MODELLING OF TEMPERATURE DISTRIBUTION IN SELF-BONDED BEECH-VENEER BOARDS DURING HOT-PRESSING

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Abstract
Auto-adhesion is a phenomenon that is in general related to the manufacture of wood-based fibreboards, e.g. to the Masonite process or similar processes based on lignocellulosic raw materials. Auto-adhesion as a mechanism for the bonding of solid wood or veneer has not met with the same industrial success, but interest is increasing for environmental reasons and as a result of the increasing cost of adhesives in wood products. The temperature in the laminate is crucial for the auto-adhesion process that will result in bonding between veneers during hot-pressing. This paper presents a model for the temperature evolution during the hot-pressing of a porous material, which was developed and verified for a five-veneer beech laminate pressed at a temperature of 250°C and a pressure of 6MPa in an open system for 280 seconds. The result shows good agreement between the model and the experimental temperature data during the hot-pressing. It can be concluded that a good control of the temperature evolution during the manufacture of adhesive-free veneer boards is of major importance to reach the target properties of the product.

Key words: heat conduction; thermo-hydro-mechanical processing; wood panels.

INTRODUCTION
This paper deals with an adhesive-free beech veneer laminate manufactured in an open-press system without any additives (Cristescu 2006, 2008). The self-bonding of veneers under pressure can be regarded as a thermo-hydro-mechanical process, and the veneers are not only attached to each other by auto-adhesion but are also densified and thermally modified.

A thorough literature review of methods to produce adhesive-free boards of lignocellulosic materials has been given by Pintiaux et al. (2015) and a review of older work can be found in Kollmann et al. (1975) and in Mobarak et al. (1982). William H. Mason invented the first process, the Masonite process, for the manufacture of adhesive-free fibre hardboards (Mason 1928), based on an apparatus called the Masonite gun (Mason 1926a,b) within which wood chips were steamed and pressurized for a certain time before the pressure was rapidly released and the material discharged through a nozzle. The steam-exploded wood fibres could then wet-processed into hardboard without adhesives. Mason (1928) reported good moisture-resistance properties for this hardboard, but a method including a more intensive use of steam explosion to produce a water-resistant board was later presented by Mason et al. (1937). In the same product area, Asplund (1934) invented a steam-pressurized refining process, leading to a new efficient and cost-effective technology for producing thermo-mechanical pulp, fiberboard and other materials from wood.

The first adhesive-free board of solid wood was presented in a patent granted to Runkel and Jost (1948). The process is called the Thermodyn process, and uses a gas-tight press (a closed system) and a cooling phase after the hot-pressing to produce a board from veneer without any pre-

treatment. The Masonite plywood process presented in a patent application by Boehm (1951) required steaming of the veneer in an autoclave prior to pressing, and a cooling phase under pressure was necessary to achieve a proper result. In a patent granted to Cristescu et al. (2007), a method to manufacture an adhesive-free veneer board without any pre-treatment of the veneers was presented. This process was developed for beech wood, but other species have later been tested with success. The beech veneers in the process by Cristescu have a moisture content between 5 and 10%, and a number of parallel-oriented veneers are hot-pressed in an open system. For a five-veneer laminate with a total thickness before pressing of 11mm, the temperature, pressure and pressing time can vary between 200 to 250°C, 4 to 6MPa, and 240 to 360 seconds, respectively. Depending on the selected combination of these process parameters, boards with different densities, water resistance, and colour can be produced. Ruponen et al. (2014) have studied the process further, with particular attention to the influence of a post-thermal modification and the initial moisture content of the birch veneers on the moisture resistance of an eight-layer adhesive-free laminate. They found that a thermal post-treatment modification at a target temperature of 200°C at atmospheric pressure for 4 hours using superheated steam eliminated the risk of delamination of the laminates under moist conditions. Laminates from initially wet veneers were found to have a better bond stability than dry veneers when the laminates were soaked in water.

The reasons behind the auto-adhesion differ depending on the type of process used, and the effects which different process parameters have on the properties of moulded specimens, as described by Pintiaux et al. (2015). With regard to the process by Cristescu, Cristescu and Karlsson (2013) analysed the differences in chemical composition of boards pressed at 200°C, 225°C and 250°C seeking an explanation of the different water-resistance behaviour of the boards. They suggested that the monosugars accumulated at the surface of the veneer were transformed during hot-pressing into hydroxymethyl-furfural which, at temperatures higher than 225°C, was transformed further into other products, including furfural. It was also suggested that degraded lignin migrates towards the bond-line where a condensation reaction may occur, especially at 250°C.

