J Wood Sci (2012) 58:417–422
DOI 10.1007/s10086-012-1269-3

ORIGINAL ARTICLE

Development of an air-injection press for preventing blowout of particleboard IV: effects of air-injection conditions on board performance and formaldehyde emission

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Received: 9 December 2011 / Accepted: 11 May 2012 / Published online: 21 June 2012

Abstract An air-injection press, which has holes punched in the heating plates, injects high-pressure air through the holes of one plate into particleboard and discharges the air through the other plate during press heating. The press can manufacture particleboard from high-moisture particles by controlling blowout of the boards. In this study, the optimum diameter and spacing of the air-injection holes and the effects of pre- and post-pressing were investigated. An optimum hole diameter was not found for the modulus of rupture and thickness swelling for a spacing of either 25 or 50 mm. In terms of internal bond strength, the optimum diameter of the holes arranged at a spacing of 25 mm was 1 mm, but the internal bond strength was not changed by the diameter of holes spaced 50 mm apart. Air injection under all hole conditions reduced the formaldehyde emission from the board. Pre-pressing was tested for further increase in the modulus of rupture and internal bond strength, but was found to have no effect. More efficient use of the air-injection press was achieved by injecting air from the early stages of pressing.

Keywords Air-injection press · Particleboard · Blowout · Formaldehyde emission · Pre-pressing

Part of this article was presented at the 29th (Okayama, October 2011) annual meeting of Wood Technological Association of Japan.

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Introduction

When manufacturing particleboard, vapor can become accidentally trapped between the wood particles during the hot pressing process and cause a blowout on the board when the press is opened [1, 2]. Since this damage occurs at the final stage of the manufacturing process, all preceding procedures are wasted and productivity is severely reduced. The effective method at present for preventing blowout is to use completely dry particles [3].

In a previous study [4], a hot press was developed that discharges the vapor trapped inside the particleboard and thus prevents blowout. The press has holes punched in the upper and lower heating plates. High-pressure air is injected through the holes of one plate to the inside of the board and is discharged from the holes of the other plate. The high-pressure air forces out trapped vapor and prevents blowout of the board. This press is called an air-injection press.

In another study [5], the effects of the diameter of the air-injection and discharge holes on the performance of the boards were investigated. It was estimated that large holes of 5 mm could discharge more vapor than small holes of 1 mm and would prevent blowouts more effectively. However, the study showed that 1-mm holes actually prevented blowouts effectively and resulted in higher internal bond strength than 5-mm holes. This is likely because large holes cause the discharge of binder as well as vapor, whereas the smaller 1-mm holes reduced the discharge of binder and increased the internal bond strength. The optimum air pressure for manufacturing boards of aimed performance was also determined.

To manufacture boards of optimum performance, it is necessary to clarify the optimum diameter and spacing of the air-injection holes. In this study, hole diameters of 1, 2, 3, 4 and 5 mm, and spacing of 25 and 50 mm between the centers of adjacent holes, were tested to determine the optimum hole diameter and spacing for manufacturing boards. Furthermore, the air-injection forces out vapor, which is likely to contain unreacted formaldehyde [6]. Therefore, the air-injection press is expected to reduce the formaldehyde contents in the boards and provide a new means of reducing formaldehyde emission. It is important to reduce it for preventing sick house syndrome [7–9]. The effects were also examined in this study, and minimizing formaldehyde emission.

The effects on board performance were also investigated in terms of pressing conditions before and after air injection to improve board performance. For example, a board was pressed for 2 min without injecting air (the process is hereafter called "pre-pressing") and then pressed for 8 min while injecting air. The performance of the board was compared with that of a board manufactured without pre-pressing but with pressing for 8 min while injecting air.

