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Vibration welding of heat-treated wood

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Abstract—Vibration welding of wood that has been preheated according to an industrial two-step process indicates that such wood can be welded and can yield welded joints of good strength. The joint strength is, however, markedly lower than obtained when welding non-heat-treated timber. In general, weld strength of the timber is poor if welding is done on hydrothermolyzed wood. The strength results are instead much better if welding is done at the end of the complete heat treatment process, i.e., after the dry heat step. The weld lines of heat-treated wood show entangled cells where there is none or very little of the molten matrix intercellular material usually observed in welded timber. Furthermore, in weldlines obtained after hydrothermolysis an increase in rigidity and brittleness of the wood cells is observed. Hence, the wood cells are not entangled at all or very little. Both observations indicate that heat treatment has affected the main melting region of the wood, namely the intercellular material. As most of this material is already either lost or heavily cross-linked during heat treatment, only little of it is now available to melt and bind the wood surfaces during vibrational wood welding.

Keywords: Heat-treated wood; dimensional stability; wood welding.

1. INTRODUCTION

Heat treatment of wood at relatively high temperatures (in the 150–280°C range) has been advanced in the literature as an effective method to improve the dimensional stability and durability of wood [1–11]. Several different heat-treatment processes have been proposed. One type of wood, Plato wood, at present commercial in the

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Netherlands, is based on a milder two-step process [12, 13]. Several authors have explained the reasons for the increased dimensional stability of wood on the basis of the modifications occurring during treatment at the molecular and anatomical levels. These were centered mainly, but not only, on modification and increased cross-linking of lignin [11, 14–16] and on anatomical level reasons based on the controlled partial degradation of the cell wall and consequent relaxation of cell wall stresses [17–19]. Irrespective of the respective contributions of these two causes, it is true, without any doubt, that extensive modifications and reactions, now well determined by all the authors already mentioned, do occur during heat treatmernt of wood.

Mechanically-induced vibration welding of wood, without any adhesive, has been shown to rapidly yield wood joints satisfying the relevant requirements for structural applications [20]. The mechanism of mechanically-induced vibrational wood welding was shown to be mostly the melting and flowing of the amorphous materials between wood cells, mainly lignin and hemicelluloses [20]. This causes partial detachment, the 'ungluing' of long wood cells and wood fibres, and the formation of an entanglement network in a matrix of molten material which then solidifies. A wood cell/fibre entanglement network composite of much higher density than wood is formed at the interface with a molten and re-solidified lignin/hemicellulose matrix.

Considering the high dimensional stability of heat-treated wood it would be of applied interest to see if a good welded joint strength could also be obtained, notwithstanding the structural modifications the heat-treated wood has undergone. Equally, it is of conceptual interest to see if enough flowability is left in the lignin/hemicelluloses of heat-treated wood to yield a welded joint. This is of interest because welding might be more difficult or more limited to achieve, since cross-linking of some wood constituents occurs during heat treatment [11, 14–16]. Cross-linked networks, even only partially/poorly cross-linked ones, flow with more difficulty, or do not flow at all, due to the increase in the glass transition temperature (T_g) of the system. Therefore, this paper deals with the investigation of these two points.

The first production step in the Plato wood treatment process is the hydrothermolysis, based on a relatively low-temperature heat-treatment in the presence of steam injection. The second step is a dry heat-treatment to 185°C. Consequently, mechanical vibration wood welding of both the intermediate wood products obtained after hydrothermolysis and of the finished heat-treated wood was carried out.

2. EXPERIMENTAL

2.1. Industrial preparation of Plato wood specimens

Beech (*Fagus sylvatica* L.), birch (*Betula alba*) and poplar (*Populus* sp.) were the wood species used for heat treatment and welding tests. For each wood species at

least 6 samples were treated. Standard sizes were used (thickness 25–40 mm width 100–150 mm; length 1600–3000 mm) and the length of the samples varied between 1.6 and 3.0 m before heat treatment. The moisture content before heat treatment was 16–20%.

