Ultrasonic Welding of Wood Veneers

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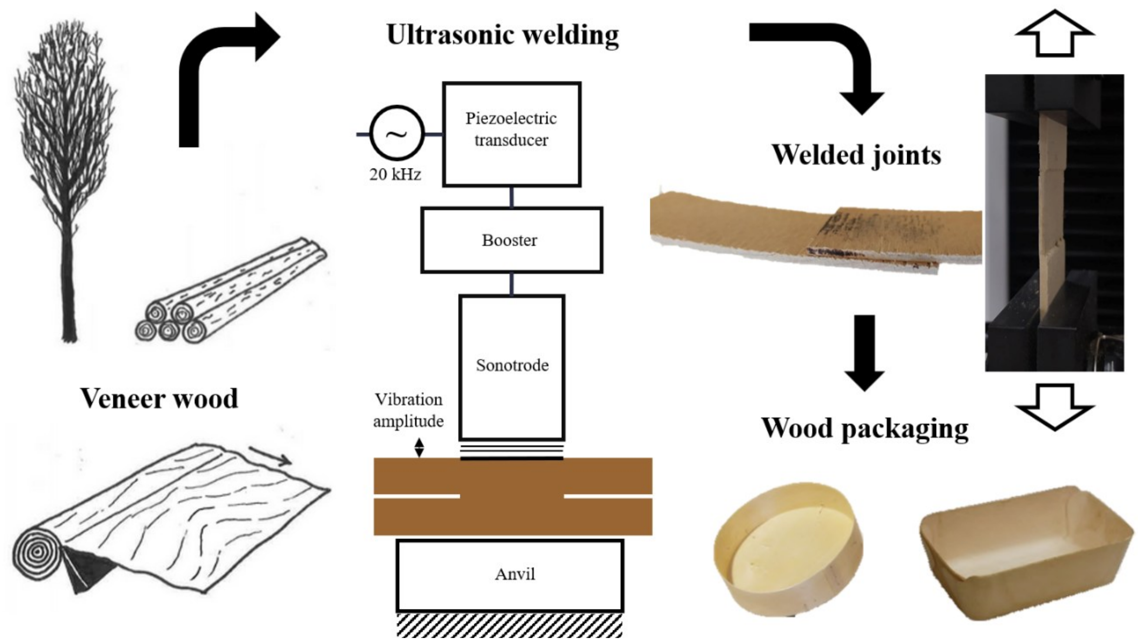
GRAPHICAL ABSTRACT



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Creating wood joints usually requires glue or staples. These items are detrimental for the end-of-life of wood products, decreasing their potential recyclability, reusability, and biodegradability. Ultrasonic welding is a processing method to assemble thermoplastic polymers, allowing the creation of joints without adhesive. Wood is composed of amorphous lignins and hemicelluloses that could, under the right conditions of heat and pressure, act as a glue to bind wood pieces together. Thus, the scope of this proof-of-concept study is to investigate the use of ultrasonic welding to assemble veneer wood for packaging applications. Wood pieces were assembled using an ultrasonic welder while screening a large range of materials and processing conditions. Mechanical performances were assessed by measuring the shear strength of wood joints. Results showed that veneer wood can be assembled using ultrasonic welding, leading to a higher resistance than stapled joints. However, the procedure is highly sensitive to wood properties, as the acoustic energy tends to be easily focused by its internal structure. It decreases the reproducibility of the welding procedure and increases the dispersion of joint properties. Achieving a better energy focus is nonetheless possible using appropriate conditions. Overall results are encouraging for further industrial development.

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Keywords: Ultrasonic welding; Veneer wood; Adhesive-free assembling; Wood-based packaging

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INTRODUCTION

To reduce the environmental impact of packaging, bio-based alternatives to plastic are currently being investigated (Su *et al.* 2018). Papers and cardboards are already common forms of packaging, and changes in legislation in several countries are likely to encourage the trend of developing bio-based alternatives. Within the European Union, for instance, the Packaging and Packaging Waste Regulation framework establishes objectives aimed at a quick diminution of single-use packaging and increasing the overall proportion of packaging that becomes recycled. In the food packaging sector, wood can be an alternative to plastic and is already used as such. Nevertheless, the assembling methods to create wood packaging require petroleum-based glues or metal staples that can be detrimental for their end-of-life. An assembling method requiring no chemical adhesives nor metal pieces would be of great interest.

