Welding of Thermally Modified Wood and Thermal Modification of the Welded Wood: Effects on the Shear Strength under Climatic Conditions

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This work investigated how thermal modification affects the shear strength of welded joints under different climatic conditions. The order of the thermal modification, before or after the welding, was investigated for its effect on the shear strength of the welded wood. Two groups of thermally modified specimens were prepared in a laboratory kiln under controlled conditions, one thermally modified before welding and the other after welding of the specimens. The shear strength of the specimens were measured at four different moisture contents of 10%, 12%, 16%, and 18%, and the results for the two different approaches were compared. Moreover, observations of the X-ray computed tomography scanning and digital microscopy were used to study the density profile and the structural details of the welded joints. The results showed that thermal treatment of the wood either before or after welding had a negative influence on the shear strength, and the modes of failure of the joints in mechanical tests were in most cases brittle. In the weld interface of the wood modified before welding, a rigid material similar to charcoal was produced as a result of the further degradation of wood by welding pressure and frictional motion. Welding of wood before thermal modification, however, yielded thicker and more densified joints with less susceptibility to higher moisture variations than the joints obtained by welding the thermally modified wood.

Keywords: CT scanning; Digital microscopy; Shear strength; Thermal modification; ThermoWood

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INTRODUCTION

In the beginning of the 20th century, heat and moisture (thermo-hydro (TH) techniques) were introduced to wood processing. Wood dried at a high temperature changes color and has greater dimensional stability and lower hygroscopicity than untreated wood (Tiemann 1906; Stamm 1964; Sandberg and Kutnar 2016). Thermal modification can be an alternative for decreasing the hygroscopicity of the welded wood instead of using toxic chemicals, which defeat the purpose of having an environmentally friendly bonding.

Wood welding is an environmentally compatible assembling and manufacturing process that has a remarkable potential as an alternative to synthetic adhesives in timber engineering. The adhesion mechanism of welded wood is based on the softening and flowing of some amorphous, cells-interconnecting polymer material, mainly lignin and hemicelluloses (Gfeller *et al.* 2003). However, there have been few studies related to structural applications, which is partially due to the vulnerability of the welded joint to damage from moisture. Therefore, welded wood cannot be used based merely on its acceptable mechanical resistance; rather, its hygroscopicity and mechanical behavior must

be considered in a coupled manner. One hypothesis that could explain the poor water-resistance of the welded joints is that uneven swelling of the welded interface and of the adjacent wood causes severe stresses that crack and open the welded joints (Vaziri *et al.* 2019). The objective of this work was to study the influence of thermal modification, before or after vibration welding, on the resistance of the welded joints to varying humidity. Among the wood constituents, hemicellulose is the most degradable and lignin is the most stable polymer during thermal treatment. The chemical structure of the lignin is altered through the demethoxylation of ether bonds, auto-condensation reactions, and cross-linking, which leads to a reduction in water absorption of the wood due to the decrease in the number of free hydroxyl group. On the other hand, degradation of polysaccharides significantly reduce the mechanical properties of wood such as flexural and tensile strength (Stamm 1956; Esteves *et al.* 2006; Živković *et al.* 2008; Mahnert *et al.* 2013). Considering the improved properties of thermally modified wood, it would be interesting to figure out how thermal modification could influence the shear strength of the welded wood, and whether it makes a difference whether the welding is done before or after the thermal modification.

Currently, there is no report on the effect of thermal modification after vibration welding (W-TH) on the shear strength. Despite many advances in thermal degradation of wood, few studies have been done on the thermal modification of welded wood, and many questions remain unanswered. Moreover, there is a lack of consensus on the reported results regarding the welding of thermally modified wood (TH-W), and both an increase and decrease in the shear strength are reported (Boonstra *et al*. 2006; Omrani *et al*. 2010; Zigon *et al*. 2015). Most studies consider the welding of hardwoods.

