Original article

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Wettability of welded wood-joints investigated by the Wilhelmy method: part 1. Determination of apparent contact angles, swelling, and water sorption

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Abstract: This study presents a novel application of the Wilhelmy plate method on welded joints of Scots pine sapwood and beech. Welding resulted in an increase in the contact angle (increased hydrophobicity) as well as a decrease in the water uptake and swelling of the welded pine-joint compared to non-welded pine. When the welding time was extended from 4 to 5 s, these properties were further pronounced. Welding of beech, on the other hand, led to an increase in the contact angle and a decrease in the water uptake, but an increase in the swelling.

Fourier Transform Infrared spectroscopy showed that welding increased the aliphatic C–H and unsaturated C=C stretching absorption bands in pine and beech. Scanning electron microscopy showed a dense structure at the welded joints of the both species, giving evidence of a lower porosity that leads to a lower permeability as a result of the welding.

Keywords: beech; fourier transform infrared spectroscopy (FTIR); pine; scanning electron microscopy (SEM); welding time.

1 Introduction

Wood welding is a comparatively novel procedure for joining pieces of wood without the use of adhesives or metal fasteners. First pioneered in 1996, the welding

process and the mechanical properties of the welded wood-joint have been studied over the past decade across Europe and the technique has shown some success not only in the furniture industry (Navi and Sandberg 2012; Stamm 2005) but also in the joining of sawn timber for construction purposes (Pizzi et al. 2004). To date, the studies related to structural applications are, however, few in part due to the vulnerability of the welded joint to damage from moisture. For industrial applications, the long-term moisture stability of the joint must be ensured. Interaction between the welded joint and water has profound impacts on mechanical properties and service life of the welded wood.

Welded pine has a greater resistance to water than welded beech. One hypothesis is that extractives in pine may have a lower affinity to water and lead to a lower water absorption in the welded area (Mansouri et al. 2011), whereas a high water uptake in the welded area results in delamination of welded beech (Vaziri et al. 2011).

Earlier studies (Amirou et al. 2017; Pizzi et al. 2013) indicate that the basic understanding of the underlying mechanisms of water permeation in welded joint is deficient. Previous studies have tested the resistance of welded woods to water in a number of ways, but none of them have investigated the dynamic (time-dependent) interaction between water and the welded joints. This study investigates wetting properties of welded woods by studying contact angle (CA), swelling, and liquid sorption of the welded joint and adjacent wood using Wilhelmy plate method.

Wetting refers to macroscopic manifestations of molecular interaction between liquids and solids in direct contact at the interface between them (Berg 1993). According to Collett (1972), in (Patton 1970), the term “wetting” is controlled by surface tension of liquid and substrate and covers the processes of adhesion, penetration, and spreading, each of these phenomena being a distinctly different type of wetting. A typical way to assess the wettability of a wood surface is to determine the CA of a liquid in contact with wood.

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The wetting of wood surfaces has been intensively investigated since the 1960s (Chen 1970; Gray 1962; Hse 1972; Jacob and Berg 1993; Wålinder and Johansson 2001; Wellons 1980). The two most widely used techniques for wettability measurements are the sessile drop (Gray 1962) and the Wilhelmy plate (Wilhelmy 1863). The Wilhelmy plate technique has been shown to provide more accurate, consistent, and reproducible data than the sessile drop method especially for rough, heterogeneous, and hygroscopic materials such as wood (Gaonkar and Neuman 1984; Lander et al. 1993; Seebergh and Berg 1992). The simplicity of the method and the fact that it measures not only the CA of water on the wood surface but also the water absorption means that it has a potential in studies of water permeability of welded woods.

To the authors' knowledge, there is no reported study on wetting properties (contact angle, swelling, and liquid sorption) of welded wood-joints. The main focus of the present work was therefore to apply the Wilhelmy plate principle to study the effect of welding on the wetting and water sorption properties of welded joints in Scots pine and European beech. Special emphasis is laid on the dynamics of the wetting process and the water sorption and the swelling of the welded surfaces. To characterize this possible effect in detail, the changes in morphology and chemical composition as a result of welding were studied by Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy and scanning electron microscopy (SEM).

