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WATER RESISTANCE OF WELDED PINE

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Abstract:
Wood welding is a novel technology to join wood elements based on friction between two wood surfaces. The crack formation in the welded joint was visualized and studied using X-ray Computed Tomography. Increasing the welding time from 4 s to 5 s could either make no difference or decrease the cracking time i.e. the time from water exposure of the specimen to the crack appearance in the welded joint, whereas increasing the welding time could improve the water resistance and shear strength of the welded joint. The incompatibility between the CT-scanning results with immersion test and the shear strength results lead to the idea that the cracking time may not be an indicator of durability and strength of the welded wood.

***Key words**: cracking; CT scanning; Micro CT scanning; shear strength; welding time.*

INTRODUCTION

Wood welding is a novel procedure for joining wood pieces without the use of adhesives or any other material than the wood itself. Solidification of the induced material flow at the interface makes a bond capable of reproducing the behaviour and performance of synthetic resins (Vaziri et al. 2015a). First pioneered in 1996, the welding process and the mechanical properties of the welded wood have been studied in the past decade across Europe and the technique has shown some success in the furniture industry (Pizzi et al. 2011, Navi and Sandberg 2012). However, to date there have been few studies related to structural applications, in part due to the vulnerability of the weld to damage from moisture. For industrial applications of the technology, the long-term stability of the joint must be ensured.

The durability of welded wood can be improved through different methods. Optimization of the welding parameters (welding time, welding pressure etc.) and parameters related to the geometry and structure of the wood (Belleville et al. 2017), dimensional stabilization of wood by thermal and chemical treatments techniques such as acetylation and furfurylation (Pizzi et al. 2012) or surface coating with naturally derived additives (Amirou et al. 2017). A majority of these processes decrease mechanical performance indicators in wood or contain components that are of environmental concern. However, efforts regarding enhancing moisture resistance of the welded wood by optimisation of process parameters and understanding of the underlying mechanisms of water damage in the welded wood joints are still comparatively rare.

OBJECTIVES

The overall purpose of this work is following up the previous studies (Vaziri et al. 2011) to gain information related to the effect of welding time on water resistance of the welded Scots pine (*Pinus sylvestris* L.) as one of the most used European species. A crack in the welded joint is the first sign of damage. Therefore, with the help of well-developed image processing algorithms and using non-destructive test methods such as X-ray Computed Tomography (CT-scanning), the cracks in the welded joints were visualized and cracking times (the time from water exposure of the specimen to the crack appearance in the welded joint) were calculated.

Related to this, an effort was also made to analyse the shear strength of the welded wood and durability of the joint in water using immersion test, in order to define if there is any correlation between cracking time, delamination time, and shear strength of the welded joint.

MATERIAL AND METHOD
PREPARATION OF THE SPECIMENS
WELDING

Wood specimens with dimensions of 20mm × 20mm × 230mm (R × T × L) were prepared from clear pieces of Scots pine. The materials were conditioned for two weeks at 20ºC and 65% relative humidity (RH) in an environmental chamber to 12% moisture content (MC) and welded together in pairs to dimensions 20mm × 40mm × 230mm (Longitudinal welding of a tangential face to a radial face). The linear vibration welding machine type M 624 (Branson) with a frequency of 240Hz and settings according to Table 1 was used for the welding procedure.

Table 1

The welding procedure and classification of the specimens

Specimen type	Welding Time (s)	Initial Welding Pressure (MPa)	Final Welding Pressure (MPa)	Holding Time after Welding (s)	Holding Pressure (MPa)
T4	2 + 2 = 4	1.3	1.7	10	2.7
T5	2 + 3 = 5				

CT SCANNING

The welded specimens were conditioned in the CT-laboratory at ambient conditions to 8% MC for 10 days before scanning. For each welding time 5 specimens were prepared. The welded specimens were placed with butt ends in 5mm deep tap water in an experimental rig (Fig. 1) and were scanned over 2 days at 30min intervals by a medical X-ray CT-scanner (SIEMENS Emotion Duo) at ambient conditions according to scanner settings in Table 2. For image reconstruction, a standard S80s algorithm was used. The X-ray sorption was measured along the welded joint in an area of 222mm × 25mm.

