Influence of Welding Time on Tensile-Shear Strength of Linear Friction Welded Birch (*Betula pendula* L.) Wood

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The purpose of this work was to determine the optimal welding time for linear friction welding of birch (*Betula pendula* L.) wood while keeping the other parameters constant and at similar levels compared to other species in a similar density range. Specimens with dimensions of 20 × 5 × 150 mm^3 were welded together, and the influence of welding time (2.5, 3.0, 3.5, and 4.0 s) on the mechanical properties of the specimens was determined. The studies included a tensile-shear strength test as well as visual estimation of wood failure percentage (WFP). Additionally, X-ray microtomographic imaging was used to investigate and characterise the bond line properties as a non-destructive testing method. The highest mean tensile-shear strength, 7.9 MPa, was reached with a welding time of 3.5 s. Generally, all four result groups showed high, yet decreasing proportional standard deviations as the welding time increased. X-ray microtomographic images and analysis express the heterogeneity of the weld line clearly as well. According to the averaged group-wise results, WFP and tensile-shear strength correlated positively with an R^2 of 0.93. An extrapolation of WFP to 65% totals a tensile-shear strength of 10.6 MPa, corresponding to four common adhesive bonds determined for beech.

Keywords: Birch; Bond line; Non-destructive testing; Parameter optimization; Tensile-shear strength; WFP; X-ray microtomography; Welding of wood; Welding time

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INTRODUCTION

The frictional welding of wood is one of the most innovative technologies for creating wood joints without additional adhesives or other chemicals. The various welding processes, *i.e.*, linear, orbital, and rotational friction welding, are environmentally friendly techniques offering advantages over traditional gluing and mechanical fastening, including short bonding times and energy savings. Linear friction welding, *i.e.*, welding with a reciprocating movement, is commonly employed in the thermoplastics and metals industries, and it has shown potential in wood-to-wood connections as well (Sutthoff *et al*. 1996). To highlight the key phenomena within the friction welding process for wood, first certain wood components soften to the point that they even melt and evaporate; second, the components and derivatives form an interphase between the two pieces of wood to be joined by a high-density composite of entangled wood fibres drowned into a matrix of molten wood-intercellular material, such as lignin and hemicelluloses (Gfeller *et al*. 2004;

Mansouri *et al*. 2009). The friction welding of wood is characterised by a rapid increase in temperature from ambient up to 220 °C or 450 °C in linear or orbital friction welding, respectively (Stamm *et al*. 2005). Mostly as a result of the temperature increase induced by frictional forces, the wood surfaces start to decompose, soften, and finally form a viscous film. After reaching the maximum temperature, the steady state conditions of constant temperature and coefficient of friction are attained momentarily. At the end of the process, pressure is maintained on the welded wood joint for a certain holding time, allowing the interfacial film forming the connection to cool down and solidify (Gfeller *et al*. 2003; Stamm *et al*. 2005).

The quality of a linear friction welded joint correlates with certain welding parameters, such as welding pressure (WP), welding frequency (WF), welding time (WT), holding pressure (HP), holding time (HT), amplitude or displacement (A), wood species, orientation of wood grains and annual rings relative to the interface, equilibrium moisture content of the wood (EMC), and specimen dimensions. The strength and the wet stability of the welded joints can thus be measured and investigated as a function of these parameters (Vaziri *et al*. 2012), which can be categorised according to whether they are machine settings or material properties.