Experimental method

Optimum hole diameter

Air-injection holes (on the lower plate) of 1, 2, 3, 4 and 5 mm in diameter at a spacing of 25 and 50 mm between the centers of adjacent holes were used. There were 121 holes in an area of 250 × 250 mm for the 25-mm spacing and 36 holes for the 50-mm spacing. Holes were also punched on the caul plate (upper plate) through which the high-pressure air and vapor were discharged. Also on the caul plate were 121 and 36 holes in an area of 250 × 250 mm for the 25- and 50-mm spacing, respectively. Grooves that were 1.5-mm deep and 1-mm wide were also cut connecting the holes on one side of the caul plate to discharge the high-pressure air. The diameter and spacing of the holes on the caul plate were the same as those on the lower plate. For example, the hole diameter and spacing on the caul plate would be 1 and 25 mm, respectively, if the hole diameter and spacing on the lower plate were 1 and 5 mm, respectively. See refs. [4, 5] and [10] for further details on the air-injection press.

The particles used in the experiment were produced from wood waste for manufacturing core layers of particleboard (Japan Novopan Industrial Co., Ltd.). The binder used was a urea formaldehyde resin (Oshika Co., Ltd., solid content 65 %, viscosity 0.17 Pa s). As a curing agent, 10 % ammonium chloride solution was added to the binder to constitute 10 % by the binder (by weight). The resulting binder mixture was added to the particles to constitute 10 % (by oven-dried weight) of the solids. To increase the moisture content of the particles to 25 %, a predetermined amount of water was sprayed on the particles prior to spraying the binder. See ref. [4] for the reason to manufacture the board from moisture content as high as 25 %. The dimensions of the board were 300 × 300 × 10 mm, and the target board density was 0.7 g/cm^3. The formaldehyde emission from the boards was measured by following JIS A 5908 [11]. Two boards were produced for each manufacturing condition.

The pressing temperature was 190 °C and the pressing time was 8 min. The injection of high-pressure air of 0.55 MPa was started when the thickness of the board reached 10 mm. Air was injected for the first 7 min and 45 s and not during the last 15 s. To investigate the effects of air-injection, the boards were manufactured from high-moisture particles of 25 % without air injection. The longer pressing time of 12 min was needed due to no air injection. Two boards were manufactured for each condition.

Pre-pressing and post-pressing

Boards were manufactured by pressing while injecting high-pressure air for 8 min and pressing but not injecting the air prior (pre-pressing) and after (post-pressing) the air injection for 1 and 2 min, respectively. The effects of pre-pressing and post-pressing were investigated for pressing temperatures of 190 and 210 °C. The hole diameter was 1 mm, and the spacing was 25 mm. The pressure of the injected air was 0.55 MPa. The boards that were manufactured and their pressing conditions are shown in Table 1. The dimensions of the board were 300 × 300 × 10 mm, and the target board density was 0.7 g/cm^3. One board was produced for each manufacturing condition. The temperature of the boards was monitored by installing thermocouples in the center layer at one end of each board according to ref. [4].

Performance tests

The moisture content of the boards manufactured was adjusted before the tests by leaving the boards in a thermo-hygrostat at 20 °C and 65 % relative humidity until the weight stabilized. The modulus of rupture, internal bond strength and thickness swelling were determined according to JIS A 5908 [11]. The number of specimens was 5, 8 and 7, respectively. The boards manufactured using the air-injection press had many tubercles formed on the surface due to the holes in the press [4]. The tubercles were not prominent when the hole diameters were 1 and 2 mm. The modulus of rupture was determined without removing the tubercles. For the boards produced with a hole diameter of 3 mm or larger, the internal bond strength and thickness swelling were measured after removing the tubercles and smoothing the surface using a knife [4].

