

MEASURING AND SIMULATING THE EFFECTS OF THE PRESSING SCHEDULE ON THE DENSITY PROFILE DEVELOPMENT IN WOOD-BASED COMPOSITES

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Abstract. The cross-sectional density profile of wood-based panels has a strong impact on many of its end-use properties. In modern panel manufacture, not only press closure but also changes in mat thickness later in the pressing cycle are of importance for density profile development, particularly in the MDF process. A full-factorial analysis of the effects of the pressing cycle on the density profile is presented, with the factors considered being press-closing time, mat thickness level after first densification, and time of secondary densification. It was found that the mat thickness level after first densification dictates the density difference between surface and core regions. For pressing schedules that include a second densification step, intermediate density maxima appear, with magnitude and position of the intermediate density peaks being determined mainly by the first density level and the time span between press closure and final densification. Computer simulations are used to link the density variations to the conditions of local temperature and moisture content during pressing.

Keywords: Wood-based composites; MDF; density profile; computer simulation; secondary densification.

INTRODUCTION

In wood-based composites, the density distribution perpendicular to the panel plane has a significant impact on its properties. In particular, the effects of the cross-sectional density profile on bending properties (eg Fahrni 1956; Kollmann 1957; Strickler 1959; May 1977, 1983b, Boehme 1992) and internal bond strength (eg Plath and Schnitzler 1974; May 1983a, Xu and Winistorfer 1995; Schulte and Fruehwald 1996) have been subject to extensive investigations. As a general trend, higher surface layer densities result in higher modulus of elasticity and modulus of rupture, while a rise in core density is positively related to the internal bond strength of

a panel. Besides the mechanical properties, other panel characteristics such as dimensional stability (eg Boehme 1992; Xu and Winistorfer 1995), surface quality and edge varnishability (Wang et al 2001), and machinability (Boehme 1992) are also strongly affected by the cross-sectional density distribution. Although some of the effects listed above may be compensated, or even reversed, by other factors such as adhesive polymerization (Strickler 1959) or particle geometry (Suchsland 1967), the density profile is one of the most important characteristics that determine the in-use properties of wood-based panels. Hence, one of the clear challenges in panel manufacture is to adapt the cross-sectional density profile to the product specifications by appropriate process technology and control strategies.

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A typical cross-sectional density profile shows density maxima near the panel surfaces and an inner zone of reduced density, which can be smooth or somewhat irregular. Panels may also display a more or less pronounced density drop from the maxima toward the surfaces. It was appreciated in early literature that the variation of temperature and moisture content causes such nonuniform densification (Fahrni 1956; Kollmann 1957). Later, fundamental work on the complex nature of wood-furnish material densification was presented by several research groups. Wolcott et al (1990, 1994) described the local deformation processes during hot-pressing of flakeboards by applying theories of the viscoelastic behavior of amorphous polymers in combination with theories of cellular solids. Another approach was chosen by Ren (1991) working with Humphrey, who proposed a five-element rheological model to describe the time-dependent deformation and development of internal stresses in wood-based composite mats. Each of the coefficients that mathematically describe the five elements is a function of temperature, moisture content, and density. Models of the densification behavior based on both approaches have been coupled subsequently with mass and heat transfer models to describe the cross-sectional density profile development during hot-pressing (Dai et al 2000 and Zombori 2001 for the former approach; Humphrey 1994 and Thoemen et al 2006 for the latter).

Clearly, the localized temperature and moisture conditions always have to be considered in relation to the external pressure acting on the material. Hence, the choice of the pressing schedule, ie the course of mat densification throughout the hot-pressing process, is crucial for the development of the cross-sectional density profile. It is not surprising that the first trials to investigate the relationship between pressing schedule and density variations were published just after the onset of industrial particleboard production about 50 yr ago. Strickler (1959) had described the effects of magnitude and duration of maximum pressure early in the pressing cycle on the cross-sectional density profile of particle-

board. Suchsland (1962) explained these effects by stating that a higher maximum pressure reduces the press closing time and thereby the depth of heat penetration at press closure, which in turn leads to thinner but more vigorously compressed high-density regions. A great number of publications relating the press-closing strategy to density profile have followed, some of which are given later.

In most of the early publications linking pressing schedule to cross-sectional density profile, it was assumed that overall mat thickness does not change after press closure. And even today, such an assumption is made in much research. Nevertheless, the interest in the link between pressing schedule and density profile gained new relevance when introducing technologies to dynamically control the position of the pressing platens in batch presses, and even more by the development of continuous presses in the 1980s and the inherent possibility to control the individual pressing frames. While stops that were typically used in batch presses for a long time impose a constant mat thickness after press closure, it became possible to affect mat densification through the entire pressing cycle. The variability of the inner portion of cross-sectional density profiles in medium density fiberboard (MDF) when pressed under different schedules has been demonstrated, for example, by Boehme (1992).

Thoemen and Humphrey (1999, 2003) were the first to explain the link between the second densification step toward the end of the pressing cycle, as typical for industrial MDF production, and intermediate minima and maxima in the density profile. Such density minima and maxima between the surface regions and the central plane of the mat are a common problem in MDF production. By modeling and simulating the thermodynamic and rheological mechanisms operative in a wood-furnish mat during hot-pressing, they showed that the density profile development during pressing depends on the development of the pressing load in concert with the cross-sectional distribution of rheological mat properties.