The frictional heat generated at the joint interface plays a key role in the density of the weld line (Ganne-Chedeville *et al*. 2006). The thickness of the welded zone also varies as a function of the maximum temperature reached during welding, whilst the maximum temperature reached at the ends of the specimen has been found to be lower than that in the central part of the specimen (Ganne-Chedeville *et al*. 2006). According to Vaziri *et al*. (2011), the degree of densification at the weld line varies from 160 to 190% of the untreated wood density. According to Properzi *et al*. (2005), bond line strength is influenced by the orientation of the wood grain on the two bonding surfaces. For instance, where the grain in the two surfaces runs parallel, there is an approximately 10% difference in bond strength between the tangential and radial wood sections. If the grains of the wood surfaces are perpendicular to each other, however, bond strength is noticeably lower, being approximately half that observed in specimens where the grain of the two surfaces run parallel to each other. These differences are explained by the effect that homogeneity of fibre orientation is known to have on fibre-matrix composites (Properzi *et al*. 2005). However, neither Omrani *et al*. (2010) nor Rhême *et al*. (2014) could find these differences to occur statistically significantly. The welding process is governed by heat generated from frictional movement in the welded area. A certain temperature is necessary to reach the “melting” state. Welding pressure has a greater influence on heat generation in the interphase than does welding time (Vaziri *et al*. 2010). When the welding pressure is increased, the frictional force and the amount of energy supplied to the interphase rises; thus, welding time can be reduced as welding pressure is increased.

In early studies, a WT of 3 to 6 s, WF of 100 Hz, amplitude of 3 mm, and WP of 1.3 to 2 MPa have been found to give the highest and least variable tensile-shear strength (Gfeller *et al*. 2003; Ganne-Chédeville *et al*. 2005). Welded joints produced by Gfeller *et al*. (2003, 2004) yielded a tensile-shear strength of more than 10 MPa in beech (*Fagus sylvatica* L.) and 2 MPa in spruce (*Picea abies* L. Karst.) with the following parameters: WT = 3 s, WP = 1.3 MPa, WF = 100 Hz, HP = 2 MPa, HT = 5 s, A = 3 mm (beech) / 1 mm (spruce), and EMC = 12%. With the same welding parameters, but maintaining A = 3 mm in all cases, Leban *et al*. (2004) obtained tensile-shear strengths of 8.7, 5.4, and 4.2 MPa on average for beech, oak (*Quercus robur* L.), and spruce wood, respectively. Since then, several researchers (Mansouri *et al*. 2009; Omrani *et al*. 2009; Vaziri *et al*. 2010) have found that a WT of 1.5 s leads to greater, yet not necessarily long-term, water resistance than a WT of 2.5 s. Mansouri *et al*. (2009) reported results on the strength of welded (WT = 1.5 s, WF = 150 Hz, and A = 2 mm) beech wood joints, finding that in dry conditions, values of around 13.4 MPa were obtained, but after 4 h of immersion in water, the strength decreased markedly. In further studies conducted by Mansouri *et al*. (2011), welded joints in high-quality Scots pine (*Pinus sylvestris* L.) wood had an average strength value of about 4.1 MPa for heartwood and 3.5 MPa for sapwood. More recently still, Vaziri *et al*. (2012) showed that with Scots pine, using a WT of 2.8 s yielded stronger joints than 2.0 s, and, by extending the WT to 3.5 s, even higher tensile-shear strengths could be produced. This optimisation test indicated that the tensile-shear strength of Scots pine welded joints is more sensitive to WT than to HT. Vaziri *et al*. (2012) concluded that they were able to produce joints with a tensile-shear strength of more than 9.7 MPa with a WP of 1.3 MPa, a WT of greater than 3.5 s, and a HT of less than 60 s.

Many wood species have been studied in previous work, especially those common to Central Europe. Northern European countries are, however, significant producers of wood products with their own distinctive variety of species. Because of structural changes that have occurred within the industry, as well as challenges arising from the cost structure of the raw materials (especially adhesives derived from crude oil), it is important to investigate new manufacturing methods to maintain industrial competitiveness into the future. This justifies an investigation into the linear friction welding of the most common deciduous wood species in Nordic countries—birch (*Betula pendula* L.)—which so far has not been intensively studied.