Table 1 Effects of pre-pressing and post-pressing on board performance

Pressing temperature (°C)	Pressing schedule	Pressing type	No.	MOR (MPa)	IB (MPa)	TS (%)
190	First 2 min, no air injection; last 8 min, air injection	Pre-pressing	1	13.1 (1.67)	0.16 (0.04)	37.6 (2.90)
	First 1 min, no air injection; last 8 min, air injection	Pre-pressing	2	16.5 (0.85)	0.23 (0.03)	34.4 (4.71)
	8 min, air injection		3	13.5 (1.02)	0.43 (0.06)	36.2 (5.94)
	First 8 min, air injection; last 1 min, no air injection	Post-pressing	4	13.1 (1.62)	0.40 (0.09)	44.1 (7.11)
	First 8 min, air injection; last 2 min, no air injection	Post-pressing	5	14.1 (1.85)	0.36 (0.06)	38.2 (5.52)
210	First 2 min, no air injection; last 8 min, air injection	Pre-pressing	6	17.4 (1.86)	0.35 (0.07)	36.9 (1.57)
	First 1 min, no air injection; last 8 min, air injection	Pre-pressing	7	17.6 (2.59)	0.31 (0.12)	34.4 (3.10)
	8 min, air injection		8	15.0 (0.52)	0.60 (0.08)	35.2 (4.49)
	First 8 min, air injection; last 1 min, no air injection	Post-pressing	9	15.5 (2.89)	0.52 (0.10)	34.3 (3.72)
	First 8 min, air injection; last 2 min, no air injection	Post-pressing	10	16.4 (1.48)	0.50 (0.06)	32.9 (3.16)

The numbers in parentheses indicate standard deviations

MOR modulus of rupture, *IB* internal bond strength, *TS* thickness swelling

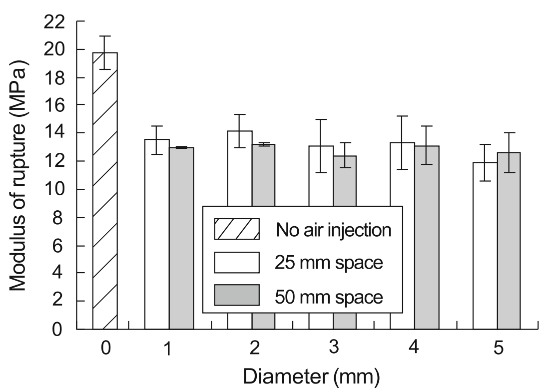

Fig. 1 Relationship between air-injection hole diameter and modulus of rupture. *Vertical bars* indicate standard deviations

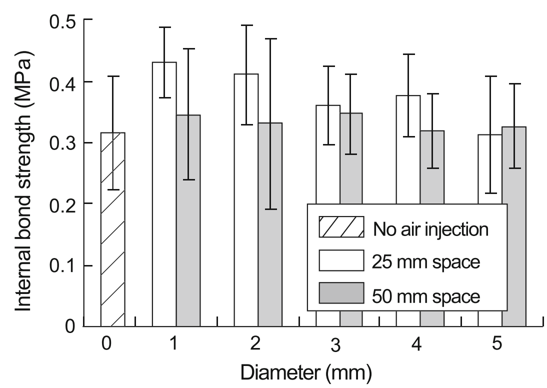

Fig. 2 Relationship between air-injection hole diameter and internal bond strength. *Vertical bars* indicate standard deviations

Results and discussion

Relationship between hole diameter and board performance

The relationship between the diameter of the air-injection holes and the modulus of rupture is shown in Fig. 1. There was no clear relationship between the hole diameter and the modulus of rupture except no air-injection board, which was 11.9–14.2 MPa, showing that the hole diameter scarcely affected the modulus of rupture. The modulus of rupture of no air-injection board was higher than that of air-injection boards, showing that air injection reduced the modulus of rupture [10]. Note, however, air injection reduced the pressing time without a blowout, which was a great advance.