Welding of Lignocellulosic Materials

Welding is a permanent assembling process aiming at the creation of continuity between distinct material pieces. It is historically associated with metals, but today the approach also has been much used for thermoplastic polymers and composites (Bhudolia *et al.* 2020; Li *et al.* 2022). Given the properties of wood polymers, some of the welding techniques developed for thermoplastics could be used on wood parts to create joints without any additional materials. In recent years, the welding of lignocellulosic materials has been getting some attention, as petroleum-based adhesives are associated with recyclability and sustainability issues. Thus far, two types of research work have been reported on the topic: about the vibrational welding of wood and the ultrasonic welding of papers. Both technics rely on the same principle that two pieces of lignocellulosic materials are assembled by the application of acoustic vibrations under pressure. Sonic waves propagate inside the thickness of the top material to convey the energy straight at the welding interface. Heat is then generated by two main mechanisms successively occurring (Zhang *et al.* 2010; Tutunjian *et al.* 2020). First, the relative motion of two pieces generates interfacial friction, which increases the temperature of the media. Then, when the latter goes above the characteristic temperatures (glass transition, melting), the energy dissipates into heat through viscous effects. The main difference between the two technics are the frequencies involved and the size of the welded pieces: about 100 Hz and 10 cm for vibrational welding, and about 20 to 40 kHz and 1 mm for ultrasonic welding.

Vibrational Welding of Wood

About 20 years ago, a joint team of French and Swiss researchers reported on the assembling of wood by vibrational welding. In a pioneer publication, Gfeller *et al.* demonstrated that this technology can yield wood joints without adhesive (Gfeller *et al.* 2003). Joints tested right after the welding showed performances above the main requirements for structural application at 20 °C and 65% relative humidity (RH). However, joint strength decreased below the requirements after ageing and exposure to moisture. Other published studies then followed to deepen the investigation on several key points, such as following the joint formation by *in-situ* monitoring the temperature (Ganne-Chédeville *et al.* 2006), mapping the variations of density in the thickness (Leban *et al.* 2004), or assessing the chemical composition in welded zones (Delmotte *et al.* 2008). As discussed by the research team, adhesion of wood pieces is expected to be caused by a "thermoplastic" mechanism, followed by a "thermosetting" one (Gfeller *et al.* 2003). The "thermoplastic" mechanism is associated to the flowing of hemicelluloses and lignins when the temperature rises above their glass transition. While flowing, amorphous wood polymers are expected to relocate at the interface, filling the pores and bonding the two materials by acting as a glue. The "thermosetting" mechanism takes place once intimate contact is achieved in the welded zone. The process involves a combination of degradation reactions (such as polysaccharide hydrolysis) and condensation reactions of sugar monomers (such as xylose into furfural) that can result in chemical bonding between the two wood pieces (Ganne-Chédeville *et al.* 2008). Despite its straightforwardness, the vibrational welding of wood is in fact a multifactorial processing method involving quite complex mechanisms. Its optimization is not that simple, as attested by the numerical study of Abbasion *et al.* (2015) on the prediction of the hygrothermo-mechanical properties of wood during welding.

Ultrasonic Welding of Papers

Being made of lignocellulosic fibers extracted from wood, paper can be considered as the closest material to wood veneer that has been assembled so far by ultrasonic welding. The flexible packaging industry has high expectations regarding ultrasonic welding that can lead to lower energy consumption and higher production rate compared to conventional heat-sealing lines. However, interest from the paper community has started to grow only recently. The first research work on the ultrasonic welding of papers was reported by Regazzi *et al.* (2019) several years ago, showing that it is possible to assemble 100% lignocellulosic papers without any adhesive using a device originally designed to weld thermoplastics. The researchers found that, for fixed operating conditions, welding joints were stronger for paper pulps containing larger amounts of lignins and hemicelluloses. Further analysis of the structural properties of paper joints confirmed the nature of the adhesion mechanisms involved, which were consistent with the hypotheses of Gfeller *et al.* (2003) for the vibrational welding of wood.

Following this pioneer work, further studies were conducted to understand and optimize the ultrasonic welding process applied to papers. Charlier *et al.* (2021) showed that performing a successful welding depends on machine parts, operating conditions, and material properties, thus confirming the multifactorial complexity of such welding process. It was also found that the peak of the power developed by the high frequency generator during the process is a good indicator of the welding intensity: the higher the power, the higher the temperature at the welding interface. Other studies were also conducted to assess the weldability of different types of papers and cardboards depending on their surface state. Monot *et al.* (2021) showed that it is possible to assemble folding boxboards by ultrasonic welding if the basis weight of the coating layer (and its amount of binders) is large enough. Charlier *et al.* (2022) found that this technology can also be used to assemble hydrophobic papers that were not considered heat-sealable. All of these results confirm the strong potential of using ultrasonic welding to assemble lignocellulosic materials without adhesive.

In this context, the objective of this proof-of-concept study was to investigate on the suitability of ultrasonic welding to assemble veneer wood for packaging application. To do so, wood samples of different species and thicknesses were assembled using an ultrasonic welder with various set-up and operating conditions. The shear strength of welded joints was then determined and analyzed regarding the process parameters to determine the optimal welding conditions. Performances of welded wood samples were also compared to stapled and glued reference joints.