The thermal modification method used in this study is based on the industrial ThermoWood principles developed at the Finnish Research Center VTT (Jämsä and Viitaniemi 2001). ThermoWood is the most widely used industrial thermal modification process that has been improving progressively (ThermoWood 2019). The present study examined the effect of thermal modification on the shear strength of the welded joint in a moist environment. Using non-destructive test methods such as X-ray computed tomography (CT-scanning) and digital microscopy, the density and structural details of the welded joints were studied.

EXPERIMENTAL

Preparation of Specimens

Four sets of the specimens were prepared: specimens welded before thermal modification (W-TH), specimens welded after thermal modification (TH-W), and their respective controls. The control specimens were prepared from non-treated wood welded with high pressure (control W-TH) and low pressure (control TH-W) according to the Table 1. The specimens were prepared from wood specimens with planed surfaces and dimensions of 20 mm × 20 mm × 230 mm (radial (R) × tangential (T) × longitudinal (L)) from clear pieces of Scots pine sapwood (*Pinus sylvestris* L.), grown in Skellefteå in the north of Sweden.

The specimens and their respective controls were conditioned for two weeks at 20 °C and 65% relative humidity (RH) in an environmental chamber to 12% average moisture content (MC). They were welded together in pairs to dimensions of 20 mm × 40 mm × 230 mm (along the end-grain-to-end-grain of the radial face-to-radial face) using a linear

vibration welding machine, Branson model M-624 (Branson Ultraschall, Dietzenbach, Germany) with a frequency of 240 Hz and settings according to Table 1. The TH-W specimens were prepared from wood pieces of the same quality as the W-TH specimens, but were thermally modified prior to welding.

The most influential welding parameters shown in Table 1 were selected based on earlier studies (Vaziri *et al*. 2012, 2020). The appropriate range of parameters that could result in the maximum shear strength of the welded joints was defined by a screening test. Notwithstanding the earlier studies (Gfeller *et al*. 2003; Boonstra *et al*. 2006), using a longer welding time and/or higher pressure for the welding of thermally modified wood caused severe degradation of the wood and delamination of the welded joint just after welding. Thus, the pressures and welding times needed to be less extreme than the conditions of welding optimized for non-treated wood. Hence, two sets of control specimens with different welding pressures were prepared.

Table 1. Welding Procedure and Classification of the Specimens

Welded Specimens	Welding Times S1 + S2 (s)	Holding Time (s)	Initial Welding Pressure (MPa)	Second Welding Pressure (MPa)	Holding Pressure (MPa)
W-TH	2.5 + 3	10	2	2.7	2.7
Control - W-TH	2.5 + 3	10	2	2.7	2.7
TH-W	2.5 + 3	10	1.4	2	2.7
Control - TH-W	2.5 + 3	10	1.4	2	2.7

Thermal Modification

The specimens were dried at room temperature to 8% average MC and were then moved to a laboratory conditioning kiln where the initial climate was 70 °C for a dry bulb and 55 °C for a wet bulb. The thermal modification process was performed according to the principles of the ThermoWood process (Finnish ThermoWood Association 2003) as shown in Fig. 1.

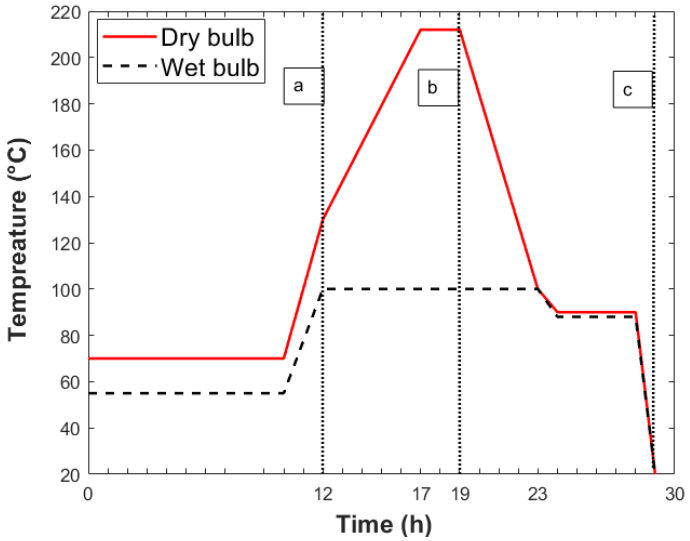


Fig. 1. Schedule of thermal modification, with the three phases of (a) drying, (b) heat treatment, and (c) cooling and moisture conditioning