Wang et al (2000, 2001) and Wang et al (2004) investigated the effects of different pressing strategies including pressing schedules with two or more densification steps on the cross-sectional density profile of MDF and oriented strandboard (OSB). By using a gamma radiation-based system they monitored the changes over time of layer density at three positions in a laboratory batch press. This method made it possible for the first time to experimentally retrace layer density variations as the mat thickness was altered throughout the pressing cycle, and thereby provided valuable insights into the development of the density profile.

It was the intention of this work to contribute to the discussion about how the cross-sectional density profile develops during hot-pressing, what role the distribution of temperature and moisture plays for this development, and by what means the profile can be manipulated. The emphasis in this paper is put on typical pressing schedules for medium density fiberboard (MDF) with a pronounced second densification step. Data generated by a simulation model are used to verify the direct link between local mat conditions, rheological material properties, and resulting density profile.

LAB PANEL MANUFACTURE

Mat Preparation and Hot-pressing

For the experimental part of this work, MDF panels were produced in a laboratory press to determine the effects of the pressing schedule on the final cross-sectional density profile. Thermo-mechanical pulp (TMP) pine fibers (*Pinus sylvestris* L.) obtained from a commercial MDF plant were treated in a drum blender with a melamine-supplemented urea-formaldehyde resin (10% resin solids based on oven-dry mass). The moisture content of the fibers after blending was adjusted to 10%.

The 600- × 400-mm fiber mat was formed manually on a 6-mm-thick aluminum platen. To avoid asymmetrical heating prior to pressing, the mat was predensified at room temperature so

that it would fit easily but with contact to both pressing platens in the hot-press. After the top surface was covered with another 6-mm aluminum platen, the mat was moved into the computer-controlled hydraulic laboratory hot-press. All panels were pressed for 240 s to a final target thickness of 16 mm with a target density of 710 kg m⁻³ (based on 8% moisture content). The temperature of the heating platens was set to 180°C over the entire pressing period. The press was operated in position-control mode; no stops or similar devices were used. Core-layer temperature and specific pressure were recorded for all panels.

A parallel test series was conducted in a 100-mm-dia partly-sealed miniature press under nearly identical conditions as were employed in the larger laboratory press. The outcome of the second series has been presented by Ruf (2003) and will be referred to when necessary to clarify the results found for the 600- × 400-mm panels.

Pressing Schedules

The progression of the mat thickness along the length of a continuous press as typical in the MDF process is displayed in Fig 1. Analogous pressing schedules are used in MDF batch presses. Typical features are the main densification (phase 1 in Fig 1) to an elevated density level (phase 2), a slight opening of the press in the intermediate stage of pressing to facilitate

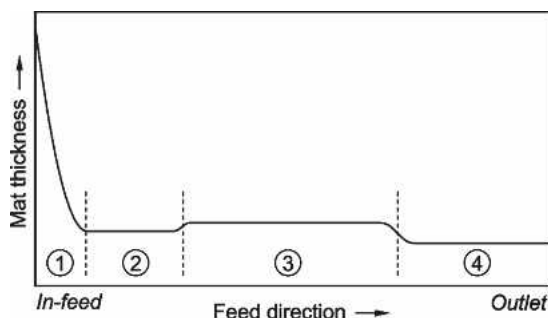


FIGURE 1. Schematic of a typical pressing schedule in a continuous MDF press, sectioned into four phases. 1 = main densification; 2 = surface layer consolidation; 3 = degassing; 4 = calibration.

escape of the gas mixture from inside the mat (phase 3), and the secondary densification of the mat at the beginning of the calibration period (phase 4). The magnitude of these features and the pace of the transition between the phases may vary considerably, depending on the panel type and on the preferences of the manufacturer. While in some cases the mat thickness in phase 2 slightly undershoots the mat thickness level of the intermediate stage (phase 3), it may even fall below the final panel thickness in other cases. The mat thickness during the intermediate stage typically ranges from 110–130% of the final panel thickness.

It was beyond the scope of this research to include all possible variations in pressing schedules. To reduce the experimental effort, the first over-densification and the subsequent slight opening of the press were omitted. The result was a simplified but still realistic MDF pressing schedule as displayed in Fig 2. The three factors considered in the analysis were press closing time T , mat thickness level after first densification L , and duration of the first densification level D . A full-factorial design was done with each factor being treated on the three levels listed in Table 1. The second densification step took 2 s from the 110% level and 4 s from the 120% level. Please note that the factor D was not relevant for the 100% level of first densification. Hence, 21 different pressing schedules were analyzed. For each pressing schedule, 3 panels were manufactured, resulting in a total of 63 panels.

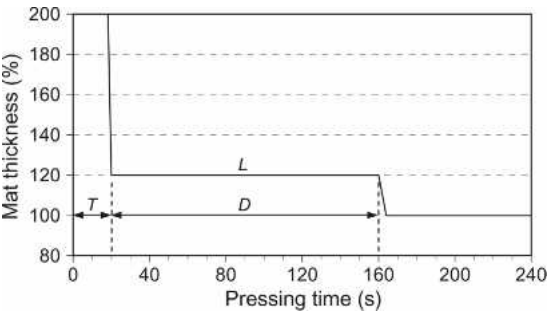


FIGURE 2. Factors of the experimental design. T = closing time; L = mat thickness level after first densification; D = duration of the first densification level.