EXPERIMENTAL

Materials

Two species of wood, beech (*Fagus sylvatica*) and poplar (*Populus* sp.), were used throughout the study. Samples were supplied by the FCBA technological institute (Champs-sur-Marne, France) either as 0.9-mm-thick veneer or 2-mm-thick sawn wood. Poplar (320 kg/m^3) was selected because it is widely used for wood packaging. Beech (670 kg/m^3) was chosen because it often serves as a reference for structural wood bonding. Sawing and planing were used to obtain a range of thickness usually not achievable for veneer obtained by unrolling. Because the preparation methods differed for the two studied thicknesses, sawn-specimens were sanded to obtain a homogeneous surface state with a roughness close to the one of industrial veneer wood. The geometry of wood pieces (length of 100 mm, width of 25 mm) was chosen following the recommendations of the NF EN 205 (2016) standard, while taking into consideration the dimension of the sonotrode. Moisture content during storage and experimentation was around 12%.

Ultrasonic Welding

An ESW ultrasonic welder, equipped with a 20 × 25 mm² sonotrode and a 20 kHz high frequency generator, supplied by SONIMAT (Europe Technologies, Carquefou, France), was used to assemble wood specimens (Fig. 1a). The device is an electromechanical press with a capacity of 200 daN that can load in the crosshead (vertical) direction. Vibration amplitude at 100% was about 90 µm and the power supply could deliver up to 1500 W. Two different toolings were used: a fixed tooling that corresponds to the most conventional utilization of the welder (Fig. 1b) and a spring tooling, which has been developed and used in previous works on the ultrasonic welding of papers (Fig. 1c) (Charlier *et al.* 2021, 2022). Two different anvils were used: a flat anvil whose surface was machined to obtain 0.5-mm-grooves separated from each other by 0.5-mm-gaps (Fig. 1d) and a cylindrical anvil with a surface radius of 5 mm (Fig. 1e). The flat anvil produced a welding area of 20 × 25 mm^2 (referred further as surface welding), while the cylindrical anvil resulted in a 25-mm-welding line whose width depended on wood species and the applied pressure (referred further as linear welding). Whatever the choice of tooling and anvil, the force was always applied by the head of the press onto the to-be-welded materials, which lay on the anvil. The latter was mounted on the tooling which can be described as the part that connects the anvil to the fixed frame of the device.

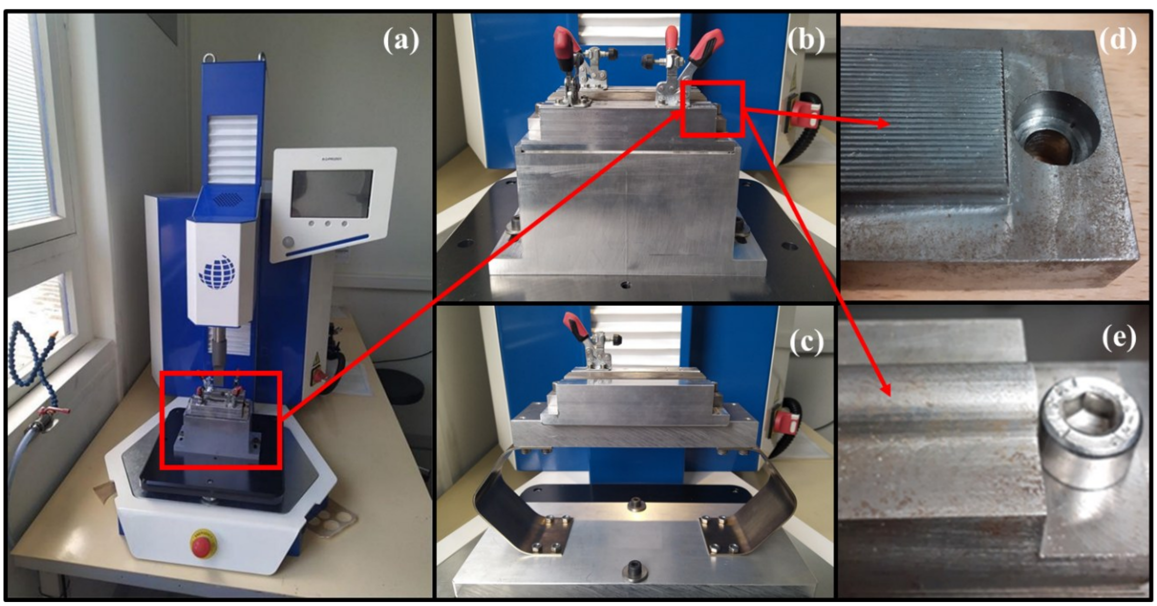

Fig. 1. Welding device (a) used to assemble veneer wood in this study equipped with fixed (b) or spring (c) tooling and surface (d) or cylindrical (e) anvil

