

STEAM VACUUM TECHNOLOGY FOR THE PRODUCTION OF SINGLE-LAYER, DOUBLE-CURVED COMPONENTS MADE OF PERFORATED WOOD-BASED MATERIAL

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Abstract:

The deformation behaviour of flat wood-based panels is very limited. Complex moulded parts have so far been manufactured primarily from comparatively expensive veneer laminate materials. However, several process steps are necessary in order to be able to produce 3D moulded parts from cost-effective wood-based materials such as high-density fibreboard. These steps were developed as part of several research projects at the Chair of Wood Technology and Fibre Materials Technology at Dresden University of Technology. Perforation patterns are applied to panel-shaped wood-based materials in order to increase their forming behaviour and obtain a semi-finished product that can be used to manufacture single-layer moulded parts in batch size 1 using simple press technology. The article describes in detail the development of the process step of forming the partially perforated wood-based materials using a vacuum steaming process. Based on the process requirements, the recently completed research project (Fachagentur Nachwachsende Rohstoffe e. V., funding code: 2220HV069A) succeeded in developing preferred parameters for the plastification, forming and fixing of plate-shaped fibreboards into a single-layer, double-curved moulded part within a single device. It was proven that vacuum presses with single-sided moulds are suitable for the process.

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Key words: Wood-based materials, 3D deformation, auxetic pattern, damping presses, vacuum.

INTRODUCTION/MOTIVATION

Flat, large-format wood-based materials used as semi-finished products in furniture and interior design have very limited elasticity and therefore allow only a very small degree of deformation. Perforating thin, high-density, adhesive-free fibreboards ($d \leq 3\text{mm}$, $\rho > 900\text{kg/m}^3$) significantly increases their deformation behaviour (Krüger et al. 2024). This perforation can be created, for example, by machining or cutting, or by means of process-free laser processing (Herold et al. 2015). To minimise the effort required to produce such a formable semi-finished product, perforation can be carried out only at those points where an increase in formability is necessary. The selection of the pattern geometry required for this, as well as its positioning and size, were investigated as part of a current research project.

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It has been shown that simply introducing deformation spaces with a corresponding pattern geometry limits the increase in possible deformation. This can be significantly increased in conjunction with hydrothermal plasticisation of the material, which shifts the neutral axis in the direction of the tension side under bending stress and reduces the proportion of material under tensile stress (Stevens and Turner 2003). In addition, it is necessary to identify an optimal processing window for material moisture through investigations into the uniform application of water to the dry starting material. It is also known from the literature that slow deformation at a constant temperature leads to a decrease in the necessary forming forces and a reduction in the susceptibility to errors (Rice and Lucas 2003). In the field of wood and wood-based materials, it has been found that plasticisation using steam at atmospheric pressure leads to a positive reduction in moisture gradients across the material cross-section, requires simpler machine technology and results in a significant increase in elongation potential (Fessel 1951). In native beech wood, a doubling of the maximum possible elongation between the dry and plasticised states was observed.

The moulded part production process is completed by forming following plasticisation, followed by re-drying and fixing in the formed state. Until now, the sub-processes of plasticisation and forming/fixing in moulded part production were separate process steps in terms of time and location.

Previous approaches to shaping used material modification through full-surface post-treatment of semi-finished products in order to increase formability. Examples of this include grooving plate-shaped materials (Scherer et al. 2010), which, however, have the disadvantage that they do not retain their shape after forming, are only suitable for metallic materials, or can only be used for simply curved components (Parkinson et al. 2022). Furthermore, the principles described in the prior art to date can only be used to achieve comparatively large bending radii, especially for timber construction using laminated veneer lumber (e.g. DUKTA) (D'Acunto and Kotnik 2013). In the field of adaptive or partial material post-treatment, Speetzen describes the introduction of bending lines which, depending on the requirements of a moulded part, are also suitable for closed cavities of medium size (Speetzen and Kobbelt 2024). The disadvantage of this principle is that this process cannot be used to achieve continuous bending radii and that complex moulded parts can only be reproduced with several individual parts.