This paper is the first of two articles related to the interaction between water and welded wood (Vaziri et al. 2020). This paper presents the first application of the Wilhelmy plate method to welded wood and a refined specimen preparation and test method. This study links wetting properties with surface chemistry and morphology and provides valuable knowledge regarding the energetic and chemistry of wood surfaces that may guide us in modifying the permeability of welded wood.

2 Materials and methods

2.1 Preparation of specimens

2.1.1 Wettability: The welded specimens were prepared from clear pieces of Scots pine sapwood (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) with planed surfaces and dimensions of 20 mm × 20 mm × 230 mm (radial (R) × tangential (T) × longitudinal (L); Figure 1a). The specimens were conditioned for two weeks at a temperature of 20 °C and 65% relative humidity (RH) in an environmental

chamber to 12% average moisture content (MC) and thereafter welded together in pairs to dimensions 20 mm × 40 mm × 230 mm (longitudinal welding of a tangential face to a radial face; Figure 1b). The linear vibration welding machine was a Branson, model M-624 (Branson Ultrasonic, Dietzenbach, Germany) that was set to a frequency of 240 Hz and the most important parameter settings listed in Table 1 that could result in a maximum shear strength of the joints.

A Wilhelmy plate is a thin, generally rectangular plate which is vertically immersed in the test liquid along one of its larger dimensions. To make plates entirely of welded wood, the welded joints of the specimens should be opened to get access to their welded area. The welded joints of the specimens were opened with a steel chisel (Figure 1c), carefully cleaned with hexane before each use. Welded areas are generally very thin and brittle and cutting them to strips thinner than 0.5 mm in order to eliminate the non-welded wood adjacent the welded areas is difficult. The welded areas were band sawn to strips with a thickness of 0.5 mm (Figure 1d) and two chips 20 mm × 10 mm × 0.5 mm in size were cut from one of the strips (Figure 1e) with a scalpel carefully cleaned with hexane. The chips were glued together on their rear sides using a waterproofing adhesive (Contact A3, Bostik) to make plates (two-sided welded specimens) with dimensions of 20 mm × 10 mm × 1 mm (Figure 1f). The cross sections of the specimens were end-sealed with an alkyd/polyurethane varnish to prevent liquid sorption through these sides of the specimens. Chips with dimensions of 20 mm × 10 mm × 1 mm were cut from non-welded wood adjacent the welded areas to be used as control specimens (Figure 1c). For each group of welded and control specimens, three replicates were tested.

2.1.2 ATR-FTIR spectroscopy: The specimens were prepared from the welded interface of the split welded-joint in Figure 1c. Tiny splints were carefully cut from the welded areas with a scalpel, and similar splints were cut from adjacent non-welded wood to be used as control specimens. The scalpel was carefully cleaned with hexane before each use. For each group of welded and control specimens, three replicates were tested using a Perkin-Elmer frontier FTIR equipment (Waltham, MA, USA) with a frontier UATR ZnSe with reflection top plate and pressure arm (Spectrum 10™ software) and four scans of a resolution of 4 cm⁻¹ were collected for each replicate at room temperature.

2.1.3 Scanning electron microscopy: After the wettability test, the glued joints of the two-sided specimens (Figure 1f) were opened to examine both surfaces of the specimens. The welded chips were split into small pieces of 10 mm × 10 mm × 0.5 mm with a scalpel carefully cleaned with hexane before each use. The control specimens from the wettability test were also split to small pieces of the same dimensions. All specimens were mounted onto standard metal stubs using carbon paste and sputter coated with a gold layer (20 nm) in a Denton Desk II sputter unit before observation. The specimens were scanned in a JEOL 5200 scanning electron microscope with magnification of 300 000 at 10 kV of accelerating voltage.

2.2 Wilhelmy method

2.2.1 Theoretical background: The basic equation of capillarity given by Laplace (1799) and Young (1805) is one of the fundamental

Figure 1: Preparation of the welded specimens.