To perform the welding, wood pieces were positioned between the sonotrode and anvil and maintained with clamping arms. The machine was calibrated by setting the zero position at a force of 20 daN. Weldings were performed using a displacement-controlled procedure with a force setpoint at which the motion is stopped, and energy consumption the end condition. The welding force, the welding speed, and the energy were changed from one welding to another. The amplitude, holding force, and time were kept constant all through the study (respectively 100%, equal to the welding force, and 1 s). Ultrasonic (US) vibrations were triggered above the zero position. For each set of wood species and welding parameters presented further in the result sections, 15 wood welded joints were prepared. The evolution of force, displacement, and power over time during welding were recorded by the machine and recovered for further analysis.

To evaluate the performances of welded joints, reference wood joints were obtained by gluing and stapling. Glued joints were obtained by depositing a single drop of a commercial isocyanate-based adhesive between two wood specimens and hand-pressing them together. Stapled joints were obtained using commercial staples. One staple was used to assemble two wood pieces. Staple orientation was perpendicular to the testing direction (*i.e.* parallel to the width of wood pieces).

Characterization

Shear strength measurement

Mechanical performances of wood welded joints were evaluated by shear testing following the recommendation of the NF EN 205 (2016) standard that describes a longitudinal tensile shear test for the evaluation of wood adhesives for non-structural purposes. The shear strength was measured using an INSTRON 3345 universal testing machine (Glenview, IL, USA) equipped with a 1 kN sensor at 2 mm/min. Specimens were attached using screw action grips and manually tightened. The shear strength corresponds to the maximal force (in N) recorded during the test that occurs just before wood joints suffer a clean failure.

Weldability assessment

Power supplied by the high frequency generator was identified in previous work as a key parameter reflecting the intensity of welding conditions (Charlier *et al.* 2021). In this study, for a given wood species and thickness, power was adjusted by changing the welding force (from 50 to 200 daN). To discuss the performances of wood welded joints, the shear strengths will be presented in the results section as a function of the maximal power supplied by the welder to establish the weldability curves described in previous research works (Charlier *et al.* 2022). During the analysis, the assessment of the weldability of veneer wood will consider the level of adhesion measured by shear tests as well as the amount of power required to obtain these performances.

RESULTS AND DISCUSSION

Processing Conditions for Surface Welding of Veneer Wood

Wood joints were successfully obtained using ultrasonic welding for the 0.9 and 2 mm poplar samples, as well as the 0.9 mm beech sample (Fig. 2). Three different levels of welding intensity were defined, form light to high, and obtained for various operating conditions (Table 1.) The welding intensity was estimated from the overall state of the welded joint after separation, with "light intensity" referring to undamaged or slightly burned wood pieces, and "high intensity" corresponding to strongly damaged or burned wood pieces. It seems that it is easier to weld thin pieces of wood as demonstrated by the welding force (70 to 100 daN) and energy (300 to 400 J) required to assemble 0.9-mm poplar or beech samples at light and medium intensities. To weld 2-mm poplar, higher welding forces and energy levels were required to reach light or medium intensities (200 daN and 550 to 600 J). At last, it was not possible to assemble 2-mm beech pieces. It must also be noted that high welding intensities lead to high degradation of wood pieces. Though these conditions enable wood welding, they do not appear suitable for any application, given the state of degradation of the resulting pieces, and the burnt smell that they generate.

The evolution of power during welding can be separated into four steps (Fig. 3a):

1. *Approaching step*: The sonotrode moves toward the specimen. Power increases from 0 to 50 W when ultrasounds are triggered a few millimeters before the sonotrode makes contact with wood pieces.
2. *Loading step*: The force progressively increases as the sonotrode progresses and keeps pressing the wood pieces. Power tends to increase as the force increases until reaching a maximal value at the welding force.
3. *Welding step*: The force stays constant and the sonotrode keeps vibrating until reaching the energy end condition. In this step, power slightly decreases while keeping a value close to the power peak reached at the end of the loading step.
4. *Post-welding step*: Vibrations stop and power goes back instantaneously to zero as the wood joint is maintained at the welding force for 1 s. Then, the sonotrode goes back to its initial position, releasing the joint.