TABLE 1. Factors and their levels of the experimental design.

Factor	Levels
Closing time T (s)	10, 20, 30
Mat thickness level after first densification L (%)	100, 110, 120
Duration of first densification level D (s)	120, 140, 160

Density Profile Measurements and Data Processing

From the middle of each panel, three 50- × 50-mm samples were cut and conditioned at 20°C and 65% relative humidity to equilibrium. The thickness of each sample was measured to a precision of 0.01 mm. A gamma radiation-based system (Raytest Isotopenmessgeraete GmbH) was used to measure the cross-sectional density profile, with one measurement every 0.075 mm over the sample thickness.

To cope with slight differences in the sample thickness caused by unequal springback effects, the thickness of each sample was normalized to 100%. The individual density profiles were averaged over the three samples from each panel. Before determining the characteristic values to describe the density profiles, the averaged profiles were slightly smoothed. The following characteristic values for the density profiles have been determined:

- Magnitude (ρ_{max}) and position (z_{max}) of the density maxima near the sample surfaces, averaged over the top and bottom half of the panel. All positions were measured from the panel surfaces.
- Average density (ρ_{core}) between 47.5 and 52.5% of the panel thickness.
- Magnitude (ρ_{inter}) and position (z_{inter}) of the intermediate density maxima. These values are given only for $L = 120\%$.
- Ratio of ρ_{inter} to ρ_{core} .

For generating density profile curve plots, the original profiles were averaged over the three replications and three panels manufactured with the same pressing schedule, and were also slightly smoothed.

From the recorded core-layer temperature curves, two characteristic values were derived, ie the time $t_{100^{\circ}\text{C}}$ when 100°C was reached and the maximum temperature T_{max} just before press opening. Characteristic values derived from the specific pressure curves were the maximum pressure p_{max} measured during main densification, the maximum pressure reached during the second densification step, $p_{2\text{nd}}$, and the pressure $p_{240\text{s}}$ at the end of the pressing cycle.

Multiple linear regression models were fitted for each characteristic value to test the statistical significance of the three factors on the responses. Interaction terms were not included in the statistical analysis. As the duration of the first densification level, D , was not relevant for those panels densified immediately to target thickness ($L = 100\%$), a two-step approach was chosen for the statistical analysis. It was first determined whether D were a significant factor on the 110 and 120% level. If D was found to be not significant, the regression analysis was repeated with all observations (including those of the 100% level), but not considering D as an explanatory variable. On the other hand, if D were a significant factor, an indicator variable was introduced, and the values of 1 and 0 were assigned to this variable for the panels manufactured with and without, respectively, a second densification step. In this case the variable D was arbitrarily set to 120 s for all observations at the 100% level.

EXPERIMENTAL RESULTS

Density Profile

The effects of the pressing schedule on the overall density maxima near the panel surfaces, ρ_{max} , are summarized in Fig 3a. This display format was chosen to simultaneously display variations between and within the levels. Each data point represents the average of typically three density profiles obtained from one panel. There is an obvious and pronounced impact of the mat thickness level after first densification, L , on the maximum density measured after conditioning.

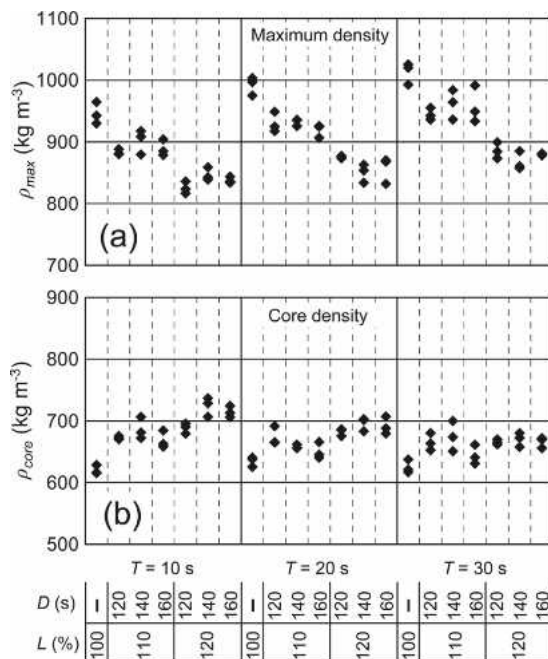


FIGURE 3. (a) Maximum density (ρ_{max}) near the sample surfaces, averaged over the top and bottom half of the panel. (b) Average density (ρ_{core}) between 47.5 and 52.5% of the panel thickness. Each data point represents the average of typically three density profiles obtained from one panel.

According to the coefficients given in Table 2, increasing L by 10% leads to an average decrease of the maximum density by 63 kg m^{-3} . Also, there is a slight but statistically significant positive effect of the closing time T on the maximum density. That is, under the conditions chosen in this research, a longer closing time results in higher maximum densities than with faster press closures. This effect was observed for all factor combinations. On the other hand, the duration of the first densification level, D , does not have a significant effect on ρ_{max} . This finding confirms what one may have assumed by intuition, namely that actions far into the pressing cycle do not influence the surface layer densities. The cross-sectional position of the density maximum, z_{max} , moved slightly toward the core layer with increasing closing time T , but there were no effects found for level L and duration D of first densification on the position (Table 2).