The temperature evolution within the laminate during hot-pressing is important for the chemical and physical processes that contribute to the auto-adhesion between veneers, and thereby also to the mechanical and moisture related properties of the board (Cristescu et al. 2015). This means, that it cannot be expected that the desired properties of the board will be reached unless the target temperature of the process is achieved in all the bond-lines of the laminate. This can be critical for central bond-lines in the laminate, especially when it is desired to have as short a press time as possible both for economic reasons and to prevent thermal degradation of the wood material. The temperature evolution within the laminate depends on e.g. specie, moisture content, and density of the veneers (i.e. the thermal diffusivity for the wood material), compression and speed of compression of the laminate (i.e. pressure and press-closing time), and the press temperature, the variation of the temperature during pressing, and the duration of compression. The interactions among these parameters are however not uncomplicated and clear.

OBJECTIVE
The purpose of this study was to obtain a better understanding of the temperature evolution within an adhesive-free veneer board during hot-pressing, and to model that temperature evolution.

MATERIAL AND METHOD
The material used in the study was rotary-peeled beech (*Fagus sylvatica* L.) veneers without defects. Veneers with dimensions of 2.2 x 140 x 140mm (thickness x width x length) were prepared and conditioned to a moisture content of 9% before the tests.

Five veneers were overlapped with a parallel grain direction and placed in a laboratory press (Fjellman® No. 2032, Mariestad, Sweden) with a press plate area of 140x140 mm^2. Thermocouples were placed between the veneers, as shown in Fig. 1, and six temperatures were recorded to show the temperature evolution in the laminate during pressing. The laminate was pressed at a temperature of 250ºC and a pressure of 6MPa for 280 seconds. These pressing conditions resulted in a water-proof laminate (Cristescu et al. 2015). Table 1 summarizes the parameters for the pressing of the laminate.

Table 1

Parameters for the preparation of laminates

Parameters	Description
Species	Beech (*Fagus sylvatica* L.)
Veneer thickness	2.2mm
Veneer density ($\rho_{9,9}$)	580kg/m^3
Initial moisture content	9%
No. of veneers in a laminate	5
Initial veneer temperature (T_0)	30ºC
Maximum press-plate temperature (T_s)	250ºC
Closing time of the press	7 seconds
Total pressing time	280 seconds
Pressure	6 MPa
Laminate density ($\rho_{4,4}$) after pressing	830 kg/m^3
Moisture content of the laminate after pressing	4%
Maximum compression, C$_{max}$	1.43 (830kg/m^3 divided by 580 kg/m^3)

Fig. 1.
Thermocouples between each veneer before pressing

A model has been developed to describe the temperature evolution in the thickness direction of the laminate during hot-pressing. The model predicts the time-dependence of the temperature through a porous media. The material model is according to Siau (1995) and the heat conduction model has been verified by experimental results from the test described above.

The compression of the laminate is assumed to follow a function:

$$C(t) = 1 + (C_{max} - 1)\left(1 - e^{-\frac{t}{\tau}}\right)$$

(1)

where:
C(t) is the compression at time t
C$_{max}$ is the maximum compression of the laminate
τ is a characteristic time, set at 2 seconds in this case due to the experimental conditions.

The temperature of the press plates follows the temperature recorded by the thermocouples located between the outer veneers and the press plates:

$$T_{PP}(t) = T_0 + (T_s - T_0)f(t)$$

(2)

where:
T$_{PP}$ is the press-plate temperature
T$_0$ is the initial veneer temperature
T$_s$ is the maximum press-plate temperature
and

$$f(t) = A\left(1 - e^{\frac{t}{\tau_1}}\right) + (1-A)\left[1 - \frac{1}{1 + \left(\frac{t}{\tau_2}\right)^2}\right] \tag{3}$$

where:
A, τ_1, and τ_2 are parameters that are least squares fitted to the experimental data for the press-plate temperature.

The heat conduction differential equation is given by:

$$\lambda \frac{\partial^2 T}{\partial x^2} = c\rho \frac{\partial T}{\partial t} \tag{4}$$

where:
λ is heat conduction
T is the temperature
c is the heat capacity
ρ is the density

The thermal diffusivity κ is given by:

$$\kappa = \frac{\lambda}{c\rho} \tag{5}$$

The compression of the wood material leads to an increase in the heat conduction, and according to Siau (1995) Eq. (5.12), the transverse thermal conductivity λ is given by:

$$\lambda = \frac{1}{\frac{1-a}{\lambda_{cwm} \cdot Z} + \frac{a}{(1-a) \cdot \lambda_{cwm} + a\lambda_a}} \tag{6}$$

where:
a is the square root of the porosity (see Siau (1995) Eq. (5.6a))
λ_{cwm} is the heat conduction of the cell wall
Z is the fraction of the total cross wall which can be considered effective for conduction (see Siau (1995) Eq. (5.15))
λ_a is the heat conduction of air

However, the heat capacity based on volume also increases, and this is the denominator in Eq. (4). The thermal diffusivity therefore increases slowly with compression. In this case, the thermal diffusivity varies by about 2% during the compression of the laminate.