Figure 2 plots the internal bond strength against the hole diameter. For the hole spacing of 25 mm, the internal bond strength was highest (0.43 MPa) when the hole diameter was 1 mm and was lowest (0.31 MPa) when the hole diameter was 5 mm. The former was higher than the latter (statistically significant at 1 % level). In the previous study [5], it was shown that the temperature changes within the board were not different between the hole diameters of 1 and 5 mm, and concluded that the high internal bond strength of the 1-mm board was not attributable to the temperature changes but occurred because the binder was more easily discharged together with the vapor through the 5-mm holes compared to the 1-mm holes. It was predicted that smaller holes would result in higher internal bond strength, but this study showed that the hole diameter of 1 mm is the optimum. Smaller holes may result in higher internal bond strength but holes smaller than 1 mm are not practical. Therefore, boards will be manufactured using a hole diameter of 1 mm for a hole spacing of 25 mm. On the other hand, when the holes were spaced 50 mm apart, the internal bond strength was almost constant at 0.33 MPa irrespective of the hole diameter. As with the modulus of rupture, the hole diameter and spacing scarcely affected the internal bond strength.

Figure 3 shows the relationship between the hole diameter and thickness swelling. The thickness swelling of no air-injection board was higher than that of air-injection boards [10]. The thickness swelling was lower when the 1-mm holes were spaced 50 mm apart rather than 25 mm apart, but was basically constant at about 40 % irrespective of the hole diameter except no air-injection board. As with the modulus of rupture, the hole diameter and spacing scarcely affected the thickness swelling.

This study showed that there was no specific optimum hole diameter for the modulus of rupture and thickness swelling for either the 25-mm or 50-mm spacing. The hole diameter of 1 mm was the best for the internal bond strength when the hole spacing was 25 mm, but there was no specific diameter for the 50-mm spacing. As shown in Fig. 2, the optimum hole diameter for internal bond strength was demonstrated, and as shown in Figs. 1 and 3, that for modulus of rupture and thickness swelling was not demonstrated. The hole diameter of 1 mm increased the internal bonding strength. It would increase the modulus of rupture and decrease the thickness swelling. However, it did not increase the modulus of rupture and did not decrease the thickness swelling. The mechanism of internal bond strength was very simple, and that of modulus of rupture and thickness swelling was too complex to understand. The internal bond strength depends on only bonding strength, while, for example, the modulus of rupture depends on particle length and density of face layer including bonding strength, and so on. In this study, the causes not to increase the modulus of rupture and decrease the thickness swelling are unknown and need to be investigated.

Figure 4 plots the amount of formaldehyde emission against the hole diameter. The formaldehyde emission of no air-injection board was 0.35 mg/L [6]. The emission from the boards with the 50-mm hole spacing was about 0.28 mg/L irrespective of the hole diameter, showing a reduction in formaldehyde emission by the injection of air. The 25-mm spaced holes also reduced the emission, to a greater extent with a greater diameter, and to 0.24 mg/L when the hole diameters were 4 and 5 mm. The air injection forced out the formaldehyde with the vapor inside the boards, resulting in the reduction of the formaldehyde emission. The 4 and 5-mm holes spaced 25 mm apart reduced the internal bond strength as well as the formaldehyde emission. The conditions will be investigated for minimizing the release of the binder, improving the internal bond strength and further reducing the formaldehyde content.

Conventional methods to reduce formaldehyde emission are to use the low formaldehyde emission binder and

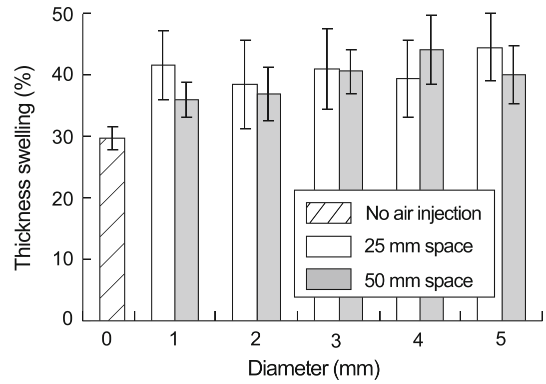

Fig. 3 Relationship between air-injection hole diameter and thickness swelling. *Vertical bars* indicate standard deviations

