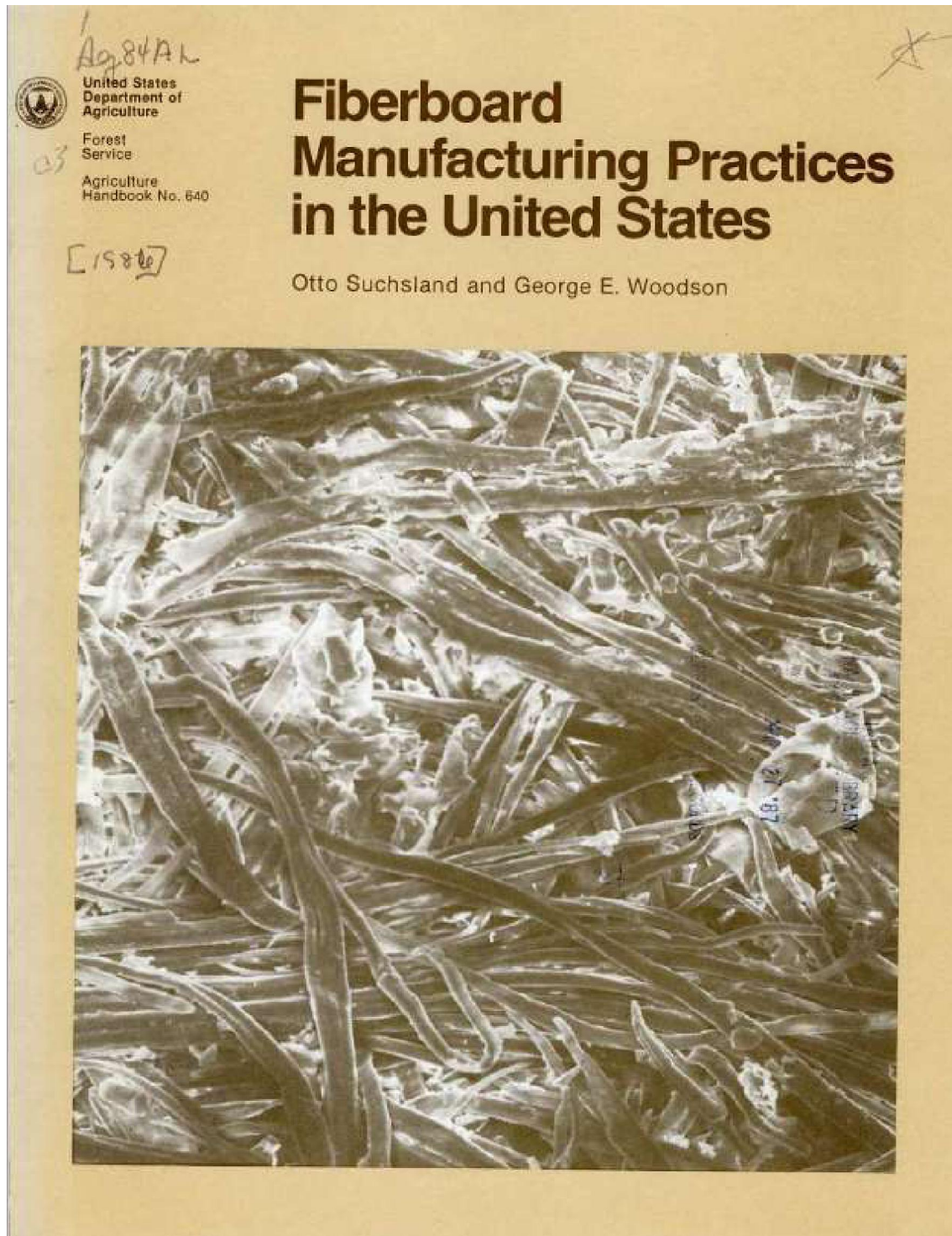


ANEXO 2.

En el documento de 1987 Fiberboard manufacturing practices in the United States Otto Suchsland & George E. Woodson_USDA_Forest Service" aparece la definición de "Moisture content"



United States
Department of
Agriculture

Forest
Service

Agriculture
Handbook No. 640

Fiberboard Manufacturing Practices in the United States

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and

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Ruston, Louisiana

EXCHANGE Rec'd

MAR 20 1987

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In the dry process, air is the conveying and distributing medium, and without water the conditions for natural bonding do not develop. The development of mechanical and other board properties relies entirely on added adhesives.

There are many significant and many subtle differences among the products of the five fiberboard processes and in the results of process variations within each of them. None of these processes is intrinsically any better or any worse than any of the others, but each may be best for making a particular end product from a given raw material. Relative advantages or disadvantages are often temporary, changing with fluctuations in price structure of important commodities like energy or chemical additives, or as manufacturing costs may be more or less unfavorably affected by environmental regulations and restrictions. The present level of technology is not static but is rather a basis from which refinements, improvements, and altogether new processes and products may evolve.

Definitions

Density. The common usage of the term *density* refers to the weight of a unit volume of a material. Units used for wood and wood products are pounds per cubic foot, grams per cubic centimeter, and kilograms per cubic meter.

Because all wood products are hygroscopic, the density depends to some extent on the moisture content. In the case of composition board, weight and volume are obtained at the same condition, that is, at the same moisture content.

$$\text{density} = (\text{weight at test condition}) / (\text{volume at test condition}) \text{ (lb/ft}^3\text{)}$$

Specific gravity. This term has no units. It is the ratio of the density of a material to the density of water (62.4 lb/ft³). It describes the same property of the material and is the preferred form for solid wood. However, here, the volume is determined at the test condition, while the weight is determined after removing the water by oven drying.

$$\text{specific gravity} = \text{weight (ovendry)} / (\text{volume at test condition} \times 62.4 \text{ (lb)} / [\text{ft}^3 \times (\text{lb/ft}^3)])$$

Disregarding the effect of moisture content, which is small at low moisture levels, density values can be converted to specific gravity by dividing by 62.4. Thus, a medium-density fiberboard with a density of 48 lb/ft³ has a specific gravity of $48/62.4 = 0.77$.

Bulk density. This term is used to describe the bulking effect of loose materials such as dry fibers, particles, or chips. It is the density of the uncompressed material. Loose dry pulp fiber might have a bulk density of 1 or 2 lb/ft³.

Moisture content and water content. In solid wood products, moisture content is expressed as the weight of water contained divided by the dry weight. Multiplying this ratio by 100 gives the result as a percentage. Wood consisting of 50% water and 50% dry wood substance has a moisture content of 100%.

In paper technology, the water content is often expressed as part of the total weight. On that basis the above piece of wood would have a water content of 50%.

When moisture contents are low, the differences between the two expressions are small, but at high moisture levels, as in wet fiber mats, the differences are large. A wet fiber mat containing 75% water and 25% dry fiber material has a water content of 75% or a moisture content of 300%.

At very high water contents, as in pulp slurries, the water/solids ratio is defined by consistency, which is the dry fiber content expressed as a percentage of the total weight of the slurry.

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ANEXO 3.

USDA_Forest_Service_General_Technical habla de las condiciones de prensado en tableros de partículas, particularmente de la humedad diferente entre capas y de la conveniencia de mayores valores en capa externa con referencias bibliográficas desde 1955

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Keep 10.

**CRITICAL LITERATURE
REVIEW OF
RELATIONSHIPS
BETWEEN
PROCESSING
PARAMETERS
AND PHYSICAL
PROPERTIES
OF
PARTICLEBOARD**



**USDA FOREST SERVICE
FOREST PRODUCTS LABORATORY
GENERAL TECHNICAL REPORT
✓ FPL-10
1977**

**U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
MADISON, WIS.**

**CRITICAL LITERATURE REVIEW
OF RELATIONSHIPS
BETWEEN PROCESSING PARAMETERS
AND PHYSICAL PROPERTIES
OF PARTICLEBOARD**

by
MYRON W. KELLY

GENERAL TECHNICAL REPORT FPL-10
May 1977

Prepared for
Forest Products Laboratory
Forest Service
U.S. Department of Agriculture

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is limited to those ligno-cellulosic materials of adequate inherent strength which can be readily broken down and glued together without unduly destroying the native strength. Cost, as influenced by resin content, is the controlling factor. Many ligno-cellulosics could theoretically be used for particleboard, but the higher adhesive contents required to obtain a satisfactory product are presently prohibitively high.

Pressing Conditions

The pressing operation is obviously an extremely critical step in particleboard production. It is during this step that many of the physical properties are determined, especially those properties influenced by the vertical density gradient. Mat moisture content, press closing speed, and press time and temperature are the most significant pressing conditions affecting the properties of particleboard.

Mat Moisture Content

The mat moisture content is an extremely critical factor not only for the total press time, but also in development of the vertical density gradient. As discussed earlier, the surface moisture evaporates and migrates to the mat center when the hot platens contact the mat. This speeds the transfer of heat to the core which allows the adhesive to react more quickly than if the heat moved by conduction through the wood and air spaces. However, excessive moisture migration to the core imposes the requirement of excessively long press cycles to allow removal of moisture through the edges to prevent delamination of the board upon pressure release. Excessive moisture also interferes with the chemical reaction of condensation polymerization, by which urea-formaldehyde and phenol-formaldehyde adhesives harden. Moisture at the mat surface also reduces the compressive strength of the wood and results in surface densification from compressive failure as the press is closed. Excessive surface densification results in low-density cores for a given average board density. The bending strength and tensile strength parallel to the board surface will increase as this densification occurs but the internal bond, interlaminar shear, and screw withdrawal will be lower as a result of the low-density core.

The method commonly used to circumvent the adverse moisture effects, but still retain the advantage of rapid heat transfer to the core, is a nonuniform moisture distribution through the mat thickness. With higher levels of moisture at the surfaces than at the core,

rapid heat transfer occurs without unduly lengthening the press cycle. This is readily accomplished in layered and homogeneous constructions in which the core material is dried and blended separately from the surface material. A homogeneous board with all material dried and blended in the same system can be given a nonuniform moisture distribution across the thickness by spraying the mat surface or cauls with water. Normally, a nonuniform moisture distribution, with the surfaces at a higher moisture content than the core, increases the vertical density gradient.

Maku and Hamada (1955) found a decreased thickness swelling and water absorption as the moisture content of the chips increased. However, it is unclear from the report whether the mats were pressed at high moisture contents or whether they were conditioned to 12 to 13 percent after blending at higher moisture contents.

Heebink *et al.* (1972) reported that a moisture distribution of 5 percent in the mat plus a 5 percent surface spray allowed the core to reach 220° F in a shorter time period than required for mats with a uniform moisture distribution of 10 percent for two different press temperatures and two different closing rates. However, the vertical density gradient data show a lower gradient for the boards with the uniform moisture content of 10 percent, although this comparison of density gradients is confounded with adhesive and press temperature differences. Heebink *et al.* (1972) reported 10 to 12 percent to be the optimum moisture content for mats with uniform distributions. Lower moisture contents required higher pressures to consolidate the mat and were characterized by poor interparticle bonding. Higher moisture contents necessitated longer press cycles to allow sufficient moisture to escape.

Heebink (1974) found that higher MOR MOE values for three-layer flakeboards than for those of an earlier study (unpublished) were partially due to a nonuniform moisture distribution. As opposed to a uniform distribution of 12 percent moisture content, a face and core moisture content of 15 and 5 percent, respectively, contributed to improved board strength.

Strickler (1959) showed that the time required for heating the mat core decreased with increasing surface moisture content. At higher surface moisture contents (above 15 percent) the MOR and MOE decreased when the core was at 9 percent moisture content. The internal bond also decreased but the thickness swelling improved as the surface

moisture content increased.

Strickler (1959) showed that the time required for heating the mat core decreased with increasing surface moisture content. At higher surface moisture contents (above 15 percent) the MOR and MOE decreased when the core was at 9 percent moisture content. The internal bond also decreased but the thickness swelling improved as the surface moisture content increased.

Kehr and Schoelzel (1965) also found a sharp decrease in the resistance of the mat to compression as increased quantities of water were sprayed on the mat surface. This, again, was the result of the reduced compressive strength of wood at higher moisture levels.

Lehmann (1960) found MOR values increased with increasing mat moisture to 13.4 percent moisture content, and then decreased at moisture contents of 16.5 and 20.0 percent. Internal bond increased as the moisture content decreased. Lehmann (1960) also showed an increased dimensional stability and a reduced water absorption as the mat moisture content increased. Rice (1960) used mat moisture contents of 9, 12, and 15 percent to study the effect of mat moisture on board properties. The MOR and MOE values were increased 18 and 13 percent respectively, by increasing the mat moisture content from 9 to 15 percent. Likewise, the dimensional stability of the panel improved substantially. The increased mat moisture content also reduced the closing time to stops with a constant pressure but the problem of thickness shrinkage in the press was greater with high moisture content mats. Gatchell et al. (1966) reported an optimum in static bending strength and internal bond at a moisture content of 12 percent.