Table 1: The initial welding pressure, p_{w1} , was applied during the first welding time, t_{w1} ; followed by the second welding pressure, p_{w2} , during the second welding time, t_{w2} ; and ending with the holding pressure, p_h , during the holding time, t_h . NOS denotes Number of Specimens.

Species	NOS	t_{w1}, t_{w2}, t_h (s)	p_{w1}, p_{w2}, p_h (MPa)
Scots pine	3	2/2/10	1.3/1.7/2.7
Scots pine	3	2/3/10	1.3/1.7/2.7
Beech	3	1/1.8/10	1.6/1.6/2.5

equations used to describe surface wetting phenomena. The Young equation was modified later by Dupré and Dupré (1869) to

$$W_A = Y_{LG}(1 + \cos(\theta)), \quad (1)$$

which is called the Young–Dupré equation or the work of adhesion equation, where Y_{LG} is the surface tension of the liquid and θ the apparent contact angle between the liquid and the substrate. The Young–Dupré equation provided a basis for advanced wetting models on rough and chemically heterogeneous surfaces (Oss 1994; Wenzel 1936). Wilhelmy (1863) first proposed indirect contact angle measurement by immersing a plate in a liquid and deriving the angle from the measured force by a simple equation originally developed for measuring the surface tension of a liquid that was later modified for the measurement of wetting forces on wood (Casilla et al. 1981; Gast and Adamson 1997; Neumann and Good 1979). The most updated model of Gast and Adamson (1997) is

$$F(h, t) = p\gamma_l \cos(\theta) + F_w(t) - \rho Ahg, \quad (2)$$

where $F(h, t)$ is the wetting force as a function of the depth of immersion h and time t , p the perimeter of the substrate, γ_l the surface tension of the liquid, θ the apparent contact angle between liquid and substrate, $F_w(t)$ the force due to wicking (capillary action) and sorption of the liquid at time t , ρ the liquid density, A the cross-sectional area of the plate, and g the gravitational constant.

A technique for measuring wetting properties of fibers based on the Wilhelmy principle was reported by Young (1976). The Wilhelmy slide method is based on the principle that a thin plate will support a liquid meniscus whose weight depends upon the surface tension of the liquid and the perimeter of the plate.

2.2.2 The experiment: This study was performed based on the Wilhelmy method described by Casilla Steiner (1981) using a Sigma 70 tensiometer from KSV Instruments with water and heptane as a non-swelling liquid (Mantanis et al. 1994). Since accurate measurement of the perimeter of a porous material like wood is difficult, and the perimeter of the specimen changes during water immersion due

to wicking and sorption, it is necessary to also use a non-swelling liquid. Drying the specimens before water immersion to zero MC could lead to opening of the glued joint. Therefore, the specimens were dried at room temperature, $22.5 \pm 0.5^\circ\text{C}$ and $35 \pm 5\%$ RH, to 7% MC and weighed immediately before the wettability measurement. Each specimen was mounted in the tensiometer and partially immersed in ultra-pure water at a speed of $12 \text{ mm} \cdot \text{min}^{-1}$ to minimize wicking effects (Gardner et al. 1991), so that the $F_w(t)$ -term in Eq. (2) could be neglected. After 50 s (corresponding to a depth of immersion of 10 mm), the specimen was withdrawn at the same speed, until the water was detached from the wet solid surface (5 mm above the surface), and thereafter, with no pause, immersed again. Changes in the force as a function of depth of immersion ($h = 0$) were recorded graphically for 20 cycles in water (Figure 2). Thereafter the specimen was immersed and withdrawn for two cycles in a non-swelling liquid (heptane) to determine its perimeter after water absorption. The specimen was again dried at room temperature to the same weight as before the measurement and immersed for another two cycles in heptane to measure its original perimeter. Measuring the original perimeter before water immersion could lead to interference of the heptane in the measurement of contact angle in water. The perimeter of the specimen can be estimated by a linear regression of the receding curve or second advancing curve, on condition that the contact angle of the heptane is zero. If the surface tension of the liquid is known, then the perimeter of the specimen can be estimated by Eq. (2). The contact angles can then be calculated. Vice versa, if the perimeter is known the liquid surface tension can be estimated (Wälinder and Johansson 2001).