The process can be divided into three main phases: (a) drying, (b) heat treatment, and (c) cooling and moisture conditioning. The drying process ended with a fast increase of kiln temperature to 130 ℃ in the dry bulb and 100 ℃ in the wet bulb to dry the wood to nearly 0% MC. The heat transferring media was superheated steam with oxygen less than 35%. The thermal modification step included increasing and holding the temperature in dry bulb at 212 ℃ for 2 h while the temperature in wet bulb was 100 ℃. The kiln was then cooled down from 212 ℃ to 100 ℃ for 4 h and then to 90 ℃ in dry bulb and 88 ℃ in the wet bulb during the following hour. The temperature was held at 90 ℃ and 88 ℃ for 4 h with high RH followed by another 1h of cooling down to 20 ℃.

Mechanical Test

The welded specimens were cut according to the EN 205 (2003) standard. Two cuts with a distance of 10 mm were made in the middle of the specimens, perpendicular to the welded joint. The specimens were formed in a way that was appropriate for the test equipment (Vaziri *et al.* 2012). Forty specimens of each type were conditioned in four different environmental chambers for approximately 3 weeks to reach average moisture contents of 10% (20 °C and 55% RH), 12% (20 °C and 65% RH), 16% (20 °C and 78% RH), and 18% (20 °C and 83% RH). The specimens were tested on a tensile-shear strength test machine (Hounsfield, model H1KS, Redhill, UK), along the longitudinal direction of the samples, in the direction of the wood fibers and at a rate of 2 mm/min. Fisher's LSD (Least Significant Difference) method was used in ANOVA to create a multiple range test with the 95% confidence intervals for all pairwise differences between shear strength results.

Digital Microscopy

A DSX1000 digital microscope (Olympus, Essex, UK) was used to see the fine structural details in the samples with high resolution. The weld lines were observed from different angles using a tilting frame and motorized XY stage with up to 90° rotation. The welded joints of the specimens were opened with a steel chisel, carefully cleaned with hexane before each use, and the weld interface was examined with a telocentric optical system. Three replicates of each type of the specimens were studied.

CT Scanning

Small samples with dimensions of 20 mm × 40 mm × 50 mm (radial (R) × tangential (T) × longitudinal (L)) were prepared from the welded specimens. The specimens were conditioned at room ambient conditions for two weeks to 8% average MC before they were scanned. For each type of specimen (W-TH and TH-W) and the respective controls, five replicates were scanned. In total 20 specimens were prepared. The specimens were scanned by a medical X-ray CT scanner (Siemens Emotion Duo; Siemens Healthcare GmbH, Erlangen, Germany) at ambient conditions with the settings listed in Table 2. The standard algorithm of the Shepp-Logan kernel was used for the image reconstructions (Shepp and Logan 1974). The specimens were scanned ten times on their cross section at a distance interval of 2 mm along the welded joint. The CT-numbers were averaged using the software Matlab® R2018b (The MathWorks, Inc., Natick, MA, USA) as shown in Fig. 2. The average CT image of each specimen was obtained by averaging ten 2 mm-distanced slices in the z-axis direction. The X-ray absorption was measured along a line of 100 pixels across the weld line, as shown with a black line in this figure and as the CT-number profiles in Fig. 4.