The characteristic time for the heat conduction is:

$$\tau_Q = \frac{d^2}{\kappa} \tag{7}$$

where:
d is the varying total thickness of the sample
κ is the thermal diffusivity according to Eq. (5)

In the present case, this value changes from approximately 400 to 900 seconds. As times lower than 400 seconds are desired, the Laplace transform method is most suitable as quite few terms are needed in the solution that is an infinite sum. The method is similar to the one used by Carslaw and Jaeger (1959 pp. 308 ff.) for the response from a unit step function, but here the response from an impulsive is used. Simple partial integration shows that they are equivalent. The measuring points move during compression in a linear manner. The compression is fast in comparison with the

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characteristic time for the heat conduction from Eq. (7). Therefore, it is assumed the laminate is compressed to the material properties that appear after 2 times the characteristic time of the compression in Eq. (1) above, and thereafter the heat from the surface plates is applied.

Standard calculations give the temperature in the transverse direction of the laminate as a function of time from Duhamel´s superposition integral:

$$T(x, t) = T_0 + (T_s - T_0) \int_0^t \dot{f}(\tau) Q(x, t - \tau) d\tau \tag{8}$$

where:
T_0 is initial veneer temperature
T_s is the maximum press-plate temperature
$\dot{f}(\tau)$ is the function given in Eq. (3)
and

$$Q = \left[\sum_{n=0}^{\infty} (-1)^n (Q]_1 + Q_2 \right) \tag{9}$$

$$Q_1(x, t) = \frac{a a_1}{2\sqrt{\pi t^3}} e^{-\frac{a a_1^2}{4t}} \quad \text{with} \quad a a_1 = \frac{(2n + 1)\frac{d}{2} + x}{\sqrt{k}} \tag{10}$$

$$Q_2(x, t) = \frac{a a_2}{2\sqrt{\pi t^3}} e^{-\frac{a a_2^2}{4t}} \quad \text{with} \quad a a_2 = \frac{(2n + 1)\frac{d}{2} - x}{\sqrt{k}} \tag{11}$$

RESULTS AND ANALYSIS

Fig. 2 shows the temperature in the laminate as a function of time, recorded by thermocouples placed between the press plates and the veneer and between the veneers (see Fig. 1). It is clear that the temperatures in the different bond-lines reach the target temperature (250°C) at different times, as a consequence of their different distances from the heated press plates. It can also be concluded that the temperature evolution is symmetrical through the thickness of the laminate.

The temperature of the surface of the laminate rises from the initial temperature of 30°C to about 200°C in about 10 seconds when the press closes, but it takes almost 2.5 minutes to reach the target temperature. This is due to the low heat capacity of the press plates, and this must be considered in the model (see Eqs. (2) and (3)). Compared to the other bond-lines, the curve showing the temperature of the innermost bond-lines differs in shape (see dotted area in Fig. 2). This cannot be explained in this study, nor does the presented model give any explanation.
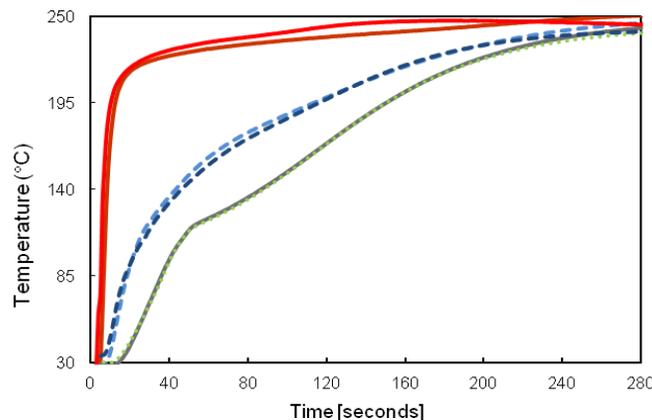

Fig. 2.
Temperature recorded by thermocouples during the pressing of the laminate at a temperature of 250°C, 6MPa, and 280s. The upper two curves show temperatures from thermocouples closest to the press plates, and the two lowest curves are from thermocouples in the central part of the laminate

Fig. 3 shows the modeled temperatures at three positions in the five veneer laminate. According to symmetry, the temperature evolution is exactly the same in the bond-lines at the same distance from the press plates. The least squares fit to the experimental data of the experimental press-plate temperature (see Eq. 3) shows that there is good agreement between the experimental and model data. The press-plate temperature determinates the temperature evolution in the laminate.

