

Ultrasonic Welding of Fiber-based Paperboard: Experimental Investigation and Optimization

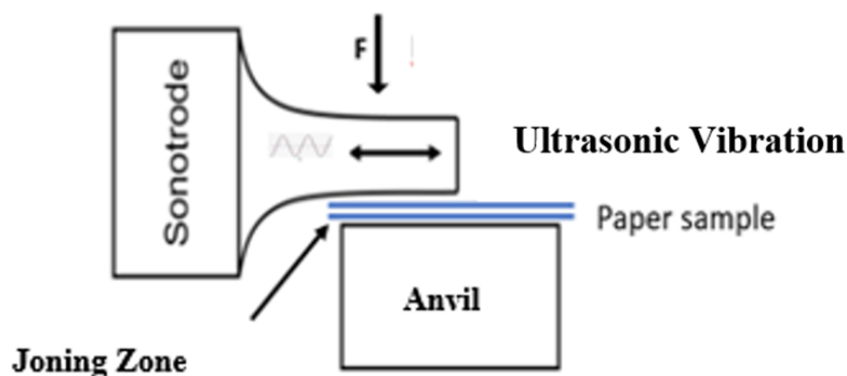
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GRAPHICAL ABSTRACT

Ultrasonic joining for Paper



Ultrasonic Welding of Fiber-based Paperboard: Experimental Investigation and Optimization

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A comprehensive understanding of the influences of joining parameters and material-related factors on the ultrasonic joining process for fiber-based materials is essential to optimize the process parameters in a targeted manner. Previous studies have been limited to commercially available materials with unknown compositions, leaving fundamental influencing factors largely unexplored. In this study, paper made from cellulose-rich natural fibers was used to systematically analyze the effects of amplitude, joining force, moistening, and joining energy. Effects of fiber type and fiber length were systematically analyzed. The joining force had the greatest influence on the joint strength across all materials analyzed, followed by humidification and joining energy. In contrast, amplitude only had a minor influence on the joint strength. The fiber type and fiber length also had a significant influence on the strength of the joint, with joints made from softwood fibers tending to have higher strength values. In addition, the bleaching process improves the joint strength because of the lignin reduction, as it promotes fiber cross-linking. Mechanically digested fibers (CTMP), on the other hand, proved to be less suitable for the ultrasonic joining process, as their increased stiffness made it more difficult to form a stable joint, compared to fibers obtained by purely chemical delignification.

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INTRODUCTION

The demand for sustainable packaging materials has increased significantly in recent years. This development is driven by regulatory requirements, growing societal awareness, and pressure on companies to offer environmentally friendly alternatives. However, the use of adhesives or coated paper materials can significantly impair the full recyclability of packaging. In particular, adhesives can cause contamination in packaging machinery, leading to unplanned production interruptions, material waste, and increased cleaning efforts. Against this backdrop, fiber-based materials such as paper, cardboard, and pulp products are gaining particular attention. Their recyclability is intuitively understandable and does not require extensive communication. They are based on renewable raw materials, for which the recycling infrastructure is well established. The recycling technologies are considered robust with regard to a wide range of materials, and the recycling rates are comparatively high. Consumer confidence in the sustainability of

these materials is currently strong, and their image is correspondingly positive, which represents significant marketing potential. However, despite these ecological advantages, the reliable and material-appropriate joining of fiber-based packaging remains a technical challenge, especially when the use of additives such as adhesives is to be completely avoided.

The ultrasonic welding process is considered a promising solution to this challenge. Since its introduction in the 1960s, it has proven to be an efficient and economically established method for joining thermoplastic polymers (Soloff *et al.* 1965). The process is characterized by short cycle times—typically between 0.2 s and 2 s—as well as high suitability for automation (Züst and Reiff 2019). In packaging technology, ultrasonic welding is already widely established and has been extensively studied, particularly for conventional polymer packaging materials (Bonnet 2009).