The heat treatment was performed in two separate stages. In the first stage of the heat-treatment the wood samples were treated in a humid environment at superatmospheric pressure (6–8 bar) using saturated steam as the heating medium to increase the temperature of the boards. This so-called 'steam hydrothermolysis' treatment was done in an industrial plant at an effective treatment temperature of 165°C. Cooling down was accomplished by a quick but controlled release of the pressure in the reactor to atmospheric conditions followed by a cold water circulation on the wall of the reactor. The wood samples were then dried using a conventional drying process at 50–60°C. After drying, the wood samples were heat treated again in a special curing kiln (second stage), under dry and atmospheric conditions, the so-called 'curing' treatment (at 170–180°C). During this process stage superheated steam was used to exclude oxygen, thus reducing fire risks and preventing undesired oxidation reactions.

The full scale industrial samples were then cut to prepare specimens for welding of dimensions 150 × 20 × 15 mm.

2.2. Preparation of joints by mechanically-induced wood flow welding

The mechanical welding machine used was a Branson 2700 welding machine (Geneva, Switzerland) capable of vibrating the wood at a frequency of 100 Hz, normally used to vibrationally weld metals.

Specimens composed of two pieces of intermediate hydrothermolyzed or fully Plato heat-treated birch, beech and poplar wood each of dimensions 150 × 20 × 15 mm were welded together to form 20 bonded joints of 150 × 20 × 30 mm dimensions for each species by vibrational movement of one wood surface relative to the other of 3 mm amplitude at a frequency of 100 Hz. The equilibrium moisture content (MC) of the samples before welding was 12%. The conditions of welding used are shown in Table 1. After stopping the vibration process, the clamping pressure was still briefly maintained until solidification of the bond. The welded samples were conditioned for one week in an environmental chamber (20°C and 65% RH) before testing.

The tensile strength was measured on samples in which saw cuts perpendicular to the longitudinal wood grain of the specimens, down to the bondline, were made. The distance between the two cuts was 2.5 cm. The specimens were then tested in tension on a Zwick 1454 universal testing machine using Zwick 8406 self-squeezing pincers at a rate of 6 mm/min according to European Norm EN 205 (2003). The results obtained and the conditions used are shown in Table 1.

Table 1.
Welding conditions and weld strength results of friction welded, heat-treated wood of different species after the first hydrothermolysis treatment step and after final dry heat curing treatment step

	WT (s)	WP (MPa)	HT (s)	HP (MPa)	Density (kg/m^3)	Strength (MPa)	Standard deviation	Max strength value (MPa)	Min strength value (MPa)
Birch, hydrothermolyzed	4	4	7	4	515	2.08	0.82	3.49	1.10
Birch, heat treated	3	4	7	4	568	3.71	1.04	5.29	2.91
Birch, heat treated	3	4	10	4	591	5.50	1.45	7.25	4.26
Birch, heat treated	3	4	7/10	4	577	4.34	1.50	7.35	2.91
Birch, untreated	3	4	7/10	4	561	5.97	0.68	6.51	5.35
Poplar, hydrothermolyzed	2	4	7/10	4.5	423	2.64	0.65	3.53	1.44
Poplar, heat treated	2	4	7/10	4.5	444	2.29	0.94	3.53	1.17
Beech, heat treated	3	4	7/10	4.5	661	4.32	2.31	8.82	1.29
Beech, untreated	3	4	7/10	4.5	657	8.07	1.06	8.61	7.44

