Manufacturing Tubular Particleboards *via* Multidimensional-interface Extrusion and Their Physiomechanical Properties

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Tubular particleboard is made of wood shavings through high-temperature extrusion. It is a particleboard with round thru-holes aligned lengthwise in the board. This paper discussed the development of multidimensional-interface extrusion technology. Process parameters were determined for the production of five different particleboard thicknesses of 24 mm, 28 mm, 35 mm, 40 mm, and 60 mm. The authors also tested the physical and lengthwise mechanical properties of the tubular particleboards. The manufactured tubular particleboards had the following properties, with respect to the above thicknesses: MOR of 4.9 to 2.2 MPa; MOE of 380 to 250 MPa; IB of 0.54 to 0.37 MPa; TS of 1.7 to 0.8%; and LDC of 9.1 to 5.2%. All met the values specified in the standards LY/T 1856 (2009) and GB/T 34717 (2017). MOR was ⩾1 and ⩾1.7; IB was ⩾0.1 and ⩾0.17; TS was ⩽5; LDC was ⩽15. It was concluded that as the thickness of the board increased, the mechanical properties decreased, but the physical properties increased. When compared to traditional extruded tubular particleboards, the multidimensional-interface extruded tubular particleboards had excellent physical and lengthwise mechanical properties. In addition, the lengthwise mechanical properties were similar to flat-pressed tubular particleboard, and ultra-thick particleboard can be produced.

Keywords: Tubular particleboard; Multidimensional-interface extrusion; Physical and mechanical properties

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INTRODUCTION

Flat-pressing and extrusion are the two most common hot-pressing processes used to produce particleboard (Zhang and Lu 2015). Tubular particleboard is developed from extruded particleboard. Vertical extrusion is a continuous production process and has the highest economic benefit in terms of large-scale production. However, due to defects in the process itself, the lengthwise mechanical properties of the produced boards are not good enough and need to be improved (Zhang *et al.* 2013, 2014). Although the physical and mechanical properties of flat-pressed tubular particleboard are excellent in all directions (Zhou *et al*. 2015; Tong *et al*. 2016), the flat-pressed process is an intermittent production process, with low production efficiency and economic benefits. Thus, it is not suitable for large-scale factory production. Tubular particleboard has many characteristics such as light weight, low manufacturing cost, high raw material utilization rate, low formaldehyde emission, higher impact resistance and ratio of stiffness to weight, good thermal insulation properties, and sound absorption properties. So it can be widely used, *e.g.*, for wooden door planks, furniture baffle plates, geothermal floors, building walls, *etc.* It has a broader potential application field as well as stronger market competitiveness compared to conventional particleboard. In addition, *Cunninghamia*, *Populus*, and *Eucalyptus* are commonly used wood materials for all kinds of wood-based panels and wooden furniture, and is widely planted in Zhejiang. So wood mills and furniture factories have a lot of waste to be processed. Using them for the manufacture of new wood-based panels is an environmentally significant measure and has a broad profit margin. Therefore, improving the physical and lengthwise mechanical properties of extruded tubular particleboard is of great importance. This paper provides a breakthrough relative to the limitations of the existing extrusion process, using multidimensional-interface extrusion, and can produce boards with a size of 2000 mm x 1200 mm x *d* (where d = 24 mm, 28 mm, 35 mm, 40 mm, or 60 mm), which can achieve both large-scale and continuous standardized production.

The Principle of Multidimensional-Interface Extrusion

Multidimensional-interface extrusion is a novel development based on the principle of vertical extrusion. Figure 1 shows that to apply the principle of vertical extrusion, the shavings between the two outer molding plates are pressed during every up and down reciprocating punch. After the shavings and adhesive (mixture) are fed into the extrusion unit, the temperature is about 45 ℃, and they are extruded in small segments. and are heated through the inner molding tubes and outer molding plates under a pressure of 3 to 5 N/mm^2 provided by the punch. The pressure is adjusted as the thickness changes, the greater the thickness, the greater the pressure required. The glue is cured to form a continuous and complete board.