The mat moisture content and moisture content distribution can be varied only within a rather limited range, hence the effect of this variable on particleboard properties is limited. With a uniform mat moisture content, the optimum range appears to be 11 to 14 percent. Much higher surface moisture contents are possible if the core region is at a correspondingly lower moisture content. Basically, it appears that the vertical density gradient is changed with changing moisture contents and distributions but the lack of vertical density gradient data prevents positive proof of this effect.

Press Closing Rate

Generally, the closing rate of most hot presses is established by adjustment of the initial pressure; higher initial pressures result in the platens closing to stops, or desired

thickness, more quickly than closing speeds attained at lower initial pressures (Kehr and Schoelzel 1967). Most authors, if they mention a closing speed, will normally give the information as the time to stops, which is the minimum time for exposure of the lower mat surface to the bottom platen before the mat has reached complete compaction. Time to stops is not the same as time of compaction; during the time from start of closing to loss of daylight between the mat and the upper platen no mat compaction occurs. The time of compaction as well as the total press closing time should be specified by researchers more frequently.

The closing rate of the press and the moisture content of the mat are both important factors in the formation of the vertical density gradient. Quickly closing the press will subject the mat surfaces to the platen heat and allow compressive failure at the mat surface before the interior has warmed sufficiently to allow distribution of the compressive failure through a greater portion of the mat thickness. Consequently, faster press closings would be expected to increase the vertical density gradient and improve the bending strength but at the expense of the internal bond and screw holding strength.

Rice (1960) reported improved MOR and MOE values as the closing rate increased but he found internal bond, springback, and swelling properties to be independent of closing times. Bismarck (1974) reported a reduction in internal bonds as the press closing speed increased above 40 in/min (inches per minute), but the bending strength continued to increase. He also reported that panels produced at the highest rate of compaction and with the shortest press cycle had the lowest formaldehyde emission. Bismarck developed a pressing technique in which the closing speed was related to the ratio of panel compression to the compressive resistance of the panel until desired thickness was attained. This technique prevented rapid compaction of a mat with low compressive strength which normally occurs with conventional press controls. Tests of his technique against the conventional procedure resulted in 5 and 9 percent improvements for bending and internal bond strength, respectively, a 10 percent reduction in thickness swelling, and a 16 percent reduction in pressing time. This technique most likely reduces the vertical density gradient although further studies are necessary to verify this.

Liiri (1969) monitored the pressure on a series of mats pressed with increasing closing times and found the maximum pressure re-

ANEXO 4.

En la publicación del *Holzforschung*, Vol. 61, pp. 74-82, 2007 “Heat and mass transfer in Wood composite panels during hot pressing: Part 3. Predicted variations and interactions of the pressing variables” se habla de la humedad y el efecto que tiene en el grado de curado de la resina.

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Heat and mass transfer in wood composite panels during hot pressing: Part 3. Predicted variations and interactions of the pressing variables

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Abstract

As a continuation of previous publications on a physical-mathematical model of heat and mass transfer and a structural model of mat permeability, this paper presents typical prediction results for 15 pressing variables for strand mats. A case study and complete solutions to the governing equations are provided. The results show how the heat and mass transfer is controlled by heat conduction and convection involving gas flow and phase change. The model predictions provide a comprehensive illustration of the temporal and spatial variations of basic pressing variables, including mat temperature, gas pressure, moisture control and resin curing rate. The model offers a powerful tool for simulating the effects of mat structure, pressing schedule and initial mat conditions.

Keywords: computer simulation; heat and mass transfer; hot pressing; modeling; wood composites.

Introduction

We previously presented in this publication series a physical-mathematical model of heat and mass transfer (Dai and Yu 2004) and a structural model of mat permeability (Dai et al. 2005). There are several models published in the literature (Humphrey and Bolton 1989; Carvalho and Costa 1998; Thoemen and Humphrey 2003; Zombori et al. 2003). Our heat and mass transfer model was a three-dimensional (3D) as opposed to a 2D (Zombori et al. 2003) or cylindrical model (Humphrey and Bolton 1989). The *in situ* formation of a vertical density profile (VDP) (Dai et al. 2000) and associated consolidation mechanisms (Dai and Steiner 1993; Dai 2001) were also explicitly factored in our model, whereas previous models either used a pre-defined VDP (Humphrey and Bolton 1989; Carvalho and Costa 1998) or implicitly considered the press closing schedule (Zombori et al. 2003). The physics of heat and mass transfer was treated here as a mathematically closed problem in which a set of 15 variables and corresponding governing equations were

explicitly established. This approach allowed for mathematically unique solutions to the governing equations, and a more complete description of the interactions between the variables. The analytical establishment of the gas flow velocities, and their relationships with the mat porosity, the mat permeability, and the wood element dimensions are also features of the model of Dai et al. (2005). The objectives of this paper were to briefly describe the numerical model, to outline the interactions between the heat and mass transfer variables and consolidation variables, and to present typical predicted results of the 15 variables through a case study of aspen (*Populus tremuloides*) strand mats.

Input and output of the numerical model

The 15 heat and mass transfer variables are closely linked to six other consolidation variables. Table 1 lists these variables and Figure 1 illustrates their coupling relationships. Owing to this coupling, none of the 21 variables can be independently solved. In this paper, the prediction results were analysed for the 15 heat and mass transfer variables only, assuming the other six consolidation variables to be known. A general description of the consolidation model has been presented elsewhere (Dai et al. 2000) and the details will be reported in a future publication.

Input conditions

The input conditions in this model concern three aspects: 1) the mathematical uniqueness of the solution; 2) the mat structure, pressing parameters and schedule; and 3) the precision, stability and convergence of the numerical calculation.

Mathematical uniqueness This requires the determination of geometric, initial, and boundary conditions. These conditions were previously described (Dai and Yu 2004) and the values of some parameters used for this case study are listed in Table 2.

Mat structure, pressing parameters and schedule

Table 3 lists the set values for strand geometry, wood density, mat target density, mat target thickness and pressing parameters. Figure 2 shows the pressing schedule, which can be divided into the following four periods (note that mat pressure and thickness are interdependent: one is an input and the other is a response calculated based on the input):

- Period 1: press closing. The mat is pressed from the initial state to a predefined mat pressure. During

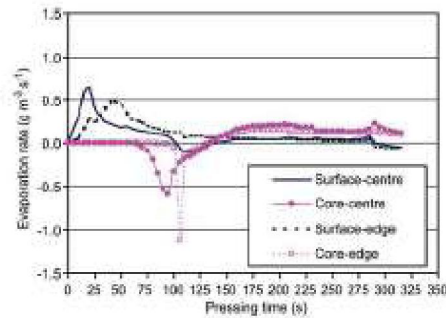


Figure 9 Changes in evaporation rate at the four representative locations.

Figure 8b shows the responses of the horizontal velocity for the four representative elements. In general, the horizontal gas velocity does not significantly increase until 100 s of pressing time. After that, gas (mainly vapour) is generated and moves to the core, creating a pressure gradient between the centre and the edges. Under this pressure gradient, notable horizontal gas movements take place, with their velocities governed by gas accumulation and mat permeability. In this context, the edges represent gateways for gas accumulated in the centre and accordingly should show greater velocity. The core layers are less dense and thus more permeable (Figure 8c), leading to higher gas flow velocities. After the press opens, the permeability of the surface layer increases notably due to springback (Figure 8c, Dai et al. 2000). As a result, the horizontal velocity rapidly increases, with the edge being higher than the centre (Figure 8b).

In general, during the early stage (0–100 s), gas mainly flows in the vertical direction (Figure 8a); however, during the later stages (> 100 s), gas flows predominantly in the horizontal direction (Figure 8b). In other words, the gas (mainly vapour) is first driven from the surface to the core, then from the centre to the edge and out to the atmosphere.

Evaporation rate Figure 9 shows the evaporation rate responses of the four representative elements. The local evaporation rate generally depends on the local gas pressure (which further depends on mat temperature) and gas flow velocity. During the early stage (0–50 s), strong evaporation takes place in the surface layers due to the high surface temperature and high gas flow velocity from the surface to the core, where there is no or little evaporation due to low temperature. The difference between surface-centre and surface-edge is due to the difference in the vertical gas flow velocity. During the second stage (50–100 s), the evaporation rate in the surface layers decreases due to the decrease in vertical gas flow velocity. At this stage, vapour is driven from the surfaces to the core, while the temperature in the core is still lower than that on the surfaces, resulting in vapour condensation (negative evaporation). Condensation starts at the

centre of the core and later extends to the edges. At approximately 100 s, maximum condensation takes place at the edges. At this stage, the dry surface-centre element seems to experience some minor condensation due to reverse flow of vapour from the core driven by increased core moisture content and temperature.

During the third stage (100–290 s), condensation in the core decreases and gradually changes to evaporation. This can be explained by the drastic increase in horizontal velocity, as shown in Figure 8b. On the surface of the mat, condensation also changes to evaporation. During the last stage (press opening), the evaporation rates in different locations show different degrees of change due to changes in the gas velocities.

Moisture content Changes in moisture content (MC) are governed by the evaporation rate. The higher the evaporation rate, the faster is the decrease in MC. Conversely, if the vapour changes from the gas state to the liquid state (i.e., condensation), MC increases. Figure 10a shows the MC responses in different layer positions in the centre of the mat. At the beginning of pressing, the surface MC decreases due to high temperature and hence rapid evaporation. The vapour from the surface then condenses and leads to an increase in MC in the sub-surface layer (C_2) where the temperature is lower. The inter-layer evaporation and condensation process leads to sequential loss and gain in MC between the lay-

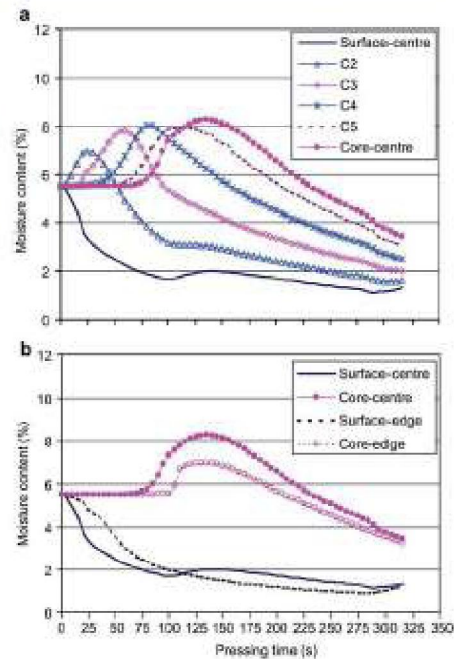


Figure 10 Changes in moisture content: (a) in the centre and (b) at the four representative locations.

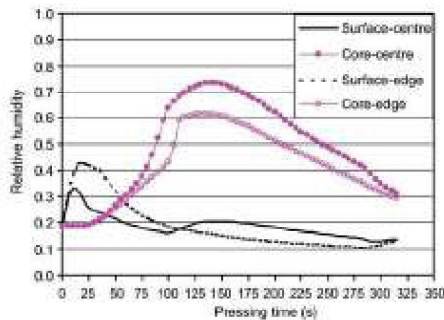


Figure 11 Changes in relative humidity at the four representative locations.

ers, resulting in inward MC peaks with pressing time. The maximum MC in a given layer is usually higher than that in the preceding layers due to a cumulative effect.

Figure 10b shows the MC responses for the four representative elements. At the beginning of pressing, on the mat surface, the MC of the surface-centre decreases more rapidly than that of the surface-edge. This is due to the higher evaporation rate in the centre. After pressing of approximately 100 s, the MC of the centre element reaches a minimum level and begins to slightly increase because of the change from evaporation to condensation. In contrast, the MC of the edge element continues to decrease, resulting in lower MC at the edge. In the core, the MC starts to increase after 75 s of pressing, with the core-edge apparently lagging behind the core-centre. This is because condensation at the edge occurs later than at the centre. In general, the MC at the core-centre is always greater than that at the core-edge during pressing. After opening, the MC on the surface slightly increases due to the occurrence of condensation (Figure 9).

Relative humidity Relative humidity (RH) is a variable that is closely linked to temperature and MC. Figure 11 shows the RH responses to the pressing time. Before pressing, the RH of the air in the mat is governed by the ambient temperature and initial MC of the mat. In the early stage of pressing, the RH on the surface increases with increasing temperature and the RH in the core remains almost constant because of little change in the temperature and MC. The RH at the edge is also higher than that in the centre owing to the higher edge MC. With increasing pressing time, the RH at the surface varies in a similar manner to the MC shown in Figure 10b. The RH in the core drastically increases due to the increase in temperature and MC. Later on, the core RH decreases due to the decrease in MC. Since the temperature and MC in the centre are greater than those at the edge, the centre RH is greater than that at the edge.

Degree of resin cure

The degree of resin cure has a direct influence on the physical and mechanical properties of wood composite

panels. For a given resin, the degree of resin cure depends on the history of the mat temperature and pressing time. Figure 12 shows the responses of the degree of resin cure for the four representative elements. The resin cures obviously much faster in the surface layers than the core because of the higher surface temperature. The curing rates are very similar between the surface-centre and the edges. However, the same cannot be said about the core-centre and edges. This is because of the slower increase in temperature around the edges than in the centre. In general, the resin curing rate is slowest around the core edges. Therefore, it may be wise to monitor resin curing at these locations to manipulate the pressing time for quality panel products.

