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Relationship between thermal conductivity and adhesive distribution of phenol-formaldehyde visualized with x-ray computed tomography on sugi (*Cryptomeria japonica* D.Don) heartwood plywood

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Relationship between thermal conductivity and adhesive distribution of phenol-formaldehyde visualized with x-ray computed tomography on sugi (*Cryptomeria japonica* D. Don) heartwood plywood

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Abstract. The relationship of transverse thermal conductivity of non-resin region and resin-rich region in softwood plywood with various relative resin thicknesses in lumen of softwood has been determined theoretically. Furthermore, Interest in influence of adhesive penetration on adhesive bond performance and adhesive behavior has been evident by using microscopy technique and X-ray apparatus for several decades. Therefore, the relationship between thermal conductivity and adhesive distribution on softwood plywood product is needed to reveal as the development of material properties by visualizing X-ray CT apparatus. Micro Focus X-ray Computed Tomography (X-ray CT) was used to analyse the adhesive distribution of sugi heartwood plywood for different amount of glue spreading rates which were applied on the veneer surface. Four plywood samples (5-ply) were produced by spreading the phenol-formaldehyde resin adhesive on the veneer surface (dimension 450 mm× 450 mm× 3.81 mm) as much 0, 75, 150, and 225 g/m² of glue spreading rates. All the veneer samples were conditioned 30 days under 20°C and 65% RH before plywood manufacturing. The veneer samples were dried at 60 temperature 60°C for 24 hours before pressing by cold press apparatus, the plywood samples were pressed (1 MPa) for 20 minutes and hot press apparatus at 125°C for 19 minutes. The analysis of thermal conductivity apparatus followed standards are JIS A 1412 and ASTM- C518. The plywood samples (dimension 200 mm× 200 mm ×thickness mm) in air dried condition were put on among plates of thermal conductivity apparatus for 40 minutes for each sample to obtain the thermal conductivity values. The results seemed to indicate that the thermal conductivity increases with increasing amount of glue spreading rates. By visualizing with the X-ray CT was revealed that the largest amount of glue spreading rate (225 g/m²) had the highest distribution of PF adhesive penetrated within the lathe checks of veneer sheet compared to 150, 75, and 0 g/m². Furthermore, increasing of the adhesive distribution into the lathe checks of veneer increased the plywood density. According to the results, we suggested that the X-ray CT images analysis was powerful to reveal the relationship between the thermal conductivity and the adhesive distribution.

1. Introduction

Japanese cedar (*Cryptomeria japonica* D. Don) is a popular commercial wood for softwood plywood manufacturing in Japan. In Japanese composite panel market, the production of domestic softwood plywood has been increasing rapidly, and plywood industry has started to peel sugi logs to produce thicker panels [1]. Thermal conductivity of wood composite materials such as plywood, OSB, particleboard, and fiberboard has varied according to wood species, direction of wood fiber, ratio of



early and late wood, thickness of composite materials, density, moisture content, resin type and additives, temperature, and flow direction of heat in several studies [2]. Therefore, the adhesion of wood adhesive in wood-working industry could be an important factor of the quality parameters of plywood which affects bonding strength, permeability, heat and moisture transfer, etc.

Controlling the amount of glue spreading rate on the surfaces of veneer in plywood production is important since it will affect the final products properties, manufacturing costs and the environmental impact as well [3]. In plywood production, human operators find it difficult to precisely monitor the spread rate of adhesive in real-time [4]. According to Lindgren (1992), Kamke and Lee (2007), and Paris and Kamke (2015), the X-ray CT had visualized the properties of wood and appearance of the adhesive distribution performance inside the wood-based panel's products [5, 6, 7]. They visualized the adhesive distribution performance for improving the technique in composite science scope. The objective of this study was to elucidate the effect of glue spreading rate of plywood on its thermal conductivity and to investigate the mechanism of the effect by visualizing the adhesive morphology across glue lines of plywood by using a micro focus X-ray CT imaging.