The objectives of this work were therefore as follows: (1) to determine whether birch (*Betula pendula* L.) wood could be employed in linear friction welding in a similar way to the species studied previously, (2) to define the optimal welding time to give reasonable tensile-shear strengths, (3) to determine the wood failure percentage (WFP) and to compare these to the results from the strength tests, and (4) to study the heterogeneity of the weld line. The fourth objective was achieved by investigating the standard deviation of the shear strengths as well as by X-ray microtomographic scanning, which provided a thickness distribution and a map of the bond line, as well as the density profile over the specimen. The X-ray microtomographic study was carried out on only one specimen representing the group with the highest mean bond strength.

EXPERIMENTAL

Wood sections of width 20 mm, thickness 5 mm, and length 150 mm, where the annual rings were oriented diagonally towards two of the surfaces (see EN205), were cut from birch (*Betula pendula* L.) grown in Finland. The density measured after 24 h of drying in an oven at 103 °C was, on average, 568 kg/m^3. The sections were welded together to form welded specimens of dimensions 20 × 10 × 150 mm^3 using Branson M-DT24L linear vibration welding equipment (BFH–AHB, Biel, Switzerland). The specimens were conditioned at 20 °C temperature and at 65% relative humidity (RH) before welding, corresponding to an approximately 11% moisture content (MC). The process parameters, shown in Table 1, were chosen based on a review of the literature and previous experimental findings.

Table 1. Welding Parameters

Parameter	Values	Units
Amplitude	3	mm
Frequency	100	Hz
Welding Pressure	1.9	MPa
Welding Time	2.5, 3.0, 3.5, 4.0	s
Holding Pressure	1.9	MPa
Holding Time	7	s

The welded specimens (20 × 10 × 150 mm^3) were prepared and tested according to EN 205 (2003). Two cuts were sawn in the middle of the specimens, perpendicular to the weld line. The distance between the cuts was 10 mm. The mechanical performance of the weld line was tested using a universal testing machine (Zwick-8406) along the longitudinal direction of the wood fibres at a testing speed of 5 mm/min. All specimens were tested immediately after the welding process. After failure, the WFP of the joints was visually determined according to ASTM D5266-99 (1999). WFP was measured from 0% to 100% at 10% intervals. In addition to this, WFP values of 1% and 5% were used to signify very minor, but recognisable, wood failure.

X-ray microtomography was used to visualise the specimen, especially the bond line. A three-dimensional volumetric image of a 20 × 14 × 14 mm^3 piece of the welded wood sample was acquired with a SkyScan 1172 tomograph (Bruker MicroCT, Kontich, Belgium) using a 7 µm pixel size, 65 kV acceleration voltage, 135 µA electron current, 0.3° rotation step, and 3.5 s exposure time. Based on the image, the mean density profile of the specimen and a map of the local thickness of the weld line were determined. In addition to the local thickness, the areal distribution of thickness was also evaluated. The density profile was calibrated using the mean gray values and the densities of wood and air (568 kg/m^3 and 1.20 kg/m^3, respectively).

RESULTS AND DISCUSSION

Figure 1 (left) shows tensile-shear strength as a function of welding time. The results show high variability in the bond strength. With the welding time increasing from 2.5 s to 4.0 s, the proportional standard deviation of tensile-shear strength decreased from 39% to approximately 16%. The highest strength, 7.91 (1.45) MPa, was found when a welding time of 3.5 s was used, a value comparable with the findings of Vaziri *et al*. (2012), where 3.5 s was stated to be the optimal welding time for the best mechanical performance welded joints in Scots pine (*Pinus sylvestris* L.).