TABLE 2. Coefficients for the multiple linear regression models.

Explanatory variables	Responses									
	Density profile			Temperature			Pressing load		Thickness	
	ρ_{max} (kg m ⁻³)	ϵ_{max} (%)	ρ_{core} (kg m ⁻³)	ρ_{inter}/ρ_{core} (-)	z_{inter} (%)	$t_{100^\circ C}$ (s)	p_{max} (MPa)	p_{2nd}^2 (MPa)	p_{240s} (MPa)	s (mm)
T (s)	2.71	2.08×10^{-2}	-1.16	—	-7.29×10^{-2}	4.29×10^{-2}	—	-5.12×10^{-3}	—	—
L (%)	-6.34	—	2.90	n/a	n/a	1.88	-8.85×10^{-2}	2.03×10^{-2}	4.17×10^{-3}	—
D (s)	—	—	—	-1.65×10^{-3}	6.41×10^{-2}	—	—	-2.80×10^{-3}	1.12×10^{-3}	6.01×10^{-3}
Indicator var.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	—	2.90×10^{-1}
Overall mean	904.5	4.12	670.2	1.354	24.43	162.4	3.37	0.59	0.23	16.05

¹) only 120% level considered
²) only 110% and 120% level relevant
n/a not applicable
— not significant at the 95% level
 T = closing time, L = Mat thickness level after first densification, D = duration of first densification level

As shown in Fig 3b, a higher mat thickness level after first densification, L , not only leads to a reduced maximum density, but accordingly to an elevated core density ρ_{core} ; an increase of L by 10% raises the core density by almost 30 kg m⁻³. This effect is clearly visible in Fig 4a. In addition, there is a statistically significant but relatively small effect of the closing time T on core density, whereas no link was found between duration of the first densification level, D , and core density.

Intermediate density maxima between surface and central plane occur most clearly for L = 120%. Therefore, the 100 and 110% levels were excluded in analyzing the intermediate density maxima. The ratio between the intermediate maximum density, ρ_{inter} , and the core density, ρ_{core} , may be used as a good measure for the height of the intermediate density maxima. For example, a ratio of 1.1 denotes that the intermediate maximum density exceeds the core density by 10%.

The duration of the first densification level, D , has a marked effect on the ratio ρ_{inter}/ρ_{core} (Fig 5a). The difference between the intermediate maximum density and the core density diminishes toward higher values for D , which is also illustrated in Fig 4b. Please note that the variations in final average density visible in Fig 4b are due to unequal springback effects. D also has a clear impact on the position of the intermediate density maximum between surface and central plane of the panel, with positions closer to the

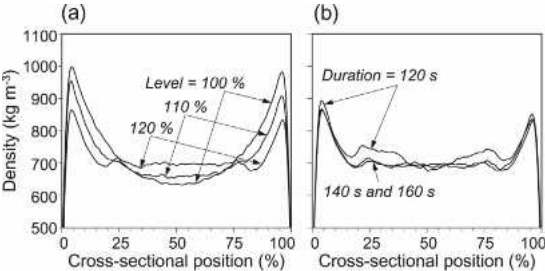


FIGURE 4. Cross-sectional density profiles for (a) different levels of first densification (T = 20 s, D = 140 s); (b) different durations of the first densification level (T = 20 s, L = 120%).

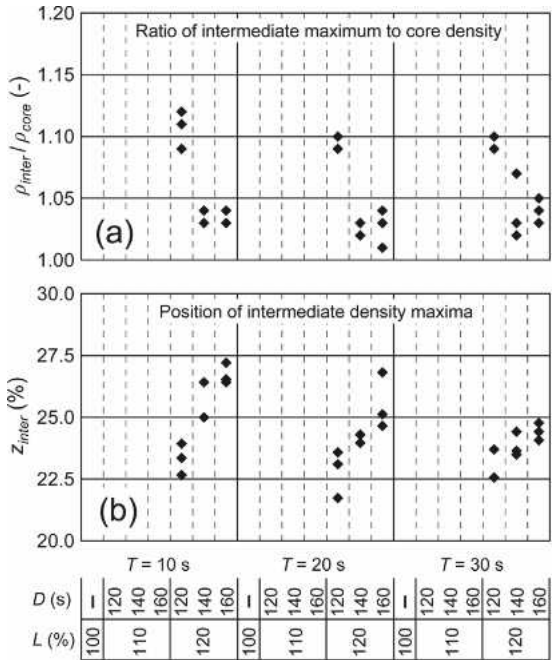


FIGURE 5. (a) Ratio of intermediate maximum density (ρ_{max}) to core density (ρ_{core}). (b) Position of intermediate density maxima (z_{inter}), expressed from the panel surface. Each data point represents the average of typically three density profiles obtained from one panel.

center for increasing D (Fig 5b). Increasing the closing time T does not influence the height of the intermediate density maximum, but causes its shift toward the surfaces.