Although ultrasonic joining has been extensively researched and successfully used for plastics, the application of this process for fiber-based materials is still in its infancy. The development of ultrasonic joining processes for paper began with the aim of joining paper without glueing - using pressure and ultrasound. An early patent describes the use of ultrasonic welding, in which the paper surfaces are guided between a roller and an oscillating disc with defined pressure (Sievers 1963). An important advancement is represented by a patent (Gmeiner and Schneider 2005), which describes a device for the continuous joining and/or consolidation of material webs using ultrasonic energy. The device enables adhesive-free bonding between at least two paper webs. Although the specific ultrasonic effects on the fiber structure are not explained in detail, the work clearly highlights the relevance and technical potential of the process. A further development was the targeted moistening of the joining surfaces with demineralized water to ensure uniform wetting. During the ultrasonic process, pressure and vibration led to felting of the fibers and the formation of hydrogen bonds, which improved the strength of the joint (Ulrich 2015). The process was also optimized by switching from longitudinal ultrasonic welding to ultrasonic friction welding. The parallel arrangement of the direction of oscillation to the joining plane resulted in higher interfacial friction, whereby stronger joints were achieved with additional joining force (Ulrich 2015). A further technical improvement consisted of roughening the joining surfaces before moistening, exposing individual paper fibers and increasing the three-dimensional structure of the surface. This modification led to better mechanical interlocking of the fibers and increased strength of the joint. Particularly good results were achieved when a defined roughness of $\pm 10\text{ }\mu\text{m}$ was reached (Ulrich 2022)

Despite these promising approaches, the scientific investigation of the process for paper materials has not yet progressed sufficiently. In particular, the role of the material-related parameters (*e.g.*, fiber type, fiber length, moisture content) in combination with the process-related parameters (*e.g.*, joining force, joining energy, amplitude of the mechanical vibrations) and their influence on the joining quality and joint strength have not yet been sufficiently studied. Further scientific analysis of these influencing factors is therefore necessary to further optimize the process stability and range of applications of ultrasonic joining for paper materials. A significant reference point in the literature is the study by Charlier *et al.* (2021), which investigates ultrasonic welding of coated paper. An industrially finished kraft paper, coated on both sides with polyvinyl alcohol, was used in that study. The coating played a crucial role in seam formation. In contrast, the present work focused on untreated raw paper without any coating or surface treatment. This fundamental difference in material resulted in a different welding mechanism, where the

direct fiber-to-fiber bonding was central, rather than bonding *via* the coating. Due to these differences, the findings of Charlier *et al.* (2021) are not directly transferable to the present study.

Regazzi *et al.* (2019) studied ultrasonic welding of 100% lignocellulosic TMP and CTMP papers, which also provided important insights into the thermoplastic bonding mechanism. This mechanism is based on the softening of amorphous wood polymers such as lignin and hemicellulose above their glass transition temperature. The softened polymers act as a matrix material, surrounding the cellulose fibers and filling the interfaces within the weld zone. Although these results are highly relevant for the fundamental understanding of the joining process, the processing conditions used in that study differ significantly from those applied in the present work. While Regazzi *et al.* (2019) investigated relatively long process durations of up to 15 s (welding time plus hold time), the total joining time in the present study was less than one second. This difference is particularly relevant from an industrial perspective, as longer cycle times are hardly economically viable. Furthermore, it is reasonable to assume that the underlying joining and bonding mechanisms differ considerably at such contrasting time and temperature profiles.

This study addresses precisely this research gap. The aim is to systematically analyze the fundamental relationships between the material properties, the process parameters, and the joining quality in the ultrasonic joining of fiber-based materials. The focus is on uncoated paper packaging, where the mechanical strength of the joint and the visual appearance of the seam are considered key quality criteria. Aspects such as tightness play a subordinate role in this application context, since such packaging is not primarily used for sealed applications according to the current state of the art. By analyzing these parameters and their interactions, specific parameter windows are to be identified that enable high joint quality and reliable joints.

EXPERIMENTAL

Materials and Measurements

The tests were carried out under controlled climatic conditions at a temperature of 23 ± 1 °C. In this work, the influence of the material and process parameters on the ultrasonic joining process and the joint strength was systematically investigated. To ensure a known and well-defined material composition, the materials used for the experiments were supplied by the Papier Technische Stiftung (PTS, Heidenau, Germany), a research and service institute for the pulp and paper industry. These materials were classified into four categories based on fiber extraction and respective preparation, as shown in Table 1.