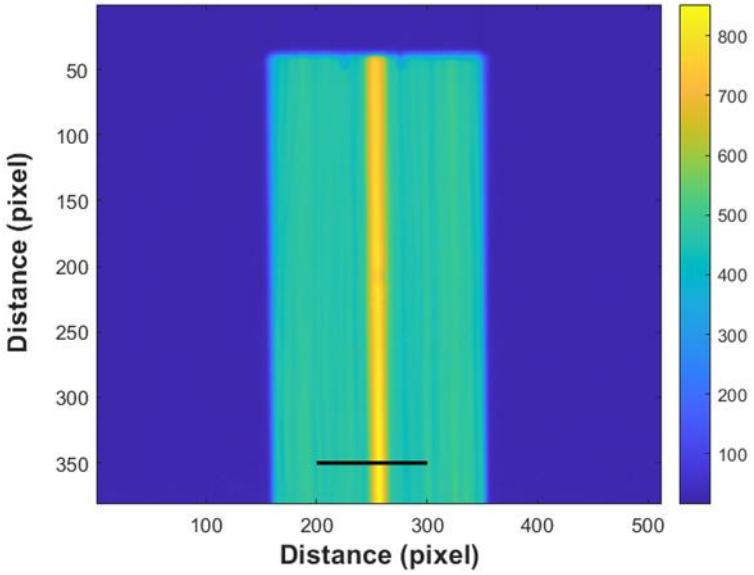


Fig. 2. An example of the average CT image taken over the five specimens (replicates) that had been heat treated after welding (W-TH). The color scale on the right hand shows the corresponding CT-numbers. The line is positioned on the 350 pixel-height in the y-axis direction and between pixels 200 and 300 in the x-axis direction

Table 2. Settings of the CT Scanner

Parameter	Unit	Value
Voltage	kV	110
Current	mA	70
Scan time	s	2
Scan thickness	mm	5
Matrix	Pixels	512 × 512 x 10
Resolution	Pixels/mm	2.3
Number of scans (in the z-axis direction)		10

RESULTS AND DISCUSSION

Figure 3 shows the results of the shear strength tests. The thermal treatment had a negative effect on the shear strength of the welded joints, and the mode of failure of thermally modified wood in mechanical tests was in most cases brittle. This result was indicated by a significant reduction in shear strength of the thermally modified specimens in comparison to non-treated control specimens. This result is in line with a previous study (Boonstra *et al*. 2006) that showed that thermal modification of wood based on an industrial two-step Plato process markedly reduced the shear strength of the joint. The joint strength was, however, markedly lower than that obtained when welding non-modified timber. The loss in strength is generally due to a degradation of the hemicellulose polymer, which results in the degradation of the cell-wall matrix (Kollmann and Fengel 1965).

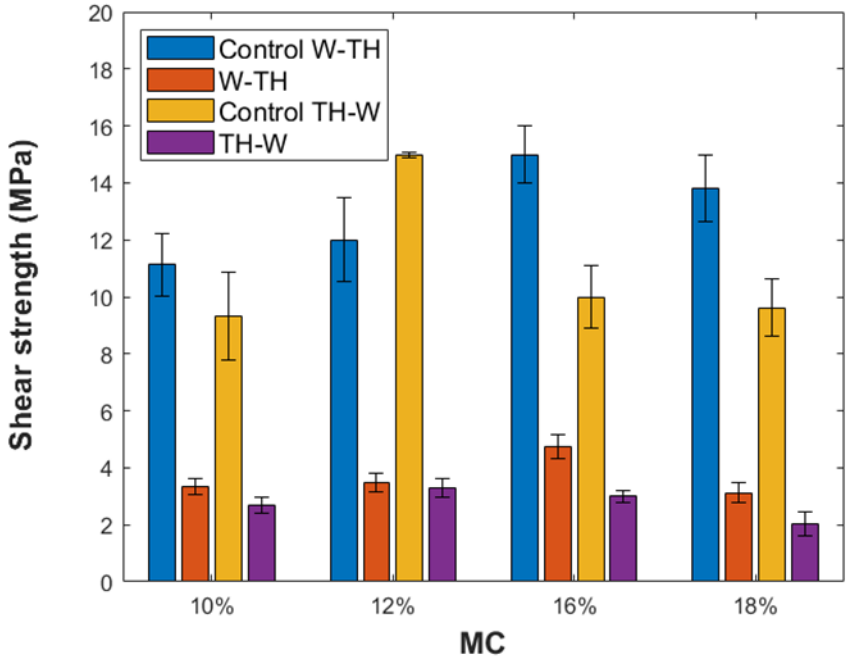


Fig. 3. Average shear strength of the specimens welded before thermal modification (W-TH), welded after heat treatment (TH-W), and non-treated welded controls (control W-TH, control TH-W) at four different MC levels