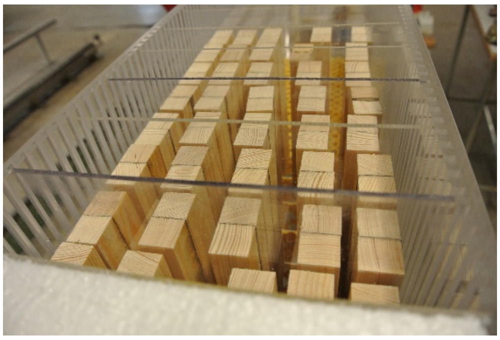

Fig. 1.
Experimental rig for CT-scanning. Two batches of welded specimens were placed in the rigs and separated with plastic walls so that all welded joints of each batch were placed along a line to be captured by one scan.

Table 2

Setting of the CT-scanner

Parameter	Unit	Value
Voltage	kV	110
Current	mA	70
Scan time	s	2
Scan thickness (depth)	mm	1
Matrix	Pixels	512 × 512
Resolution	Pixels/mm	0.58

The CT scanning generates images with greyscale values that corresponds to the attenuation coefficient of the materials. This coefficient is in turn related to density of the scanned material, which is shown by an intensity profile (Lindgren et al. 1992, Vaziri et al. 2010). The MC of the scanned wood specimens can be determined by a complementary scan of the same specimens at 0% MC. The calculated X-ray linear attenuation coefficient in each small volume element (voxel) was normalized by the corresponding linear attenuation coefficient for water according to Equation (1). This normalized value was referred to as the CT-number (Herman 1980).

$$y = 1000 \cdot \frac{\mu_x - \mu_{water}}{\mu_{water}}, \qquad (1)$$

where: y denotes the CT-number, μ_x the attenuation coefficient for the tested material, and μ_{water} the attenuation coefficient for water. A CT-number of -1000 indicates an object or a voxel within the object that has the density of air and a CT-number of zero indicates a region in the slice of the object with the density of water. Water movement and crack propagation were traced in the weld interface by CT-image analysis using the software Matlab R 2018b.

Water movement and crack propagation was traced in the welding interface by CT image analysis with the same software. The positions of the welded joints were changed by swelling of the specimens and were not along a line. Therefore, CT-number profiles of the specimens were created separately. Variation in the welded joints position indicates that the specimens have moved because of swelling and a big reduction in the top of the density profiles implies a crack forming in the welded joint (Vaziri et al. 2011).

SHEAR STRENGTH AND WATER IMMERSION TEST

30 welded specimens consisting of 15 specimens welded for 4s and 15 specimens welded for 5s, were prepared and conditioned for 10 days in an environmental chamber (20°C and 65% RH) to 12% MC before testing. The specimens were cut according to the method described in European standard EN 14080 (2013) and tested using Instron Universal testing machine (ASTM D143-14) along the longitudinal direction of the specimens at a rate of 2mm/min. The average value and standard deviation of the bond strength and the average wood failure were calculated for each set of specimens (Table 3).

For water immersion test the welded specimens of original size of 20mm × 20mm × 200mm were conditioned to 12% MC in the conditionings room and then were put in cold tap water in the ambient room temperature (22°C) until delaminating of the welded joints.

RESULTS AND DISCUSSION

CRACK DETECTION BY CT-SCANNING

Figures 2 and 3 show typical CT-number profiles of two groups of the specimens when a crack appears in the welded joint of at least one of the specimens in comparison to their dry profiles (dot lines in Fig. 2 and 3) and the previous time of scanning (dash-dot lines in Fig. 2 and 3). The CT-number of some of the specimens welded for 4 s (S2, S4, and S5) fell below their original (dry) CT-number after 2.5 hours of water sorption which indicated a crack formed in their welded joints (Fig 2). For welded specimens in 5s also 3 specimens (S3, S4, and S5) cracked after 2.5 hours of water sorption (Fig 3). The average cracking time of the specimens welded for 4 s (T4) and those welded for 5s (T5) were 8h and 2h, respectively (Table 3).