The forming process of semi-finished products into moulded parts is very often carried out using conventional single-stage presses. The established configuration of the forming process involves forming the semi-finished product using a die-and-mould assembly, thermally activating an adhesive if necessary, and fixing the multi-layer material composite in its final contour until it has cured. The machine technology used is very expensive and complex, but it allows very high press pressures to be applied.

However, the comparatively high press pressures are undesirable from a material perspective, as they often lead to partial material failure in existing materials, since without homogeneous plasticisation, the formability of commercially available materials is also limited. In contrast, simpler and more cost-effective press technology (e.g. vacuum presses) can be used to apply lower press pressures. There is currently a technical gap between the press pressures required for forming specific materials and the capabilities of vacuum presses, which is to be closed by plasticising the material.

This article therefore essentially describes the process development for plasticising the undeformed, perforated semi-finished products, the shaping and the permanent fixing of the shape of the formed material within a single operation and within a device using a single-sided die as a further key focus of the recently completed research project (Fachagentur 2025). This enables the production of single-layer moulded parts, which until now has only been known for solid wood in this way.

The focus is particularly on the use of simple machine technology for small and medium quantities for small and medium-sized moulded part manufacturers and the reproducible use of the new material in combination. A distinction was made between this and processes using conventional, unperforated wood-based materials, which are already offered in large-scale industrial presses/processes with little potential for customisation as semi-finished products for moulded part production.

RESULTS AND DISCUSSIONS

Wood-based material and perforation pattern

As a panel-shaped material mainly intended for use in furniture and interior design, fibre-based wood-based materials have very limited formability. As part of the fundamental material investigations, the selected wood-based materials were tested for their elasticity under the following conditions:

- I Dry and unperforated (air-conditioned in standard climate 20°C + 65% relative humidity)
- II Steamed and unperforated (plasticised)
- III Dry and perforated (air-conditioned in standard climate 20°C + 65% relative humidity)
- IV Steamed and perforated (plasticised)

Adhesive-free fibreboards manufactured using the wet process are used for this purpose (Fundermax 2025). The perforation through the pattern geometry is applied using a CO₂ laser for variants (III) and (IV). The following test procedure was established in a universal testing machine (Inspect 10 Hegewald & Peschke,

Nossen, Germany, 10kN load cell), which allows the sample to be damped and then immediately deformed (Fig. 1). The sample, measuring 20mm x 250mm (width x length) for the solid material and 42mm x 250mm for the pattern geometry, is enclosed by a heating plate (1) with a textile moisture reservoir (2) and a sponge (5), which isolate the area of the sample to be steamed from the environment and thus prevent the escaping of the water vapour produced. To avoid accidental cooling and drying processes, the deformation tests were carried out immediately after plasticisation.

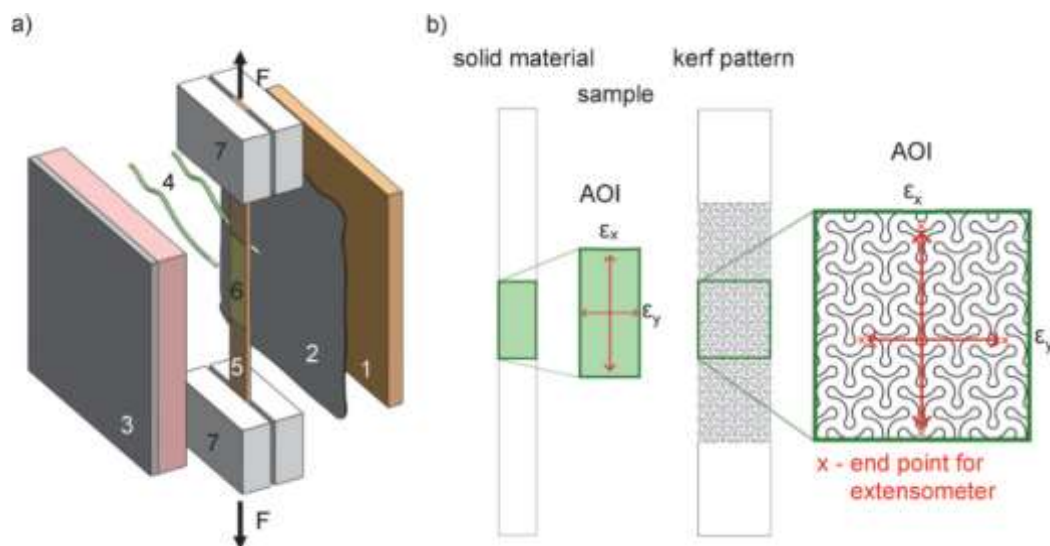


Fig. 1.