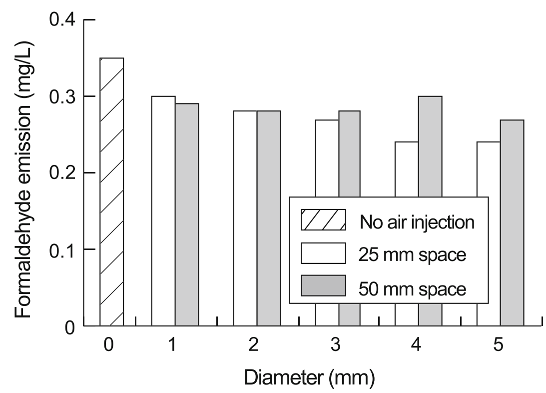

Fig. 4 Relationship between air-injection hole diameter and formaldehyde emission

formaldehyde adsorption materials [7]. This is a novel method of reducing formaldehyde emission and is a major benefit of the air-injection press.

Effects of pre-pressing and post-pressing on board performance

As described above, air injection lowered the modulus of rupture. To increase it, boards were pre-pressed prior to the air-injection pressing. Air injection lowers the temperature at the board surface at the start of pressing [4], which would likely inhibit the binder from curing at the surface layer from which the air is injected (injection side). Air injection is also highly likely to cause the discharge of the binder from the injection side [5], reducing the bonding strength. As a result, the modulus of rupture also reduced, because the modulus of rupture depends on the strength at the surface layer [12]. To prevent these reductions, the boards were pre-pressed. Because pre-pressing does not involve air injection, the injection side is thoroughly heated from the start of pressing, and thus the binder cures sufficiently. Pre-pressing does not cause discharge of the binder from the injection side either, and thus the binder remains and bonds the particles in the injection side. Due to these two reasons, pre-pressing was predicted to increase the modulus of rupture. After the pre-pressing process, air was injected to force out vapor, cure the binder in the center layer, and increase the strength in the center layer. For comparison, post-pressing was also tested.

The performance of the boards manufactured is shown in Table 1. There was no statistically significant difference in modulus of rupture at 190 °C between pre-pressed and post-pressed boards except board No. 2. Similarly, there was no statistically significant difference in thickness swelling between pre-pressing and post-pressing. On the other hand, the internal bond strength of post-pressed board Nos. 4 and 5 was 0.40 and 0.36 MPa, respectively, and that of pre-pressed board Nos. 1 and 2 was 0.16 and 0.23 MPa, respectively. The pre-pressing reduced the internal bond strength. Also, at 210 °C, there was no statistically significant difference in the modulus of rupture and thickness swelling between pre-pressing and post-pressing. The internal bond strength was more greatly reduced by the pre-pressing compared to the post-pressing.

Changes in temperature in the center layer

Figure 5 shows the pressing time and changes in temperature in the center layer of the board. Figure 5a shows the temperature changes of pre-pressed (No. 1) and post-pressed (No. 5) boards by pressing at 190 °C. As predicted, the temperature rose sharply after the start of pre-pressing. In particular, the temperature reached 100 °C in 50 s and stabilized at that level until the air injection started. Given that the particles used in this study had a moisture content as high as 25 %, it is likely that the center of the board was under high-pressure steam, which inhibited the binder from curing [13, 14], until the air was injected. The subsequent air injection sharply lowered the temperature of the board. The temperature of the pre-pressed board was lower than that of the post-pressed board. Thus, high-pressure steam and subsequent low temperature inhibited the curing of the binder.

Figure 5b shows the changes in temperature of board Nos. 6 and 10, which were pressed at 210 °C. The overall trend was the same as at 190 °C, particularly at the start of pre-pressing. However, the temperature of the board rose higher when pressed at 210 than at 190 °C after 3 or 4 min. The internal bond strength of the board pre-pressed at 190 °C (No. 1) was only 44 % of the board post-pressed (No. 5), but the board pre-pressed at 210 °C (No. 6) retained 70 % of board post-pressed (No. 10). This is likely because the temperature of the board pre-pressed at 210 °C did not decrease as much as at 190 °C but only to the level of the post-pressed board.