Conclusions

This paper provides a comprehensive prediction of the variations of the 15 pressing variables mathematically described in the first part of this series (Dai and Yu 2004). These variables, which include mat temperature, internal gas pressure, moisture content, and resin curing rate, as well as their related variables, are dependent on the pressing time and mat location. They vary in a highly interactive, dynamic and complex manner, so that no variable is independent and none of the variations is linear. Heat conduction plays a dominant role in governing the steady increase in mat core temperature. Coupled with heat conduction, heat convection manifests itself by gas flow and phase change, which can significantly accelerate the temperature rise (due to condensation) during the initial stage of pressing, but decelerate it (due to evaporation) in the later stages. The flows of gas (a mixture of vapour and air) are highly unstable, mainly due to variations in the pressure gradient and the influence of local mat MC and porosity/permeability. By changing the mat structure, pressing parameters and initial conditions, the model can help in understanding the extremely complex mechanisms of heat and mass transfer in composite mats during hot-pressing, and offers a powerful tool for conducting sensitivity studies of pressing variables.

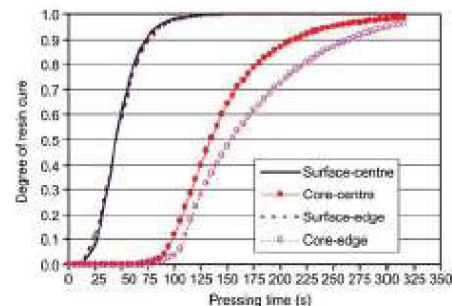


Figure 12 Changes in the degree of resin cure at the four representative locations.

ANEXO 5.

2002_ COST Action E13 Wood Adhesion and Glued Products_State of the art-Report habla de la conveniencia de humedad alta en capa externa y baja en capa interna



COST Action E13

Wood Adhesion and Glued Products

Working Group 1: Wood Adhesives

State of the Art – Report

Editors:

Manfred Dunky

Tony Pizzi

Marc Van Leemput

1st Edition - February 2002
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which reduces the water content of the glue line and hence also reduces the increase of moisture content of the wood to be bonded. On the other side a too long open time might cause a too high increase of the viscosity of the applied adhesive due to the loss of water; additionally the forming of a dry film on top of the adhesive layer might occur. Both effect will lead to a decreased wetting behaviour, which might cause low bonding strengths.

During the closed assembly time, which ends with the application of the press pressure, water also can penetrate into the second wood surface, causing e.g. even strong swelling of veneers, which might be the reason for cracks in the veneered board during use in dry conditions.

4.2.4.3 Steam Shock During Press Cycle and Warming of the Mat

The warming up of the core layers is based on the evaporation of water in the face layer and the transportation of the heat via the steam shock; in the cold core layer of the mat the vapour condenses and warms up the core layer. The higher the amount of vapour and the steeper the vapour pressure gradient, the quicker is the warming up of the core layer, enabling shorter press times. However, this vapour contributes to the overall moisture content of the core layer. The moisture content of the face layer therefore always should be as high as possible, the moisture content of the core layer as low as possible.

A too high moisture content within the mat and the board also (i) causes long venting times during the press cycle (in order to prevent blistering), (ii) hinders the chemical hardening reaction and (iii) leads to high densities in the face layer and a steep density profile between face and core layer.

During the hot pressing of a particle or fiber mat, resp., quick changes in temperature, moisture content and vapour pressure occur. The resulting gradients of temperature and moisture content significantly influence the forming of the bond strength and the hardening of the resin. All these processes together with the applied mechanical pressure determine the formation of the density profile and in this way the mechanical and other properties of the boards.

Questions and topics of R&D:

How to calculate the heating up of a particle or a fiber mat within the press?

4.2.4.4 Steam Pressure within the Mat and the Produced Board

Due to the moisture content of the glued core layer particles as well as due to the vapour flowing from the face layer to the core the vapour pressure in the core increases with elongated press time. If the vapour pressure is too high, it will exceed the bonding strength of the still hot board at the end of the press time (at the end of the continuous press), in such a case blistering occurs. Influence factors are the moisture content of the glued surface and core particles (especially determined by the composition of the glue mix and the gluing factor), resp., the portion of core and face layer in the board, press temperature and press time and the density and venting behaviour of the mat and the board.

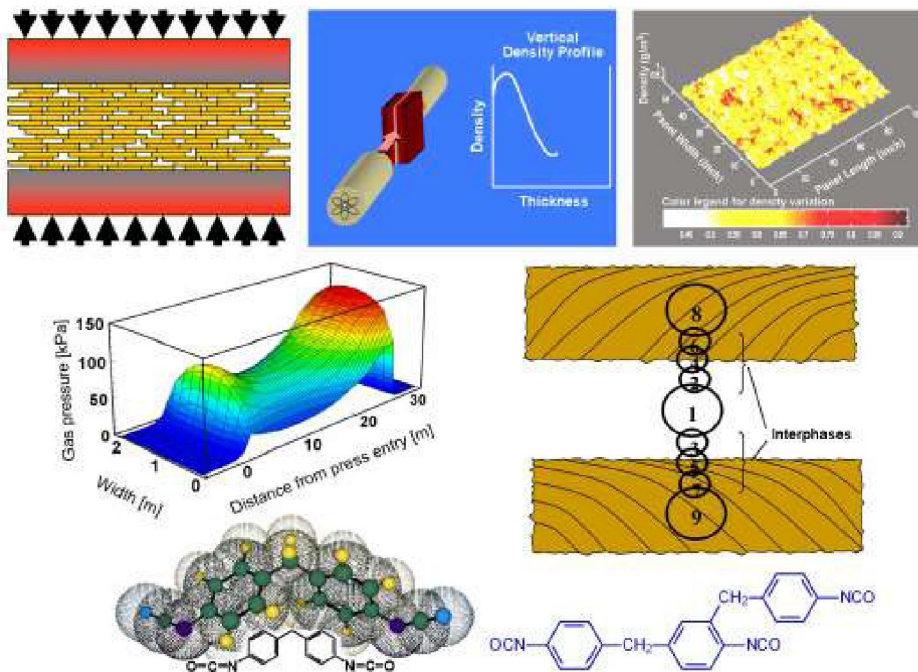
Very recently presses have been built with a special cooling zone in the approx. last third of the length of the press. At the moment only little (though promising) results are known. A final judgement on this technology is not yet possible.

Questions and topics of R&D:

- Which effects of the new cooling zone at the end of the continuous press are possible? Can the steam pressure be decreased significantly?*
- Which strategies are necessary to obtain a strong steam effect and a quick heating up of the core layer but nevertheless to avoid a too high vapour pressure in the core, causing in case blistering?*

ANEXO 6.

En el doc del 2004_ **Fundamentals of Composite Processing Proceedings of a Workshop USDA FPL_ Press Control for Optimized Wood composite processing and properties**, se explica cómo influye la humedad en el perfil de densidad



Presented by the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin in cooperation with the Wood-Based Composites Center, Virginia Tech, Blacksburg, Virginia

Abstract

The USDA Forest Service, Forest Products Laboratory (Madison, Wisconsin) and the Wood-Based Composites Center of Virginia Tech (Blacksburg, Virginia) co-sponsored a conference, held November 5–6, 2003, in Madison, Wisconsin, on the fundamentals of composite processing. The goals were to assess what we know, define what we need to know, and then establish the state of the art in hot-pressing of wood-based, particulate composites. Academic and industrial professionals from around North America and Europe were invited to participate because of their expertise and interest in this area of research. The workshop covered four critical topics associated with hot-pressing of composites: resin curing and bonding, press control, physics of hot-pressing, and computer simulations of the pressing process. This report is the official record of the presentations and discussions that occurred during this workshop.

Keywords: composites, processing, engineered wood

June 2004

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Press Control for Optimized Wood Composite Processing and Properties

Part 1: Pressing Variables and Sensors

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Introduction

Hot-pressing is a key operation in wood-based composite manufacture. During such an operation, mats of resinated wood fibers, particles, or flakes are consolidated under heat and pressure to create close contact and form bonds between the wood constituents. Due to limited amount of resin usage, effective bonds rely on a high degree of mat densification. Increasing mat density, on the other hand, causes negative effects such as heavier products, more wood consumption and more importantly excessive thickness swell in service when the product is subjected to high humidity conditions (Kelly 1977). The necessity and detrimental effects of mat densification suggest the importance of process optimization.

The pressing of a wood composite mat involves physical, mechanical, and chemical interactions. Once the press closes, moisture and heat transfer takes place between the hot platens and the mat. During the course of pressing, temperature and moisture content inside the mat are both spatially and temporally dependent (Humphrey and Bolton 1989). At the same time, the platens exert compressive forces onto the mat causing reduction of voids and compression deformation in wood constituents (Dai and Steiner 1993, Lang and Wolcott 1996). The mat deformation is usually not uniform across the mat thickness due to the variations of heat and moisture content from the surface to the core layers. Besides softening the mat, elevated temperature also accelerates resin polymerization, which combines with mat deformation to form permanent bonds between wood constituents. With little springback, the glue bonds also freeze the overall and layered mat deformation upon press opening. This leads to formation of the well-known vertical density profile (VDP) in pressed wood composite panels, which in turn has a significant effect on the physical and mechanical properties of the final products (Suchsland 1959; Kelly 1977; Harless and others 1987; Wolcott and others 1990; Winistorfer and others 2000; Wong and others 1999, Dai and others 2000).

Press control is important not only because pressing affects the board properties but also it is closely associated with the production costs. Regardless of product types, board dimensions always need to be controlled within specifications. In this regard, pressing plays a critical role in maintaining the final board thickness or minimizing the sanding waste. While heat is necessary to soften the mat and accelerate the resin curing, the combination of high temperature, moisture content, and time can sometimes lead to development of excessive gas pressure inside the mat and therefore cause blows upon press opening. Thus, certain press opening procedures are needed to vent the gas, which often means extra pressing time. The press opening time and the total pressing time should be minimized from the productivity standpoint. Less pressing time normally means higher productivity and lower manufacturing costs. The manufacturing costs can be further reduced by the control of the hot-pressing operation because it also represents one of the biggest energy consumption items in wood composites manufacture.

The general objective of the paper is to provide a state-of-the-art analysis of press control for wood composites. The specific objectives for Part 1 of this publication series are

- to introduce the basic concepts and variables of press control,
- to evaluate the responses of press variables during hot-pressing, and
- to review the sensing and control technologies for hot-pressing.

Basics of Press Control

Automatic Control Process

Process control is widely used in our daily life and manufacturing operations. Control of ambient temperature in a room and driving speed of a car are common examples. Figure 1 identifies the elements of a typical process control

system: process, measurement, controller, and control element (Johnson 2000). In general, a process can consist of a complex assembly of phenomena which relate to some manufacturing sequence. The process may involve many variables. Therefore one must define the control variable (c) first. To control a variable in a process, information about the variable must be gathered usually through measurements using a sensor or sensors. The measurements are usually in the form of electrical signals (e.g., 4-20 mA) which can then be further converted to real values (b) meaningful to the controlled variable. The measured values are compared with the reference points (r). If an error is detected between the real value and the reference value, the controller will send a signal (p) to the control element for necessary adjustments to the process (u) until the controlled variable reaches the reference value. Since the variable is controlled automatically in real time, such a control is often referred to as automatic control.

The automatic control process is applicable to control some hot-pressing variables such as platen temperature, pressure, and position. Here, the pressing process involves changes in thickness and pressure of resinated wood furnish mats. The mat pressure and position are measured using pressure probes and LVDT sensors, respectively. The measurement and the error detection along with the controller are all enclosed in a programmable logic controller (PLC) in which input (I) and output (O) signals are linked from the sensors and to the control element—servo valve (Fig. 1). The hydraulic valve can regulate the pressure and position based on the output signals from the PLC.

Program Control and Press Control Variables

When it comes to control hot-pressing, not all the variables can be controlled automatically or in real time. Probably due to lack of effective monitoring sensors, most of the pressing variables are currently controlled by predetermined programs or often known as pressing schedules. The pressing schedules control such important variables as mat core temperature and gas pressure, vertical density profile, degree of resin cure, and minimum pressing time. The key to the program control of hot-pressing is solid understanding and accurate modeling of the responses of these control variables during hot-pressing and their relationships with all other variables before and after pressing. The pre-press variables include species, furnish types and dimensions, moisture content, resin content, mat density, and mat structure. The post-press variables are product types and dimensions as well as board properties. Variations of these variables would require adjustments of the pressing schedules to achieve maximum product performance and minimum production costs.

Responses of Press Variables During Hot-Pressing

Significant progress has been made in understanding hot-pressing processes over the past 15 years both through modeling and experimentation. Bolton and Humphrey (1988) were among the first to provide a comprehensive investigation of the heat and mass transfer process in hot-pressing. An excellent review on hot-pressing was first reported and then followed by the development of a model for heat and mass transfer (Humphrey and Bolton 1989). Their stimulating work identified primary physical mechanisms of the hot-pressing process and at the same time revealed the complexity and interactive nature of the subject. Three main aspects of hot-pressing: heat and mass transfer, mat consolidation, and resin curing will now be discussed with respect to press control.

