Water Resistance of Heat-treated Welded Iroko, Ash, Tulip, and Ayous Wood

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The friction welding method has been an effective criterion in determining the mechanical performance of wood joints in wood industry applications compared to traditional methods. Although it is used in structural applications, joints from linear vibration are quite sensitive to water. In this study, the water resistance of the heat-treated woods, iroko (*Chlorophora excelsa*), ash (*Fraxinus excelsior* L.), tulip wood (*Liriodendron tulipifera*) and ayous (*Triplochiton scleroxylon*), were investigated by friction linear welding. The weld line density profiles were examined. The resistance of heat-treated welded wood joints to water remarkably decreased compared to the control sample, depending on water immersion time. The highest shear strength loss was found in tulip wood (60% to 65%) and the lowest shear strength loss was found in ash wood (3%) for the heat-treated group and in Iroko wood (17%) for the control. The heat-treated samples increased in density with welding but had a slightly lower density than the control group. According to the TGA results, it was found that the thermal degradation of untreated welded woods was lower than that of heat-treated welded woods. This difference could be due to the chemical constituents of hardwood and tropical wood. X-ray computed tomography (CT-scanning) is feasible and usable for welding line density change.

Keywords: *Water resistance; Density profile; Welding; Heat-treated wood*

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INTRODUCTION

The friction welding method of wood, which has been added to engineering methods in recent years and still subject to research by scientists, is a fastening method that has the advantage of being fast and economical and not requiring the use of additional materials such as mechanical fasteners or synthetic adhesives. The first research on welding wood, which is an alternative method to traditional joints, was conducted by Suthoff *et al.* (1996). Later, these authors reported that friction welding had a serious effect on wood-wood combination. The first studies on linear vibration friction welding were conducted in 2002 at the Berne University of Applied Sciences (HSB), Biel, Switzerland. It has also been suggested that it may be possible to join pieces of timber with a wood dowel using rotary frictional welding (Suthoff and Kutzer 1997). As a result of the study, the applicability of high value, environmentally friendly wood combinations was revealed (Gfeller *et al.* 2004). In addition to the advantages, such as friction welding, timesaving, and no synthetic adhesives or special treatment, however, so far there have been few studies on structural applications. This may be due to the low defense of the friction welding against moisture effects (Pizzi *et al*. 2006; Omrani *et al.* 2009; Mansouri *et al.* 2009; Vaziri *et al.* 2009, 2010; Vaziri 2011; Mansouri *et al.* 2011; Pizzi *et al.* 2011, 2013; Ganier *et al*. 2013; Ruponen *et al.* 2015; Amirou *et al*. 2017). Some studies have been carried out by scientists with the goal of increasing water resistance, and the main problem of mechanisms underlying water permeability in welded connections has not been explained yet. This negatively affects the durability of the material at the place of use.

Heat treatment, which is one of the wood modification methods to develop wood properties, such as dimensional stability, water resistance, and biological durability without using harmful chemicals, has been thought to be compatible with this new technology in the last few years (Esteves and Pereira 2009; Navi and Sandberg 2012). Some researchers have stated that the reasons for determining the dimensions of wood are based on changes in anatomical conditions when exposed to heat (Yıldız *et al.* 2006; Barcík *et al.* 2015; Aydemir *et al.* 2016; Fu *et al.* 2019). Accordingly, they focused only on lignin modification and varying cross-linking. Gfeller *et al.* (2003) stated that the temperature during welding exceeds the glass transition point of lignin and hemicelluloses; thereby plasticization and flowing occurs. The lignin-hemicellulose matrix, which melts and solidifies again, interacts more closely with wood in the interface. It is stated that it is difficult to realize whether welding can occur or not, because some components in wood material become cross-linked during heat treatment (Weiland and Guyonnet 2003; Nuopponen *et al.* 2004; Repellin and Guyonnet 2005; Windeisen and Wegener 2008; Kačík *et al.* 2016).

