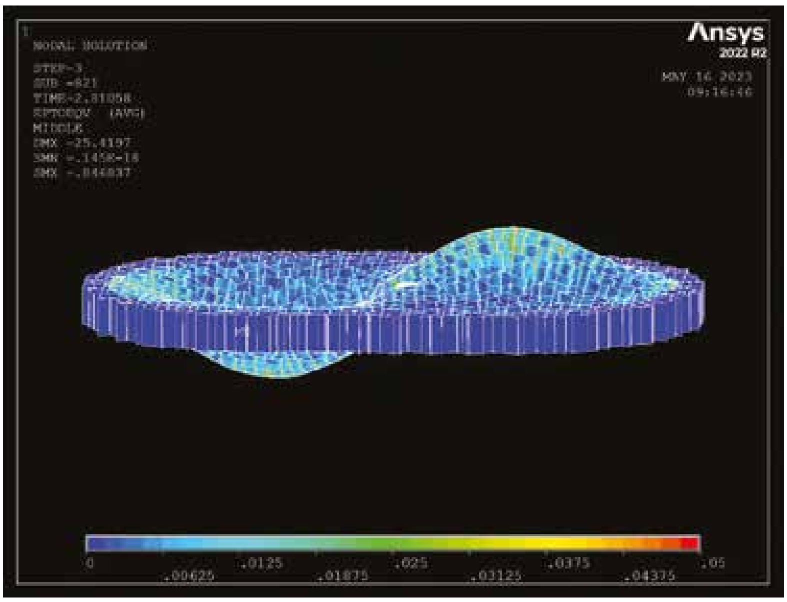


Figure 3: Simulation of the forming of a flexibilized honeycomb core.

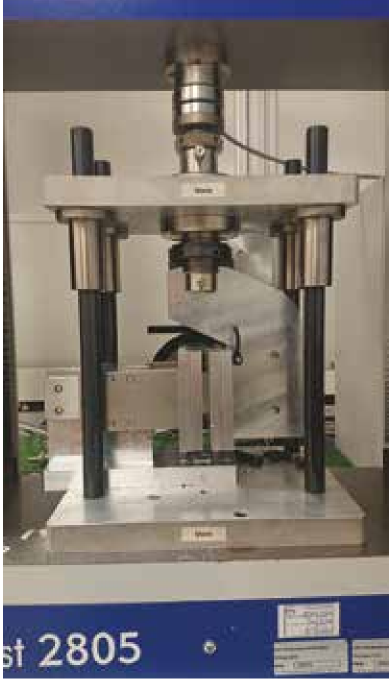
Prediction of Packaging Paper Formability in Deep-Drawing and Hydroforming Processes

The geometry of packaging is one of the most important design factors for creating the highest possible identification effect with the product or brand. Extensive research in recent years has made it possible to greatly expand the material limits of paper in 3D forming processes such as thermoforming or hydroforming, so that packaging with high degrees of forming can be produced in very good quality, making it a promising alternative to thermoformed plastic trays.

However, the fact that the suitability of a paper for 3D forming is not standardized and cannot be predicted using conventional material parameters continued to be a problem for industrial distribution, making it significantly more difficult for paper processing and packaging companies to select a certain material.

Motivated by this, PTS launched the cooperative research project “UniVorsUm” together with Steinbeis University and TU Darmstadt (PtU) in 2020. This collaboration bundled Germany-wide expertise in the field of 3D paper forming with regard to material development and process development for both deep drawing and hydroforming of paper as well.

The aim of UniVorsUm was to develop a standardization and prediction of formability for papers and related materials in 3D forming processes with both rigid and flexible blank holders by defining the essential material properties. For this purpose, a new test strategy and associated characteristic values were developed firstly in order to be able to assign effects and defects to the shape changes or material damage (tolerable to a small extent, undesirable to a large extent) responsible in the 3D forming process. In addition to well-known standard tests such as the tensile test, special measuring methods developed at the research institutes were also used to characterize the materials. These methods are able to reproduce the often-complex stresses during the forming process more accurately. These include, among others: In-plane and out-of-plane shear tests (shear in the plane and across the thickness of the material, see Fig. 4), the Curvature Resistance Test (CRT, bending test without shear component, see Fig. 5), mixed-mode tests (tension/ compression superimposed with compression in the thickness direction) but also the cupping test known from the metal sector. The analysis of the stresses acting on the material during forming was also supported by analyses using FEM (see Fig. 6).