Heat and Mass Transfer

The variations of mat internal environmental conditions have been extensively documented in many studies both through experimentation (Maku 1954, Strickler 1959, Kamke and Casey 1988) and modeling (Humphrey and Bolton 1989, Zombori and others 2003, Dai and Yu, unpublished data). Figure 2 shows typical variations of mat core temperature and core gas pressure for a 11-mm-thick, 0.9- by 0.9-m (7/16-in.-thick, 3- by 3-ft) laboratory oriented strandboard (OSB) panel. Due to the nature of the heat and mass transfer process, the core temperature change is highly nonlinear. Particularly, the core temperature does not experience significant changes until 40 s after pressing. Then, it quickly rises probably due to convective flow and condensation of steam generated from moisture evaporation in the surface layers. As the core temperature rises, the steam accumulates and gas pressure starts to build up. The increased core gas pressure forces the trapped steam to escape from the edges, which leads to energy loss. As a result, the core temperature starts to level off and the core gas pressure usually reaches a maximum before it starts to drop. At the end of pressing, the press starts to open allowing the internal gas to release its pressure by flowing from the core to the surface and to the atmosphere, which also leads to a drop in the core temperature.

The fore-mentioned core temperature and gas pressure variations are typical of small panels. In the cases of commercial production, both the core temperature and the gas pressure usually experience some noticeable changes. First, the use of a screen caul plate can slow down the heat transfer from the platen to the mat surface, leading to slower core temperature rise (Fig. 3). Second, larger panel size reduces the energy loss from the edges, resulting in higher maximum core temperature and much higher core gas pressure. Particularly, the core gas pressure tends to always increase with pressing time again due to the reduced edge

effect. Because of this, a prolonged degas time is usually needed to allow for gas pressure release before press opening. Finally, the increased panel size can magnify the effects of furnish moisture content, furnish geometry, and mat density on the core temperature and gas pressure.

Mat Consolidation

Nonlinear Compression Stress–Strain Relationship

A simple compression test of a composite mat can reveal a highly nonlinear stress–strain curve, which is characterized by an extended low-stress plateau at the beginning and steep stress rise towards the end. Such a relationship is similar to pure transverse compression behavior of solid wood except that solid wood clearly exhibits a linear elastic behavior at the start. Figure 4 compares the compression stress–strain relationships between solid wood (or stack of strands) and a randomly formed strand mat. The similarity in both compression trends is probably due to the fact that wood substances are under compression in both cases whereas the difference can probably be attributed to random mat structure. This phenomenon was first identified by Suchland (1959) and then later modeled by Dai and Steiner (1993). The model was based on the Poisson distribution of random strand overlaps (Dai and Steiner 1994a, b) and a modified Hooke's law for transverse wood compression (Wolcott and others 1994). The strand overlap variation results in uneven stress distribution; only higher density areas contribute to load bearing at the beginning and lower density areas do not bear significant load until larger deformation occurs. The nonlinear compression behavior of mats was later reported with presentation of similar models by Lang and Wolcott (1996) and Lenth and Kamke (1996).

Viscoelasticity and Elastoplasticity

Since wood is a viscoelastic material (Wolcott and others 1990), mats of wood elements exhibit qualitatively similar but quantitatively different time-dependent behavior, namely strain creep under constant load and stress relaxation under fixed deformation. The difference is also attributed to the random mat structural formation. The knowledge of mat structure allows for the derivation of viscoelasticity relationships between mats and wood elements (Dai 2001).

The combination of high pressure and heat also results in both permanent mat deformation and springback upon and after pressing. Such mat behavior can be best described by the concept of elastoplasticity (Dai and others 2000). Elastoplasticity states that the mat compression stress–strain curves go through different paths during loading and unloading, and the mat deformation only recovers to a limited extent upon load removal. This implies that the

mat properties can be manipulated by both pressing closing and opening.

Mat Pressure and Thickness Relationship

The hot-pressing process is mechanically controlled by mat thickness and pressure through controlling the total deformation and stresses equally applied to each layer. At any given time in pressing, the overall mat deformation is controlled either by position or pressure. Thus, one is the resultant of the other.

Figure 5 is a predicted relationship between overall mat pressure and thickness for OSB hot-pressing (Dai and others 2000). During the first stage of press closing, the press platens are usually controlled by position. Mat pressure increases as mat thickness decreases. The variation of mat pressure and thickness is governed by the mat stress–strain relationships, which vary from surface layers to core layers due to the variations of temperature and moisture content. During the second stage, the mat reaches maximum pressure and the press is switched to pressure control. Mat thickness is determined by the layer stress–strain relationships and creep properties at the maximum pressure. Each layer behaves differently again due to the difference in temperature and moisture content. During the third stage, the mat reaches the target thickness and maintains it for resin curing. In the same time, mat pressure sharply drops and then gradually levels off. The decrease in mat pressure is a coupled response of mat softening (decrease of compression modulus) and viscoelastic stress relaxation (Fig. 5). During the last stage of pressing, the press is switched back to pressure control during which the mat pressure linearly drops to zero. This allows the internal gas pressure to release before the press opens. The removal of mat pressure also leads to a certain degree of mat thickness springback. The springback is characteristic of elastoplasticity which is affected by degree of resin cure, mat densification, temperature, and moisture content. The springback varies from surface layers to core layers and always results in the out-of-press panel thickness being greater than the press opening (Wang and Winistorfer 2002).

Vertical Density Profile

At any given time, the stresses applied to each layer are the same and equal the mat pressure. While the total mat deformation is controlled by the press opening, the deformation in each layer is distributed according to its viscoelastic and elastoplastic properties, which are functions of temperature, moisture content, and degree of resin cure. Figure 6 shows predicted density profiles at various stages of pressing (Dai and others 2000). Before pressing, the mat density is assumed to be uniform in all layers. During press closing (Fig. 5), the layer deformations are calculated based on their stress–strain relationships. The layer and overall mat densities in this stage incur the biggest increases. Particularly, the surface densities increase at

remarkably higher rates than core densities because of their lower compression modulus due to higher temperature. The density differences are much less noticeable in surface layers. This stems from the fact that mat softening due to high temperature in the surface layers adjacent to the heated platens is masked by the hardening effect of rapid moisture loss and thus softening effect of increased moisture content in the subsurface layers. Such a dry-out effect becomes more pronounced as the mat continues to be consolidated. By the time the mat reaches the target thickness, a slightly lower density is formed in the outer layer, leaving the density to peak in the inner surface layers. At this point in pressing, most of the density profile is formed. In other words, VDP is substantially formed during press closing.

After the mat reaches the target thickness, VDP seems to experience only minor changes (Fig. 6). As mentioned earlier, mat pressure decreases rapidly during the early stage of the period of holding target thickness (Fig. 5). The elastoplastic nature of mat deformation implies that a certain degree of springback can occur in the low temperature core layers, leading to further deformation in the softer surface layers. Such a give-and-take phenomenon of mat deformation may or may not lead to density changes because of the concurrent mass movement due to moisture flow between layers. As shown in Figure 6, neither the core density nor the surface density changes appear to be noticeable. This is because the core layers experience significant increases in moisture content, while the opposite is true in the surface layers at this time of pressing. The opposite mass movement seems to counter out the mat deformation exchanges, leaving the layered density more or less unchanged in this case (Wang and Winistorfer 2000).

In Figure 7, the mat exhibits some immediate (and delayed) springback upon press opening. It is believed that springback occurs mostly on the surface layers immediately adjacent to the platens due to so-called resin pre-cure (resin is exposed to premature heating and dry-out before the surface layers reach their maximum densities). In fact, springback due to pre-cure can lead to significantly lower density surfaces. In some cases, the surface density is even lower than the core.

Resin Curing and Bond Strength Development

One of the fundamental objectives of hot-pressing is to accelerate resin curing and develop bond strength between wood elements. Pressing operations can be best controlled if the conditions for optimum curing and bonding are known. Although the chemistry of resin curing for pure adhesives is well documented (Pizzi 1994), the curing and bond strength development of resin-wood mix seems much less understood probably due to several general reasons.

First, the resin amounts for most of the wood composite products are very low (usually much less than 15% by oven-dry weight of wood) and yet the resin distribution and penetration are not well defined. The amount of resin added to OSB furnish is low and is typically about 2% (wt.) resin solids based on oven-dry weight of wood. These factors can significantly affect the accuracy and variability of resin analyses. Second, the common chemical analytical methods can no longer be applied to analyze resin curing when resin is mixed with wood. Third, the physical, chemical, and mechanical properties of wood can change dramatically when wood is subjected to compression stresses and elevated temperatures. These changes, which should have a significant effect on resin curing and bond strength development, are not well defined. Finally, the interactions between resin and wood also need to be taken into account when resin is analyzed. Nevertheless, several studies have been performed to understand the curing mechanisms (Troughton and Chow 1968, Chow and Steiner 1969, Humphrey 1997, Geimer and Christiansen 1996). Some of the details were discussed in the previous papers in this proceedings by Frazier and Frihart.

It is generally understood that resins accelerate curing under elevated temperature and curing needs time to complete. Therefore, most of the pressing schedules are developed to achieve a certain core temperature and maintain the temperature for a certain period of time. Table 1 lists curing conditions for some typical composite products. Besides product types, resin types and board thickness also have defining effects on pressing schedules. For example, methylene diphenyl diisocyanate (MDI) resins seem to accelerate curing at a lower temperature than phenol formaldehyde (PF) resins. Thicker boards create a greater heat-sink effect after pressing and therefore usually require lower core temperatures.

Table 1—Curing conditions for some typical composite products^a

Product type	Thickness (in.) ^b	Resin type	Target core temp (°C)	Holding time (s)
Plywood	3/8	PF	110–115	
LVL	1.5	PF	100–105	
OSB	7/16	PF	>100 130	60–80 10
OSB	7/16	MDI	100–110	30
MDF/PB	3/4	UF	95	100

^aLVL, laminated veneer lumber; OSB, oriented strand board; MDF, medium-density fiberboard; PB, particleboard; PF, phenol formaldehyde; MDI, methylene diphenyl diisocyanate; UF, urea formaldehyde.

^b1 in. = 25.4 mm.

ANEXO 7.

En el **8th European Panel Products Symposium**, Heinemann et al. en su publicación **THERMOKINETIC SIMULATION OF A HOT PRESS CYCLE IN THE PRODUCTION OF PARTICLEBOARD AND MDF** refleja la influencia de la humedad de capa externa en el grado de curado

3 - 11

THERMOKINETIC SIMULATION OF A HOT PRESS CYCLE IN THE PRODUCTION OF PARTICLEBOARD AND MDF

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SUMMARY

It is fact that amino adhesive systems as they are widely used in the panel board production process cure and develop strength at rates that are highly dependent on the temperature conditions in the wood furnish mat being hot pressed. In this paper an approach is introduced to assess the degree of cure of adhesive systems by using thermokinetic simulation. Using Virtual Hot Press Software (vhps) as an analytical model describing various physical processes during a hot-pressing cycle, the temperature development within different particle mats has been simulated as a function of pressing parameters. On the basis of these simulated temperature conditions as a function of pressing time, the degree of cure of a variety of adhesives could be determined using a thermokinetic model derived from Differential Scanning Calorimetry (DSC) measurements. The chemical cure (exothermic energy) of two different commercially available adhesive systems has been monitored with DSC. A reaction model (multivariate non-linear regression) was fitted to the obtained data of exothermic energy values at different heating rates. The 'partial area' as evidence of the progress of the curing reaction can be determined with the reaction model. Consequently, the degree of cure could be predicted within well defined positions of wood furnish mats during the hot-pressing cycle.

INTRODUCTION

The mat temperature developing in the vertical direction from each surface layer to the core layer and also horizontally depends on pressing parameters e.g. densification speed, venting and second densification steps as well as on a variety of mat properties.

A variety of analytical models have been developed within the last two decades describing physical processes in wood furnish mats during the hot pressing cycle. The first model was presented by Humphrey (1982). Humphrey described the fundamental physical processes of heat and moisture transfer considering vapour convection, heat conduction and convection, and phase changes. Heat and moisture transfer processes as well as the rheological response due to densification processes of dry-formed wood-based composites have been summarized in a series of publication by Bolton and Humphrey (1988), Humphrey and Bolton (1989), and Bolton *et al.* (1989a, 1989b). The complexity and interactions of different mechanisms during the hot-pressing cycle of wood-composite mats was illustrated by Humphrey (1994).

More recently Thoemen (2000) and Humphrey and Thoemen (2004) presented results of simulating the physical processes of temperature development in different layers and gas pressure values during the hot-pressing cycle of dry-formed wood-fibre mats. The numerous equations describing physical principles during hot pressing have been derived from empirical tests published by von Haas (1998). The mathematical solution of these equations is based on a first approach presented by Humphrey (1982) where algebraic equations have been used.