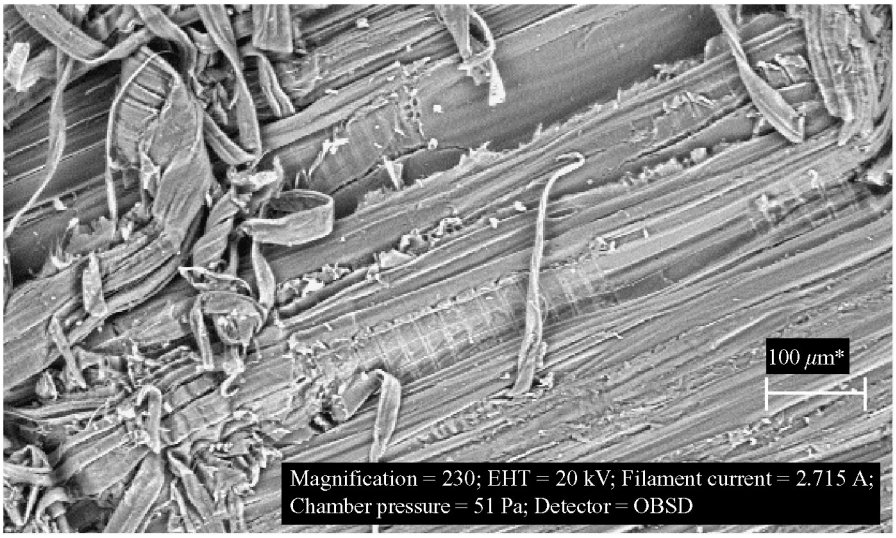
WT, welding time; WP, welding pressure; HT, holding time; HP, holding pressure.

2.3. Scanning electron microscopy (SEM)

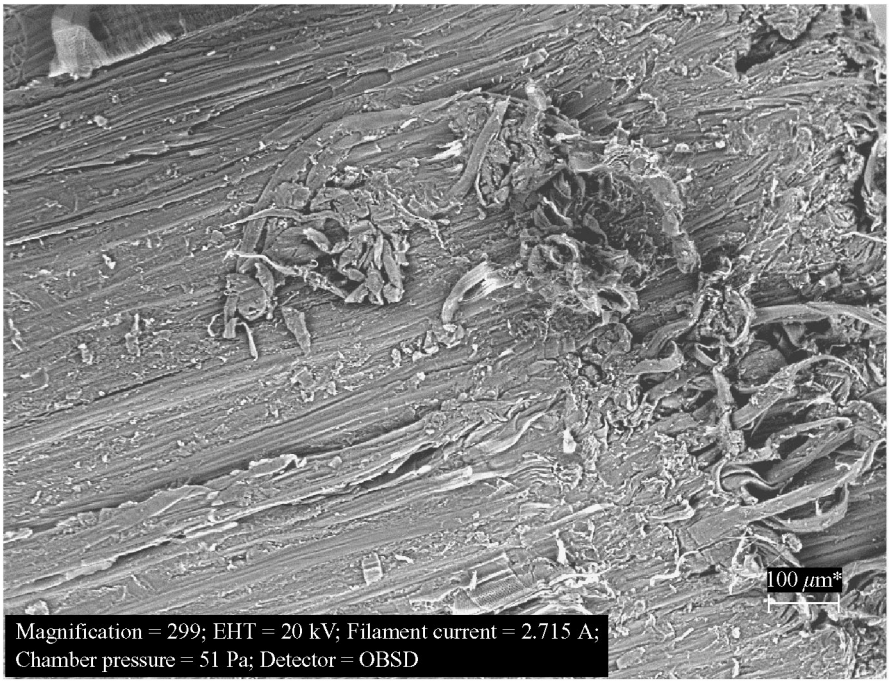
The surfaces of the joints were analysed with SEM after metallizing with gold-palladium. The SEM equipment used was a Hitachi S-520 scanning electron microscope. A LEO 1450 VP scanning electron microscope with variable pressure was used. The samples were introduced in the chamber without any carbon coating. All images were obtained with an acceleration voltage of 20 kV, the filament current was 2.715 A. The pressure in the chamber ranged between 50 and 54 Pa. The magnification was 230× for Fig. 1a, 299× for Fig. 1b, 123× for Fig. 2a and 1020× for Fig. 2b.