Mat Temperature

The time $t_{100^{\circ}\text{C}}$ necessary to reach 100°C in the central plane of the mat is strongly dictated by the mat thickness level after first densification, L (Fig 6). When this level is increased by 10%, the point of 100°C is reached almost 20 s later. There is also a slight but statistically significant impact of the closing time T on $t_{100^{\circ}\text{C}}$. No effect was found for the duration of the first densification level, D , even though the point of 100°C falls, in some cases, behind the second densification step. The maximum temperature just before press opening averaged 113°C . It was relatively consistent for all panels manufactured and therefore is not displayed.

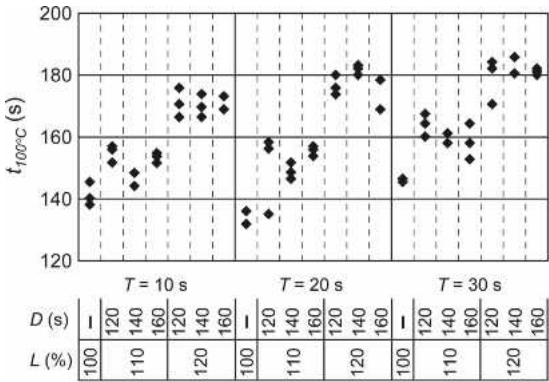


FIGURE 6. Time to reach 100°C in central mat plane. Each data point represents the value obtained from one panel.

Specific Pressure

Typical specific pressure curves for pressing programs comprising a second densification step are shown in Fig 7. The pressure reaches its overall maximum p_{max} early in the pressing cycle, rapidly declines to a value below 0.3 MPa, then attains the secondary maximum p_{2nd} during the final densification step, and eventually drops to the pressure p_{240} just before press opening. See Fig 8 for a complete depiction of the characteristic specific pressure values.

The mat thickness level after first densification, L , shows a clear effect on all specific pressure values. The less the mat is densified early in the pressing cycle, the lower must be the pressure p_{max} applied in this stage, but the higher the pressure p_{2nd} necessary to calibrate the mat to

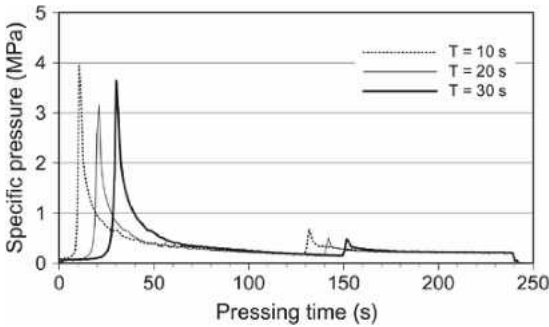


FIGURE 7. Typical curves of the specific pressure for different closing times ($L = 110\%$, $D = 120\%$ s)

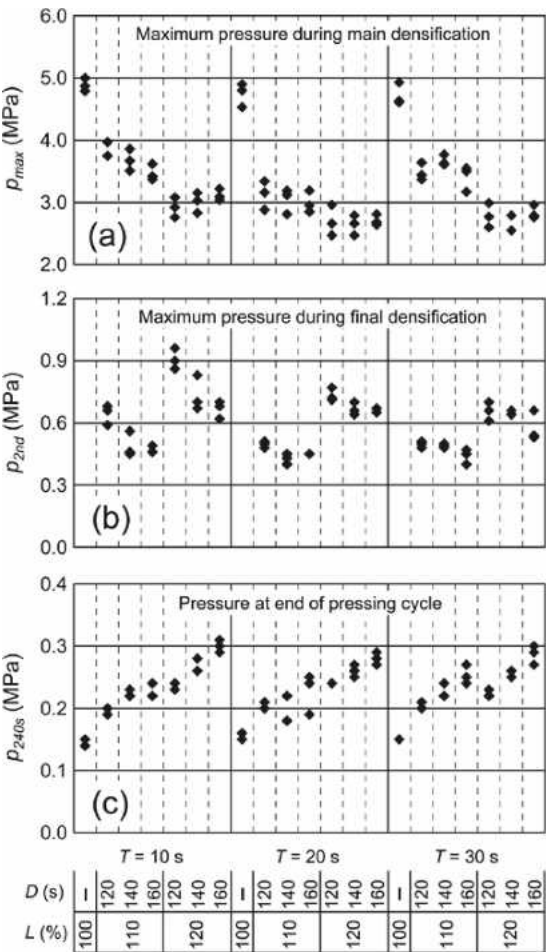


FIGURE 8. (a) Maximum specific pressure during main densification (p_{max}). (b) Maximum specific pressure during secondary densification (p_{2nd}). (c) Specific pressure at the end of the pressing cycle (p_{240s}).

final thickness. This higher pressure level persists until press opening.

Of course, the duration of the first densification level, D , cannot affect p_{max} . However, extending the first densification level reduces p_{2nd} and increases p_{240s} . Interestingly, there was also no significant effect of the closing time T on p_{max} and p_{240s} found in this study (see Fig 7 as an example). In contrast to this, p_{2nd} was significantly, although only slightly affected by T . This is not surprising, since increasing T shifts the time of secondary densification back, even if D is kept constant.

As can be seen in Fig 9, the final panel thickness after conditioning was not affected by the mat thickness level after first densification, L , but significantly raised when increasing the duration of the first densification level, D . Apparently, the springback of the panel upon press opening is related only to residual pressure when changing D , but not when altering L .