Tensile test, a) Test setup with damping device with 1 – heating plate, 2 – textile moisture reservoir, 3 – sponge, 4 – temperature sensors, 5 – sample, 6 – measuring range (AOI), b) Strain measurement on the solid material and the sample geometry in the measuring range.

A stereo camera system (Aramis adjustable 12M, Carl Zeiss GOM Metrology, Braunschweig, Germany) was used to measure the strain. The strain ϕ of the sample in the tensile direction is the measure of the deformation potential of the material (Eq. 1).

$$\phi = \left(\frac{l_1}{l_0} - 1 \right) \cdot 100 [\%] \quad (1)$$

where: ϕ is the strain in N/mm²

l_1 length after deformation in mm

l_0 length before deformation in mm

To this end, the deformation in the x-direction and perpendicular to it in the y-direction was measured for 15 test specimens per series. From this, Poisson's ratio (ratio of ϵ_y to ϵ_x) and the modulus of elasticity could be determined. Fig. 2 shows the strain in the x-direction plotted against the modulus of elasticity. The available strain increases both by perforating the solid material and by steaming. The combination of both modifications offers the greatest deformation potential with up to 10% strain at approx. 3 MPa stress. The investigations also showed that the moisture and temperature-related transport processes in the material are very strongly determined by time. The times determined in the laboratory for steaming the material are < 2 minutes and imply high dynamics, which must be taken into account in the future. The temperature reached was identified as the leading variable for the complete plasticisation of the material. Further information on this can be found in Krüger et al. (2024).

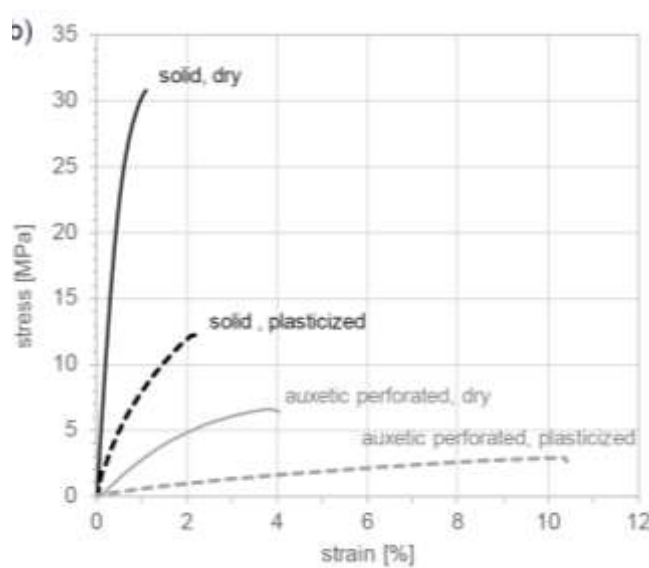


Fig. 2.

Example measurements of the elongation capacity in the x-direction of the variants examined.

From this, it was deduced for further investigations that the production of double-curved components with small bending radii requires a combination of processes involving material modification through perforation and direct coupling of plasticisation of the material and forming into the moulded part.

Process requirements for manufacturing double-curved components

The following input parameters were defined as basic boundary conditions for process development. Firstly, the smooth side is designated as the visible side in the forming tests and, for visual reasons, is oriented in such a way that any subsequent lamination of the flat surface is easier to carry out. In any case, the most common application for moulded parts is characterised by the fact that the components are only visible on one side. Secondly, in all tests, the screen side is facing the moisture because water absorption and the associated plasticisation of the material work better than on the smooth side and any surface irregularities that may occur due to partially swollen fibres or surface areas ('orange peel effect') do not negatively affect the overall visual impression.