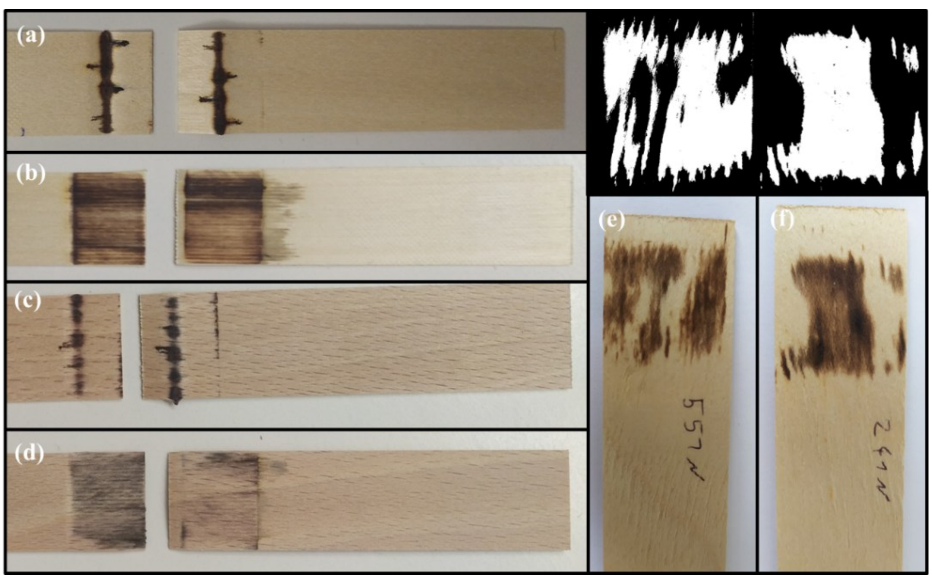

Fig. 2. Characteristic poplar (a, b) and beech (c, d) joints after separation by shear testing assembled using cylindrical (a, c) and surface anvils (b, d); photos and binarized images of two 2 mm poplar joints after separation by shear testing assembled using the same welding set-up and parameters but showing different contact surfaces (e, f)

The main operating parameter influencing the power response when assembling wood specimens at a fixed vibration amplitude is the welding force, which is consistent with previous observations on papers (Charlier *et al.* 2021). The energy has no effect at all on the maximal power; rather, its value is adjusted from one welding to another to ensure that the welding force set by the operator is reached. The welding speed has almost no influence in the studied range. It is highly probable that changing the order of magnitude of the welding speed could influence the loading and the maximal power. Optimizing the speed also presents an applicative interest as it could reduce cost and increase productivity.

Power response is affected by a material's characteristics (Fig. 3b). The evolution of power over time is influenced both by wood species and sample thickness, which is consistent with what was previously observed for the ultrasonic welding of papers (Charlier *et al.* 2021). Power peaks ranging from 500 to 800 W were recorded for poplar and from 700 to 1200 W for beech, depending on welding intensity and sample thickness (Fig. 4). Stronger intensities and larger thicknesses tend to increase the peak power. A sharper power increase can be observed for beech compared to poplar (Fig. 3b). This can be attributed to the difference in properties of the two wood species. Beech is denser and stiffer, so for a fixed range of displacement the increase in force is larger than for poplar. Moreover, wood pieces are generally damaged by the procedure, as the sonotrode tends to penetrate in the thickness of the top piece. Poplar was found to be especially sensitive to this phenomenon, which contributed to its apparent lower stiffness. Severe welding conditions, in particular high welding forces, can even lead to specimens breaking during the process. That is another reason why it is not much desired to work at high intensities.

Table 1. Summary of Process Parameters Required to Obtain Wood Joints of 20 x 25 mm² Welded at Different Levels of Intensity for Several Wood Species and Tooling Types

Wood Sample	Tooling Type	Welding Intensity	Welding Force (daN)	Welding Speed (mm/s)	Energy (J)
Poplar 0.9 mm	Spring	Light	90	2.5	300
	Spring	Medium	100	3	400
	Fixed	Medium	100	3	400
	Spring	High	140	3	480
Poplar 2 mm	Spring	Light	170	6	450
	Spring	Medium	200	7	550
	Fixed	Medium	180	5	600
	Spring	High	200	8	600
Beech 0.9 mm	Spring	Light	70	2.5	300
	Spring	Medium	90	3	400
	Fixed	Medium	150	3	400
	Spring	High	200	8	600
Beech 2 mm	Not weldable in any conditions				

In a previous study, it was observed that the use of a spring tooling allowing a displacement of the anvil in the direction of the head of the press was beneficial to weld thin materials (Charlier *et al.* 2021). Veneer wood seems unconcerned, as both fixed and spring tooling can weld wood pieces. Moreover, medium welding intensities are obtained for close operating conditions and associated power peak values (Table 1). This is probably due to the larger thicknesses of wood pieces compared to papers (about 100 µm).