The average shear strength of the specimens welded before the thermal modification (W-TH) was greater than that of the specimens welded after thermal modification (TH-W). However, the multiple range test with the 95% LSD (Least Significant Difference) procedure indicated that these differences were not statistically significant. Increasing the moisture content from 10 to 18% resulted in an insignificant decrease in the shear strength of the specimens that were thermally modified before welding (TH-W). The W-TH specimens were less susceptible to humidity changes than TH-W in the range of 10 to 18% MC.

Figure 4 shows the CT-number profile of two groups of specimens: those welded before and after thermal modification, and their respective non-treated controls. The average CT-image was taken over the five replicates of each group in the z-axis direction and over all the 10 slices, which were distanced 2 mm from each other. The X-ray absorption was measured along a line of 100 pixels across the weld line, as is shown in Figure 2. Welding wood before thermal modification (W-TH) yielded thicker and more densified joints than those obtained by welding thermally modified wood (TH-W), and the average density of the welded joints in W-TH and TH-W samples were 89% and 24% greater than that of the adjacent wood, respectively. Thus, thermal modification affected the main melting region of the wood, namely the intercellular material. The thermally-modified wood materials had undergone chemical reactions so that inadequate material remained in the welding interface to build a strong welding joint (Boonstra *et al.* 2006).

Figure 5 shows microstructural differences between the non-treated (Fig. 5a) and thermally modified wood (Fig. 5b). The effect of the thermal modification became evident by a visible dark discoloration of the treated wood. Figure 5c and 5d show the microstructure of the welded interface in non-treated control specimens. The wood fibers were torn out, destroyed, and crushed by high welding pressure so that the wood lost its

original cellular structure (Fig. 5c). Using lower welding pressure, however, the wood cells were only partially destroyed and traces of unaffected wood were seen next to the welded wood (Fig. 5d). This could be one of the reasons for the lower strength obtained in welding non-treated wood at low pressure (control TH-W) than that obtained in welding non-treated wood at high pressure (control W-TH).