It is clear from the literature that it is most advantageous to increase the use of heat-treated lumber and thereby improve the durability characterization, especially for outdoor materials. Heat-treated ash and iroko wood are used for cladding and decking in moist environments, *e.g.*, in bathrooms, saunas, and exterior (Klement *et al.* 2008). Ayous wood is an important element in local house building and is widely used as sawn timber. It is used from interior joinery to pencils and is especially suitable for making shipping crates and boxes, due to its light weight (Bosu and Krampah 2005). Most commonly, tulipwood is the greenish yellowish wood yielded from the tulip tree, found on the Eastern side of North America and also in some parts of China. In the United States, it is commonly known as a tulip poplar or yellow poplar, even though the tree is not related to the poplars. It is strong and used in many applications, including furniture, joinery, and moldings. It can also be easily stained and is often used as a low-cost alternative to walnut and cherry in furniture and doors (Miller 1999). Ayous and tulipwood, which have been used as a local resource for the last 10 years, are widely used in the author's country as floor and facade cladding. Ash and iroko woods are preferred for outdoor use because of their high density and good dimensional stability, which are frequently researched by scientists.

The production of these heat-treated materials includes four tree species highly preferred for interior, furniture, and other woodwork industries in Turkey. The best engineering approaches and different joining methods can be tried without any loss in strength values. The durability of thermally treated wood material has been checked in outdoor applications (Tankut *et al.* 2014), and the information about the performance of the heat-treated welded wood is insufficient. The only limitation of welded wood is that the strong joints obtained are unable to meet the properties of the outdoor application, because their resistance to water is poor. Until now, water resistance and mechanical tests have been made on softwood and some hardwoods, but no studies have been found on the effect of weld joining on the strength of tropical woods. For this reason, the resistance of water was investigated as a result of the heat-treated welded hardwood and exotic species that are frequently used in outdoor applications.

EXPERIMENTAL

Wood Material and Welding Process

Heat-treated and untreated (control) woods of Iroko (*Chlorophora excelsa*), ash (*Fraxinus excelsior* L.), tulipwood (*Liriodendron tulipifera*), and ayous (*Triplochiton scleroxylon*), were provided from Nova ThermoWood in Gerede, Turkey (in April of 2019). Prior to heat treatment, the planks that were used for control samples were then dried in industrial drying kilns at a temperature of approximately 70 °C and 65% relative humidity (RH), with a moisture content of 11% to 15%. Half of these planks were subjected to the ThermoWood heat treatment process (Finnish ThermoWood Association, 2003). The total time of the heat treatment was 63 h, and the time of exposure to the highest temperature was 2 h for 190 °C. The heat treatment process was performed quite slowly because of a risk of cracks forming while drying. The samples were shipped after these processes and brought to Lulea Technology University Wood Welding Laboratory (Skellefteå, Sweden), where they were conditioned for 7 days prior to welding process (in May of 2019). The moisture content of the untreated control samples was approximately 10% to 12%, and that of the heat-treated samples was approximately 8% to 9% for welding. A total of 24 specimens with dimensions of 200 × 20 × 20 mm^3 (L × R × T) were cut from wood and welded together two-by-two (i.e., longitudinal welding of tangential face to a radial face) in a linear vibration welding machine (LVW 2061; Mecasonic, Annemasse, France) and were welded according to welding parameters in Table 1. They were welded together two at a time to form a bonded sample of dimensions 200 × 20 × 40 mm^3 by a linear vibration-welding machine.

Table 1. Welding Procedure for the Preparation of Specimens

Welding Times S1+S2 (s)	Holding Time (s)	Initial Welding Pressure (MPa)	Second Welding Pressure (MPa)	Holding Pressure (MPa)	Frequency (Hz)
2.5 + 3	10	1.3	1.8	2	150

Shear Strength and Water Immersion

The specimens were cut according to the method described in European standard EN 205 (2003). Two cuts were made in the middle of the specimens, perpendicular to the weld line. The distance between the two cuts was 10 mm. The samples were formed in a way that they were appropriate for the test equipment. The welded samples were conditioned for 7 days in an environmental chamber (20 °C and 65% relative humidity) before testing. The resistance of the welded connections was tested by means of a shear test machine along the longitudinal direction of the samples, in the direction of the wood fibers, and at a rate of 2 mm/min. In this study, specimens were immersed vertically in a water bath with a temperature of 20 °C ± 1 °C. Shear strength performance of the samples were determined after 1.5 h and 3 h water immersion periods. Each water-immersion period sample contained 12 replications. After the experiment, the average strength values and standard deviations of the samples were calculated. After the experiment, the average strength and standard deviations of the bond strength and the average wood failure were calculated for each set of samples (Vaziri *et al.* 2020).