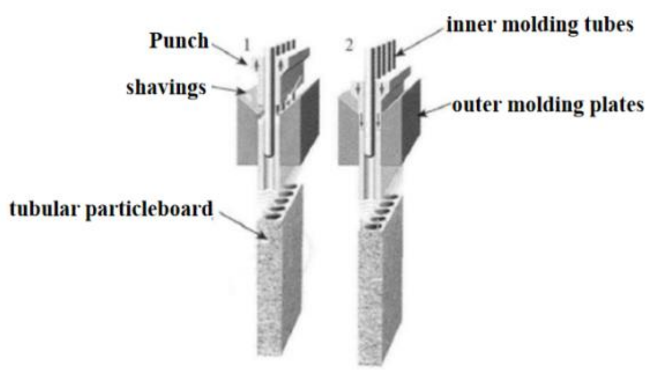

Fig. 1. The schematic diagram of vertical extrusion

Figure 2 shows a picture of a traditional flat punch. Due to the pressure of the flat punch on the shavings that have just fallen, along with the supporting force of the lower extruding interface, a pair of couples form on the fallen shavings. Thus, the direction of the shavings is reversed and is arranged crosswise under the action of these pairs of couples. A sheet-shaped unit is formed *via* one punch at a time, and each unit is made of wood shavings crosswise distributed and bonded with adhesive. After multiple continuous punching cycles, each formed sheet-shaped unit is arranged and bonded along the length of the tubular particleboard, as shown in Fig. 3. The mechanical properties of the board depend on the tensile strength between the shavings. However, in flat punch extrusion, each unit is a flat unit, and every two adjacent units only rely on adhesive gluing to ensure bonding between the units. Since it is flat gluing, the crosswise properties of traditional extruded tubular particleboard are much better than the lengthwise properties. Traditional tubular particleboard is easy to break along the lengthwise cross section, which causes inconvenience during transportation. Moreover, veneer treatment is required when the mechanical properties especially the MOR of the board are required for its use, which increases the length and cost of the treatment process.

Fig. 2. The flat surface punch

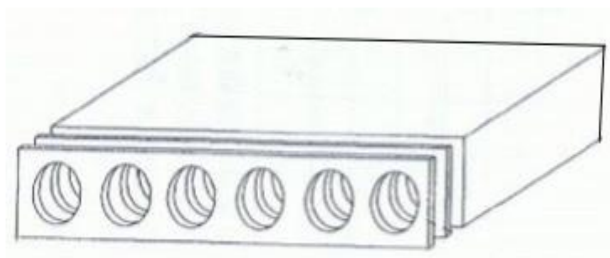

Fig. 3. The schematic diagram of the sheet-shaped units with a flat unit

Figure 4 shows that the punch had been modified from a flat surface to a concave and convex trapezoidal surface. Each sheet-shaped unit had a concave-convex staggered multidimensional structure. The bonding surfaces of every two adjacent units were inserted into each other in a concave and convex pattern, then heated and glued (Fig. 5), so that the connection strength was greatly increased. Since the bonding surfaces between two adjacent units are interlocked with each other in a concave and convex pattern, the amount of bonding area of the glue layer is increased. The larger the bonding area, the higher the bonding strength and the better the lengthwise mechanical properties of the board.

In the length direction, the shavings are interlocked with each other due to the uneven interface, which increases the mutual pulling force between the shavings. Compared with the flat glued shavings in the traditional flat extrusion, this novel gluing method drastically improves the lengthwise dimensional stability of the board. Moreover, wood is an anisotropic material, and the longitudinal change rate is minute, generally 0.1% to 0.3%. The radial change rate is in the middle, which is approximately 3% to 6%, and the chordwise has the largest change rate, which can reach up to 6% to 12%. Due to the multidimensional-interface extrusion process, the arrangement direction of a portion of the shavings form a certain angle in the crosswise direction, which improves the lengthwise dimensional stability.

Fig. 4. Trapezoidal slope multidimensional-interface punch

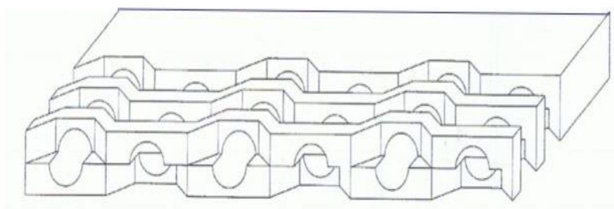

Fig. 5. The schematic diagram of the sheet-shaped units with multidimensional-interface

EXPERIMENTAL

Materials

The adhesive used was urea-formaldehyde (UF), which was produced by Dehua TB New Decoration Material Co. Ltd. (Zhejiang, China), with the following characteristics: a solid percentage of 51%; a density of 1.21g/cm^3; a pH of 7.8; a viscosity of 74.5 cps; a free formaldehyde percentage of 0.2%; and a gel time of 80 s. Compared with other adhesives, UF has a short gel time, is convenient to use and is cheap. The board made of it has high mechanical strength, and certain cold water resistance, heat resistance and durability, which is very suitable for extrusion process.