The process requirements developed were categorised and are summarised in detail below:

- Procedural requirements
 - Simultaneous plasticising and forming into moulded parts
 - Suitability of the process for small quantities or batch size 1 production
 - Development of a pressing regime for the use of a modified vacuum damping press
 - Exploitation of the auxetic material behaviour of the sample geometry by fixing the position of the semi-finished product during pressing
 - Minimisation of material-induced restoring forces at small bending radius
- Material requirements
 - Achieving maximum bending and torsional stiffness for the end product/moulded part with the smallest possible perforation area or minimal effort
 - Determining the minimum possible bending radii while maintaining material cohesion (interaction of plasticisation and forming)
 - Avoiding telegraphing during surface lamination with a top layer
- Machine requirements
 - Use of relatively simple machine technology
 - Low manufacturing costs for mould and construction
 - Possibility of producing moulded parts in real 1:1 size during the course of the project

Process concept and parameterisation

In particular, the requirement to produce single-layer moulded parts and the direct succession of plasticisation and forming represent a significant advancement over the state of the art. This was addressed with a new process concept and tested as part of the ongoing project.

3: The current status of the process concept is described by the following sequence and illustrated in Fig.

- 1) Perforation of the flat starting material to form a semi-finished product
- 2) Direct application of water to one side by spraying, using a transfer layer
- 3) Insertion of the flat, partially or completely perforated and moistened semi-finished product into the press
- 4) Fixing the semi-finished product between two membranes, contacting the flat heating surface and heating up to the target temperature, as well as forming into the moulded part and fixing and cooling in the formed state

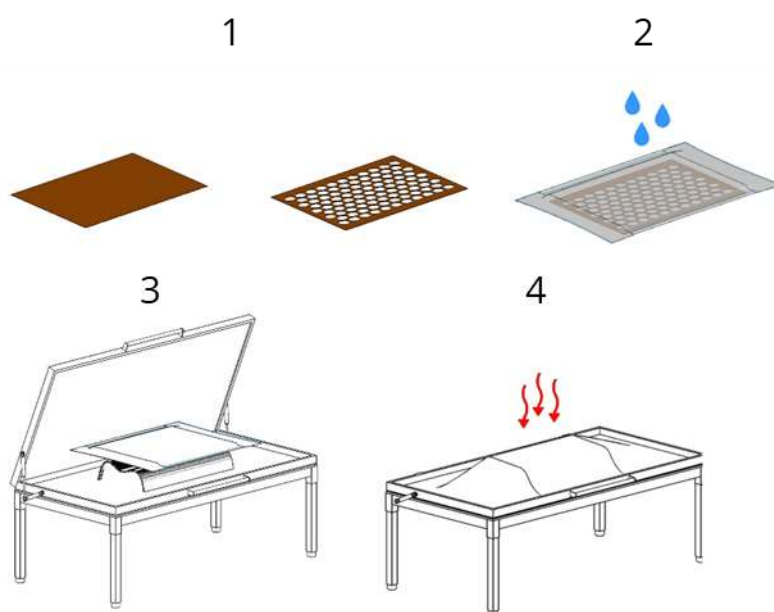


Fig. 3.

Schematic representation of the developed process concept with 1) partial or full-surface perforation, 2) one-sided water application in spray form using a transfer layer 3) insertion of the prepared semi-finished product into the membrane press onto the die covered by a membrane, and 4) fixing of the semi-finished product and forming under heat application, followed by cooling in the formed state.

The test setup also stipulates that only the membrane and the undeformed semi-finished product in contact with it are heated. The steam produced when heated to the target temperature plasticises the wood-based material. The investigations focused in particular on using as little water as possible for humidification in order to minimise recooling effects caused by evaporating water during plasticisation, for example. The process parameters recorded and varied during the investigations were the amount of water applied per area, the temperature above and below the partially perforated material and its temporal progression, and the pressing time (see Fig. 4). By varying the heating rates, interactions with the applied water were observed and preferred parameters were determined in spot tests. The results showed that the temperature of the material is the key variable in the process and determines when the forming process is triggered.