Another approach to modelling the transient effect during hot pressing of wood-based composites was presented by Zombori (2001). Herein a numerical model based on fundamental engineering principles was developed and validated to establish a relationship between process parameters and the final properties of wood-based composites. The heat and mass transfer as one part of the model predicts the change of air content, moisture content and temperature at designated positions of the cross section of the mat.

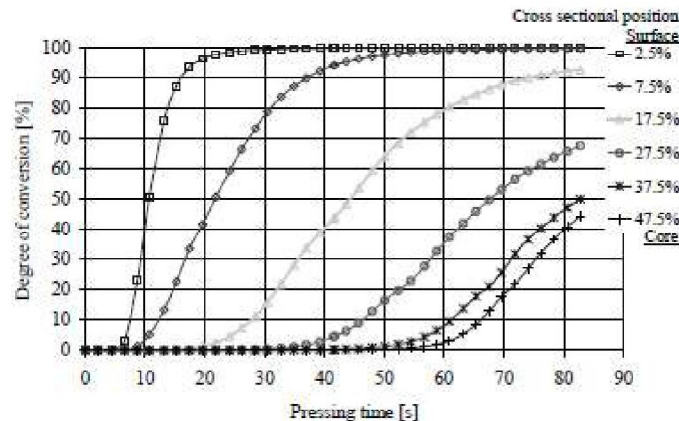


Figure 7: Predicted degree of conversion of the UF adhesive system within selected cross sectional positions of a three-layer particle mat during a hot-press cycle.

In order to gain an insight into the effect of the temperature development in the core layer of a hot-pressed particle mat on the degree of chemical cure, two different adhesives systems have been compared.

The temperature developing in the core layer is dependent upon certain pressing conditions. For the example presented, the initial surface layer moisture content was increased from 10% to 14%. Keeping all other input parameters unchanged the heat transfer, from the surfaces into the core of the three-layer particle mat, is accelerated. Within the first 20 s of the press-cycle hardly any change in temperature is observed for both settings (Figure 8). Then the temperature rises more rapidly for the particle board pressed with 14% initial moisture content of the surface layers, whereas the temperature for the one with 10% rises more moderate. A level of 100°C is attained after 52 s for the first and after 65 s for the latter pressing conditions. Higher convective and conductive heat transfer rates result in faster temperature increase. Upon press opening a temperature difference of 16°C can be detected, which might be caused by a higher steam pressure within the voids due to the higher overall amount of initial water.

Based on these temperature curves the partial area of the sub-reactions was predicted using the thermokinetic reaction model. Although the temperature rises at 20 s after the mat entered the press it takes additionally 30 s before a measurable response of the curing reaction can be detected. Corresponding to the faster temperature increase of the boards with higher initial moisture content (14%), the exothermic curing reactions starts at moderate rate for both, UF and MUpF, adhesive systems. Then, after 55 s the condensation reaction of the UF accelerates at higher rates than the MUpF adhesive system until a level of 61% respectively 48% are reached upon press opening. After the board is released from the press the exothermic curing reaction still proceeds at slower rates caused by the instantaneous drop in temperature. Due to the high temperature level in the core layer of the mat the degree of cure increases linearly with pressing time until a final level of 73% for UF and 59% for the MUpF co-condensate is reached after 83 s.

At a reduced temperature increase in the core layer due to lower initial moisture content of 10% in the surface layers the degree of cure follows a more moderate progress. When the mat is released from the press a cure level of 26% for the UF adhesive and 15% the MUF system is observed. Because the temperature drop in this case is not as high as in the scenario mentioned above, the curing reaction for both adhesives still proceeds and reaches levels of 50% and 28%. Obviously the UF resin kept some potential under these specific temperature conditions and the degree of cure increases by almost 50%.

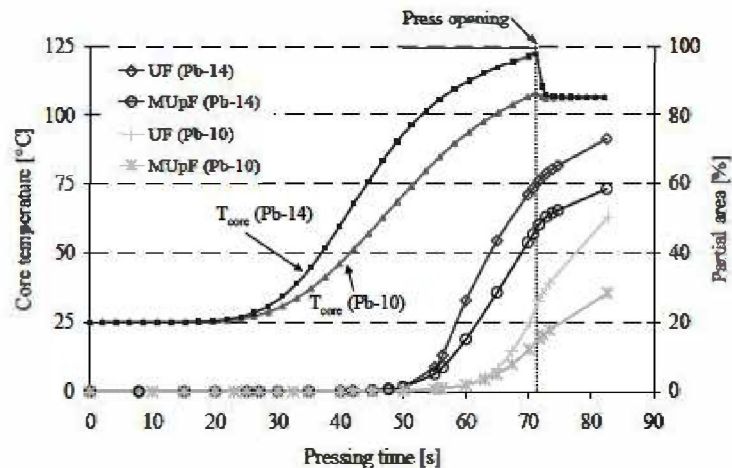


Figure 8: Degree of cure (partial area) based on simulated temperature development in the core layer of a three layer particle mat with different initial moisture content in the surface layers ($u=10\%$ and $u=14\%$) and for two different adhesive systems.

The data obtained within this project corresponds to the results published by Christiansen *et al.* (1993) where they compared the degree of mechanical cure measured with dynamic mechanical analysis (DMA) and the degree of chemical cure determined with DSC. The mechanical cure attained a nearly asymptotic value above the 80% cure level, whereas the chemical cure reached its asymptotic value at the 20% to 40% cure range. It can be concluded that at a lower chemical degree of conversion the stiffness - which reflects the progress of the condensation reaction - and certainly the attained strength gained to withstand the internal forces of the released boards.

At this time two interesting questions should be addressed in more detail. Firstly, is it possible to reach a level of total chemical cure in a wood-based composite mat and secondly, how long does it take under well defined temperature conditions after the board is released from the press? The first part of the question includes an important feature: The applicability and validity of the superposition principle. Humphrey and Ren (1989) applied the superposition principle for their approach of data derived from steady-state techniques being transferred to estimate bonding under the unsteady-state thermodynamic conditions during a hot-press cycle. Wang *et al.* (1995) and Wang *et al.* (1996) evaluated the effects of temperature and relative humidity on phenol formaldehyde resin bonding. As one of many results they pointed out that a resin pre-cured under well defined conditions could not reach the level of cure,

Hemmermann *et al.*

Como refuerzo a la invención en el Anexo 8 (próximo documento), **CHEM-E2105Wood and Wood Products_Manufacture of wood-based panels (manufacturing dry-formed wood-based composites: particleboard, medium density fibreboard etc.)** de Mark Hughes 23rdMarch 2016 se habla de tableros no equilibrados en las pag 38-39. También se hacen referencias a granulometrías y humedades (partículas más finas y más húmedas en capa externa)

CHEM-E2105

Wood and Wood Products

Manufacture of wood-based panels

(manufacturing dry-formed wood-based composites:
particleboard, medium density fibreboard etc.)

Mark Hughes

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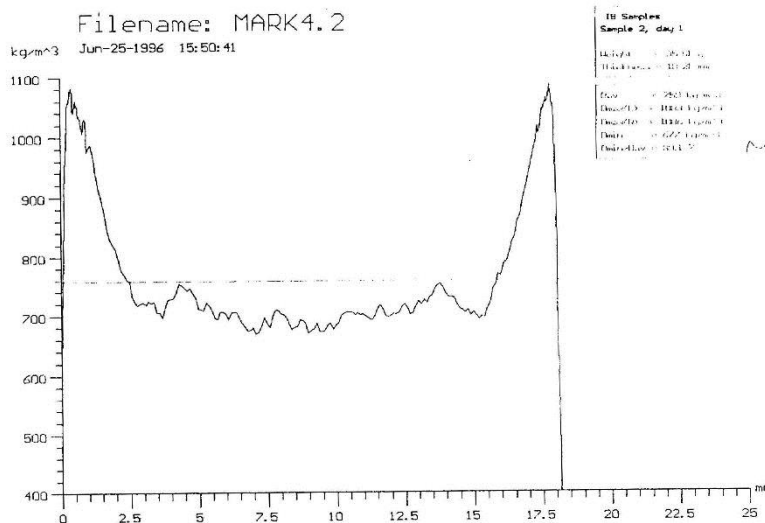
Today

- To provide an **overview** of the manufacture of dry-formed wood-based panels (particleboard, MDF, OSB), using **particleboard** as an example
- To introduce how the parts of the process affect the panel board properties
- To explain the **hot-pressing** process, particularly with regard to how the process affects the development of the structure and the properties of the panel
 - Although the focus is on particleboard, similar reasoning applies to other panel products and engineered wood products

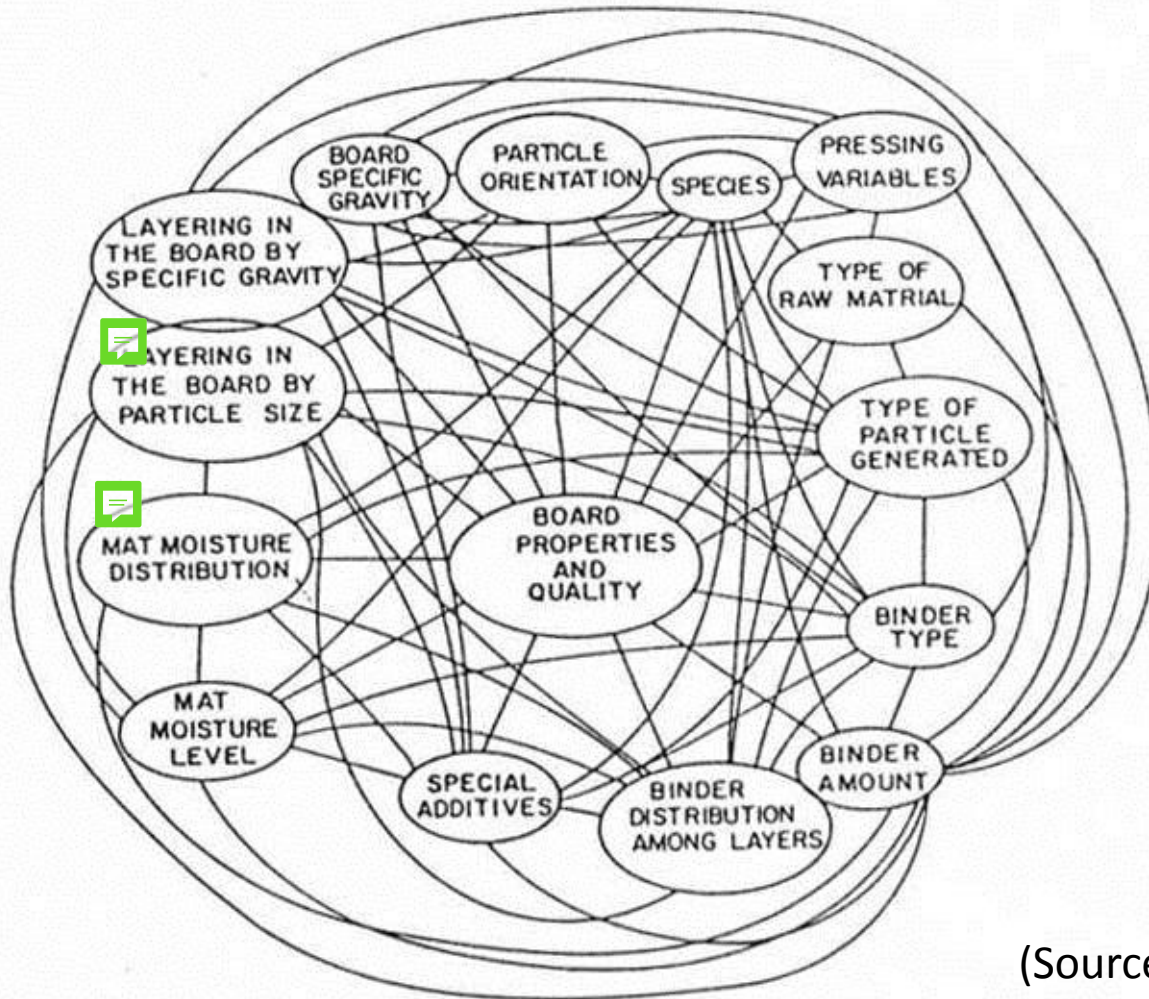
Structure of PB



- Particles of mm dimensions
- Typically 3 layers – surface or face material of fine particles
- Core material of coarser material (larger chips)
- Density profile developed during manufacture
 - Improved properties in bending
 - Harder surface



Some factors that affect the properties of a panel board....