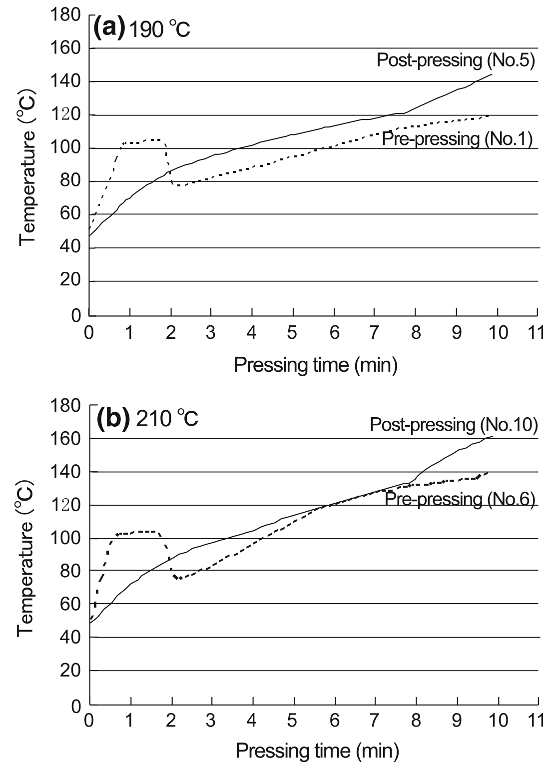

Fig. 5 Relationship between pressing time and temperature in the center of the board. **a** Pressing temperature 190 °C, **b** pressing temperature 210 °C

Board Nos. 3 and 8 were manufactured without pre-pressing or post-pressing but by pressing at 190 and 210 °C, respectively, while injecting high-pressure air for 8 min. Of the boards pressed at 190 °C, board No. 3 showed the highest internal bond strength; and board No. 8 marked the highest internal bond strength among the boards pressed at 210 °C, showing that pre-pressing reduced the internal bond strength and post-pressing did not increase the internal bond strength. Therefore, it is likely that pre-pressing is not effective and injecting high-pressure air from the start of pressing is effective for increasing the internal bond strength.

Conclusions

In this study, the optimum diameter and spacing of injection holes and the effects of pre-pressing and post-pressing were investigated, and the following results were obtained.

(1) There was no specific optimum hole diameter for the modulus of rupture and thickness swelling for either spacing. The hole diameter of 1 mm was optimum for the internal bond strength for the 25-mm spaced holes, but no specific diameter was found for the 50-mm spaced holes.

(2) Formaldehyde emission was 0.35 mg/L when the board was manufactured without injecting air. Air injection through the 50-mm spaced holes reduced the emission to about 0.28 mg/L irrespective of hole diameter. Through the 25-mm spaced holes, the reduction by air injection was more prominent as the hole diameter increased, with emission values of 0.30 mg/L for 1-mm holes and 0.24 mg/L for 4- and 5-mm holes. The air-injection press is a novel method of reducing formaldehyde emission.

(3) Pre-pressing did not improve the modulus of rupture, internal bond strength, or thickness swelling, showing that pre-pressing was ineffective. Injecting high-pressure air from the start of pressing was found to be effective in increasing the internal bond strength.

Acknowledgments This study was supported by grants from the "Research and development projects for application in promoting new policies of agriculture, forestry, and fisheries" from the Ministry of Agriculture, Forestry and Fisheries. The authors express their gratitude to Mr. Hiroshi Tanaka of Oshika Corporation for providing the binders, Mr. Kazuo Hattori of Japan Novopan Industrial Co., Ltd. for providing wood particles for particleboards, which was helpful in conducting the experiment in this study.

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