2.4. X-ray microdensitometry analyses

Sections of 1.88 ± 1 mm in thickness were obtained from each sample and analyzed by X-ray microdensitometry [21]. The X-ray microdensitometry equipment used consisted of an X-ray tube producing long waves 'soft rays' (low energy level) emitted through a beryllium window. These were used to produce X-ray negative photographs of approx. 2-mm-thick samples, conditioned at 12% moisture content, at a distance of 2.5 m from the tube. This distance is important to minimise blurring of the image on the film frame (18 × 24 cm) used. The usual exposure conditions were: 4 h, 7.5 kW and 12 mA. Two calibration samples were placed on each negative photograph in order to calculate the wood density values. The specimens were tested in this manner on an equipment consisting of an electric generator (Inel XRG3000), an X-ray tube (Siemens FK60-04 Mo, 60 kV, 2.0 kW) and a Kodak film negative, Industrex type M100.

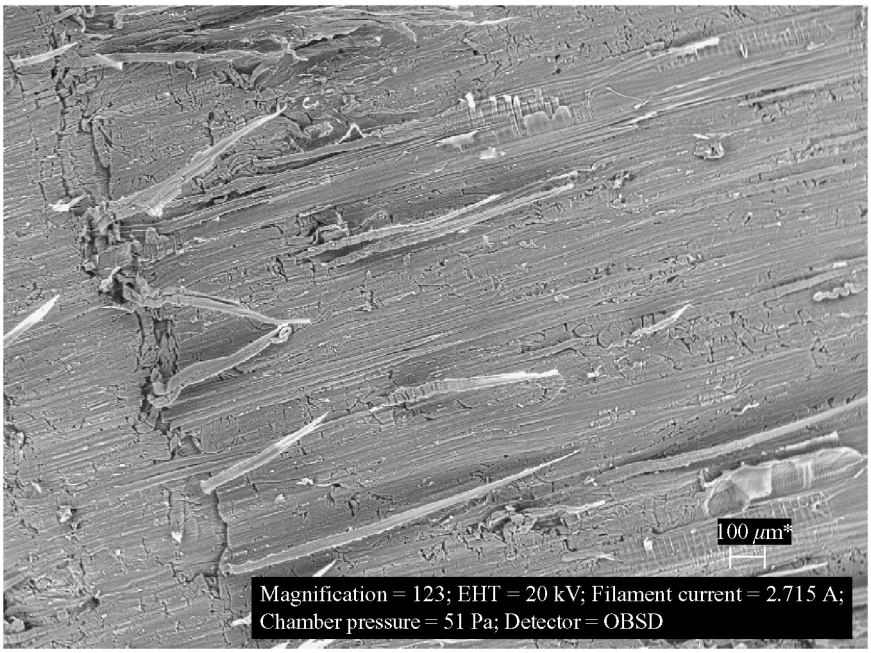


(a)



(b)

Figure 1. (a) Scanning electron micrograph of heat-treated poplar wood after the last dry heat curing step showing entangled cells where there is none or very little of the molten matrix intercellular material usual in welded timber. (b) Scanning electron micrograph of heat-treated birch wood just after the first hydrothermolysis treatment step showing entangled cells where there is none or very little of the molten matrix intercellular material usual in welded timber.