2. Materials and Methods

2.1. Materials

2.1.1. Veneer sheets

The plywood samples were produced made by veneer sheets of heartwood of the Japanese cedar or Sugi (*Cryptomeria japonica*, D.Don) grown in Shizuoka Prefecture, Japan. Twenty heartwood veneer sheets with the dimension average was 450 mm × 450 mm × 3.81 mm (thickness) made from Japanese cedar were prepared and conditioned at 20°C and 65% RH at least for 30 days. The dimension and weight of each sheet was measured and its density also was calculated (Table 1).

2.1.2. Phenol-formaldehyde resin adhesive. Phenol-formaldehyde resin adhesive was prepared with the following ratio: PF resin = 76.3%, CaCO₃ = 11.6%, Wheat powder = 6%, Distilled water = 3.8% and Na₂CO₃ = 2.3%.

2.2. Methods

2.2.1. Plywood Manufacturing

The veneer sheets were dried at temperature 60°C for 24 hours in a drying oven prior to plywood manufacturing. Four specimens of 5-ply plywood were made with the veneer sheets with the glue spreading rate of 0 (no adhesive), 75, 150, and 225 g/cm² (single glue line) with 20-minutes cold press at room temperature (1 MPa) followed by hot press at 125°C for 15–19 minutes (1 MPa). The samples were then conditioned at least for 30 days and had air dried condition before testing of the thermal conductivity (Table 1).

Table 1. The properties of plywood materials.

No sample	Veneer density of sugi heartwood (g/cm ³)	Spread rate (g/cm ²)	Plywood density (g/cm ³)	Plywood thickness (mm)
1	0.319, 0.334, 0.335, 0.341, 0.343	0	0.366	18.88
2	0.321, 0.334, 0.345, 0.335, 0.340	75	0.397	17.68
3	0.344, 0.336, 0.339, 0.323, 0.333	150	0.425	17.04
4	0.346, 0.325, 0.337, 0.331, 0.338	225	0.448	16.27

2.2.2. Thermal conductivity measurement

The plywood specimens were cut into 20×20 cm in the air dried conditions (10-12 % MC). The thermal conductivity of each specimen in the thickness direction was measured with a heat flow method between two plates set at 10 and 40°C (AUTO-Λ HC073, Eko Instrument Trading Co.LTD). The thermal conductivity apparatus was following standard are JIS A 1412 and ASTM- C518 (Figure 1).



Figure 1. Thermal conductivity measurement apparatus.

2.2.3. X-ray CT Scanning

The X-ray CT images of the four specimens were taken with a micro focus X-ray CT scanning system (Inspexio SMX-225 CT, Shimadzu Corporation) with 80 kV tube voltage and 150μA tube current (Figure 2).



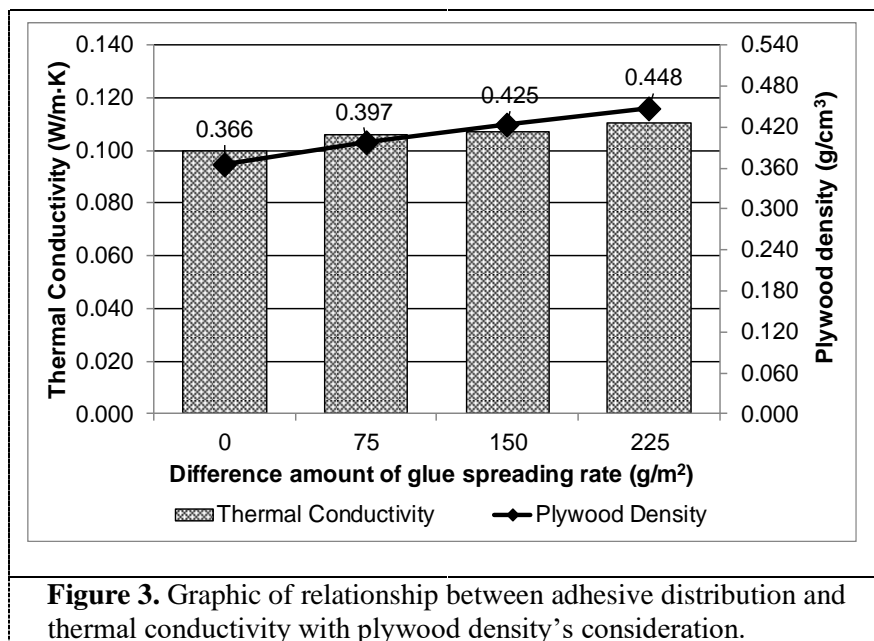
Figure 2. A micro focus X-ray CT system.