Compared to data from reported works on the ultrasonic welding of other lignocellulosic materials, assembling veneer wood seems to necessitate stronger operating conditions. For the same welding surface, power peak values close to 500 W were reported when welding machine-glazed kraft paper of 80 g/m² coated with 2.7g/m² of polyvinyl alcohol (amplitude 100%, 250 J) (Charlier *et al.* 2021). Moreover, welding forces required to assemble 2-mm poplar and 0.9-mm beech samples at medium intensity were close to the limits of the machine (2000 N, 1500 W), which confirms that the process is demanding.

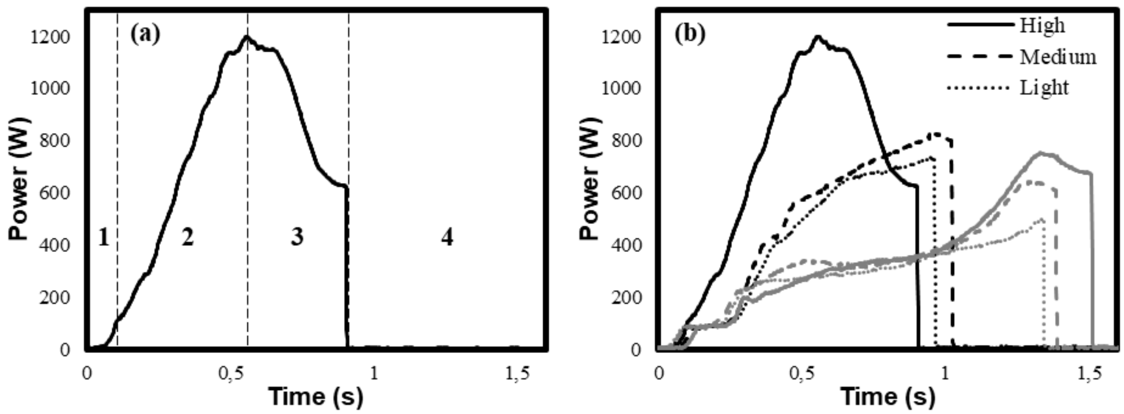

Fig. 3. Characteristic power response illustrating the different steps of the procedure when welding 0.9 mm beech specimens (a). Characteristic power responses when welding 0.9 mm beech (black) and 0.9 mm poplar (grey) specimens (20 x 25 mm²) using a spring tooling at light, medium and high intensities.

Mechanical Performances of Surface Welding Joints

Shear strengths from 200 to 500 N were recorded for poplar for a power ranging from 500 to 800 W (Fig. 4). Shear strength from 150 to 700 N were recorded for beech for a power ranging from 700 to 1200 W. The shear strength of welded joints increases with the power peak similarly to what was observed for the ultrasonic welding of hydrophobic papers (Charlier *et al.* 2022). However, the magnitude of recorded forces is not comparable between the shear testing of welded wood and the peeling of welded papers (up to 15 N for a width of 15 mm). Two main types of failure were observed: clean separation of the welding joints and failure of a wood piece. Poplar specimens were more subjected to failure due to the fact that they are more damaged by the welding process than beech. Considering that it was not possible to assemble 2-mm-beech pieces, thin wood pieces seem better suited for ultrasonic welding. The 0.9- and 2-mm-poplar joints showed close performances, but 0.9-mm joints could be obtained in less severe conditions and using a lower amount of energy. This observation is aligned with previous results on the ultrasonic welding of papers showing that joint performances at fixed operating conditions are strongly influenced by the thickness of the assembly (Charlier *et al.* 2021). For a stack of papers, joint properties were maximal for a thickness between 0.5 to 1.2 mm. In this study, it seems that an assembly of two wood pieces of 2 mm is a little too thick for the welder. The shear strength of reference wood joints obtained by gluing was around 900 N for poplar and 2000 N for beech. It can be noted that it was the wood itself that failed, and not the joint. For stapled joints, shear strength was around 100 N for poplar and 150 N for beech. Thus, the shear performances of welded wood joints were overall quite good, and superior to stapling, which is already commercially used for wood packaging.