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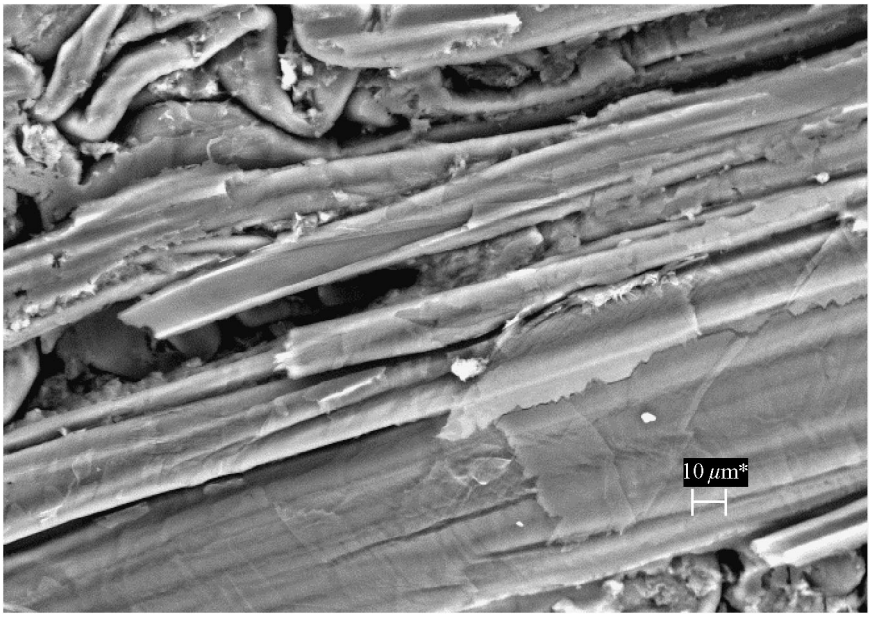

(b)

Figure 2. (a) Scanning electron micrographs of heat-treated poplar wood just after the first hydrothermolysis treatment step showing apparently rigidified wood cells that have not detached from the wood surface, that have not entangled and where there is none or very little of the molten matrix intercellular material usual in welded timber [20]. (b) Higher magnification detail of (a).

3. RESULTS AND DISCUSSION

The results in Table 1 indicate that the heat treated wood can give good strength results but, in general, the values are lower than that obtained with untreated wood [20] as indicated by the birch and beech untreated controls in Table 1. This is expected because cell walls degradation induced by heat treatment [18, 19] is well known to induce lower strength and greater brittleness of the treated wood [18]. Heat treatment of timber especially decreases the tensile strength of wood (cellulose hydrolysis causing cleavage of the fibrils), whereas its compressive strength (and hardness) is slightly improved (due to an increased cross-linking of lignin due to chemical reactions the lignin undergoes under heat treatment) (Ref. [11] and data not shown).

This result is also expected as a certain amount of cross-linking of wood constituents does occur during heat treatment [11], increasing the Tg and decreasing the flow of the 'melt' at any given temperature or increasing the temperature at which flow starts. That this is one of the main causes of the lower strength obtained in welding heat treated timber can also be deduced by the scanning electron microscope pictures of the interface in Figs 1 and 2. In Figs 1 and 2 one can see that:

(1) the long wood cells are only partially detached and entangled, less than that observed in normal timber welding [20], but with a lack of molten amorphous material surrounding and binding them, or underneath them (Fig. 1). This means that the material that normally melts to form the interfacial welded composite is present in much lower proportion than usual, or is not present at all. This is a consequence of the heat treatment of the wood and the concomitant loss of intercellular material. This means lower wood cells entanglement, much lower proportion of molten material binding the cells, and hence the interfacial strength is lower.

(2) in Fig. 2 the cells have not detached and have not entangled as normally observed when welding untreated timber. They appear rigid and unaffected by the welding process. This may indicate that it is the increased rigidity of the cell walls introduced by the heat treatment that stops the cells from detaching and entangling during welding.

The conditions of welding thus need to be more extreme than the pressures and holding times optimized for untreated wood [20]. Thus, in Table 1 higher pressures and longer holding times had to be used for heat-treated wood. Also, the much greater variability in the results obtained with heat-treated wood as can be seen by the high values of the standard deviations for the different cases in Table 1 should be noted. In this regard the max and min values in Table 1 (some very high strength results were obtained too) indicate a high variability at the anatomical level of heat-treated wood. The variability at the anatomical level is due to the effect of physical and/or chemical processes during heat treatment on the different wood structural constituents [11, 14, 17, 19].