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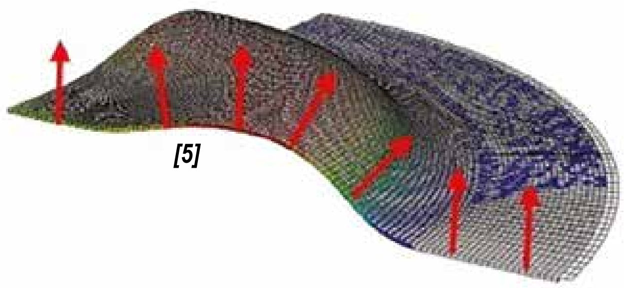

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Figure 4: Out-of-plane shear test rig to determine the shear modulus and shear strength across the material thickness
Figure 5: Curvature Resistance Test (CRT) to determine the thickness-independent bending properties of natural fibre materials
Figure 6: FEM analysis of hydroforming during compression in the thickness direction and representation of different stressed areas of the mould pattern

Furthermore, test scenarios and test conditions (near-process conditions) were identified, which provide information about the formability of materials. Quality parameters agreed with the industry were used to assess the forming process. These could be divided into several categories and influence each other. An example of this for deep drawing is the question of the degree of forming (drawing depth) in relation to the resulting number of folds (see Fig. 7). In hydroforming, the focus was particularly on mould filling in the two spatial directions MD and CD.

The targeted combination of input and output variables was then used to predict the forming limits. Finally, the test methodology for the different 3D forming process variants of deep drawing and hydroforming was harmonized so that a standard was created that then characterizes a paper material in terms of its forming ability. The correlation analysis has shown that in some cases there are very high correlations between the material parameters and the forming quality. This is particularly evident in the characteristic values determined from the cupping test and the tensile test. Models created from parameters assigned to these two methods have already shown good (preliminary) calculations for new combinations of material and forming quality. If this parameter set is specifically extended with test results from the methods of splitting strength, CRT, the above-mentioned shear methods and 2-point bending, the models can make even more detailed predictions.

The project results will enable users to estimate the forming quality of a material for deep drawing and hydroforming in the future without the need to carry out extensive test series. This means that papers can be tested for their suitability before they are used in 3D forming and a targeted selection can be made for practical trials.

Scientifically based Predictions about the Creasing Behavior of Corrugated Board

The functionality of corrugated board packaging depends to a large extent on the design of the box edges created by creasing and bending or folding. Various aspects have to be taken into account, such as the perfect appearance, strength-relevant packaging properties and the desired hinge effect of the creasing. The industry's lack of knowledge about creasing corrugated board in light of the ever-increasing demands on high-quality corrugated board packaging, the trend towards lower grammages and increased productivity requirements leads to increased rejects due to product quality defects and system downtimes. The defects on the product side relate to the cracking of the creasing directly during creasing and after the folding process, an inadequate reduction in bending stiffness and deviations from the internal dimensions of the erected carton. This leads to machine downtimes, especially during further processing in automatic raising machines if the deviations are too large. However, the direct causes of creasing errors are usually unclear, making a targeted solution to the problem difficult or even impossible. At present, it is not possible to estimate potential problems that may occur during creasing in advance and thus avoid them.

The Papiertechnische Stiftung Heidenau (PTS), together with the Leipzig University of Applied Sciences (HTWK), has been working on this topic since June 2021 as part of a research project ("Creasing of corrugated board" IGF 21804 BR). The project, which was completed in July 2023, focused on developing a applicable knowledge base on the mechanical-physical relationships in the process of creasing corrugated board.

Figure 7: Different results of deep drawing in terms of the degree of deformation and number of folds due to the use of different materials.