A concerning observation is the reproducibility of experiments. As shown in Fig. 4, standard deviations associated with power peaks and shear strengths were quite large. The variation coefficient for power peaks was on average close to 10% and reached up to 30%. This was regarded as unusual, considering that previous work on the ultrasonic welding of papers have shown that the power response is highly reproducible from one experiment to another in identical conditions (Charlier *et al.* 2021, 2022). The same observation can be made for the shear strength with an even larger variation coefficient on average close to 40% and up to 55%. Several causes could explain this behavior. Regarding the shear strength, scattering is probably due in part to the heterogeneity of welded joints (Fig. 2e,f). The welding surface is not in a homogenous state, revealing areas where the wood appears intact and others where the wood is burnt. From one specimen to another, the location and the amount of burnt areas can widely change and do not correspond at all to the surface state of the anvil, whose texture is supposed to focus the energy. Consequently, it is highly probable that the actual amount of surface in intimate contact does not correspond to the dimension of the sonotrode (20 × 25 mm²). Thus, the breaking force measured by the machine does not necessarily correspond to the same welded area. This is why it was chosen to represent the shear strength as a force rather than a stress, given that it was not always possible to determine the actual contact surface in the joints. The dispersion of power peak values is probably caused by the way the energy is focused in wood pieces. During ultrasonic welding, soundwaves progress mostly in the thickness of materials through the stiffest regions. With the set-up used in this study, the texture of the surface anvil is expected to act as an energy director: when the sonotrode applies pressure on the materials, the actual contact is made on the top of the anvil grooves, *i.e.*, the force is locally applied, which should focus the energy. Given the appearance of welding joints, this was clearly not achieved here. Wood pieces are heterogenous by nature: dimensions, internal structure, and mechanical properties of veneer wood in the thickness can locally differ following the peeling process. In this study, it is believed that the energy was actually focused by the characteristics of the wood itself. Burnt areas are expected to correspond to zones where the energy was focused because the wood piece was either thicker, denser, or stiffer. As a consequence, the power response when welding wood was more dispersed than it is for papers or plastic parts, and the power peaks show a higher dispersion.

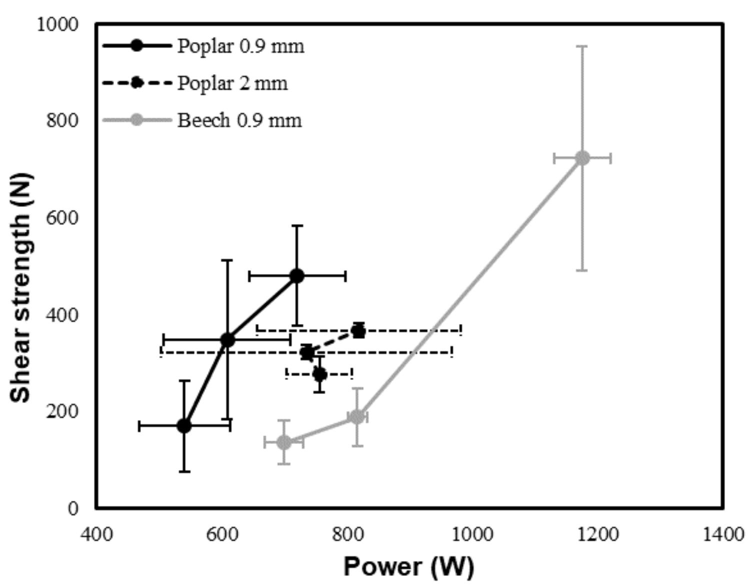

Fig. 4. Weldability curves obtained for the weldable wood samples assembled using a spring tooling and a surface anvil. The three coordinates for each wood species correspond to the light, medium, and high intensity conditions.

Finally, it was also observed that the toughness and the ageing of welded wood joints seemed quite poor. Though it was not properly measured, changes in ambient conditions have resulted in the apparition of cracks. Some joints were also debonded quite easily while manipulating welded specimens, unfortunately, when applying torsion or cleavage. Further investigation could be required to better assess these limitations.

Optimization of the Ultrasonic Welding of Veneer Wood: Toward Better Focus of the Energy

From an applicative point of view, having such a high variation in results could be prohibitive for further development. Thus, efforts were made in this study to investigate technical solutions to render the ultrasonic welding of veneer wood more reliable and reproducible. To do so, a similar study was conducted again while changing the flat anvil (Fig. 1d) for a cylindrical one (Fig. 1e) with the hope that the latter would be able to better focus the energy when welding wood pieces. Processing conditions of the obtained welded joints at medium intensity are reported in Table 2. A first important result was that, using this set-up, it was possible to assemble 2-mm-beech pieces with a welding force almost at the maximal setting. When passing from a flat to a cylindrical anvil, the actual amount of surface that is pressed is reduced, thus increasing the pressure applied on the wood pieces. In this case, it seems that this increase in pressure was enough to trigger adhesion in the 2-mm-beech joints. This illustrates the importance of forces and pressures in ultrasonic welding, which was already reported in previous works (Charlier *et al.* 2021, 2022). A second important observation concerns the state of separated joints (Fig. 2a,c). Wood pieces are homogeneously darkened and the whole welded area seems to correspond to the actual surface contact between the sonotrode and anvil, thus suggesting a better focus of the energy. Reproducibility is also improved. Compared to operating conditions leading to weldings of medium intensity for the flat anvil, using the cylindrical anvil leads to lower welding forces and quantity of energy, which is probably caused by the decrease in the amount of surface in contact. The decrease in energy is actually welcomed for development prospects.