Computed Tomography (CT)-scanning Studies

Heat-treated and control wood specimens were studied by CT scanning in a medical CT scanner (SIEMENS Emotion Duo medical X-ray CT-scanner, Erlangen, Germany) for each pixel along the weld line in an area of 3 × 202 pixels. In this study, an X-ray CT scanner was used to measure the average density profile of the weld line. Density values of all test specimens were measured before welding.

Thermogravimetric Analyses

Thermogravimetric analyses (TG) measurements were carried out using Perkin Elmer TGA 6. The TG analyses was performed using 10 mg of powder for each test (Tan et. al, 2006), over temperature of 25ºC to 700ºC at a heating over rate of 10ºC/min. In this experiment, nitrogen gas was used at a flow rate of 20 mL/min to prevent oxidation**.**

RESULTS AND DISCUSSION

Water Resistance and Mechanical Strength Results

Figure 1 shows the effect of water resistance on the mechanical properties combination of heat-treated welded wood.

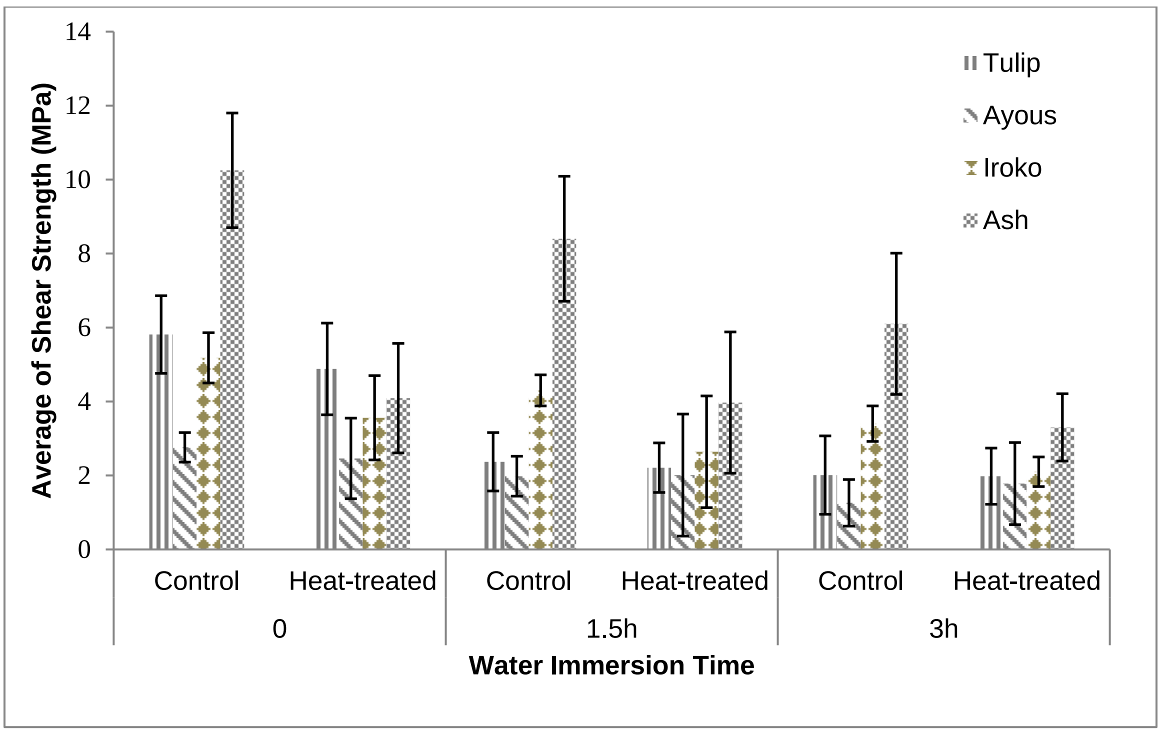

Fig. 1. Average of shear strength test result

According to the test results, the average shear strength decreased in all of the heat-treated test samples, depending on the water immersion time. In the control groups, shear strength decreased from 5.81 MPa to 2.37 MPa (1.5 h) and 2.01 MPa (3 h) for tulip wood; from 2.76 MPa to 1.98 MPa (1.5 h) and 1.26 MPa (3 h) for ayous; from 5.18 MPa to 4.30 MPa (1.5 h) and 3.40 MPa (3 h) for Iroko; and from 10.25 MPa to 8.4 MPa (1.5 h) and 6.10 MPa (3 h) for ash. In heat-treated groups, shear strength decreased from 4.88 MPa to 2.21 MPa (1.5 h) and 1.98 MPa (3 h) for the tulip wood sample; from 2.46 MPa to 2.01