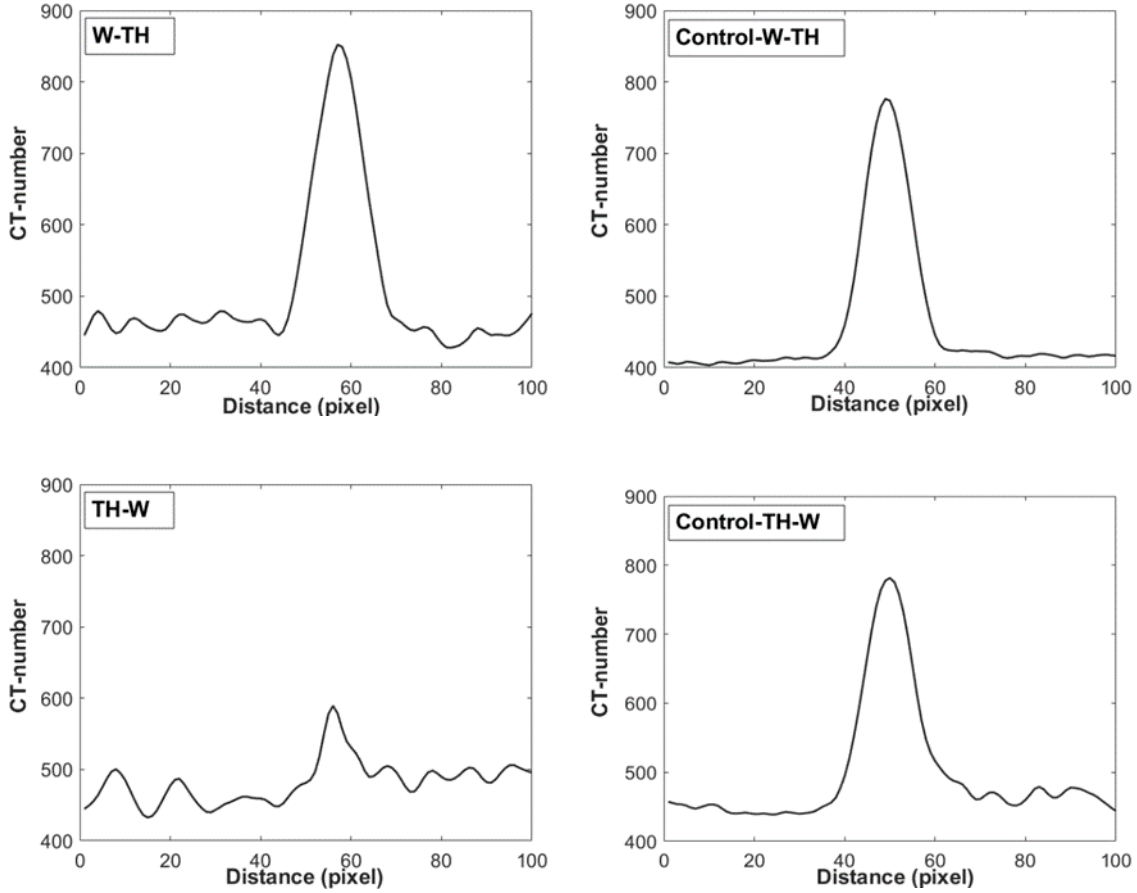
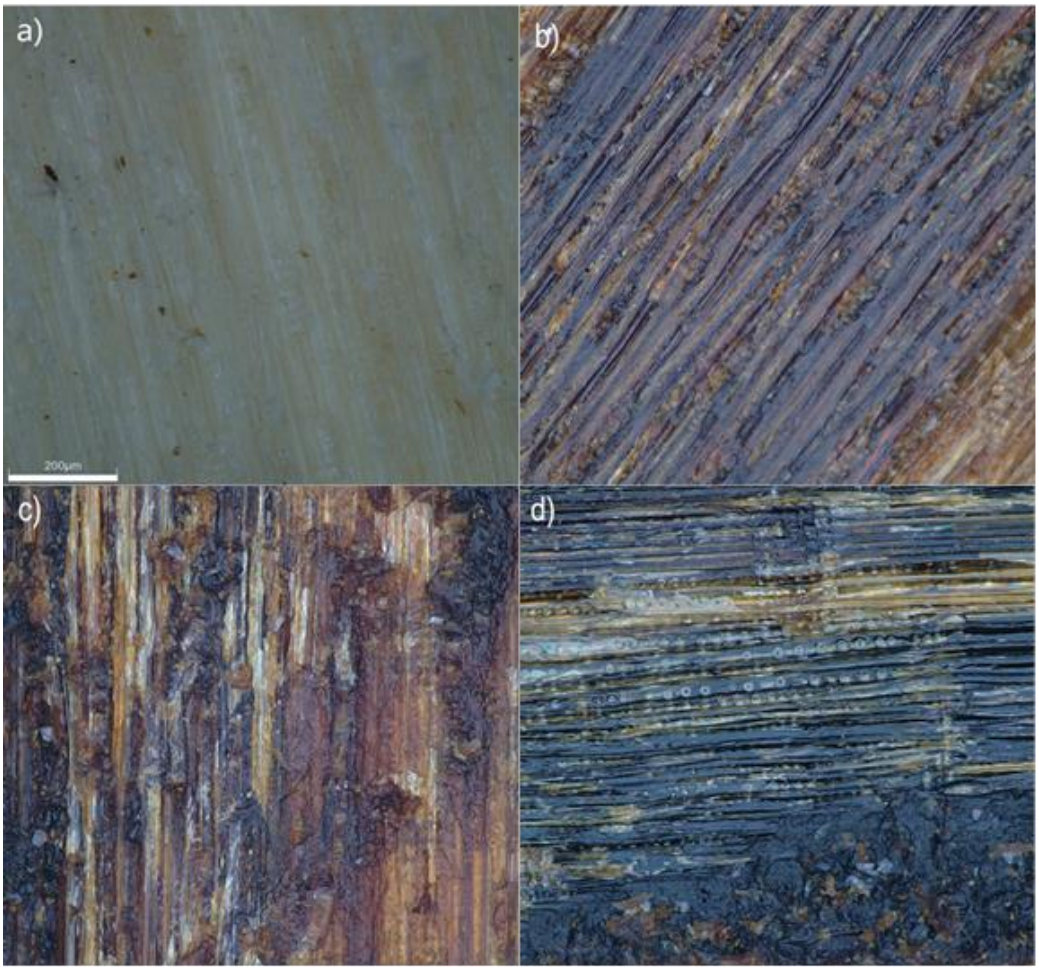