The liquids used were distilled water (surface tension and density of $72.0 \pm 0.2 \text{ mN} \cdot \text{m}^{-1}$ and $0.997 \text{ g} \cdot \text{cm}^{-3}$, at 25°C) and heptane (surface tension and density of $21.3 \text{ mN} \cdot \text{m}^{-1}$ and $0.397 \text{ g} \cdot \text{cm}^{-3}$, at 25°C). The measurements were performed at about 22°C and 50% RH. Three independent replicates were tested, and fresh liquid substrate was used for each specimen.

The dynamic force measurements were made as described in the literature (Gardner et al. 1991; Mantanis and Young 1997; Wälinder and Johansson 2001) and are shown in Figure 2k. The advancing force F_A and receding force F_R were measures by linear regression of the advancing and the receding curves, respectively (Figure 2k). F_f is the final force, i. e. equal to the amount of sorbed liquid during a test cycle or $F_w(t)$ -term in Eq. (2) at the time after the rupture of the meniscus ($h = 0$). $F_w(t)$ is assumed to be zero when the specimen touches the liquid in the first test cycle (at $h = 0$).

The advancing contact angle θ_A and the receding contact angle θ_R were determined by linear extrapolation of F_A , F_R , and F_f at zero depth ($h = 0$) in water, respectively

$$\cos(\theta_A) = \frac{F_A}{p\gamma_l} \quad (3)$$

Figure 2: Typical Wilhelmy curves showing force normalized with the sample perimeter (F/P) versus immersion depth (h). The dotted circles show the initial uptake (non-linearity at the beginning of the first cycle), the dashed squares show a drop in the advancing curves, and the rectangles show a dip at the right-hand end of the cycles.

$$\cos(\theta_R) = \frac{F_R - F_f}{p\gamma_l} \quad (4)$$

Dynamic sorption by the wood specimens was determined by extrapolation of the final forces F_f to zero depth in both water and heptane curves (Figure 2k), i. e., the force that remains after each cycle due to liquid sorption and wicking (Wälinder and Johansson, 2001). The liquid uptake by the specimens after cycle n was calculated as follows:

$$L_n = \frac{w_n - w_0}{w_0} = \frac{F_{f,n}}{g \cdot w_0} \quad (5)$$

where w_n (g) is the specimen weight after cycle $n \in \{0, 1, \dots, N\}$, w_0 (g) the initial weight of the specimen before testing, $F_{f,n}$ the final force of cycle n (gms^{-2}), and g the gravitational constant (ms^{-2}). By definition, the final force of the zeroth cycle, $F_{f,0}$, is zero. The initial and final perimeters of the specimen (after wetting) were directly determined by immersion in heptane, but the specimen perimeter at intermediate cycles was estimated based on a linear combination of the measured force and final change in specimen perimeter (Sedighi Moghaddam et al. 2013):

$$P_n = P_{n-1} + \frac{(F_{f,n} - F_{f,n-1})\Delta_P}{\Delta F_f} \quad (6)$$

where P_n and P_{n-1} are the perimeters of the specimen after n and $n - 1$ cycles, respectively; $F_{f,n}$ and $F_{f,n-1}$ the final forces of cycle n and cycle $n - 1$, respectively; Δ_P the perimeter difference between the initial perimeter P_0 (after drying) and the perimeter after the final cycle, P_N ; and ΔF_f the final force difference between the initial and final cycles ($\Delta F_f = F_{f,N} - F_{f,1}$).