Table 3

Cracking time (h) for specimens welded in 4 s (T4) and 5 s (T5)

Specimen group No.	S1	S2	S3	S4	S5
T4	31.5	2.5	0.5	2.5	2.5
T5	0.5	0.5	2.5	2.5	2.5

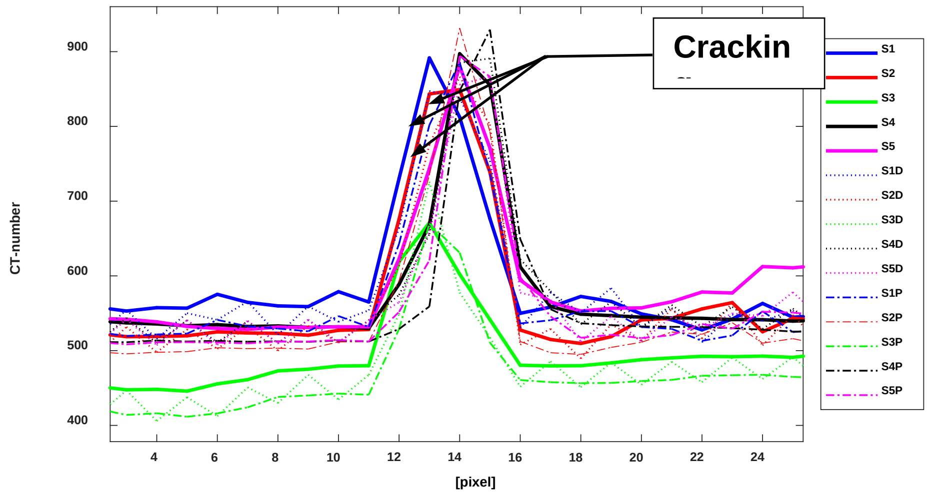

Fig. 2.
CT-number profile of welded joints for 5 specimens welded for 4 s (T4). S1-S5 are welded specimens after 2 .5 h water sorption; S1P-S5P are previous scanning (2 h after water sorption); S1D-S5D are dry welded specimens (before water sorption).

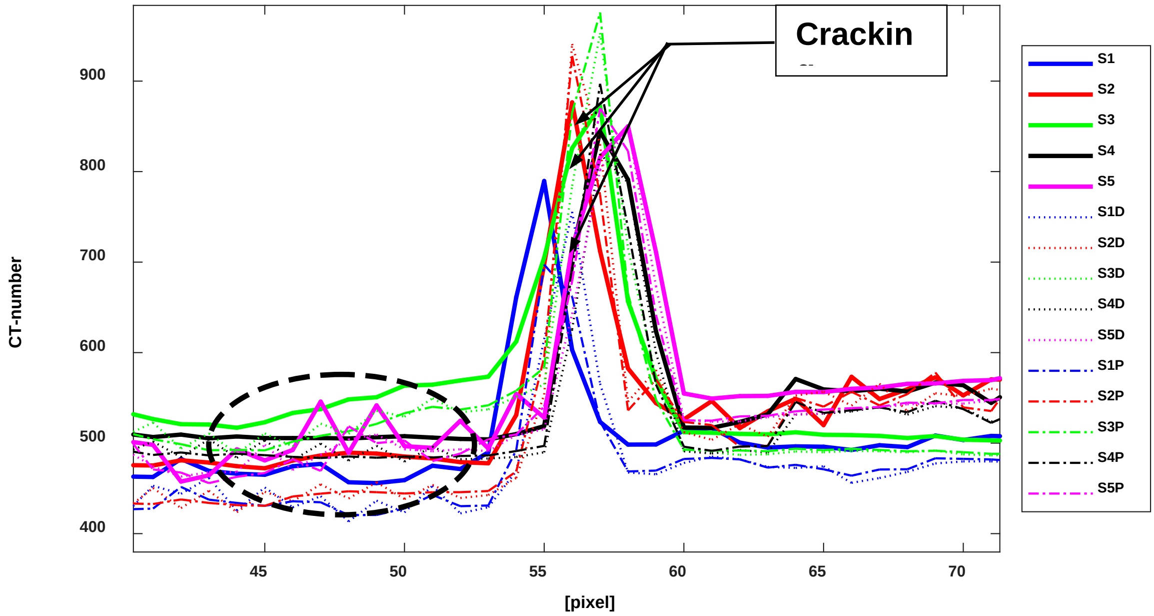

Fig. 3.
CT-number profile of welded joints for 5 specimens welded for 5 s (T5). S1-S5 are welded specimens after 2 .5 h water sorption; S1P-S5P are previous scanning (2 h after water sorption); S1D-S5D are dry welded specimens (before water sorption). The dotted ellipse shows the density profile of early wood and late wood within the growth ring.