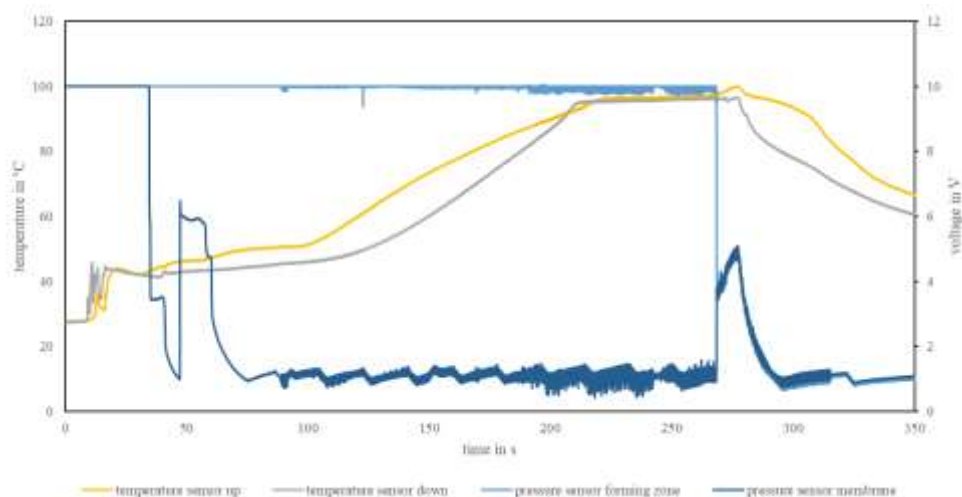


Fig. 4.

Temporal progression of temperature and pressure during a forming process with an upper (yellow curve) and lower temperature sensor (grey curve) as well as a pressure sensor for the forming zone (light blue curve) and (dark blue curve) pressure sensor for the membrane gap.

In particular, it is necessary to reach/exceed a temperature of the upper sensor above 97°C in order to achieve sufficient plasticisation of the volume or to utilise the maximum possible forming capacity of the material. Below this temperature, the forming processes often lead to material damage on the tensile side as a result of insufficient plasticisation or insufficient forming with a high degree of deformation after removal of the moulded part. It has been shown that the measured value at the lower temperature sensor must reach at least 95°C and that both temperature values from the upper and lower sensors must be as close to each other as possible. Exceeding a temperature of 103°C for a longer period of time leads to drying and a reduction in the flexibility or plasticisation of the wood-based material. After the forming process has been initiated, there is a drop in force at the upper force sensor and an increase at the lower force sensor until, after complete forming, this leads to a congruent curve at the die. This condition also persists during the cooling process.

It was determined that the temperature sensors used (type K thermocouples, d=0.5mm) could cause condensation to form as a result of the material heating up, leading to measurement deviations and thus distorting the temperature-based process control. Further challenges in the qualification and calibration of the temperature sensors were the placement of the sensors in the test setup, the expansion of the sensors as a result of heating and forming, and the inertia of heat transfer through the membrane and the transfer layer.

The aim of further, immediate investigations is to evaluate the dimensional stability of the formed component and to identify deviations between the final contour and the original CAD model in order to adjust the model-based dimensioning of the sample geometry or the press mould in a necessary iteration step and to take into account constant overforming due to material-related relaxation. Fig. 5 a) shows that the target/actual comparison reveals only minor deviations. These occur at the transitions between convex and concave deformation. In the selected reference pattern (see Fig. 5 b)), it was also observed that the required material elongation resulted from the perforation pattern introduced, as the edges of the test specimens were firmly clamped.