3 Results and discussion

3.1 Multicycle Wilhelmy plate experiments—basic considerations

Figure 2 shows typical multicycle Wilhelmy curves while the specimen were immersed and withdrawn from the liquid for 20 cycles. In order to make Figure 2 more comprehensible, Figure 2k was added at the end. The force detected by the instrument is normalized with the sample perimeter (F/P) as a function of immersion depth (h). At first, the specimen is immersed into water, illustrated by the bottom red curve. The almost affine part of the first advancing curve between the origin and “a” in Figure 2k was used to determine $F_{A,1}$ (Wälinder and Johansson 2001). At the point “a” in Figure 2k, the curve changes into blue as it is receding up from the water. The affine part of this curve, marked “b”, determines $F_{A,1}$. The almost horizontal part at the end of the first receding curve (and—at the same time the beginning of the second advancing curve) makes up the first final force $F_{f,1}$. For the second advancing, the curve becomes red again until it is discontinued. In reality, it continues again as receding, but in order to keep the illustrating figure clear, no more data was included. The

affine part of the curve representing the second advancement of the specimen into the water can be used for the determination of $F_{A,2}$ —see the black line marked “c”. The data used for creating Figure 2k was a single cycle taken from Figure 2e.

For the test cycle in water, there was a considerable hysteresis between the advancing and receding curves and the shapes of the curves were different for pine and beech. For non-welded and welded pine immersed in water a distinct drop in the advancing curves was observed before 5 mm immersion depth (dashed square in Figures 2a,c), but this was not observed in the beech specimens (Figures 2g,i).

From the change in force after removing the sample from the liquid, it is seen that sorption increases with time (i. e., with number of cycles) for welded and non-welded specimens due to swelling the voids of the wood cell structure and due to bulk sorption in the cell walls by water, the latter sorption resulting in swelling of the wood (Sedighi Moghaddam et al. 2013; Skaar 1988). For non-welded specimens, the water uptake increased with every cycle, but the rate of this increase diminished with increasing the number of the cycles. In the welded specimens, on the other hand, the water uptake increased almost equally each cycle. The welding process is associated with increased temperature, pressure, and shearing that results in collapsing of cell cavities and transforming the wood to a dense amorphous mass containing fragments of wood cells (Stamm 1964). It is possible that there are almost no voids left in welded specimen and the water uptake is mainly into compressed and partially damaged cell walls. The right-hand end of the Wilhelmy plots dip to almost the same level as for the first cycle as long as the water-line comes close to a non-wetted region. This phenomenon can be seen for the first couple of cycles in the both welded and non-welded specimens (the dashed rectangles in Figure 2a,c,g and i). In the later cycles, this part of the curve dips more in the welded than in the non-welded specimens, indicating that the welded wood is less affected by the water and still has non-wetted regions. On immersion in heptane, almost similar wetting behavior was observed for beech and pine specimens. With heptane, there is no or very little hysteresis. An initial uptake of heptane can be observed (dotted circle in Figure 2b,h), but heptane, as a non-swelling liquid, only enters the voids in the wood.

3.1.1 Water uptake

Figure 3 shows the water uptake as functions of the number of cycles. The sorption of water by welded pine and beech was respectively 2.5 and 6 times less than that by their

controls, in line with previously published statements by Kollmann and Schneider (1963) and by Skaar (1988) that the water uptake in thermally modified wood is lower than that in non-welded wood.

The water sorption of non-welded specimens was initially very high, but it decreased rapidly after some cycles. The average water sorption was however significantly higher than that of the welded specimens. The average water sorption was significantly lower in the welded beech than that in the welded pines (WP4W and WP5W).

The sorption of heptane was also lower in welded than in non-welded specimens and pine specimens welded for 4 and 5 s showed similar heptane sorption (Figure 3, WP4H and WP5H). However, a two-cycle test was not sufficient to distinguish all the wetting kinetic regimes of heptane uptake. Similar heptane sorption indicates a similar micro-morphology for the welded pine specimens.

3.1.2 Contact angle

The multicycle Wilhelmy method was used to investigate dynamic contact angle changes of the welded and non-welded wood specimens after 20 cycles. Figure 4 shows the advancing contact angle, θ_A , and the receding contact angle, θ_R , where the terms “advancing” and “receding” refer to the movement of the liquid in relation to the specimen, advancing over a surface to be wetted (immersion), and receding from the same surface after being wetted (emersion; Casilla et al., 1981).