COMPUTER SIMULATIONS AND DISCUSSION

Modeling Cross-sectional Density Profile

The densification of wood-furnish materials is dictated by factors already defined when entering the hot press, eg wood species and particle characteristics, and by others that are subject to considerable changes during the pressing process. The most important variable factors are mat temperature, moisture content, and, to a lesser extent, state of adhesive cure, as will be discussed later. The levels of these factors determine the local compressibility of the mat material. For example, under the same pressing load of 3 MPa, a 110°C warm resinless fiber mat having 10% moisture content is compressed almost twice as much as an identical mat of 20°C and 5% moisture content (Fig 10). Thus, considering uneven temperature, moisture, and possibly adhesive cure conditions in the different mat layers while the mat is pressed, the layers will be irregularly compacted, and a cross-sectional density profile develops.

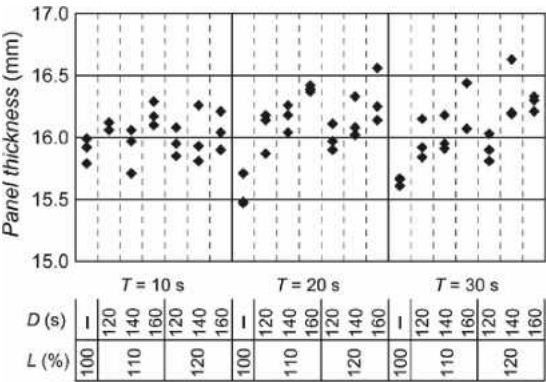


FIGURE 9. Panel thickness after conditioning. Each data point represents the value obtained from one panel.

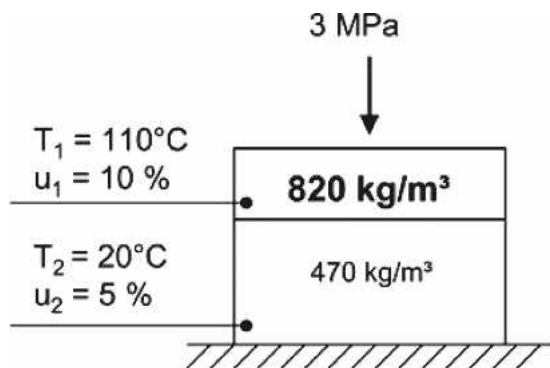


FIGURE 10. Example of density as a function of temperature and moisture content in a resinless MDF mat (computed from data published by von Haas and Fruehwald (2000))

This relatively simple explanation helps to understand the broad concept of density profile formation, although it still ignores important aspects such as time-dependent events during mat consolidation. To describe the cross-sectional density profile development in its broader complexity, and in particular to analyze the effects operative during the second densification step, a mathematical-physical model developed by Thoemen and Humphrey (2006) and Thoemen et al (2006) was used. This model accounts for heat and mass transfer in three dimensions inside the wood-furnish mat during hot-pressing, as well as for material densification and the development of internal stresses. Furthermore, a routine to compute the bond strength development in the individual mat layers is included in the model (Thoemen et al 2004).

For the model simulation runs conducted in this research, the boundary and initial conditions were defined by broadly following the specifications for the lab panels. Data for a typical pine fiber material determined by von Haas et al (1998), von Haas (2000), and von Haas and Fruehwald (2000, 2001) were used as material property input data, such as thermal conductivity, permeability, and rheological coefficients. Clearly, as the material properties depend on many factors including fiber processing parameters, the data provided by von Haas and co-workers do not exactly describe the fiber mate-

rial used for the lab panels in this research. Some adjustment factors for the property data were therefore necessary to fit the predicted density profiles to the measured ones.

Simulated cross-sectional temperature, moisture content, and density profiles for different stages in the pressing cycle are displayed in Fig 11. Please note that all profiles depict the status as indicated in the schematic pressing schedule in Fig 11, but not the final situation at press opening. However, the simulations suggest that for the cases indicated by 3a and 3b, the displayed density profiles are almost identical with the final ones. The simulations in Fig 11 will be used to explain and discuss the experimental results, starting with the effects of the second densification step for consistency. We will refer to batch presses in the discussion, although all of the findings can be applied within broad limits to continuous presses.

Secondary Densification

The intermediate density maxima form during final densification. The specific pressure during this stage typically stays far below the maximum pressure during main densification, so that high density regions near the surfaces cannot be further compressed. The attained localized temperature, moisture content, and density level control the regional softening of the mat material. As the pressure transferred from the heating platens to the mat acts identically on all mat layers, the softest layers experience the most vigorous density rise. If these layers are between the central plane and the surface regions, intermediate density maxima develop. The development of intermediate density maxima when introducing a second densification step has also been described by Wang et al (2001); in addition, they showed that further densification steps may result in additional intermediate density maxima.