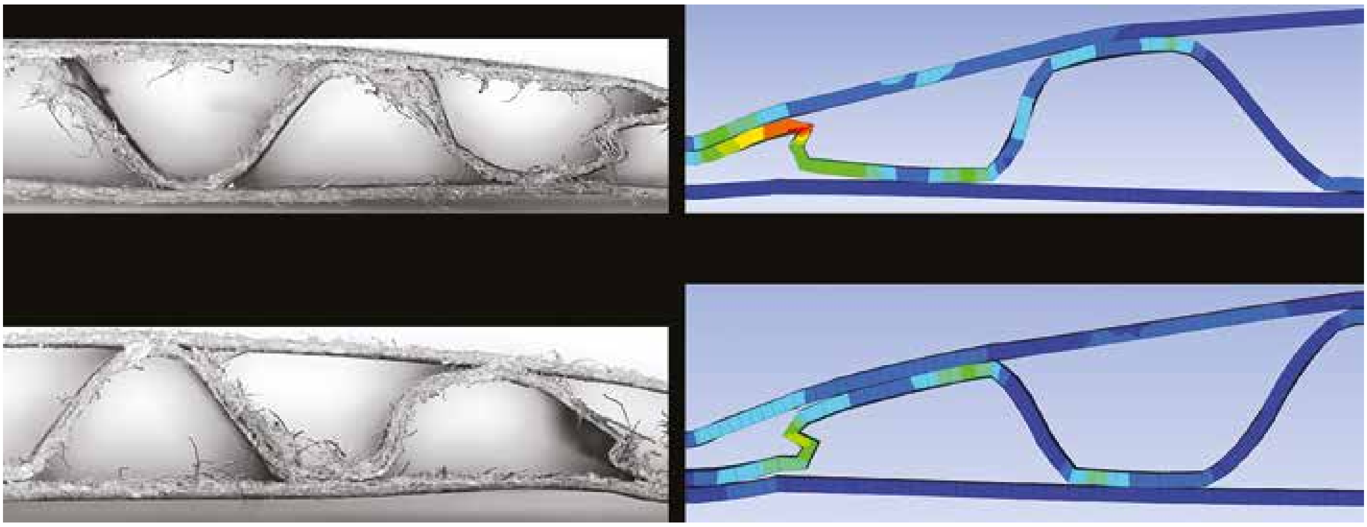

Figure 8: High-resolution image (left) and FEM model (right) of a mountain groove (top right) and a valley groove (bottom right) of corrugated board.

Against the background of the current state of technology, research and development, there was a lack of a holistic and systematic consideration of the interactions and phenomena that occur during the creasing processing step. The aim was to investigate the influence of the properties of the corrugated base paper, corrugated board grade, processing conditions, creasing tools and creasing parameters on the creasing result. The available knowledge on the creasing of corrugated board was essentially empirical. Experience from other creasing processes, such as those available for creasing folding boxboard, could not be used, as completely different mechanisms are involved in the design of a crease.

The result of the research project was the development of improved knowledge of the mechanisms of action in discontinuous hollow creasing and the correlations between the material properties of the corrugated board (e.g. grade, grammage, type of base paper) and process parameters with regard to creasing quality. From these results, measures could be derived that can increase the quality of the packaging produced and thus customer satisfaction, as well as avoid complaints and loss of image in the long term. Furthermore, this knowledge can significantly reduce the use of resources in production, tool design and process optimization.

In order to be able to make predictions about correlations between material parameters, process conditions and creasing quality, a mathematical-statistical model was developed. A statistical design of experiments (DoE) was also used in the project in order to reduce the overall scope of the necessary tests and material characterizations for the exact determination of the interdependencies to a minimum. The data collected on the material properties and test results from the creasing tests formed the basis for setting up a model, which can be regarded as the main result of the project. This provides general predictions of creasability and supports the root cause analysis of creasing errors. As part of a sensitivity analysis, the main influencing factors that significantly determine creasing behavior were also identified. The model was implemented using tools based on automated machine learning. The results were also relevant for the parameterization of the material-side modelling.

The simulation model based on the finite element method is capable of mapping the creasing behavior of corrugated board and making a valid prediction of creasability based on individual material properties. The starting point for the model was the data generated from the basic material characterization of corrugated base paper and corrugated board.

With the help of the model shown in Figure 8, it is now possible to investigate the influence of the material and the creasing parameters and to carry out parameter studies, such as investigating the location of the creasing, alternating between peak and valley creasing or gradually in between. It is also possible to compare different material combinations in the top and flute layers. Until now, creasing tools have only been designed on the basis of geometric dimensions (thickness of the corrugated board and thickness of the compressed corrugated board), without taking into account the properties of the materials used in the corrugated board. Furthermore, results on the creasing process could be incorporated into the model through real tests on creasability. In addition to the metrological recording, an image analysis was implemented using Digital Image Correlation (DIC) in order to validate the model accordingly.

The findings on predictions for the creasability of corrugated board, the main factors influencing the creasing result and the evaluation criteria for creasing quality can be used and implemented immediately by corrugated board base paper manufacturers, corrugated board manufacturers and processors. Without additional investment costs, companies are able to avoid creasing problems that lead to complaints and machine downtime. Optimized material selection in the design and dimensioning of their packaging can lead to immediate cost savings. For corrugated base paper and corrugated board manufacturers, knowledge of the main influencing factors on the material side in particular allows them to adapt their products with regard to improved creasability properties.

However, the results of the project have also shown that not all questions relating to the creasing of corrugated board can yet be answered. Further investigations into specific issues are planned. PTS welcomes any feedback and inquiries from industry in this regard.