The contact angle of water on the welded specimens did not reach zero until 7, 10, and 20 cycles respectively for pine welded for 4 s (WP4), pine welded for 5 s (WP5), and welded beech (WB), implying that the wood surface did not become completely wet until these cycles. The multiple range test with the 95% Least Significant Difference procedure indicated that the contact angles on the welded specimens were significantly greater than that on the respective non-welded specimens. Welded beech specimens showed a significantly higher contact angle than welded pine specimens (Figure 4). The welded pine specimens welded for a longer time (5 s) showed a significantly higher contact angle than welded pine for 4 s.

The initial value of the contact angle shows the affinity of the wood surface to water and is mainly influenced by the surface structure of the wood species. The dynamic contact angle is additionally directed by the extractives, the capillary and the topographic structure, and the density of the wood (Boehme and Hora 1996).

The magnitude of contact angle hysteresis (difference between advancing and receding contact angles) is dependent on roughness, topography, morphology, and

chemical homogeneity of the solid surface. Good (1979) suggested that the advancing contact angle represents hydrophobic areas on the surface, while the receding contact angle characterise hydrophilic areas.

3.1.3 Perimeter change

The relative change in the perimeter of the specimens after each of the 20 cycles of water immersion is presented in Figure 5. The swelling of the welded specimens was significantly lower than that of the non-welded specimens. Non-welded pine and non-welded beech differed in their wetting properties.

The total amounts of absorbed water were almost the same, but the swelling of the beech was significantly greater than that of the pine. Beech has higher density than pine, which probably explains the higher swelling (Stamm 1935). Welding reduced the water uptake of beech, but the swelling of welded beech was significantly greater than that of welded pine. The swelling of the pine welded for 4 s (WP4) was greater than that of the welded beech, but the swelling of the pine decreased when the welding time was extended to 5 s (WP5). Unexpectedly, welding pine for 4 s did not decrease the swelling compared to non-welded pine, as shown in Figure 5 for cycle six and later.

Figure 3: Average liquid uptake in water and heptane expressed in % of the specimen's weight vs. cycle number. PW denotes non-welded (control) pine in water, PH non-welded pine in heptane, BW non-welded (control) beech in water, BH non-welded beech in heptane, WP4W welded pine for 4 s in water, WP4H welded pine for 4 s in heptane, WP5W welded pine for 5 s in water, WP5H welded pine for 5 s in heptane, WBW welded beech in water, and WBH welded beech in heptane.

3.2 ATR-FTIR spectroscopy

The results of ATR-FTIR for both species are presented in Figure 6. Regarding to pine specimens, Figure 6c shows that carbonyl stretching band ($\text{C}=\text{O}$) at 1735 cm^{-1} was broadened and shifted by the welding treatments to a band appearing at 1712 cm^{-1} . Such behavior has been observed during welding of wood (Delmotte et al. 2008). Acetic acid has been suggested to form by the cleavage of acetyl group in O-acetyl-galactoglucomanan during wood welding (Gfeller et al. 2003). Formation of low molecular weight acids could be a reason for broadening of the $\text{C}=\text{O}$ stretching band as acids absorb infrared light at a lower wave number than the corresponding ester (Pretsch and Biemann, 1983). Formation of new carbonyl structures has also been suggested to occur during wood welding (Stamm et al. 2006). The absorption at 1599 cm^{-1} (Figure 6c) that may be related to unsaturated and aromatic carbons

shifted to a higher wave number after a longer welding time (WP5).

Hydroxyl stretching bands could be found around 3300 cm^{-1} in non-welded and welded pine. Ratio between signal intensity for O–H and C–O stretching band at 1030 cm^{-1} increased from 0.24 to 0.32 by welding for 4 s (WP4). This indicates that simple dehydration of alcohol into a carbon–carbon double bond structure is not the only reactions occurring. Cleavage of alpha- and beta-ether bonds in lignin with formation of phenolic groups as well as cleavage of glycosidic bonds has been reported to occur during wood welding (ibid.). At the longer welding time (WP5) the ratio decreased to 0.28, which indicates that other reactions became prominent (Figure 6b). Dehydration could result in formation of unsaturated carbon–carbon ($\text{C}=\text{C}$) bonds and ether bonds that could be seen in furfurals, which are thermal degradation products from carbohydrates (ibid.). Broadening of the absorption band around 1600 cm^{-1} related to $\text{C}=\text{C}$ stretching (Figure 6c) after welding, is probably due to formation of such structures. The intensity of the absorption bands at 2900 cm^{-1} , corresponding to aliphatic C–H stretching increased after welding.