MPa (1.5 h) and 1.78 MPa (3 h) for ayous; from 3.56 MPa to 2.64 MPa (1.5 h) and 2.10 MPa (3 h) for Iroko; and from 4.09 MPa to 3.97 MPa (1.5 h) and 3.30 MPa (3 h) for ash. In Fig. 5, the proportional decreases of shear strength of heat treatment and control samples after 1.5 h and 3 h in water immersion are given.

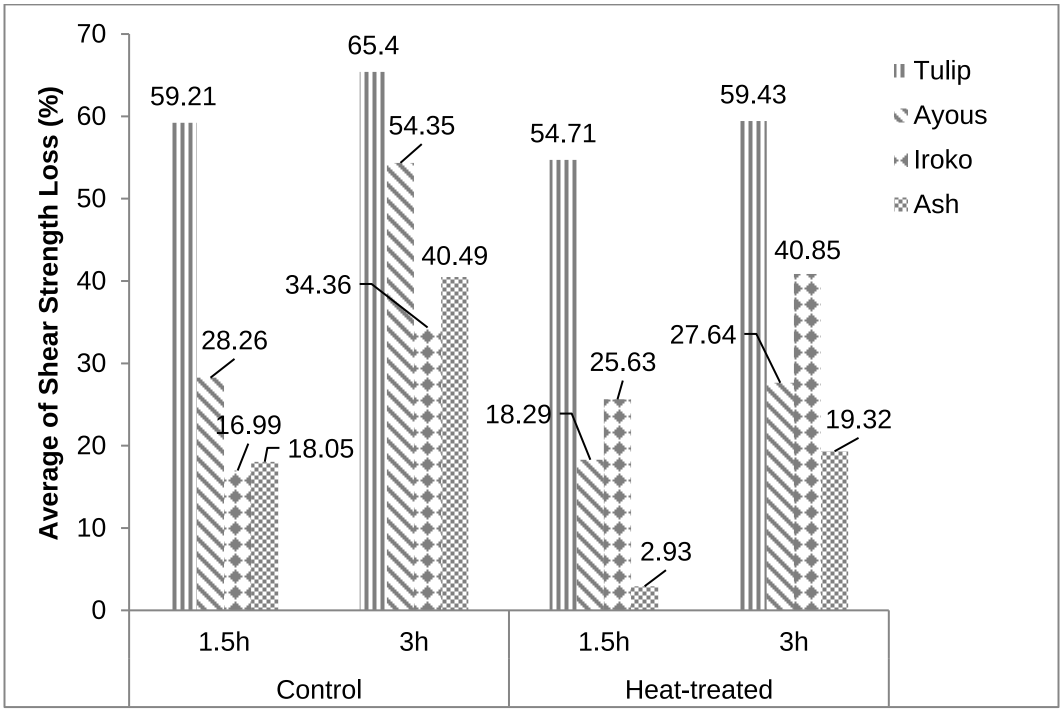

Fig. 2. Average of shear strength loss (%)

According to Fig. 2, for both groups, the highest shear strength loss was found in tulip wood and the lowest proportional loss was found in ash wood. In the control group, after 1.5 h of water immersion, shear strength losses were 60% for the tulip wood and 15 to 30% for the other wood types; after 3 h, the shear strength losses were between 50 to 70% in tulip and ayous wood, and between 30 to 40% in Iroko and ash wood. In the heat treatment group, the shear strength losses after 1.5 h of water immersion were approximately 55% for tulip wood, 15 to 30% for ayous and Iroko wood, approximately 3% for ash wood; after 3 h, the shear strength losses were at 40 to 60% for tulip and Iroko wood, and approximately 25 to 20% for ayous and ash wood. According to the results, the water resistance of the heat-treated samples showed a lower value than the control group. This situation is attributed to the destruction of wood components with high temperature during heat treatment and subsequent failure to re-bond with the welding process. Although the average shear strength of the welded joints was acceptable, the percentage of wood failure was relatively low (The failure average value of heat-treated weld samples is 15%, and that of samples without heat treatment is 10%). Boonstra *et al.* (2006) stated that when the wood components that were lost or heavily cross-linked during heat treatment were exposed to the friction welded wood, there was only a small part of the wood to melt or bond the surfaces.