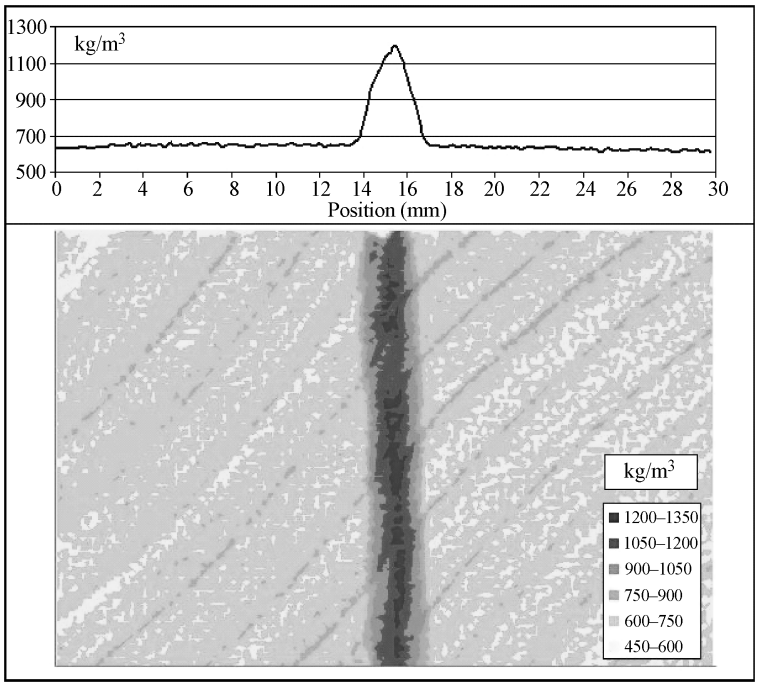

Figure 3. X-ray microdensitometry map of friction welded hydrothermally treated birch wood. Upper microdensitometry graph expresses density in kg/m^3 of the wood as a function of the sample weld interface position in mm. The bottom panel is the color intensity microdensitometry map expressing increasing density in kg/m^3 by progressive darkening. Scale of sample weld interface position is the same for the two panels.

Fully heat-treated wood, however, appears to give better results than the intermediate hydrothermolyzed wood. This is shown in Table 1 and in the X-ray microdensitometry maps of welded joints just after the first wet step of the process (the hydrothermolysis) (Fig. 3) and at the end of the second and final treatment, i.e., the dry heat curing (Fig. 4). Unusual and unexpected is the wider densified weldline of the hydrothermally treated wood in comparison to the cured wood (Figs 3 and 4). This means that (i) the second dry heating step in the Plato treatment process is essential to obtain good strength results. (ii) The high temperature reached for a very short time in wood welding cannot, under any circumstances, replace the 4-h heating of the second dry treatment in the heat treatment process.

However, that fully-treated wood welds are better than the intermediate hydrothermolyzed wood welds is a rather unexpected result. During the first hydrothermal treatment rearrangements and condensation reactions occurred extensively and have been reported [11, 14–19]. During the same hydrothermolysis step extensive hydrolysis reactions of wood constituents also occur [11, 14–19]. The presence of all these reactions in the wet step of the process implies that their mechanisms depend on and are favoured by the presence of water in the form of steam. Furthermore, the use of water in the form of steam at high temperature and pressure definitely