The tensile-shear strength values obtained in this study for birch wood (*Betula pendula* L.) are comparable with previously published values, *e.g*., 8.72 MPa for beech (Leban *et al*. 2004) or 9.7 for pine (Vaziri *et al*. 2012), and higher than those for oak, spruce, and pine: 5.4, 4.2, and 4.1 MPa, respectively (Leban *et al*. 2004; Mansouri *et al*. 2009). Possibly the most relevant comparison can be made with the results of Boonstra *et al*. (2006), who obtained a tensile-shear strength of 5.97 (0.68) MPa with birch (*Betula alba* L.), the density of which was, on average, 561 kg/m^3. However, the parameter set used in their study was as follows: WT= 3 s, WP= 4 MPa, HT= 7 s, HP= 4 MPa, A= 3 mm, f= 100 Hz, MC= 12 %. The biggest contrast to this study is, therefore, a shorter welding time and greater welding and holding pressures. Considering this, the result is not too different from the average strength reached for the specimen group with a WT= 3 s, which was found to be 5.64 (1.59) MPa. The highest average strength of the welded birch joint is also comparable with the shear strength of solid wood (8 to 13 MPa for birch, 6.8 MPa for spruce, 10.2 MPa for oak, and 6.1 MPa for poplar) (Wood Handbook 1999). This is reflected in the WFP, which yielded a higher share as the tensile-shear strength increased. As mentioned by Vaziri *et al*. (2011), examination of the tensile-shear strengths reveal that adhesion in the welded joint is a function of welding time and most probably passes through various characteristic phases. Similar behaviour occurred in the present study, *i.e.*, the strength improved with increased welding time before encountering a drop after a certain point in time (3.5 s). Finally, the welding time influences the tensile-shear strength but apparently without a linear correlation as there is a clear peak between the minimum and maximum welding times. In addition to this, it was studied how the tensile-shear strength is depicted as a function of wood failure percentage (WFP). This is shown in Fig. 1 (right).

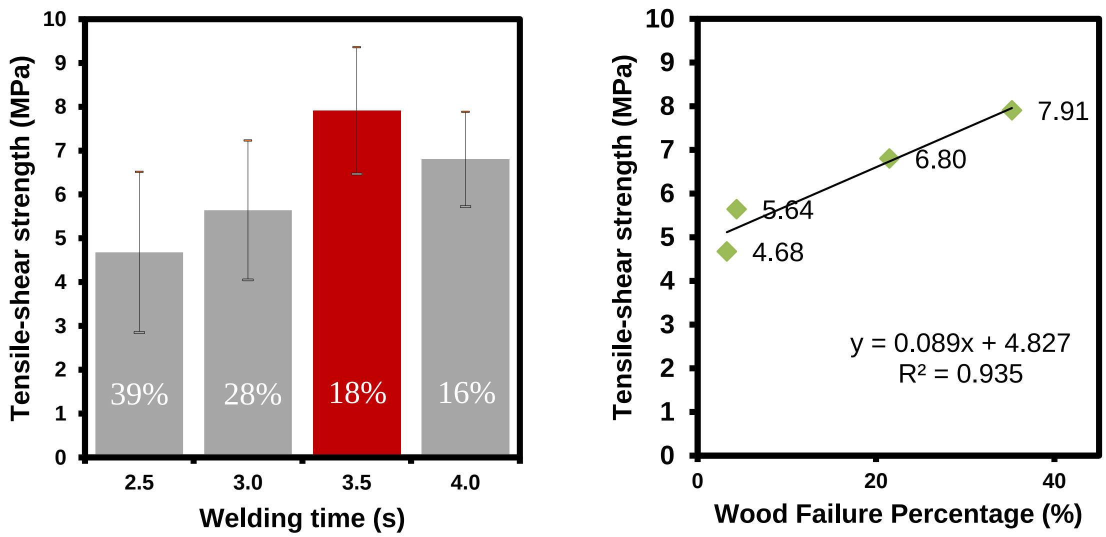

Fig. 1. Tensile-shear strength as a function of welding time, standard deviation is expressed as a percentage (left). Tensile-shear strength as a function of WFP, including linear regression model obtained with the method of least squares (right).