The shavings used are described as follows: various wood-based (*Cunninghamia*, *Populus*, and *Eucalyptus*) particleboard waste was used as the primary components.

The formaldehyde scavenger used is described as follows: It is a colorless and transparent liquid, which eliminates the free formaldehyde in the urea-formaldehyde resin.

The extruder and its auxiliary equipment were adopted from the production line of the Taijin Wood Industry Co. Ltd. (Zhejiang, China).

Production of Boards

After the wood shavings dried to a moisture content of 5% to 7%, they were then sieved through size 5.0 mm and size 1.0 mm meshes, respectively. The particles larger than 1.0 cm and smaller than 3.0 cm were called coarse, and the particles smaller than 1 cm were called fine. Each particleboard consisted of a one-third coarse particles and two-thirds fine particles. After spraying glue through the screw conveyor and applying UF and formaldehyde scavenger, the moisture content of the shavings became 10% to 12%. The heat of the steam, which was injected into the outer molding plates and the inner molding tubes through the heat-source heating mechanism, was used to extrude the shavings into the tubular particleboard. The ideal moisture content of the produced tubular particleboard is 10%. The thickness of the board was adjusted by the thickness valves. The primary parameters of the multidimensional-interface extrusion process are shown in Table 1.

Table 1. Production Parameters of the Multidimensional-Interface Extruded Tubular Particleboards

Parameters	Measurement				
Thickness (mm)	24	28	35	40	60
Diameter of the tube (mm)	18	20	25	25	40
Distance between adjacent tube holes (mm)	5	5	5	5	10
Wall thickness (mm)	3	4	5	7.5	10
Pressing temperature (°C)	160	160	160	160	180
Sizing amount [a] (%)	10	10	10	10	10
Formaldehyde scavenger [b] (%)	4	4	4	4	4
Extrusion speed (m·min^{-1})	0.44	0.40	0.36	0.33	0.12

Note: [a] The sizing amount is based on the mass of dry wood shavings; [b] The formaldehyde scavenger amount is based on the quality of the liquid adhesive

When the thickness of the tubular particleboard produced *via* traditional technology exceeds 40 mm, it is difficult to ensure that the mechanical properties meet the required standards. However, it was found that multidimensional-interface extrusion can produce tubular particleboard with a thickness of 60 mm (sample is shown in Fig. 6). The round thru-holes in the tubular particleboard are evenly distributed, the surface is smooth and bright, the structure is compact, and the density is uniform. The grooves on the surface of the plate correspond to a number of protrusions provided on the wall of the inner cavity, which increase the surface decoration effect of the hollow particle board, and the apparent quality is excellent. The thickness of the board is determined by adjusting the distance between two outer molding plates. During the extrusion process, the two outer molding plates have little force and almost no deformation, so the thickness of the boards can be easily guaranteed, and the thickness tolerance of the boards can reach ±0.1 mm.

Fig. 6. A 60 mm thick tubular particleboard sample

Mechanical and Physical Testing

The boards were conditioned to a constant mass under atmospheric conditions of a relative humidity of 65% and at a temperature of 23 °C. Afterwards, the test samples were cut from the boards, and the following properties were determined, according to the appropriate standard: the modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB), density (D), thickness swelling (TS), and lengthwise dimension change (LDC) (GB/T 17657 2013; LY/T 1856 2009). Since the lengthwise mechanical properties of traditionally extruded tubular particleboards are low, the lengthwise strength could not be specified by a standard. Thus, the authors made changes when they cut the samples. The test samples used to determine the mechanical properties were cut along the length of the board to test the lengthwise MOR, MOE, and IB. The TS samples were submerged in distilled water for 24 h, and the LDC samples were submerged for 2 h (LY/T 1856 2009) for non-equivalent use (BS EN 14755 2005). The production of the test pieces to determine MC and D were carried out according to BS EN standard 322 (1993a) and BS EN standard 323 (1993b). The MOR, MOE, and LDC were determined according to BS EN 14755 (2005) and GB/T standard 17657 (2013). Six replicates were made for the mechanical property tests, and three replicates were made for the physical property tests. The minimum property requirements for the particleboards, according to LY/T standard 1856 (2009) are listed in Table 2.