The development of the final properties are dependent upon either the raw material or the **manufacturing process!**

(Source: Maloney, 1993)

Properties

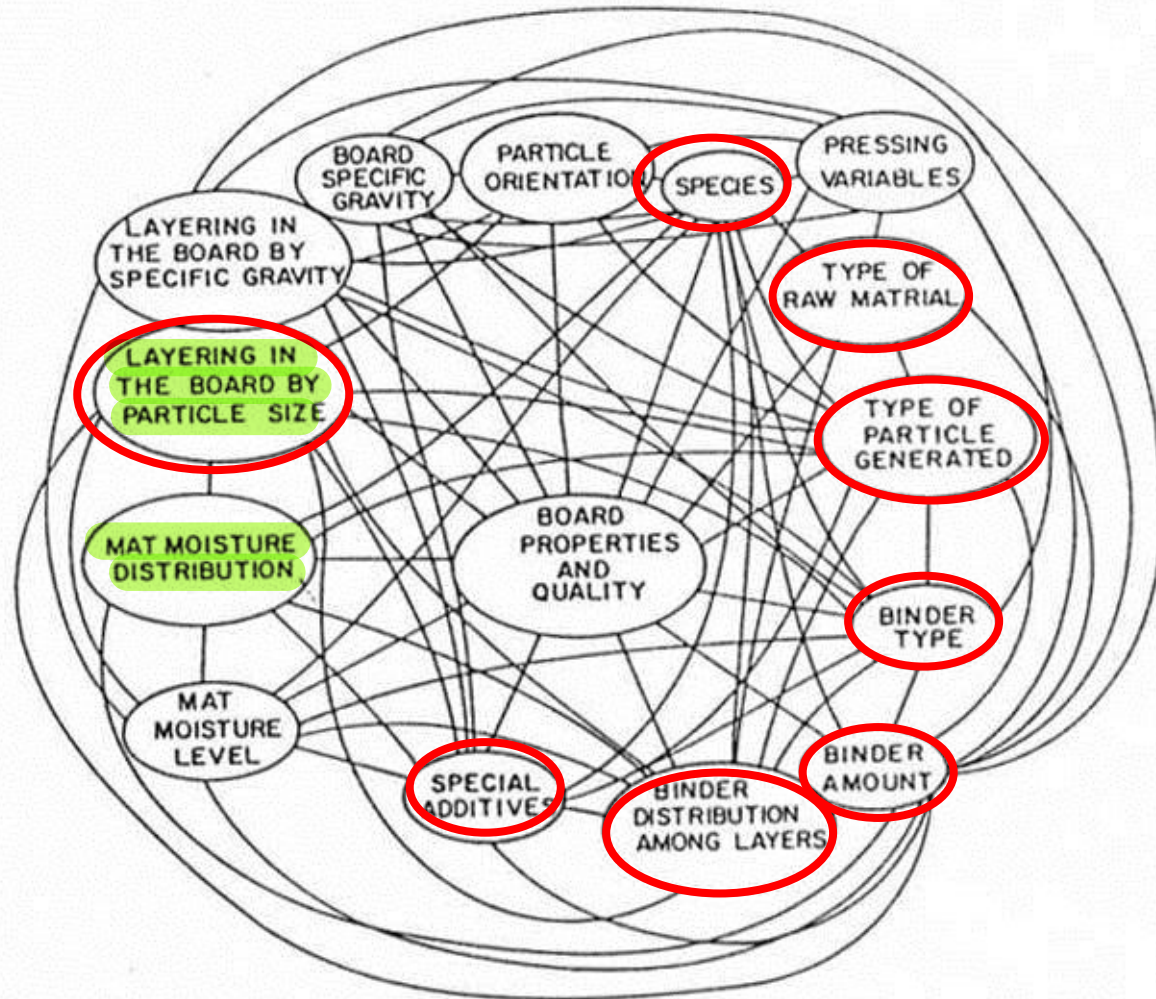
- Importance of property depends on application:
- Range of differing physical, mechanical & other properties, including:
 - Strength (bending, transverse tensile, shear)
 - Stiffness (bending)
 - Density
 - Surface hardness
 - Screw holding
 - Colour
 - Surface “finish” (roughness)
 - Moisture resistance
 - Creep (long term deformation under a sustained load)
 - VOC emissions

Panel properties affected by

- Raw material characteristics
 - Strength, chemical composition, density
- Interaction between particles
 - Particle to particle bonding
- Structural organisation of constituents
 - Size and shape of the particles
 - Orientation of particles
 - Packing
 - Relative proportions of the constituents

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Some factors that affect the properties of a panel board....

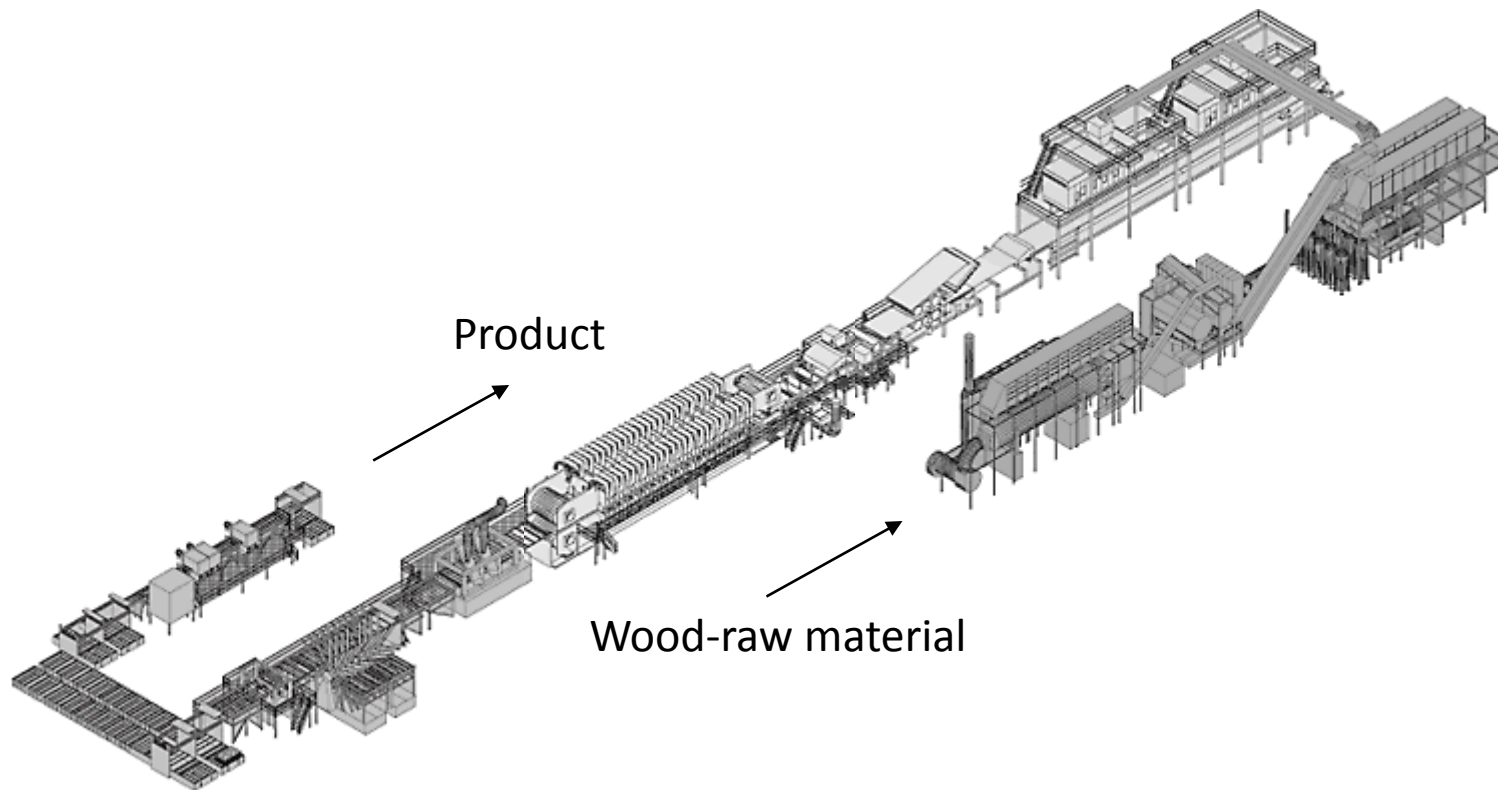


(Source: Maloney, 1993)

Basics steps in the process

1. Raw material prepared
2. Converted into particles
3. Particles dried
4. Particles classified
5. Blended with a resin and additives
6. Particle/resin/additive blend (“furnish”) is formed into a mattress
7. Hot pressed to compact the particles together and cure the resin
8. Cooled and finished

The particleboard process



(Source Diffenbacher: <http://www.dieffenbacher.de/index2.html>)

Raw materials

(Particles, adhesive & additives)

Particle

- Raw material properties influence many board properties, including board density, strength and stiffness etc.
- Can also influence the manufacturing process....
- Wood:
 - Virgin wood, mainly softwood, but other species can be used
 - Round wood
 - Co-products (sawdust, slabs, etc.)
 - Short rotation coppice (poplar)
 - Recovered/recycled wood (“urban forest”)
 - Pallet wood, packaging etc.
 - Management can be problematic due to difficulties in identifying contaminants (polymeric – paints and varnishes; preservatives - CCA).
- Non-wood:
 - Agricultural by-products
 - Wheat straw, bagasse, hemp, rice straw
- Basically any fibrous lignocellulosic material!

Wood raw material

- Species:
 - Density (affects the “compaction ratio” and the way the chip deforms under compression during pressing), strength and stiffness
 - Chemistry: pH, buffering capacity, affect resin cure
 - Extractives: may “interfere” with the bonding process or lead to emissions problems
- Recovered wood:
 - Contaminants:
 - Metallic (large! Easily dealt with, but in preservatives such as copper chrome arsenate – CCA – more problematic)
 - Inorganic (grit, sand, cement...)
 - Organic (e.g. paints/varnishes - problems with pressing; creosote)
 - Identification of contaminants (materials management)

Non-wood raw material

- Basically any lignocellulosic material!
- E.g. wheat straw:
 - High inorganic content
 - Waxes
- See, for example, CS Process Engineering [website](#)

Raw material for particleboard (Koskisen Oy, small PB mill in Finland)



(Courtesy: Koskisen Oy)

- By-products
- Spruce - 80 %
- Birch - 15 %
- Pine - 5 %
- Saw dust
- Mini chips
- Cutter chips
- Chips/board
- 4,5 m³ / m³

Adhesives

- Primarily thermosetting resins
 - Main type (90%) is Urea formaldehyde (UF)
 - Low cost
 - Rapid cure
 - Adequate properties for many applications (brittle and susceptible to hydrolysis)
 - “Low” formaldehyde emissions “E0”, E1 (E1 Classification <8m g HCHO/100g oven-dried board)
 - “Fortified” UF (melamine urea formaldehyde)
 - Phenol formaldehyde (PF)
 - MDI (methylene diphenyl diisocyanate) and pMDI. Zero formaldehyde release, but careful handling needed
- Other adhesives
 - Inorganic (cement bonded)
 - Thermoplastics
- Renewable resource-based adhesives
 - Tannin-based adhesives
 - Lignin-based adhesives
 - Glues based on vegetable oils
 - Soy flour-based adhesives
 - Furan polymer-based adhesives
- Binder-less boards using “activated” chips/particles (enzymatic or chemical)

Additives

- Waxes (reduction in moisture uptake)
 - Emulsion
 - Molten wax
- Fungicides
- Flame retardants

The Process

Process steps

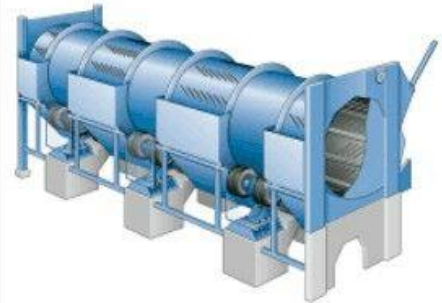
1. Raw material preparation
2. Converted into particles
3. Particle drying
4. Particle classification
5. Blended with a resin and additives
6. Particle/resin/blend (“furnish”) is formed into a mattress
7. Hot pressing to compact the particles together and cure the resin
8. Cooled and finished

1. Raw material preparation

- Debarking undertaken to remove bark which can reduce the properties of particleboard if present in quantities more than a few per cent
 - Rotary debarker
 - Drum debarker
- Sorting classification of waste wood for further processing
- Removal of metallic and other contaminants
- Problems in identifying some treatments that have previously been applied to wood. In particular, polymeric substances can cause problems in processing, for example



(Source: Andritz)

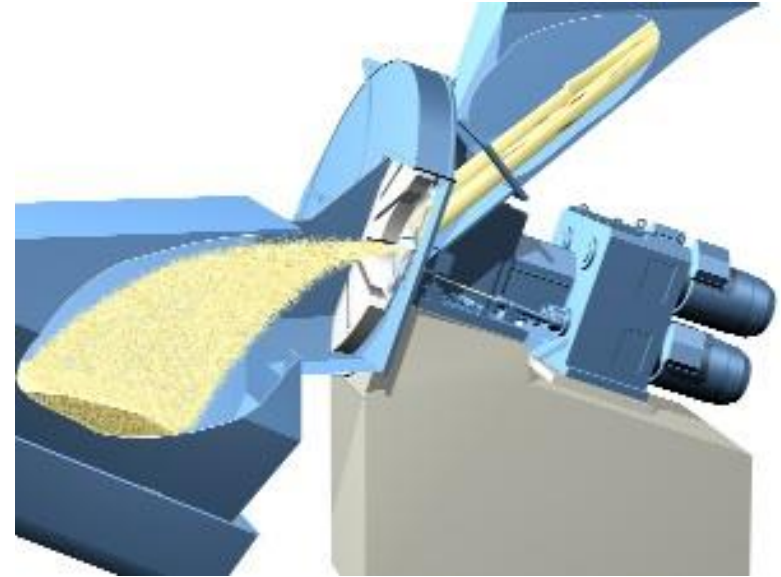


Process steps

1. Raw material preparation
- 2. Conversion to particles**
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2. Conversion to particles (chipping)