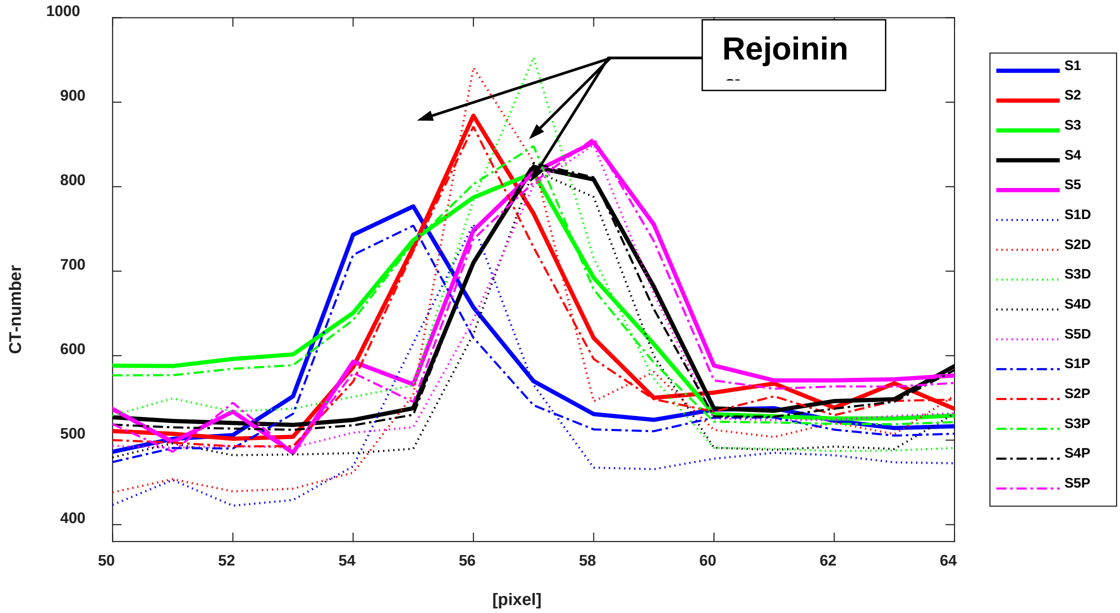

Fig. 4.
CT-number profile of welded joints for 5 specimens welded for 5 s (T5). S1-S5 are welded specimens after 6.5 h water sorption; S1P-S5P are previous scanning (6 h after water sorption); S1D-S5D are dry welded specimens (before water sorption). Arrows show the CT-number profiles of three specimens (S2, S4, S5) have increased after cracking to the same level as the previous ones (S2P, S4P, S5P).

The CT-number profiles of the joints of the specimens increased again after cracking by continuing the water sorption and reached to the same level or above as before (Fig. 4). This might be explained by the cracks being filled with water or by swelling of the welded joint and/or wood around it and re-joining of the wood pieces.

The density of the welded joints and the adherent woods increased with water sorption and the zigzag pattern of the wood profiles disappeared due to water sorption and homogenising the densities of earlywood and latewood (Fig.3). If the specimen T4, S1 (Table 3) with longest cracking time is considered as an outlier, then two groups (T4, T5) show almost the same cracking time.

SHEAR STRENGTH AND WATER RESISTANCE

The average shear strength of the specimens welded for 5s were higher than that of the specimens welded for 4s (Table 4). The average shear strength of the joints were acceptable, but the percentage of the wood failure was relatively low.