Table 2. Physiomechanical Property Values Required by LY/T 1856 182(2009) and GB/T 34717 (2017)

Properties	MOR (Crosswise) (MPa)	MOE (MPa)	IB (MPa)	D ($g \cdot cm^{-3}$)	TS (%)	LDC (%)
Extruded tubular particleboard	≥ 1.0	-	≥ 0.1	< 0.55	≤ 5	≤ 15
Extruded particleboard	≥1.7	-	≥0.17	-	≤ 5	≤15

RESULTS AND DISCUSSION

Mechanical Properties

The MOR, MOE, and IB generally decreased as the thickness of the tubular particleboard increased (Fig. 7), *i.e.*, an increase in thickness negatively affected the mechanical properties of the board.

Table 3. Comparison of Mechanical Properties of Tubular Particleboards

Properties	Production Method			
	Flat-pressing	Extrusion	Multidimensional-interface extrusion	
Thickness (mm)	≤ 40 mm	≤ 40 mm	≤ 40 mm	60 mm
MOR (Crosswise) (MPa)	-	1.15 to 3.51	-	-
MOR (lengthwise) (MPa)	1.43 to 3.51	0.6 to 0.9	3.8 to 4.9	2.2
MOE (crosswise) (MPa)	-	102 to 380	-	-
MOE (lengthwise) (MPa)	154 to 511	85 to 100	310 to 380	250
IB (MPa)	-	0.26 to 0.39	0.45 to 0.54	0.37

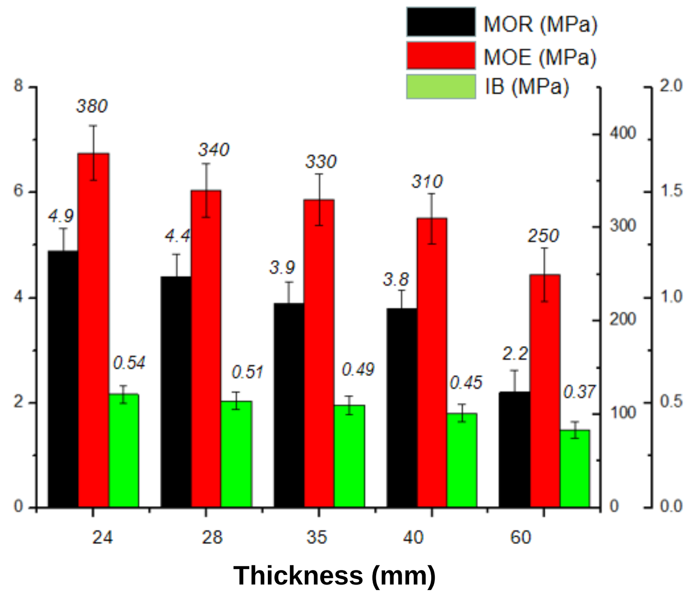

Fig. 7. Evaluation of mechanical properties

The wood samples had good thermal insulation. Due to the increase in thickness, the heat transfer during hot pressing was hindered, which affected the needed curing time of the adhesive, and weakened the bonding force between the shavings, which resulted in reduced mechanical properties. Consulting the results of related research data (Guo 2010; Tu 2014; Zhou 2015, 2016), a comparison of the mechanical properties of tubular particleboards are listed in Table 3.

Table 3 shows that the lengthwise MOR and MOE values of the multidimensional-interface extruded tubular particleboard were similar to the lengthwise MOR and MOE values of the flat-pressed tubular particleboard as well as the crosswise MOR and MOE values of the traditional extruded tubular particleboard. Compared with the lengthwise mechanical properties of traditional extruded tubular particleboard, the MOR and MOE values increased by approximately 5.8 times and 3.7 times, respectively, and the IB increased by approximately 1.4 times. The MOR (lengthwise) and IB values of the multidimensional-interface extruded tubular particleboards for all manufactured thicknesses considerably exceeded the requirements of LY/T 1856 (2009) and GB/T 34717 (2017). The improvement of the lengthwise mechanical properties made the board less easy to break along the lengthwise cross section during transportation. In addition, this method can produce thick boards, so that the boards do not need to be veneered when the thickness and mechanical properties (especially for MOR) are required during use.