The mass loss due to the disintegration of hemicelluloses, the most hydrophilic component in the cell wall of wood, during heat treatment indicates reduced wood hygroscopicity (Bourgois and Guyonnet 1988). During the heat treatment period, the covalent bonds between lignin and hemicellulose are broken and lignin particles are formed with low molecular weight (Arif and Kautek 2013). Therefore, it can be stated that heat-treated samples show low values in welding by sticking.

CT Scanning Study

As shown in Fig. 3, the average wood density of ayous (405 kg/m^3) increased to 1033 kg/m^3 and the tulip (480 kg/m^3) to 840 kg/m^3 in the control groups, the average wood density of ayous (340 kg/m^3) increased to 871 kg/m^3 and the tulip (385 kg/m^3) increased to 768 kg/m^3 in heat-treated groups as a result of welding.

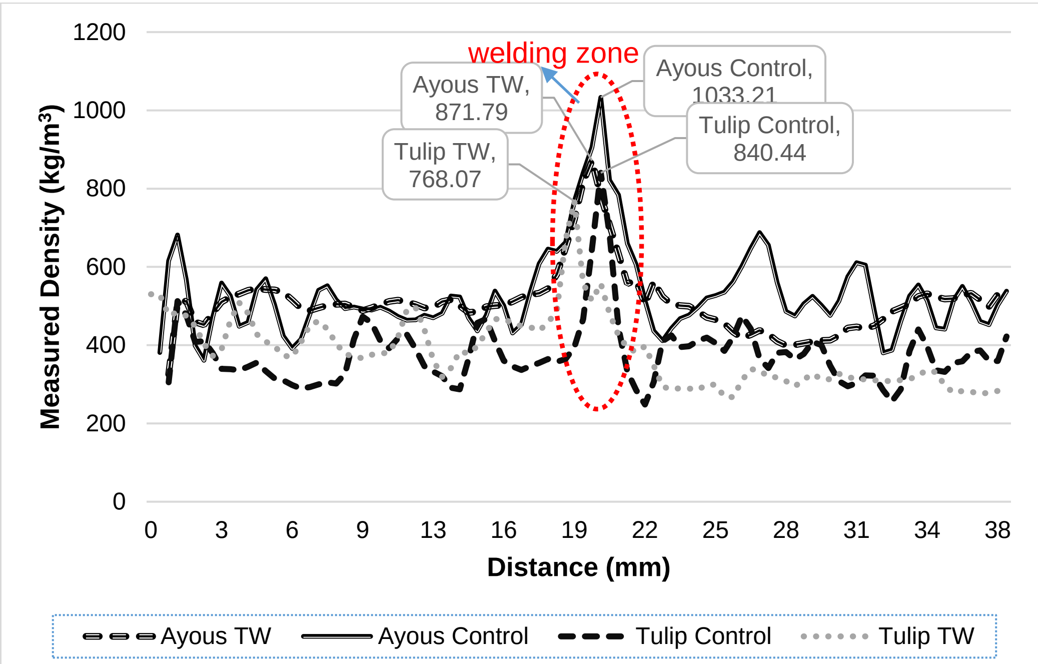

Fig. 3. Measured density profile of tulip and ayous

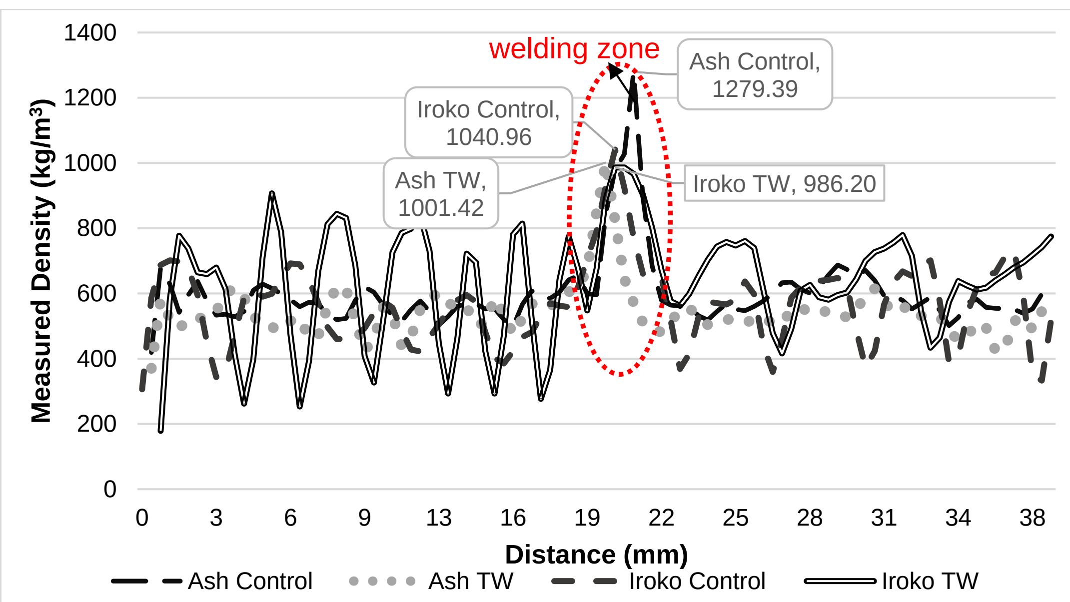

Fig. 4. Measured density profile of Iroko and ash

As shown in Fig. 4, the average wood density of the ash (710 kg/m^3) increased to 1279 kg/m^3 and of the Iroko (620 kg/m^3) to 1040 kg/m^3 in the control groups, whereas the average wood density of the ash (618 kg/m^3) increased to 1001 kg/m^3 and of the Iroko (435 kg/m^3) to 986 kg/m^3 in heat-treated groups by welding.