The WFP results are presented in more detail in Table 2 and include the average and standard deviation as well as the 25%, 50%, 75%, 85%, and 100% fractiles. When comparing group-wise the averaged WFP results to the averaged tensile-shear strength values, it can be easily seen that the results correlated positively, *i.e.*, the average WFP increased as the average tensile-shear strength increased. This could be seen in Fig. 1 (right). Both magnitudes peaked at WT= 3.5 s, and the correlation equation was y = 0.0889x + 4.83, with an R^2= 0.93. Extrapolation of WFP to 100% and 65% equated to tensile-shear strength values of 13.7 MPa and 10.6 MPa, respectively. A WFP of 100% would thus clearly be stronger than several ordinary glued bonds, whereas the latter, with a WFP of 65%, would correspond to four common commercial adhesive bond strengths determined for beech, *i.e.*, 10.7, 10.0, 10.5, and 9.7 MPa with PVAc, MUF, PRF, and PUR glues, respectively. With spruce, the same glues yield somewhat weaker bonds: 7.3, 5.7, 7.8, and 8.0 MPa (Konnerth *et al*. 2006). Therefore, the potential of linear friction welded birch is clear even without a full wood failure, which is commonly required for a proper adhesive bond. The requirement of a 100% WFP (or a value close to that) for a decent bond is actually followed by the common rule of fasteners or bonding agents: the material itself should always be the weakest part to fail. Moreover, in normal testing WFP has a secondary role; the tensile-shear strength is namely the primary value to be observed and reported frequently and whether it is below the acceptable limits, the WFP is to be evaluated. In the case of a poor WFP, the bonding process is then considered to have failed for any number of reasons; for example, the adhesive may have cured before hot pressing, or it did not have enough time to penetrate the wood, or the wood may have become too hydrophobic during the process. Regarding the aforementioned extrapolations of a 65% or a 100% WFP for linear friction welded birch, the values for tensile-shear strength are highly speculative, especially because a value of 13.7 MPa predicted from the WFP of 100% may be unreachable, as it exceeds the shear strength limit of birch wood, which is generally in the range of 8 to 13 MPa (Wood Handbook 1999). Finally, it is notable that the average tensile-shear strength for linear friction welded birch is on a relatively high level despite the moderate level of WFP. This would not be expected with the ordinary bonds but also the WFP would most likely be observed as a high value. Additionally, it is noteworthy that wood failure in general could be reported in case of a welded bond line. Previously this was not commented or reported too often within the literature. However, some authors, for instance, Tondi *et al*. (2007) have reported that “the fracture occurred within the weld line” in the case of ultrasonic welding of beech and oak.

Table 2. Wood Failure Percentage (WFP) Results

WT	Average (St. dev.)	Fractiles				
		25%	50%	75%	85%	100%
2.5s	3.3 (6.4)%	0%	0%	5%	10%	20%
3.0s	3.2 (6.3)%	0%	1%	1%	10%	20%
3.5s	35.3 (41.7)%	1%	10%	50%	100%	100%
4.0s	21.5 (27.9)%	1%	10%	30%	40%	100%

The fractile division presents a low WFP for 2.5 and 3.0 s WT throughout the group. Additionally, half of the specimens in each group totals maximally 10% WFP. The share of 100% WFP is the greatest at WT= 3.5 s.

The three-dimensional volumetric image (acquired with X-ray tomography) in Fig. 2 shows, for instance, the dense welded bond line oriented along the surface determined by the X and Y axes, as well as the anatomy of birch wood, *e.g.*, the pores and annual rings. The variation in the thickness of the bond line is shown as topographic contour lines, where “valleys” indicate thinner parts of the bond line and “hills” are the thickest parts of the bond line. At the edge of the image, a thicker bond line can be distinguished as a broader white line.

A single cross-sectional slice of the image is shown in Fig. 3 (left), visualising the cross-section of the interface as a horizontal, dense area in the middle. The heterogeneity of the bond line can be clearly seen as a variation in the thickness and as undulations–waviness–in the bond line. Figure 3 (right) shows the mean density distribution of the welded specimen as a density profile along a line normal to the interface. The profile presents altogether three different zones that are mirrored along the bond line. The zones, marked in Fig. 3 (right), are bond line (1), densification zone close to bond line (2), and non-influenced part of wood (3).