- Aim to manufacture a homogeneous product
- Need therefore to produce chips of a suitable size & shape to form the furnish for the board



Chipping



(Courtesy: Koskisen Oy)

Particles (chips)

- Depends on raw material. For example, if the raw material is in log form or is already reduced in size, e.g. shavings
- Reduction may therefore be a two stage process. For example, primary reduction of debarked logs to give large, coarse chips, followed by further milling to produce more “engineered” chips
- Different equipment may be used to prepare chip of the required type

Types of equipment

- Knife systems
 - Use knives cut or slice chips from the raw material
 - Disc/drum chippers
- Hammer mill systems
 - Use hammers to grind, break, tear shred raw materials into smaller particles
- Attrition systems
 - Grind the wood raw material into fibre – similar to TMP (thermomechanical pulp)

Particle engineering

- Each particle reduction (milling) process will produce a range of particle sizes
- Different chip size/type used for surface and core layers – fine chips or particles on the surface (good finish), coarser chips in the core
- Important to produce chip surfaces with as little damage as possible to improve particle-particle bonding:
 - A mechanically weak surface layer will lead to possible break-down of the glue-line, resulting in degraded board properties

Process steps

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3. Particle drying

- Why?
- High MC of chips from green wood too high (>100%) for pressing – can lead to the development of high vapour pressure in boards leading to delamination or “blows”
- Ensure that the “furnish” has a homogeneous MC
 - Core and surface layers may have different MC
- Some moisture is necessary to assist in heat transfer during the pressing process (see later lecture)
 - Remember: most commonly used commercial resins (e.g. UF/MUF) are water-based and this needs to be taken into account when determining the final moisture content of the particles..... Typically for UF around 65% solids content
 - Also wax emulsions contain water!
- Typically final MC of chips in the region of 2.5% after drying, but before resin blending
- Drying is a BIG consumer of energy!

Particle drying

- Optimisation of MC important: too much and this will cause problems with board blows, too little will lead to poor heat transfer in the press and incomplete resin cure, resulting in poor mechanical properties
- Driers work on the principle of passing the particles through a stream of hot air (180-200°C)

Dryer types

Various types of dryer e.g.

- Drum type (rotary/fixed)
- Belt dryers
- Paddle trough dryers
- Suspension-type
- “Flash” driers (high temperature)
- See for example, [Diffenbacher](#)

Process steps

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4. Classification

- Why?
- Control particle size distribution – important so as to optimise the position and size of the particles relative to their position in the board – small particles on the surface, bigger particles in the core
- Need to ensure that the board is “balanced”, i.e. the same amount of surface particles on both faces of the board (c.f. plywood). Otherwise may result in distortion of the board
- Note: very small particles (fines) will consume more resin (high surface area to weight ratio)



Classification systems

- Sieving – pass particle through different sized sieves, larger particles are retained, smaller particles pass through to the next size down
- Air classification – suspended in an air stream; the smaller, lighter, particles are carried away in the air stream, leaving the larger heavier particles (lower surface area to weight ratio)
 - Can form part of the drying process – simultaneous drying and classification

Process steps

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5. **Blending with a resin and additives**
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5. Gluing/blending

- An adhesive or glue needs to be applied to the surface of the particles to bind the particles together
- Different resins have different performance characteristics:
 - UF; brittle and subject to hydrolysis
 - MUF; better moisture resistance than standard UF
 - PF; more resilient and less subject to hydrolysis
 - MDI; highly reactive and bonds well
- The resins are generally applied as liquids in the form of an atomised spray
 - Note: can also be applied in solid (powder) form that forms a liquid on heating, before reverting to an insoluble, infusible, solid form (e.g. PF)
- Additional mechanical blending can enhance the coverage of the resin over the particle

Glue factors influencing board properties....

- Amount of resin
 - Generally, more resin, better properties (but more expensive!), therefore a balance...
 - Varies from resin type to resin type and is typically 8% (solids on oven dry wood) for UF in PB (or MDF), but can be as low as 2% (for MDI in MDF)
- Resin properties
 - Viscosity (depends on resin itself and “solids content”)
 - Solids content (weight of solid resin to total weight of resin)
 - pH and buffering capacity
- Distribution of resin
 - Droplet size (spray type and nozzle design)
 - Generally smaller droplets preferred, giving better resin distribution (see e.g. Kelly, 1977)
- Cure characteristics
 - Heat and/or catalyst needed to cure resin
 - Gel time/cure time depends on several factors

More on glues & additives

- Resins frequently manufactured on site, particularly UF and MUF. Storage conditions and duration important to prevent degradation (short shelf-life)
- Other additives (e.g. waxes, fungicides, flame retardants) may be blended in at the same time
- Typically, wax is added at around 0.5-1.0% (solid on OD wood)

Process steps

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Forming

- Laying up the “furnish” prior to pre-pressing and hot pressing (consolidation)
- Important process in the formation of the structure of the board and therefore strongly affects the board properties:
 - Improved bending properties
 - Good surface finish
 - Optimised density
- Boards may be “single layer”, “multi-layer” (3,5), or “graduated”
- Must always be a “balanced” structure to prevent distortion or poor properties (i.e. 2 or 4 layer no good)
- Surface layers of “fine” particles, “core” of coarser particles
- MC of surface layers 8-15%; core 4-8%
- Resin content of surface layers may also be higher to give improved strength

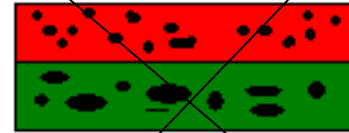
Forming



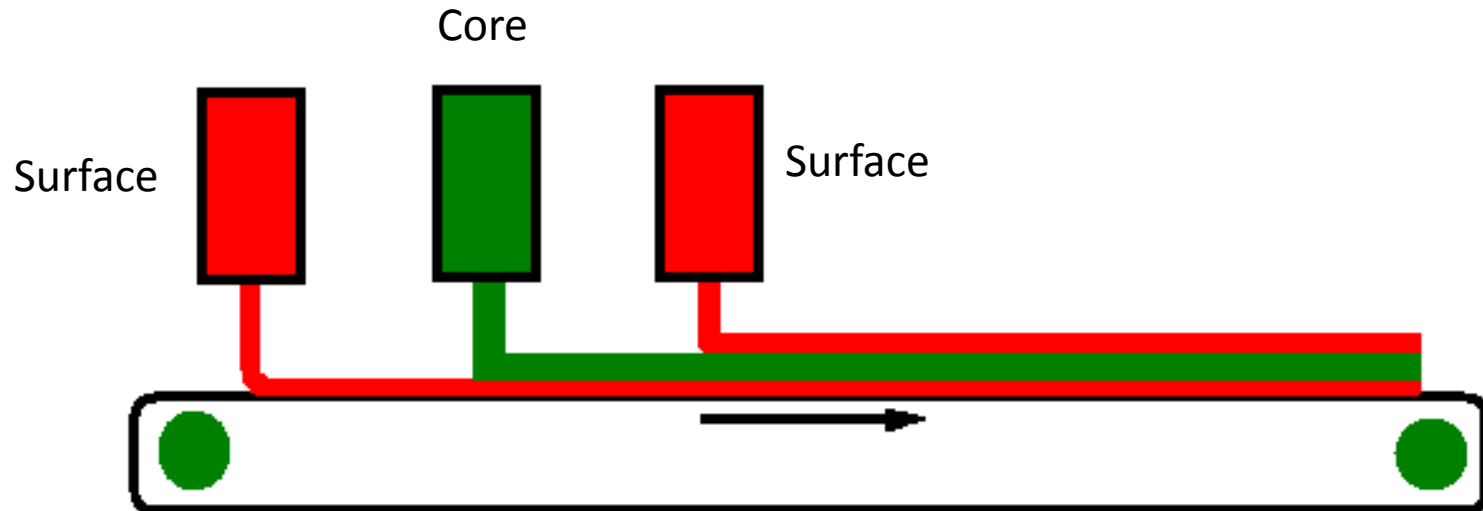
3 layer



Homogeneous



2 layer - unbalanced

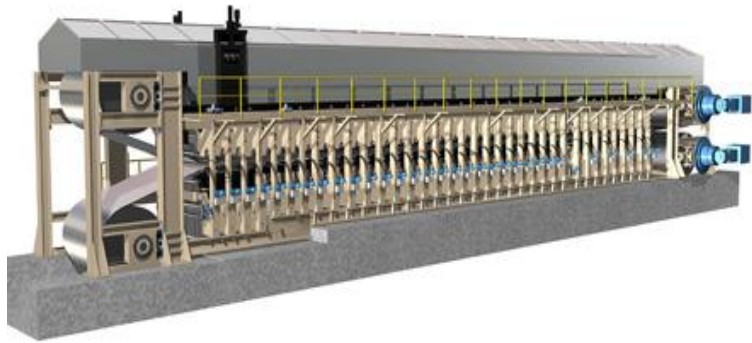


Forming

Process steps

1. Raw material preparation
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4. Particle classification
5. Blending with a resin and additives
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7. **Pre-pressing & hot pressed to compact the particles together and cure the resin**
8. Cooled and finished

Pre-pressing & hot pressing



- Pre-pressing of the furnish to reduce the bulk and give some mechanical strength to the mattress
- Hot-pressing, to finally consolidate the board and cure the adhesive. Density profile generated during hot-pressing
- Various types of press, the most common being a continuous press.

Pre-pressing

- Part of the consolidation process
- Pre-pressing undertaken to:
 - *Reduce the thickness of the mattress (i.e. increase the bulk density of the mattress)*
 - *Give the mattress some mechanical strength for handling*
 - *Speed up the hot press process, reduce pre-cure*
- Important that the mattress has some “tack” (slightly sticky), provided by the glue
- Pre-pressing may be cold or hot, important not to pre-cure the resin, but can help in getting heat energy into the mattress

Hot-pressing

- Main mechanism for consolidation of the mattress, the development of the board internal structure (in combination with forming etc...) and curing the adhesive binding the particles together
- Pressing may be batch-wise in a single or multi-opening press, or in a continuous press (“contipress”)
- Press control vital in the development of board properties and much research directed towards understanding what is going on in the press and in modelling this behaviour

Press types

- Opening presses:
 - Single-
 - Multi- daylight presses
- Continuous presses



(Source: Siempelkamp.com: <http://www.siempelkamp.com/Products.552.0.html>)

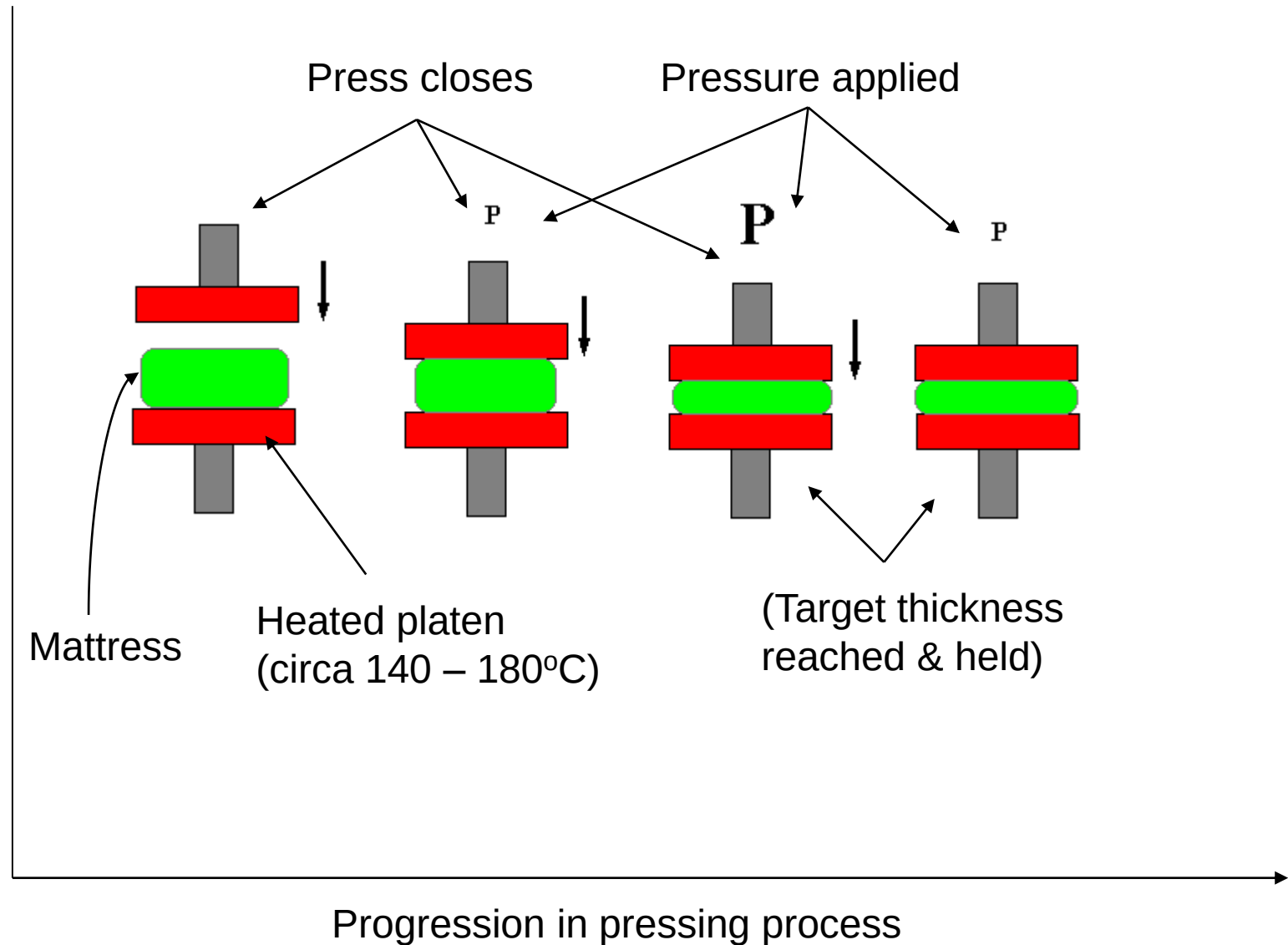
What is going on in the pressing process?