As shown in Figs. 3 and 4, the heat-treated samples increased in density with welding but had a slightly lower density than the control group. Adhesion of wooden surfaces with vibration welding is accompanied by a considerable increase in the density of wood in the connected interface (Leban *et al.* 2004). Different types of wood react differently to the welding process.

This behavior can be attributed to differences in anatomical structure and chemical composition (Morsing 2000). The properties of the densified material also depend on the density, latitude share of wood, cell wall quantity, and the cross-sectional direction of the wood is also effective in densification (by welding) (Kutnar and Sernek 2007; Laine *et al.* 2014).

The friction welded jointing process and the process of compressing wood-wood parts under friction heating and pressure is similar to the condensation process (surface intensification) applied to wood. In the condensation process, the voids of the cell components of the wood is narrowed and collapsed, providing mechanical resistance (Pelit 2008). This process is similar to the welding joining process; it aims to increase the density of the wood to resist the material and it is stated that it has recently become widespread to obtain high value materials (Blomberg *et al.* 2005; Kutnar and Sernek 2007; Pelit 2008).

TGA/DTG Analyses

Gravimetric analysis was used to compare the pyrolysis behavior of heat treated welded and untreated welded wood samples. TG and DTG (differential thermogravimetry) curves of the samples are shown in Figs. 5, 6, and 7. A summary of thermogravimetric analysis is given in Table 2.