The time of the second densification step affects the density profile in two ways. First, when the secondary densification is delayed, the intermediate density maxima diminish, and second the

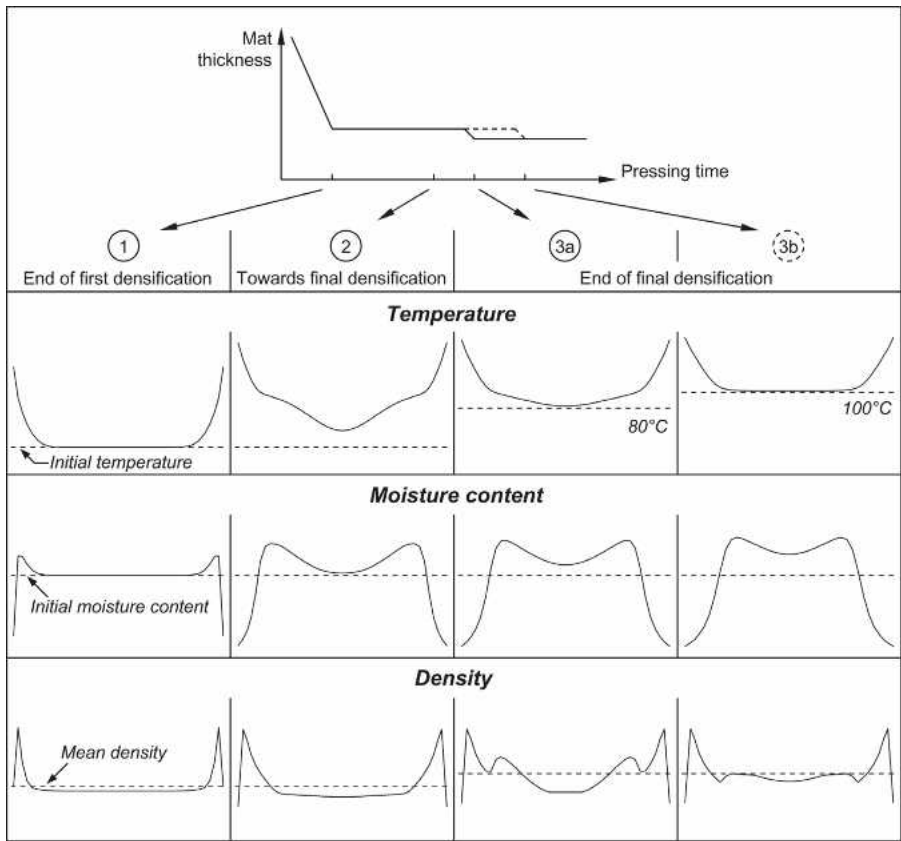


FIGURE 11. Cross-sectional temperature, moisture content and density profiles at different stages of the pressing cycle, based on computer simulations. Displayed is the absolutely dry density.

position of the maxima shifts toward the central plane of the mat. The simulation results displayed in Fig 11 suggest that, for stage 3a, the core layer, having reached 80°C, was plasticized less than the surrounding layers, resulting in a central density dip. The longer the second densification step is set, the higher and more even is the temperature distribution in the inner portion of the mat, and the further the moisture maximum has moved toward the central plane. When matching the density profiles and core temperatures measured in this research, it appears that the core temperature must be above 90°C during secondary densification to avoid excessive intermediate density maxima.

On the other hand, both experiments and simulations suggest that the overall density minimum

may jump from the core to an intermediate position when the secondary densification is delayed and thereby increasing the core density. Presumably, the low moisture content at this position is not compensated by the higher temperature, and therefore leads to an elevated compression resistance of the mat.

The reasoning given above on the development of intermediate density maxima is in accordance with an explanation already proposed by Suchland (1962) for particleboard, namely that the densification of the individual layers under a given pressure is a function of temperature and moisture content of the particles. Although he considered only relatively simple pressing schedules in his study, the explanation can also be applied to more complex situations and to

other wood-based panels such as MDF and OSB.

Mat Thickness Level after First Densification

Considering the early phase of the pressing cycle, it is not surprising that the mat thickness level after first densification has a profound effect on the cross-sectional density profile. Closing the press to a higher mat thickness reduces the maximum pressure necessary to compress the mat to this thickness, and consequently lowers the preliminary density level both in the surface and core regions of the mat. When further compacting such a mat later in the pressing cycle, and ignoring effects of intermediate density minima and maxima for a first consideration, it is mandatory that the core density will reach an elevated level, as the surface density does not change significantly during secondary densification. This effect of the maximum pressure during main densification on the cross-sectional density profile has already been described by several researchers in the past (Strickler 1959; Kehr and Schoelzel 1967; Wang et al 2000, 2001), and was confirmed in this study.

Besides such direct effects of the maximum pressure and first densification level on the density profile, these factors also indirectly influence the shape of the final density profile. Lower densities in the surface regions early in the pressing cycle reduce the heat transfer into the mat, and thus delay the temperature rise and associated softening of the inner regions. As a consequence, if the time of the second densification step has not changed, the risk of generating intermediate density maxima and of a reduced core layer density increases. Such indirect effects antagonize, to some extent, the direct effects on the core layer density. It becomes apparent in this example that changes in the pressing schedule may have counteracting effects on the density profile, which makes it so difficult to draw general conclusions solely from one series of experiments.

Press Closing Time

The experimental results in this study show evidence that, with increasing press closing time, the density peaks near the mat surfaces move toward the central plane of the panel, and that the maximum density increases. The same effects were observed on the samples manufactured under similar conditions in the miniature press (see Ruf 2003).