3. Results and discussion

Figure 3 shows the thermal conductivity increases with increasing the amount of glue spreading rate of sugi heartwood plywood. The big amount of glue spreading rate 225 g/m² had the highest thermal conductivity value, followed by plywood had amount of glue spreading rate were 150, 75 and 0 g/m². As shown in figure 3 that the highest plywood density had the largest thermal conductivity, which agrees with results presented by Sonderegger and Niemz (2009) and Tanaka et al, (2012) [8, 9]. The density of plywood was influenced by the amount of glue spreading rates, which were spread on the veneer surface (Figure 3). The biggest amount in application of resin adhesive had the biggest adhesive distribution are

spread wider and deeper within the plywood (Figure 5). Increasing of the adhesive distribution into the lathe checks of wood increased the plywood density. There are seems small effects with increasing of amount of spreading rate on thermal conductivity.

Figure 4 shows the differences of adhesive distribution appearance by using micro focus X-ray CT vary in amount of glue spreading rates (0, 75, 150 and 225 g/m²). By visualizing of the X-ray CT investigated that the largest amount of glue spreading rate (225 g/m²) (Figure 5) had the highest distribution of PF-adhesive penetrated within the lathe checks of veneer sheet compared to 150, 75, and 0 g/m² (Figure 6, 7 and 8). Figure 5 showed that the transverse view of veneers bright part is distribution of resin in glue lines and lathe checks of veneer dominantly and black parts are veneers. Rohumaa et al., (2013) studied the influence of the lathe check depth and orientation on bond quality of phenol-formaldehyde bonded birch plywood [10]. The study had revealed that by the deeper checks allowing the adhesive penetrates much more deeply into the veneer which makes strong influence on the measured shear strength. As depicted in Figure 6 and 7, the adhesive distribution performances (150 and 75 g/m²) were found penetrating on the glue lines and lathe checks very slight which affected thermal conductivity values smaller than 225 g/m². As visible in figure 8, the plywood with 0 g/m² amount of glue spreading rate had the smallest thermal conductivity. The result was supported by visualizing images that there were air contact lines depicted as black parts. The air contact lines on among veneers make the plywood could not bond tightly when thermal conducted transversely. According to the results, Interest into influence of adhesive penetration on adhesive bond performance and adhesive behavior of different wood-adhesive glue lines has been evident by using microscopy technique and X-ray apparatus for several decades [6,7]. Therefore, we suggested that the X-ray CT images analysis was powerful to reveal the relationship between the thermal conductivity and the adhesive distribution.



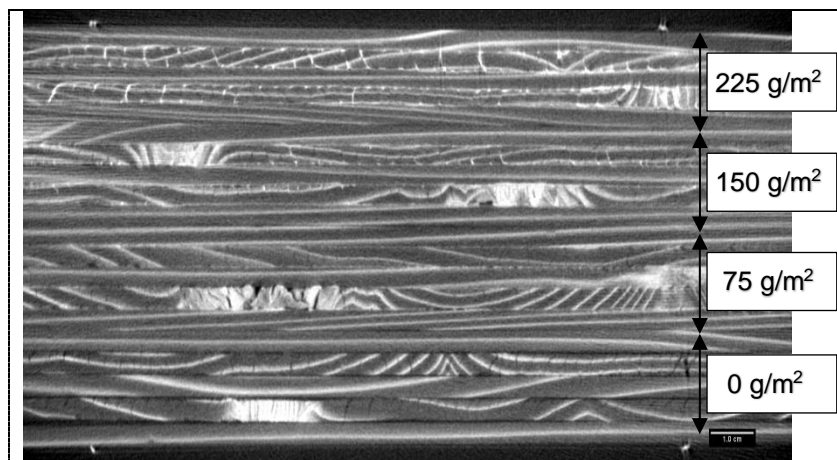


Figure 4. Micro Focus X-ray Computed Tomography data image of PF-adhesive distribution within sugi plywood.