Fig. 4. Average CT-number profiles of four groups of specimens: welded before thermal modification (W-TH), welded after thermal modification (TH-W), and non-treated welded controls (control W-TH, control TH-W).

The softening or glass transition (T_g) of three major compounds of wood (Lignin, cellulose, hemicellulose) occurs at rather high temperatures. The glass transition for dry lignin and hemicellulose are around 124 to 235 °C and 167 to 217 °C respectively, but these values are highly related to the moisture content. Moist samples showed significantly lower softening temperatures, which averaged out at 78 to 128 °C for lignin and 54 to 142 °C for hemicellulose (Goring 1963; Horvath *et al.* 2011). According to the examinations of Gfeller *et al.* (2003), the temperature during welding exceeds the glass transition point of lignin and hemicelluloses. The presence of moisture and suitable heat during the welding and thermal modification can lead to softening and flowing of wood compounds mainly lignin.

Figure 5e and 5f show the welded interface of thermally modified specimens (TH-W and W-TH). During welding of the thermally modified wood (TH-W) the contact zone is exposed to further decomposition due to the welding pressure, and frictional motion and rigid products similar to charcoal are produced (Fig. 5e). Figure 5h shows the welded joint of the W-TH specimen in which a gap appeared. Thermohydro treatment of the welded wood may have caused softening and loss of the material that forms the interfacial welded composite and resulted in a gap in the welded joints.

The thinner welded joints in the TH-W specimens compared with the W-TH specimens were visible in microscopy images as well as in CT-number profiles in Fig. 4. This may indicate that due to the rigidity of the thermally modified wood, the cells were not detached and were not entangled as normally observed when welding non-treated timber and hence the interfacial strength was lower.