Beech also contains acetyl groups bonded to hemicellulose, in this case O-acetyl-(4-O-methylglucurono) xylan. In welded beech, a shift of absorption to 1714 cm^{-1} of $\text{C}=\text{O}$ absorption band was observed (Figure 6c). Ratio of O–H and C–O stretching bands were similar in non-welded (0.20) and in the welded beech (0.21). A broadening toward higher wave numbers for C–H stretching at 2900 cm^{-1} as well as a broadening of absorption band around 1600 was seen which could be due to the formation of carbon–carbon double bonds. Formation of such structures should

(a) Advancing contact angle

(b) Receding contact angle

Figure 4: Average dynamic contact angles of welded and non-welded pine and beech specimens for 20 cycles. P denotes non-welded (control) pine, WP4 welded pine for 4 s, WP5 welded pine for 5 s, B non-welded (control) beech, and welded beech.

Figure 5: Average perimeter change as a function of time (cycles) for pine and beech specimens. P denotes non-welded (control) pine, B non-welded (control) beech, WP4 welded pine for 4 s, WP5 welded pine for 5 s, and welded beech.

(a) full spectrum

(b) magnification at 2900 cm⁻¹ (c) magnification between 1550 and 1750 cm⁻¹

Figure 6: FTIR spectrum of pine (P), welded pine for 4 s (WP4), welded pine for 5 s (WP5), beech (B), and welded beech (WB).

contribute to an increase in the hydrophobicity of wood associated with a partial decomposition of predominantly hemicellulose, the most hygroscopic cell wall constituent (Stamm, 1964). The higher proportion of dehydration products in welded pine for 5 s and welded beech could be due to the degradation of wood constituents in wood cells by welding, and the formation of hydrophobic compounds leading to a larger observed contact angle.

3.3 Scanning electron microscopy

Beech and pine specimens demonstrate different sorption, swelling, and dimensional stability properties, probably due to morphological differences. Figure 7 shows microstructural differences between the welded and the non-welded wood. During welding, the wood fibers were torn out, destroyed, and crushed so that the wood lost its

Figure 7: Scanning electron microscopy of a typical specimen of (a) non-welded beech, (b) welded beech WB, (c) non-welded pine (P), (d) welded pine for 4 s (WP4), and (e) welded pine for 5 s (WP5).

original cellular structure. The welded wood had a dense structure giving evidence of a lower porosity that leads to a lower permeability.

Welding creates an interfacial layer from solidified molten inter-cellular material. This material is arranged in a cellular structure resulting in a surface roughness on a microscopic and macroscopic scale at the opened welded joint of the specimens (Figures 1c,f). A quantitative description of surface roughness was not the case of this study, but at a higher magnification and on a macroscopic level welded pine specimens had more heterogeneous and rougher surface than welded beech. The uneven degradation of tracheids of pine resulted in a welded joint with varying thickness, thicker around early wood and thinner around latewood. The varying thickness gave a rough and heterogeneous appearance to the welded interface in pine specimens. The welded pine specimens (WP5 and WP4) showed a similar micro-morphology (Figures 7d,e), except for the more dense structure of WP5 (Figure 7e).

4 Conclusion

As a result of welding, the contact angles of water on wood generally increased, and the uptake of water and the swelling decreased. Increasing the welding time from 4 to 5 s further pronounced these results for pine. The high swelling of the welded beech may lead to low water resistance and delamination of the welded beech in water.

The FTIR spectroscopy and SEM results show that with increasing the welding time more carbonized and dense materials were formed in the welded interface which had a more hydrophobic chemical structure. The higher hydrophobicity can be seen in the larger contact angle and the lower water uptake of the welded specimens, especially the welded beech. However, the lower water uptake may be simply due to a lower porosity. Welded pine specimens had more heterogeneous and rougher surfaces than WB.

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