Table 4

Average shear strength of the specimens

Specimen type	Average Shear Strength (MPa)	Maximum Shear Strength (MPa)	Average Wood Failure (%)
T4	4.93 ± 2.3	9.8	5
T5	6.3 ± 3.31	11.8	10

More notable, however, is the time that these joints are capable to withstand immersion in water without falling apart. More than 46% of the specimens welded for 4s (T4) delaminated within the first 24 hours of water sorption and about 30% delaminated during the second day. However, the specimens welded for 5s (T5) delaminated with delay of about 26 hours. They survived the first 24 hours of water sorption without delaminating and then about 50% of them fell apart during the second day and 30% within the third day. Two specimens of each group are still kept together for 120 -and 90 days for T4 and T5, respectively without delamination.

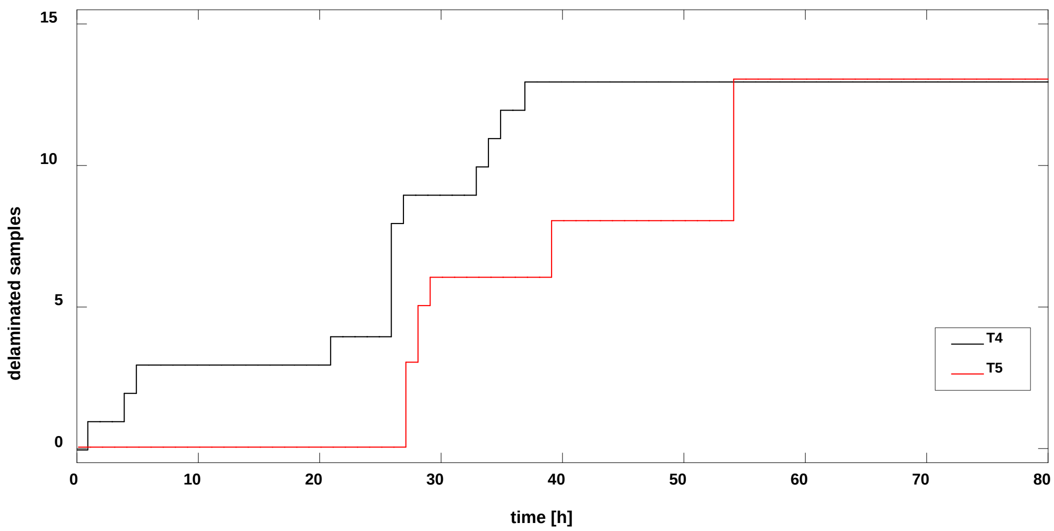

Fig. 5.
Accumulated number of delaminated specimens versus immersion time in water for 2 different groups of welded specimens, each of which consisted of 15 specimens; T4-specimens welded for 4 s and T5-specimens welded for 5 s.

Based on the previous results (Vaziri et al. 2015b), longer welding time seemed to enhance formation of dehydration carbohydrate products like the furfurals and levoglucosan as well as phenols from lignin degradation (Vaziri et al. 2015). Condensation reaction between aldehydes and phenols may also take place during welding which results in forming cured resins under hot and alkaline conditions. Such materials may enhance the water resistance and mechanical strength of the welded joint (Pizzi et al. 1994).

CONCLUSİON

The analysis of crack formation in the welded interface using CT-scanning revealed that, in the frame of welding parameters used in this study increasing the welding time for 1 second could either make no difference or decrease the cracking time. Based on the water immersion and shear strength tests, increasing the welding time had a clear tendency toward enhanced water resistance and improved shear strength of the welded wood.

The incompatibility between the CT-scanning results with immersion test and the shear strength results leads to the idea that the cracking time may not be an indicator of durability and strength of the welded wood. Since the specimens containing crack are still able to withstand the water without falling apart it can be concluded that the size, depth, and distribution of the cracks have also some effect on the water resistance of the welded wood. Using a high resolution CT-scanner and introducing different methods of crack detection may lead to different results than that obtained in this study.

The results of this study is indicative, but not really, a verification of behaviour of the welded wood for different welding times. Therefore, it is recommended for future work to study the cracking times and water resistances of more specimens welded in many different welding times to gain a clear pattern of correlation between these properties.

Furthermore, to study the ability of a joint to withstand the outdoor climatic variations from wet to dry, it is recommended for future work in addition to water immersion tests to expose the welded specimens to extreme weather variation such as the north European climate for a couple of months and test at regular intervals.

This study provides new knowledge for enhancing the moisture resistance of welded wood through optimization of process parameters and/or wood modification technique.

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