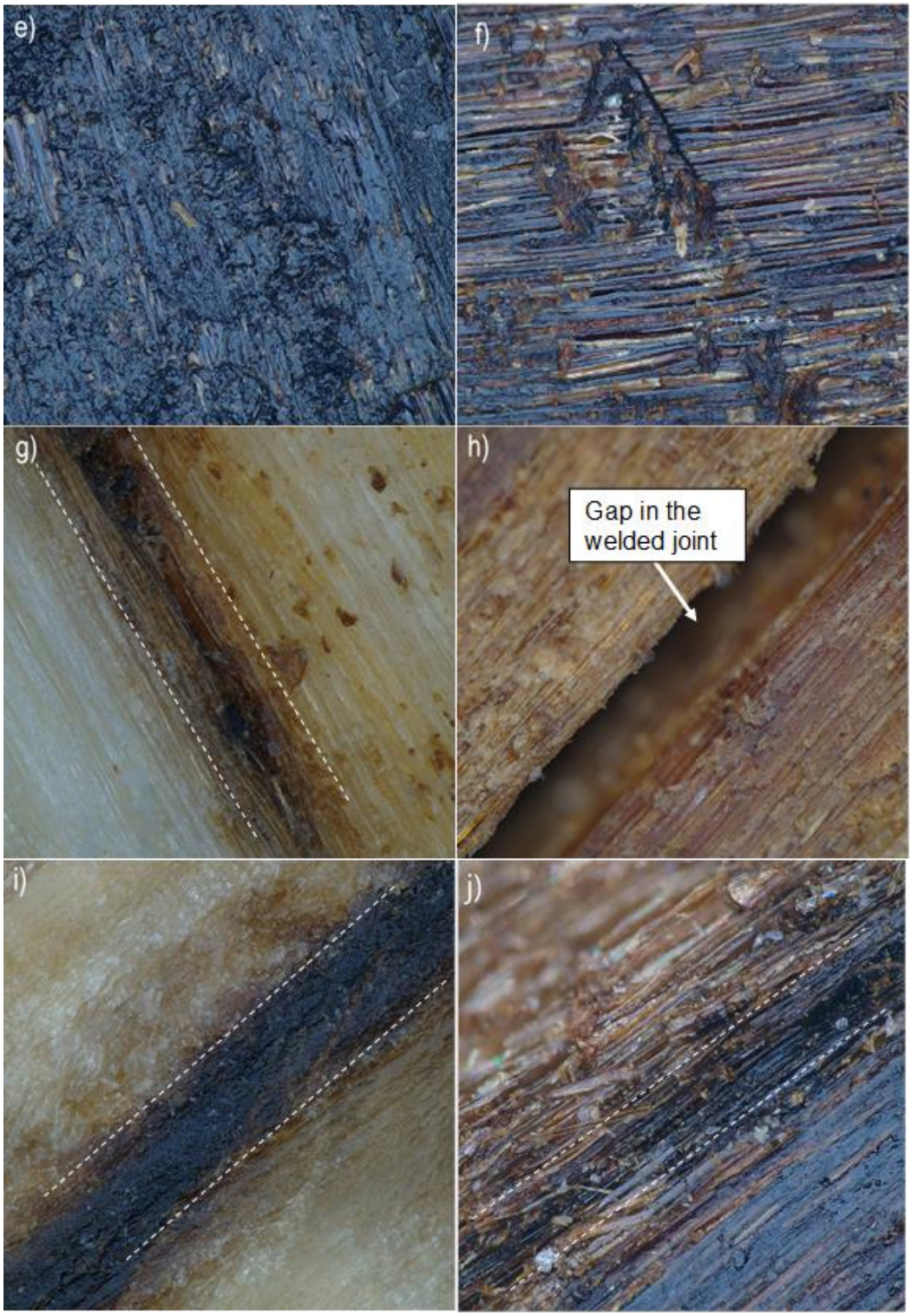


Fig. 5. Digital microscopy images of the thermally modified and non-treated specimens: a) non-treated pine sapwood, b) thermally modified pine sapwood, c) welded interface of control W-TH, d) welded interface of control TH-W, e) welded interface of TH-W, f) welded interface of W-TH, g) welded joint of control W-TH, h) welded joint of W-TH, i) welded joint of control TH-W, and j) welded joint of TH-W. The welded joint are marked with dotted lines in Figs. g, i, and j. All the images have the same scale as Fig. a (200 µm).

CONCLUSIONS

1. The shear strength of the thermally modified specimens was significantly lower than that of the respective control untreated specimens.
2. The shear strength of the welded joints were lower if thermal modification was done before welding rather than after welding. In vibration welding, the contact zone is exposed to welding pressure and frictional motion. For already thermally modified wood, this will lead to further decomposition and degradation of the wood and produce rigid chemical products similar to charcoal. This can be one of the reasons causing the lower shear strength of this type of welded joints (TH-W).
3. Thermal modification is not a suitable approach to improve the resistance of welded wood to water due to the considerable reduction in shear strength.

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