The compression of the laminate is very fast. Its characteristic time is chosen to 2 seconds. In the model, it is assumed that the temperature starts after a delay, which is a multiple of this time. This multiple factor is a free parameter that can be adjusted to experimental values.
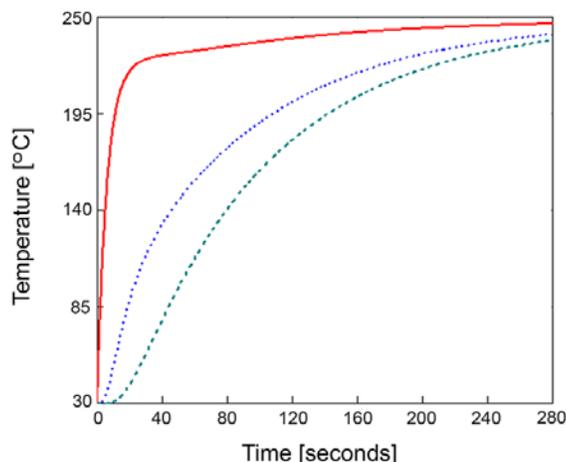

Fig. 3.

Modeled temperature during pressing of the laminate at a temperature of 250°C, 6MPa, and 280s. The upper curve shows the temperature close to the press plates, the two lower curves show temperature at the more central position in the laminate

CONCLUSIONS

In this study, the temperature evolution in the thickness direction of the laminate during hot-pressing has been studied both experimentally and by modelling. The results obtained demonstrate the importance of having good control of the temperature evolution in the manufacture adhesive-free veneer boards. The analytical heat conduction model showed good agrement with experimental data, and can be a valuable tool in further stuides.

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REFERENCES

Asplund AJA (1934) Method of manufacture of pulp. US Patent No. 2008892.

Boehm RB (1951) Process of making a plywood product. US Patent No. 2557071.

Carslaw HS, Jaeger JC (1959) Conduction of heat in solids. Oxford, Oxford Science Publications, Clarendon Press, 2nd edition.

Cristescu C (2006) Bonding laminated veneers with heat and pressure only. Proceedings of the 2nd International Conference on Environmentally-Compatible Forest Products "Ecowood", 20-22 September, Porto, Portugal, pp. 339-348.

Cristescu C (2008) Bonding veneers using only heat and pressure. Focus on bending and shear strength. Licentiate thesis (Luleå: Luleå University of Technology).

Cristescu C, Johansson D, Chen Y (2007) Method of producing a laminate compricing at least two layers of lignocellulosic material joined by heat treatment and pressing. Swedish Patent No. SE529747 C2.

Cristescu C, Karlsson O (2013) Changes in content of furfurals and phenols in self-bonded laminated boards. BioResources 8(3):4056-4071.

Cristescu C, Sandberg D, Ekevad M, Karlsson O (2015) Influence of pressing parameters on mechanical and physical properties of self-bonded laminated beech boards. Wood Material Science & Engineering 10(2):205-214.

Kollmann FP, Kuenzi EW, Stamm AJ (1975) Wood-based materials. Principles of wood science and technology, Vol. 2, Berlin, Springer-Verlag.

Mason WH (1926a) Process and apparatus for disintegration of wood and the like. US Patent No. 157860.

Mason WH (1926b) Low-temperature explosion process of disintegrating wood and the like. US Patent No. 1586159.

Mason WH (1928) Press-dried structural insulating board and process of making same. US Patent No. 1663504.

Mason WH, Boehm RM, Euclid KW (1937) Molding composition and process of making same. US Patent No. 2080078.

Mobarak F, Fahmy Y, Augustin H (1982) Binderless lignocellulose composite from bagasse and mechanism of self-bonding. Holzforschung, 36(3):131-135.

Pintiaux T, Viet D, Vandenbossche V, Rigal L, Rouilly A (2015) Binderless materials obtained by thermo-compressive processing of lignocellulosic fibers: a comprehensive review. BioResources 10(1):1915-1963.

Runkel R, Jost J (1948) Verfahren und Vorrichtung zur Herstellung von Formungen aus Holz, Holzabfällen oder verholzten Pflanzenteilen unter Druck, bei höheren Temperaturen. [Method and apparatus for the production of mouldings from wood, wood waste or woody part of plants under pressure at elevated temperatures]. German Patent No. DE841055.

Ruponen J, Rautkari L, Belt T, Hughes M (2014) Factors influencing properties of parallel laminated binderless bonded plywood manufactured from rotary cut birch (*Betula pendula* L.). International Wood Products Journal 5(1):11-17.

Siau JF (1995) Wood: influence of moisture on physical properties. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University.