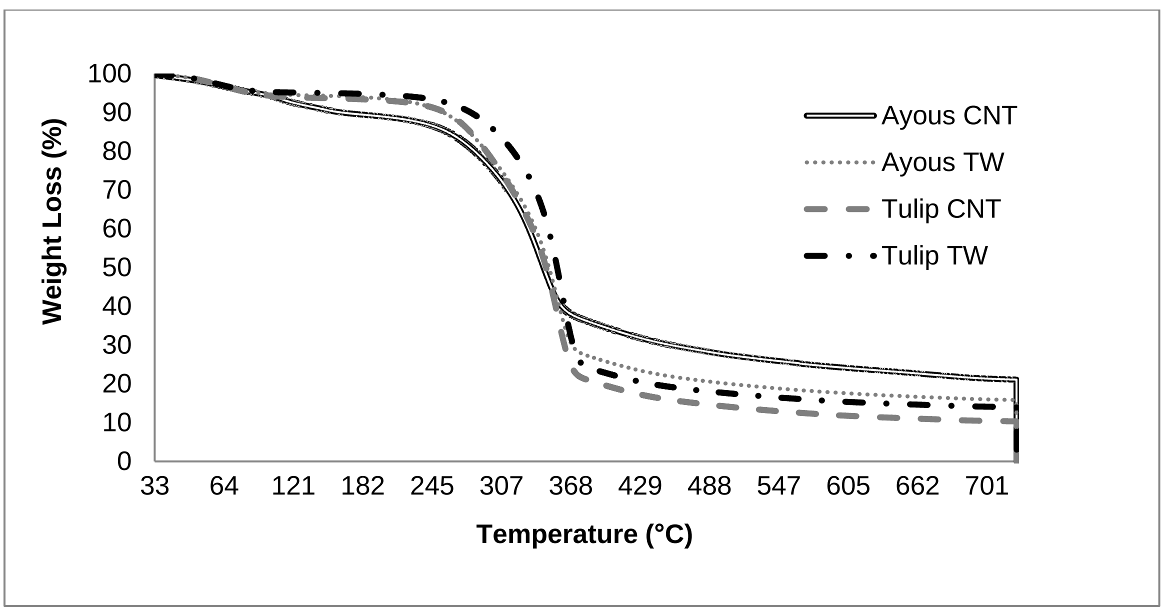

Fig. 5. TGA curves of ayous and tulip

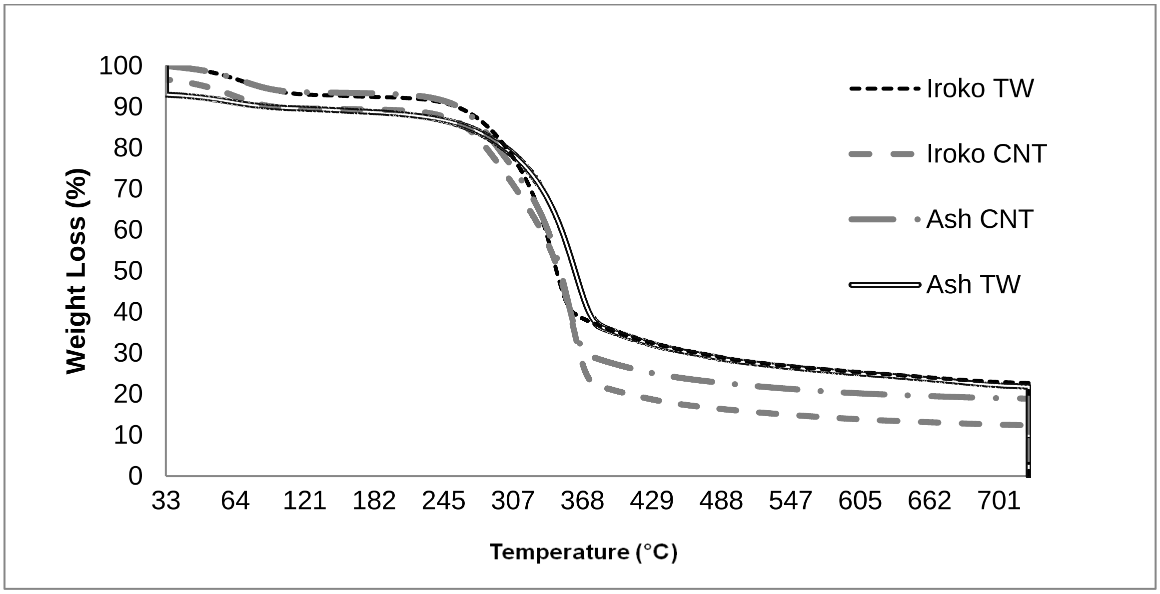

Fig. 6. TGA curves of Iroko and ash

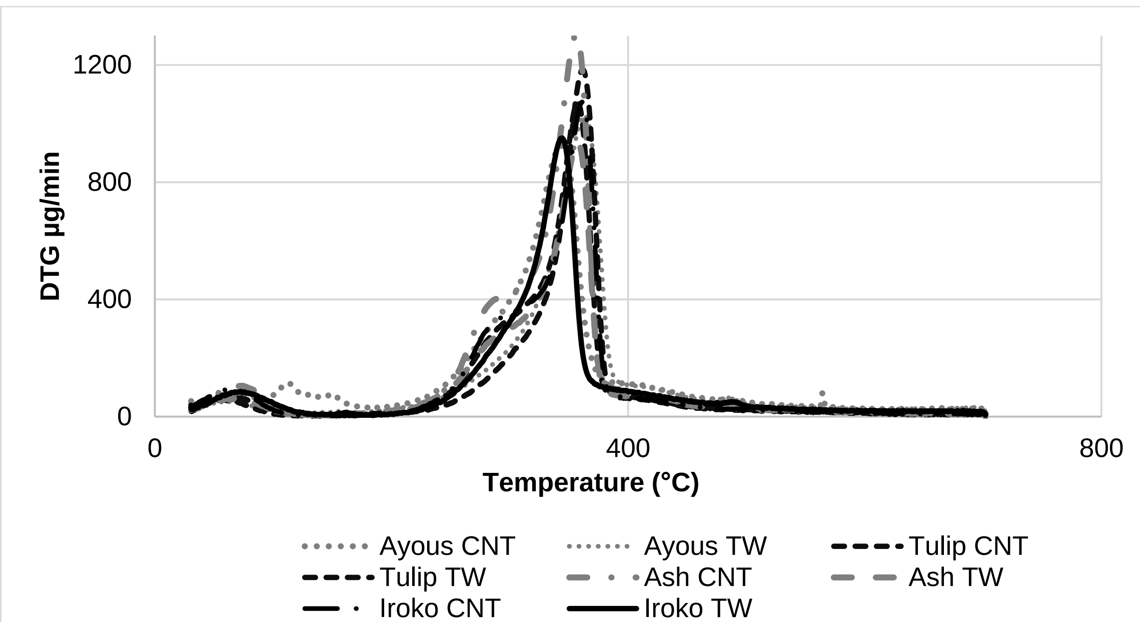

Fig. 7. DTG curves of welded samples

Table 2. Summary of Thermogravimetric Analysis

Samples	T%10 (°C)	Max. Weight Loss (°C)	Residue (%)
Ayous CNT	163,22	344,26	21,08
Ayous TW	254,60	349,10	15,85
Tulip CNT	256,30	346,45	10,33
Tulip TW	279,18	356,31	13,98
Iroko CNT	95,93	347,17	22,69
Iroko TW	256,57	349,49	12,39
Ash CNT	258,08	348,93	18,90
Ash TW	91,47	361,75	21,80

Mass loss due to dehydration was observed up to the first 100 (°C). All samples showed a single major deterioration behavior. In general, the main degradation temperature of the samples was observed at 345 (°C). It can be seen that welded wood species that had been heat treated had higher thermal resistance compared to the control samples. For example, heat-treated welded ash wood showed max mass loss at 361 (°C), while un-treated ash welded wood showed max mass loss at 348 (°C). For this reason, it is seen that the thermal resistance of the heat-treated welded samples was stronger. It has been reported that the decomposition temperature of hemicellulose structures of lignocellulosic biomass is between 220°C and 315 °C and that of cellulose structures decompose in the range 315 to 400 °C (Yang *et al.* 2007). Holocellulose structure shows that when one looks at the curves, the decomposition starts at ~ 200 °C and ends around 350 to 400 °C. Another weight loss of samples within the range 30 to 100 °C is due to the removal of moisture.

For future work, by changing the welding parameters, wood type, and its properties, the water resistance of the welded wood can be examined from other terms. The aim is to process the weld line with environmentally friendly water-repellents and look for ways to increase strength.

CONCLUSIONS

1. This study showed that the heat treatment effect and wood properties have certain effects on the water absorption in the weld line. It can be said that the decrease in the amount of water in the wood due to the heat treatment effect has lower mechanical resistance loss compared to the control sample.
2. The heat-treated samples increased the density with the weld, and slightly higher densities were observed compared to the control group. It can be said that holocelluloses break down during heat treatment, and the existing lignin increases the internal adhesion strength and surface density by melting with heat (plasticization).
3. According to the TGA analysis results, it was observed that the thermal degradation curves of the heat-treated samples occurred at higher temperatures than the control samples.
4. In industrial applications, heat treated wood obtained under controlled conditions can be used to obtain welded wooden joints by mechanical vibration welding.

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