Table 2. Summary of Process Parameters Required to Obtain 25 mm Linear Wood Joints Welded at Medium Intensity Using a Fixed Anvil

Wood Sample	Tooling Type	Welding Intensity	Welding Force (daN)	Welding Speed (mm/s)	Energy (J)
Poplar 0.9 mm	Fixed	Medium	40	4	150
Poplar 2 mm			150	4	300
Beech 0.9 mm			100	4	150
Beech 2 mm			180	5	400

Several noteworthy results can be extracted from the weldability curves comparing the mechanical performances of 0.9-mm welded joints obtained using different anvils and tooling set-ups (Fig. 5). First, the use of the cylindrical anvil caused a strong reduction of the variability of results for beech and poplar, both in power response (from about 10% to less than 5%) and shear strength (from about 40% to 30% on average). It confirms that this anvil was more efficient to focus the energy and thus more suitable for the ultrasonic welding of veneer wood. Secondly, both average power responses and shear strengths were lower for the joint achieved with the cylindrical anvil, which is probably associated with the lower welded surface as previously discussed. Finally, it was observed that many poplar specimens were badly damaged by the welding using the cylindrical anvil even at 40 daN (apparition of cracks, failure during shear testing). It is assumed that the loss of integrity of wood pieces themselves also contributes to the decrease in shear strength compared to surface weldings.

Regarding the welding procedure itself, it was noticed while experimenting that for a same wood species, the initial thickness of the two stacked pieces varied by up to 10%. In such case, if the zero position of the machine is not corrected, it can result in different loadings and power responses. This phenomenon contributed quite noticeably to the overall dispersion, as systematically calibrating the device between two weldings further decreased the scattering of shear strengths from about 30% to 20%. This is an issue for industrial development as systematic calibration will obviously not be considered for mass production. Nevertheless, the shear strengths of 0.9-mm poplar and beech joints were above their stapled reference, which is encouraging for further development.

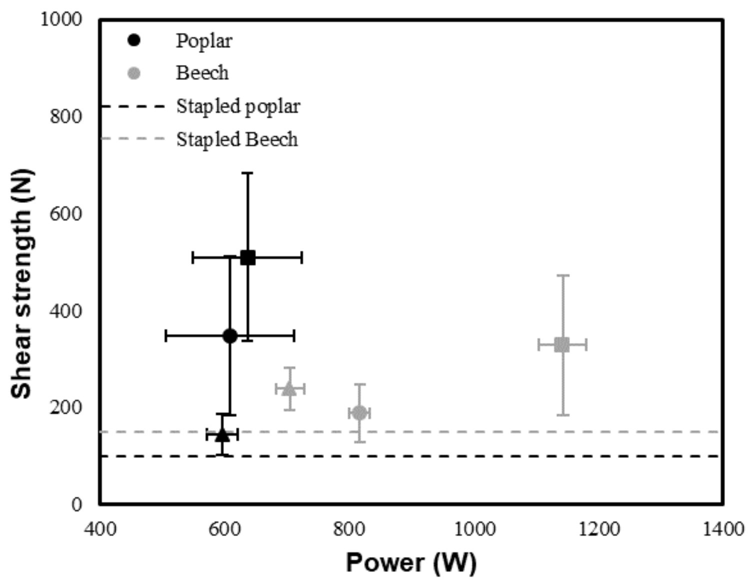

Fig. 5. Weldability curves for 0.9 mm poplar and beech samples assembled at medium intensity using a spring tooling and a surface anvil (●), a fixed tooling and a surface anvil (■), and a fixed tooling and a cylindrical anvil (▲); comparison to the shear strength measured when testing stapled reference sample

CONCLUSIONS

1. Veneer wood can be assembled using ultrasonic welding. The mechanical performances in longitudinal tensile shear of welded joints (from 150 to 700 N for beech and poplar, depending on welding set-up and operating conditions) were above those of the stapled reference sample (100 N for poplar, 150 N for beech), which can be regarded as encouraging, given that stapling is already used commercially for wood packaging.
2. Wood pieces can react differently to the ultrasonic welding, depending on wood species and geometry. The procedure is sensitive to wood properties (density, stiffness), thickness, and heterogeneity. Overall, this leads to a high dispersion and a low reproducibility of the welding procedure itself and of the shear strength of welded joints. This result was attributed to a bad energy focus, which appears to be strongly driven by wood's internal structure. In this, the behavior of wood is quite different from

what has been previously observed when welding other lignocellulosic materials such as papers and carton boards.

3. Nonetheless, it is possible to achieve a better focus of the energy inside wood specimens using appropriate welding set-up and operating conditions. In particular, the use of a cylindrical anvil with a large bending radius seemed to improve the energy focus, thus reducing the dispersion of the power response and welded joint properties, offering valuable prospects for industrial development.

ACKNOWLEDGMENTS

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