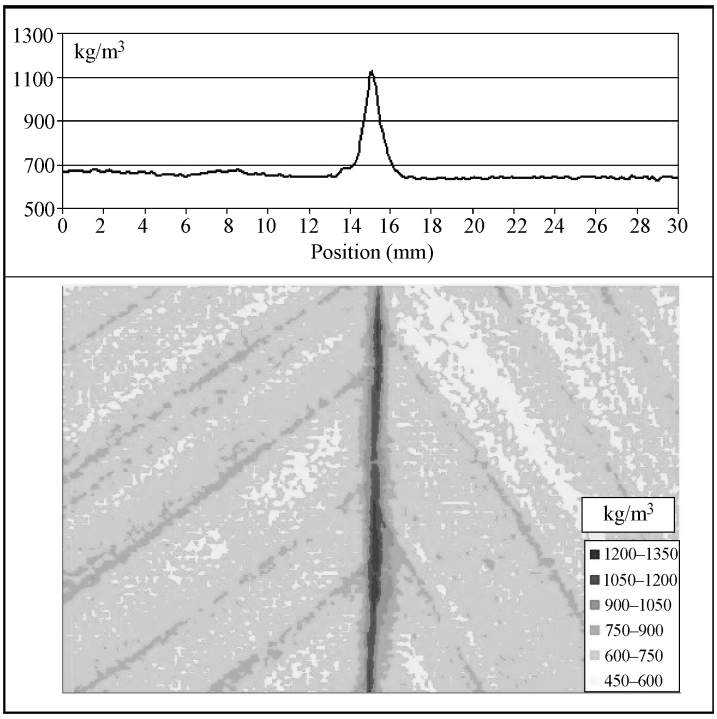

Figure 4. X-ray microdensitometry map of friction welded birch wood after final dry heat cure treatment. Upper microdensitometry graph expresses density in kg/m^3 of the wood as a function of the sample weld interface position in mm. The bottom panel is the color intensity microdensitometry map expressing increasing density in kg/m^3 by progressive darkening. Scale of sample weld interface position is the same for the two panels.

lowers the softening point of the main wood constituents. It is, however, difficult to say whether this softening is due to the reduced interaction between the different wood components, which definitely occurs [11, 14–19], or to a decrease in cellulose crystallinity during hydrothermolysis. During the second dry heat phase of the treatment instead, condensation reactions still occur, but not hydrolysis, as water is absent [11, 14–19].

Thus, hydrothermolyzed wood yields welded wood joints of lower strength, while the fully-treated wood after the dry heat phase yields welded wood joints of higher strength.

There can be several reasons for the difference in strength between hydrothermally treated and fully treated wood:

- chemical and physical differences, such as an increased rigidity of the cell walls and loss of a large proportion of intercellular material, as discussed above
- the difference in moisture content between hydrothermally treated wood (*ca.* 14–18%) and fully treated wood (5–7%) before welding. This affects both the chemical reactions and physical processes during welding [20].

- the quality of the surface of the specimens of hydrothermally-treated wood is inferior to that of fully treated wood. It is not possible to produce hydrothermally-treated wood with a smooth surface during planing, because fibres are torn out of the wood surface (data not shown). This again indicates chemical differences in the intercellular material.

The results in Table 1 indicate that there is some sort of correlation between the density of wood before treatment and the welded joint strength but such a correlation is not direct. Thus, the low strength values of poplar welded joints are definitely due to the much lower density of poplar compared to that of birch and beech. However, the welded joint strength differences between birch and beech are not explainable on the basis of density alone (Table 1: birch 4343 MPa at 577 kg/m^3, compared to beech 4321 MPa at 661 kg/m^3 density).

4. CONCLUSIONS

Heat-treated wood obtained in industrial production under controlled conditions has been used to obtain welded wood joints by mechanical vibration welding. The strength of the welded wood joints was lower than of welded untreated wood joints. The joints were produced both with the hydrothermolyzed wood obtained after the first wet step of the heat-treatment process, and with the wood obtained after the two-step heat treatment process was completed. The weld strengths obtained after the full treatment has been completed were markedly better than those obtained with hydrothermolyzed wood.

The weld strengths of heat-treated wood were lower than in the case of untreated wood because the molten intercellular material was markedly less and cells entanglement at the interface was also markedly lower. Increased rigidity and brittleness of the wood cells at the welding interface, induced by the heat treatment, were inferred by the much lower level of cells entanglement observed. This effect was very marked in all the weldlines of hydrothermolyzed wood explaining the lower strength obtained with it. It appears that heat treatment affects the main melting region of the wood, namely the intercellular material. As most of this material is already either lost or heavily cross-linked during heat treatment only little of it is now available to melt and bind the wood surfaces during vibrational wood welding, with a consequent decrease in strength.

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