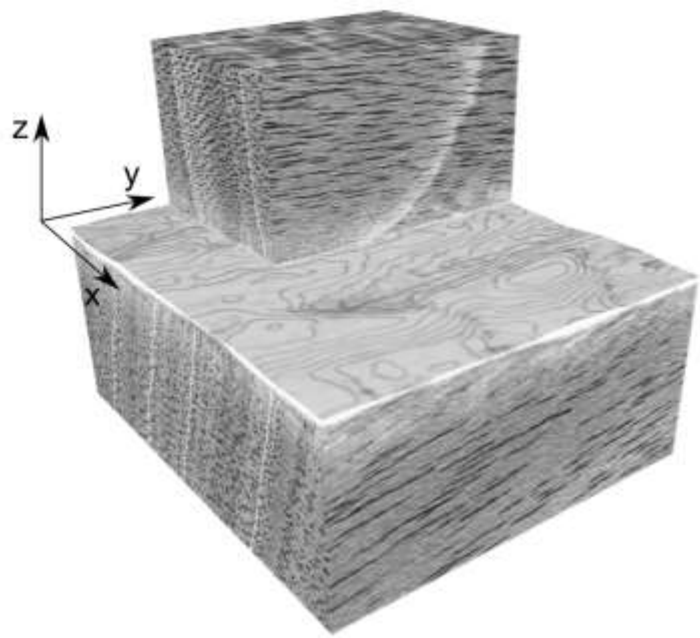

Fig. 2. Three-dimensional volumetric image of a welded specimen. Part of the material above the bond line was removed digitally. The welded bond line follows the X and Y axes, yet is presented as a non-planar shape showing variation in the thickness of the bond line as well.

The densest part of the bond line is circa 1000 kg/m^3, which corresponds to some extent to previous results by Boonstra *et al*. (2006), who reported the maximum weld line density for birch (*Betula alba* L.) circa 1100 kg/m^3 and by Leban *et al*. (2004) who reported the maximum weld line density for beech (*Fagus sylvatica* L.) circa 1100 kg/m^3, for oak (*Quercus robur* L.) circa 1100 kg/m^3, and for spruce (*Picea abies* L.) circa 1000 kg/m^3. However, also maximum densities lesser to these were reported by Ganne-Chedéville *et al*. (2006) who studied maple (*Acer* spp., L.) and yielded circa 930 kg/m^3 maximum weld line density. Additionally, Ganne-Chedéville *et al*. (2008) studied how the density ratio and the weld line width of welded beech develop as functions of time (from 0 to 11 s with an increment of 0.5 s). According to them, the width of the densified zone kept constant between the welding times of 2 and 5 s. Beyond that, the width increased as the welding time increased. The density ratio, signifying the share of the maximum density to undensified wood, oscillated between 1.45 and 1.70. Within this study the maximum density ratio is short 1.75.

Furthermore, the bond line presented as a peak in Fig. 3 (right) was segmented from the image using the carpet method (Edwards and Wilkinson 1982; Mettänen *et al*. 2011), resulting in a map of its local thickness (Fig. 4, right). Figure 4 (left) shows the areal distribution of thickness, ranging from 0.02 to 0.32 mm, being on average 0.18 (0.053) mm. The range of the undulations in the bond line is 0.50 mm, which is 56% greater than the maximum thickness. The undulations seem to occur such that the denser latewood is thrusting towards the less dense earlywood, in situations where the latewood portions are not adjacent to one another.