- Heat transfer and flow of gasses
- Phase change of water
- Densification of material
- Adhesive cure
- Development of internal stresses

Basic steps

- Board (mattress) fed to the press
- “Daylight” closes
- Press closure to target (thickness, pressure) – pressure increase
- Pressure/thickness maintained: resin cure
- Daylight opens: pressure reduced
 - May be done in stages
- Boards removed

Hot-pressing

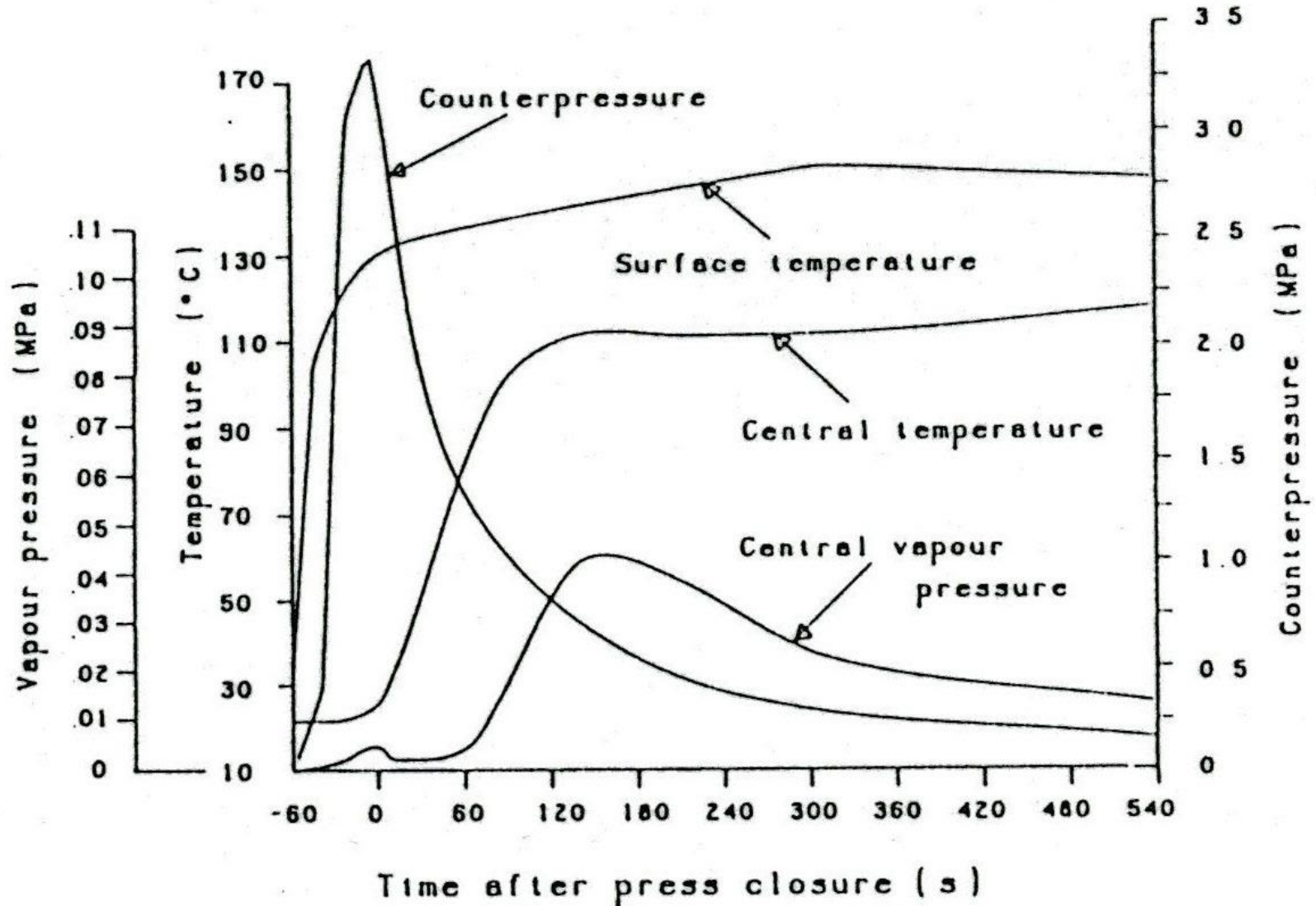


What happens to:

- Mat thickness
- Counter pressure
- Surface temperature
- Core temperature
- Core vapour pressure

During the pressing process?

Pressing physics

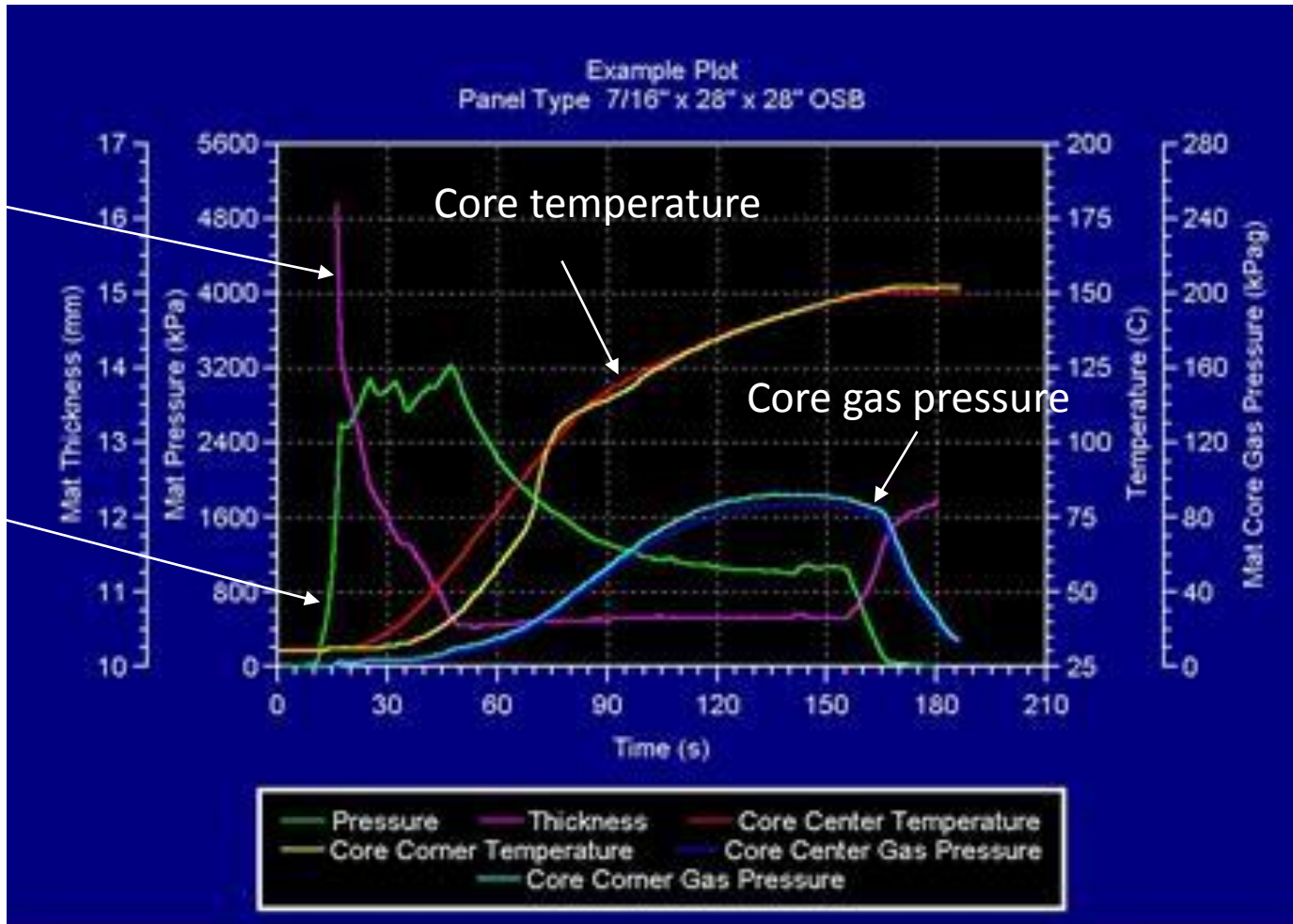


(Source: Kavvouras, 1977)

Press control/monitoring

Mat thickness

Pressure



Output from PressMan control unit
(Source: Alberta Research Council)

**Factors that affect the pressing process
and influence the final board properties**

Raw material

- Particle type and geometry – whether it is “granular” (chips), flakes or strands
 - Internal structure and ability of gasses to move around the interior of the mat: easier if it is granular, less so if it is composed of flakes
- Mat moisture content
 - Overall
 - Distribution
 - Higher on surfaces
 - Heat transfer, plasticisation of chips, but...
 - ...higher internal vapour pressure, possible delamination

Heat transfer mechanisms

- Conduction
- Convection
 - Change of phase: liquid-vapour-liquid
- Radiation
 - Negligible

Development of adhesive strength

- Gel time: liquid to solid....
- Time to reach full cure

Densification, internal stresses and spring-back

- Wood undergoes both instantaneous and time-dependent deformation when load is applied:
 - Elastic
 - Delayed elastic
 - Viscous
 - Plastic/microstructural failure
- “Trapped” elastic and delayed elastic stresses lead to internal stresses

Development of density profile

- Higher face moisture content will favour relaxation of the chips and so lead to higher face densities
- Faster press closure times will tend to result in higher density surfaces
- Higher density surfaces:
 - Increased bending properties and strength parallel to the board surface
 - ... but reduced internal bond strength (transverse tensile strength), inter-laminar shear strength and screw holding characteristics

Edge effects

- Vapour/gasses in the mat during pressing will tend to escape from the edges (not sealed)
- Leads to a lower gas pressure at the edges
 - Difficulty of scaling: e.g. simulating processes on a laboratory press

Limitations

- Thick panels
- Low density panels
- How to overcome these:
- External heating sources....
 - Steam injection
 - Radio Frequency (RF) and microwave heating

Cooling and finishing

- At exit from press, adhesive cured sufficiently to retain board integrity
- Some further “curing” may take place (used to be common to “hot stack” finished panels to cure the resin further)
- Panels need to be cooled before finishing (e.g. sanding) as if done too soon, board properties may be affected and tools will become clogged
- On exit boards trimmed before cooling

Cooling & finishing

- Cooled in e.g. “star cooler”
- After cooling the boards are sanded to the final thickness and to give good surface finish, especially if subsequent processing takes place, for example, lamination



Adding value

- Frequently the “raw boards” undergo further processing to add value
- Example is lamination or overlaying a decorative finish to the board
- Speciality boards (“moisture resistant”, “flame proof”)

References and further reading

- Chapman, K. (2006). Zen and the Art of making MDF. In: proceedings of the 10th European Panel Products Symposium, 11-13 October, Llandudno, Wales, UK
- Halligan, A.F. (1970). A review of thickness swelling in particleboard. Journal Wood Science and Technology, 4(4), 301-312
- Kavvouras, P.K. (1977). Fundamental Particleboard Process Variables, PhD thesis, University of Wales, Bangor
- Maloney, T.M. (1993). Modern Particleboard & Dry-process Fiberboard Manufacturing (available in library).
- Kelly, M. (1977). A critical review of relationships between processing parameters and physical properties of particleboard (available at: <http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr10.pdf>)
- Philip E. Humphrey (undated) Temperature and Reactant Injection Effects on the Bonding Kinetics of Thermosetting adhesives

Further information

- Manufacturers:
 - Egger (www.egger.com)
 - Kronospan (<http://www.kronospan.co.uk/>)
 - Norboard (<http://www.norbord.com/>)