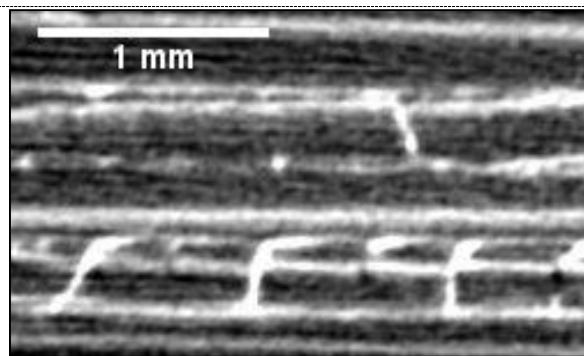


Figure 5. Micro Focus X-ray Computed Tomography (X-ray CT) image of PF- adhesive distribution (225 g/m²) in sugi plywood. The transverse view of veneers bright parts are distribution of resin in glue lines and lathe checks of veneer dominantly and black (dark) parts are veneer sheets.

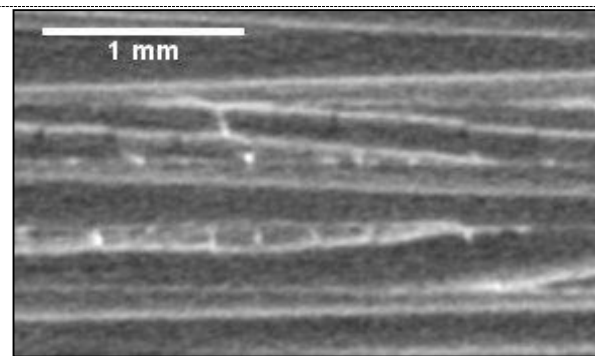


Figure 6. Micro Focus X-ray Computed Tomography (X-ray CT) image of PF- adhesive distribution (150 g/m²) in sugi plywood. The transverse view of veneers bright parts are distribution of resin in glue lines and lathe checks of veneer also appearance of the annual growth rings of wood.

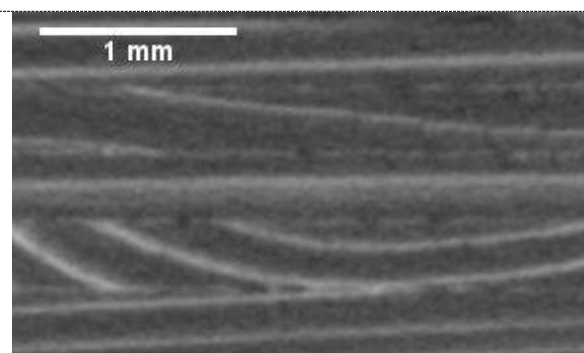


Figure 7. Micro Focus X-ray Computed Tomography (X-ray CT) image of PF- adhesive distribution (75 g/m²) in sugi plywood. The adhesive distribution is slight to visible by X-ray CT of glue spreading rate is 75 g/m². The view of veneers bright parts are visualized of the annual growth rings of sugi.

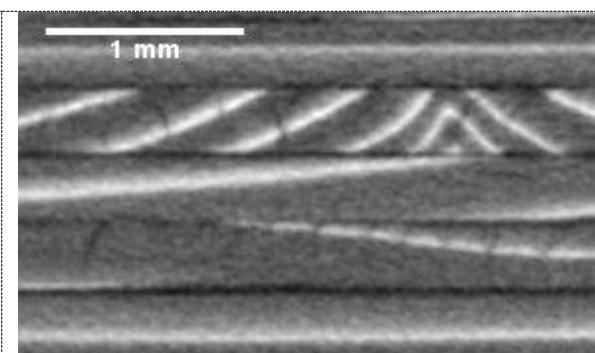


Figure 8. Micro Focus X-ray Computed Tomography (X-ray CT) image of the plywood sample without the application of adhesive in sugi plywood. The view of veneers bright part are visualized of growth annual rings of sugi and black (dark) views are the air contact lines.

4. Conclusions

Based on the results, the following conclusions could be concluded:

- Thermal conductivity of sugi heartwood plywood increases with increasing the amount of glue spreading rate by using phenol-formaldehyde resin adhesive.
- X-ray CT images analysis are powerful to reveal the relationship between the thermal conductivity and the adhesive distribution.

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