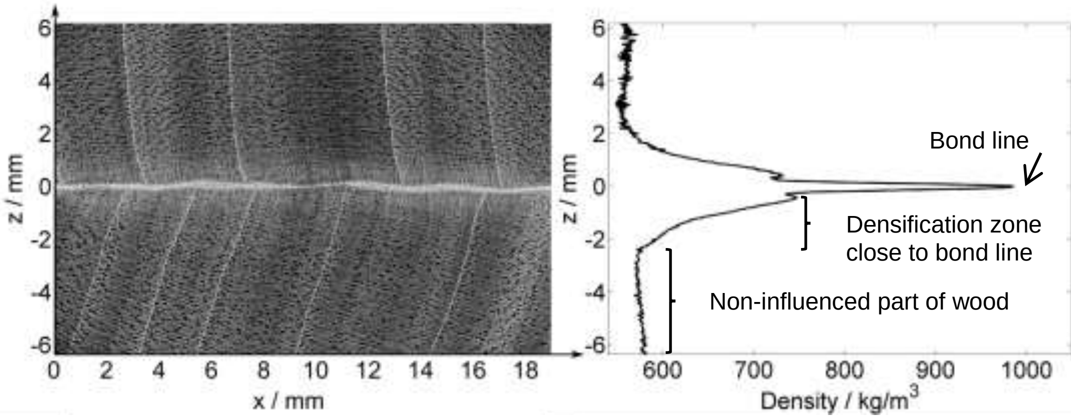

Fig. 3. A cross-sectional X-ray tomographic slice showing the weld line as well as densified zones on both sides of the weld line (left). Mean density profile of a welded specimen (right).

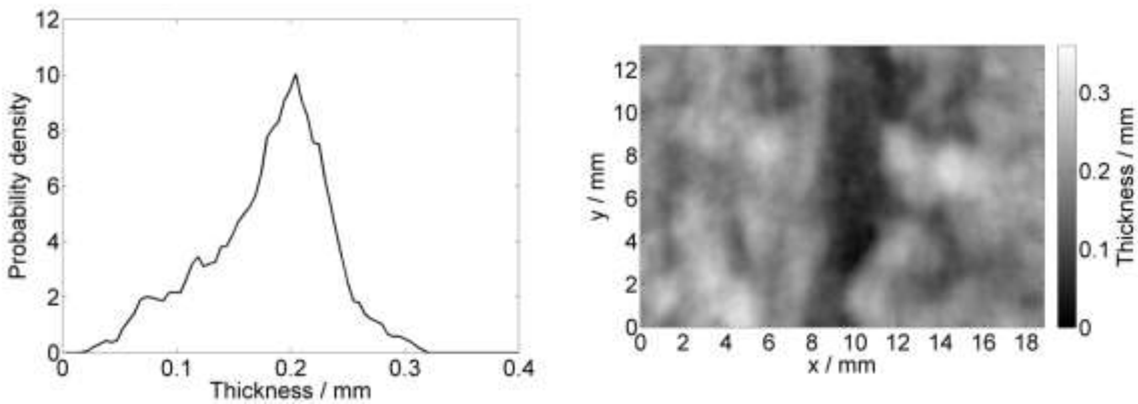

Fig. 4. Thickness distribution of the weld line (left). Thickness map of a part of the weld line. The reciprocating movement in the welding process follows the Y axis. The dark "valley" in the middle of the specimen indicates poor bonding whereas a thicker bond line is seen closer to the edges (right).

CONCLUSIONS

1. The applicability of birch (*Betula pendula* L.) wood to linear friction welding was tested with four welding times. The results of this work support the hypothesis that birch wood can be utilised as a material to manufacture linear friction welded joints with a promising tensile-shear strength.
2. In general, the tensile-shear strength data acquired shows a high proportional standard deviation that decreases, however, as welding time increases. In addition to the standard deviation, the notable heterogeneity of the welded bond line is shown in cross-sectional slices and in thickness distribution, as well as the thickness map of the bond line, all acquired through X-ray tomographic imaging.
3. From the four tested welding times studied, a welding time of 3.5 s resulted in the highest mean tensile-shear strength (7.9 MPa) with a moderately low (16%) proportional standard deviation. The quantified mean strength corresponds to four

common commercial adhesive bond strengths determined on spruce (*Picea abies* L.). The acquired mean and maximum values of tensile-shear strength are in line with previously published values for birch and other European deciduous species within the same density range.

4. As expected, the wood failure percentage increased as tensile-shear strength improved. It is noteworthy that strong bond strengths were measured in cases of rather moderate wood failure percentages as well. Typically, this is not expected with ordinary bonds based on adhesives.

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