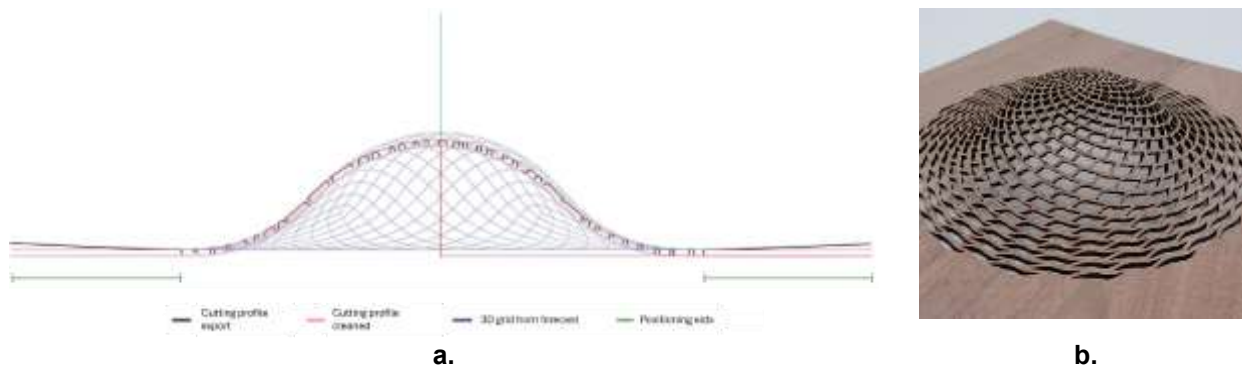


Fig. 5.

Target/ actual comparison between the formed sample part and the CAD model (a) and manufactured, partially perforated sample part with convex and concave formations (b).

CONCLUSIONS

In summary, it can be said that the project succeeded in producing single-layer, permanently double-curved moulded parts from partially or completely perforated wood-based materials that exhibit only minimal elastic deformation after being removed from the press. Laser cutting has proven to be a very suitable and form-adaptive cutting method for the current state of development and, in the future, for the production of small and medium-sized product series. In addition to the product-related requirements, important process-related principles have been developed, making it possible to carry out plasticising, forming, fixing and recooling within a single workpiece clamping. Furthermore, it is possible to use press technology, which is a cost-effective alternative to flatbed presses, for example, especially for small and medium-sized companies, and enables batch size 1 production (Fig. 6). The single-sided die means that lower costs for tool production and mould construction can be expected.

The plasticisation of the wood-based material can be achieved with minimal use of water (application quantity $\approx 50\text{g/m}^2$), which means that little energy is required for the heating process and yet a significant reduction in forming forces is achieved. Compared to the production of classic plywood moulded parts, this has made it possible to achieve permanent forming without internal material stresses.

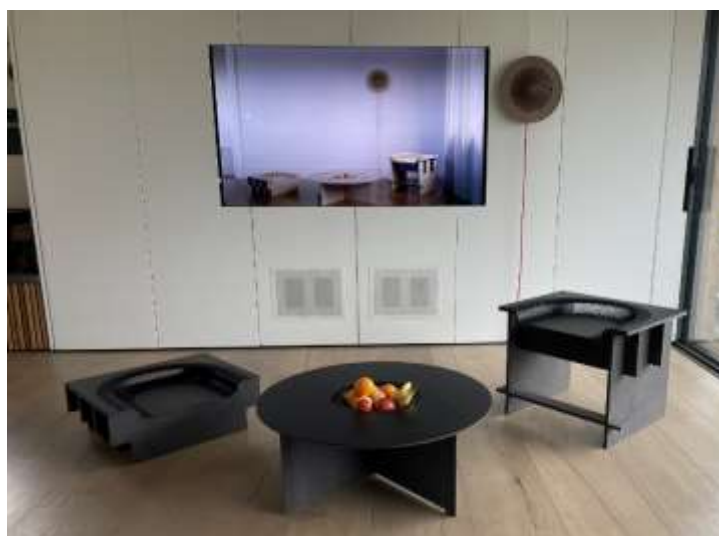


Fig. 6.

Furniture series implemented by the consortium partner as part of the project.

Current research questions include the possibilities for double-sided surface lamination of the component without telegraphing the perforated areas of the moulded part, as well as testing the reproducibility across a larger number of identical moulded parts. The aim here is to also carry out coating in the same device. Further investigations should address the topic of active die cooling in order to identify its potential for an even faster process flow.

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