While the first of these findings are confirmed by measurements presented by Bismarck (1974) for one- and three-layer particleboard, Smith (1982) for waferboard, Winistorfer et al (1996), Zombori (2001) and Pichelin et al (2001) for strandboards, and Buchholzer (1990) and Wang et al (2001) for MDF, most of these authors report a reduction of the density maximum when increasing the closing time, that, at a first glance, contradicts the observations in this study. However, when comparing the results given in the literature with this research, one has to consider that all of the authors used longer closing times than was the case in this study, where closing times were 10, 20, and 30 s. Moreover, when looking only at those findings reported for MDF, it becomes apparent that the maximum density drops considerably when changing the closing time from 110 to 300 s (Buchholzer 1990), but stays almost constant when comparing closing times of 15 and 60 s (Wang et al 2001). Only those density profiles measured by Zombori (2001) for strandboards show a rise in density maximum when increasing the press closing time from 40 to 80 s.

To explain the different effects of long and short press-closing times on the density maximum, two extreme but unrealistic situations may be considered. First, if the press were closed infinitely fast, with no time delay between first mat contact and final position, no temperature and moisture gradients could develop inside the mat during press closure. The result would be a perfectly flat density profile, at least at the time when the press has reached its final position. Considering now the other extreme, ie avoiding temperature and moisture profiles by an extraor-

dinary long closing time, that would also create a flat density profile. Between these two extreme situations there is a maximum ratio of surface-to-core density, with a decrease toward longer and shorter closing times. Apparently, most measurements reported so far in the literature relate to the decline toward longer closing times, while our own measurements were in the range of shorter closing times. Please notice that the time required for the composite mat to move in a continuous press from the point of first steel belt-mat contact to the point of maximum pressure is typically less than 20 s.

Adhesion Effects

Doubtlessly, temperature and moisture content have a strong effect on the rheological properties of the wood-furnish mat, and consequently on the development of the density profile, but not much is known about the influence of adhesive cure on these parameters. For particleboard, Treusch et al (2004) found a slight effect of the adhesive content on the maximum density in the surface layers. Heinemann (2004) reported that the specific pressure required during secondary densification is lower in resinless fiber mats, compared with mats with a urea-formaldehyde adhesive content of 10%. On the other hand, our results show that the pressure required during the second densification step declines when delaying it (Fig 9), indicating that adhesive cure effects on overall mat compressibility are overcompensated by temperature and possibly moisture effects. It appears to be reasonable to conclude that there is only a minor impact of adhesive cure on mat densification and density profile development. However, a more detailed analysis will certainly have to distinguish between compression and springback processes that occur subsequently in the individual mat layers, as discussed by Wang and Winistorfer (2000). It can be hypothesized that the compressibility of a wood-furnish mat does change little with progressing adhesive cure, while the ability of a mat layer to reexpand clearly diminishes under similar conditions.

SUMMARY AND CONCLUSIONS

Experimental findings and simulation results show evidence that the pressing schedule decisively determines the cross-sectional density profile in wood-based panels. In particular, there are two major effects that became noticeable in this research: first, the mat thickness level after first densification dictates the density difference between surface layer maxima and core minimum. And second, for pressing programs in which the mat is compressed to a relatively low density level during main densification, intermediate density maxima appear, with magnitude and position of the intermediate density peaks being determined mainly by the time span between press closure and final densification. These effects can be conclusively explained by linking the pressing schedule to the local rheological mat conditions, which change over time and are functions of mat temperature, moisture content, and possibly state of adhesive cure. The higher the local temperature and moisture content, and the poorer the state of adhesive cure is, the less resistance of the respective mat layer can be expected against the external pressing load, and the higher will be the resulting density for a given specific pressure.

For large industrial MDF presses, and in particular for continuous presses, differences in the final density profile across the width of the mat appear to be a common problem. Typically, the core layer density at the middle position is significantly reduced, compared with the core layer density near the edges. Using the same rationale as for cross-sectional density variations, differences in the density profiles over the mat width are at least partly caused by an uneven horizontal temperature and moisture content distribution. One important reason for such temperature and moisture content variations is the intrinsic gas pressure decrease from the middle toward the edges of the panel. This gas pressure distribution prohibits homogeneous thermodynamic conditions across the width of the mat. When trying to overcome the resulting differences in the final density profile, one should realize that there are only limited chances to manipulate the

horizontal gas pressure, temperature, and moisture content distributions. Therefore, variations in the internal mat conditions should be compensated by locally adjusting the pressing load acting on the mat. Clearly, such adjustments are only possible in continuous presses, and within limits, depending on the mechanical flexibility of the heating platens of the press.

Linking pressing schedule and relevant mat conditions to the cross-sectional density profile has been difficult in the past, as in-situ measurements inside the mat are only possible, so far, for temperature, but not for moisture content and state of adhesive cure. Also, in-situ measurements of the density development during hot-pressing have been limited to three cross-sectional positions (Winistorfer et al 2000), but do not show the complete density profile. As a complement to such experimental findings, simulation models based on fundamental principles can provide important additional information to generate a fundamental understanding about the development of the cross-sectional density profile. In particular, the modeling approach permits one to include information that is continuous over space and time on the internal mat conditions, rheological mat properties, and resulting density variations.

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