Physical Properties

The density required to produce tubular particleboard is 0.4 g/cm^3, and the density of the produced particleboard is a similar value. The TS and LDC increase as the thickness increases, as shown in Fig. 8; this increase in thickness is beneficial to both the TS and LDC. The reason for the decrease in physical properties is due to the large thickness, which can withstand greater internal stresses and reduces the rebound of the tubular particleboard due to the release of internal stresses when it becomes damp. Consulting the results of related research data (Guo 2010; Tu 2014; Zhou 2015, 2016), a comparison of the physical properties of the tubular particleboards is listed in Table 4.

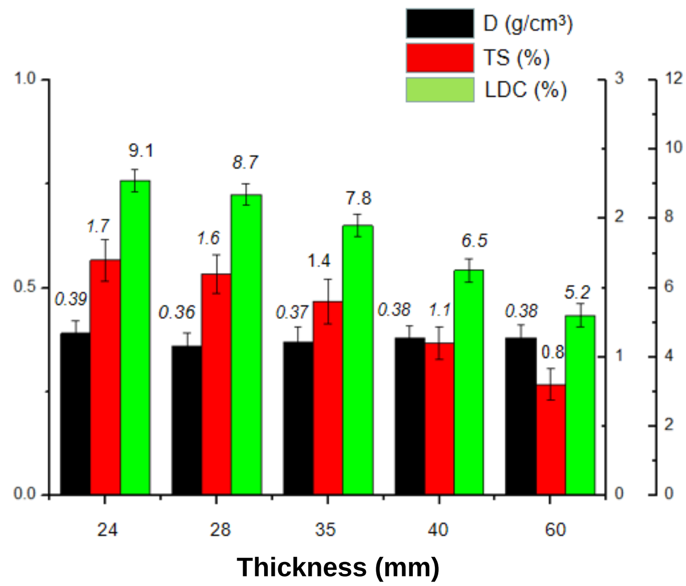

Fig. 8. Evaluation of physical properties

Table 4. Comparison of Physical Properties of Tubular Particleboards

Production Method	Thickness (mm)	D (g·cm^{-3})	TS (%)	LDC (%)
Flat-pressing	≤ 40mm	0.32 to 0.40	7.27 to 18.53	-
Extrusion	≤ 40mm	030 to 0.38	2.0 to 5.4	9.2 to 15.7
Multidimensional-interface extrusion	≤ 40mm	0.36 to 0.38	1.1 to 1.7	6.5 to 9.1
	60mm	0.38	0.8	5.2

Table 4 shows that the TS and LDC values of the multidimensional-interface extruded tubular particleboard were 38% and 62% of the traditional extruded tubular particleboard values, respectively. In addition, the TS is only 11% of the flat-pressed tubular particleboard. The TS and LDC of the 60 mm thick tubular particleboard even reached 0.8% and 5.2%, respectively. The TS and LDC values of the multidimensional-interface extruded tubular particleboards for all manufactured thicknesses considerably exceeded the requirements of LY/T 1856 (2009) and GB/T 34717 (2017).

The improvement in the physical properties reduces the impact on use due to dimensional changes and decreased mechanical properties caused by the expansion of the board due to water absorption.

CONCLUSIONS

1. Compared with standard particleboard, tubular particleboard can have a thicker thickness, higher raw material utilization, lower formaldehyde emission, higher impact resistance and ratio of stiffness to weight, better thermal insulation performance and sound insulation performance.
2. The multidimensional-interface extrusion process effectively improves the physical properties and lengthwise mechanical properties of traditional extruded tubular particleboard. In addition, it produces an ultra-thick tubular particleboard (60 mm

thickness), which is difficult to produce via the traditional process. The boards do not need to be veneered when the thickness and mechanical properties (especially for MOR) are required during use. In addition, they also reduce the impact during use due to dimensional changes as well as having decreased mechanical properties caused by the expansion of the board due to water absorption.

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