Table 1. Test Materials and their Properties

Sequence Number	Fiber			SR	Fiber Length (mm)	Thick-ness (mm)	Density (kg/m ³)	Residual Lignin (%)
	Extraction	Bleach	Kind					
M1	Cellulose	Bleached	Spruce/pine	24	1.82	192	0.63	<1.0
M2			Eucalyptus	36	0.92	209	0.60	<1.0
M3	Cellulose	Unbleached	Spruce/pine	30	1.88	213	0.57	6.7
M4	CTMP	Unbleached	Spruce/pine	29	1.03	578	0.22	28.4
M4-Calendered	CTMP	Unbleached	Spruce/pine	29	1.03	364	0.34	28.4

As the papers were not freely available on the market, they were labelled using the serial number assigned by PTS. None of the papers were coated. Apart from starch (HiCat 35844, Cargill 1%) and alkylketene dimer (AKD-Aquapel F220, Solenis - 0.7 %), no other additives were used in the production process. The pulps used were produced using the kraft (sulphate) process, the dominant process for pulp production. The mechanical pulps, by contrast, were produced using the chemi-thermomechanical process (CTMP). Table 1 shows the paper materials used in this study and their properties.

All materials used in this study had a comparable basis weight of approximately 122 ± 3 g/m² according to DIN EN ISO 536:2020-05 (European committee for standardization 2020), but differed significantly in their properties due to the different fiber types and methods of fiber isolation. The materials M1 and M2 both consisted of cellulose but varied in their origin and structure of the fibers. M1 is based on softwood, specifically a mixture of spruce and pine (Stendal ECF) and contains correspondingly longer fibers, M2 is derived from hardwood, namely eucalyptus (UPM eucalyptus), which has shorter fibers. These differences allow a precise investigation of the influence of fiber type and fiber length on the joint strength.

In addition, the comparison of the joint strength between M1 (bleached) and M3 (unbleached) allows the effect of the bleaching process to be analyzed. The comparison between M1 and M4 produced by MM also offers the opportunity to investigate the influence of different fiber extraction methods, in particular the difference between the fibers obtained by the sulfate (kraft) process and CTMP fibers. This systematic analysis helps to develop an understanding of the relationships between material properties and joining processes.

Sample strips with a width of 15 mm were cut from the paper sheets using a cutting device, ensuring a clamping length of 50 mm. To minimize possible influences from different fiber directions, all samples were taken along the machine direction (MD) of the paper. Subsequently, the area to be moistened, which also serves as the joining area, was marked on the samples. This area measured 5 by 15 mm and was located on the top side of the paper, that is, the side facing away from the forming fabric, at a defined distance of 5 mm from the upper edge of the sample. On the wire side, a distance of 10 mm from the upper edge was additionally marked to ensure precise and reproducible positioning of the samples between the sonotrode and the anvil during the joining process. A schematic representation of the sample preparation is shown in Fig. 1.

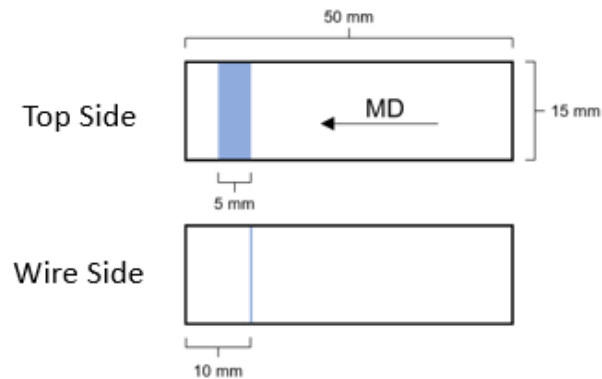


Fig. 1. Illustration of sample preparation and marking of the joining surface

Test Equipment and Devices Used

The influence of material-related and process-related parameters on the joining zone in the ultrasonic joining process was analyzed on an ultrasonic test stand from Herrmann Ultraschalltechnik (Fig. 2).

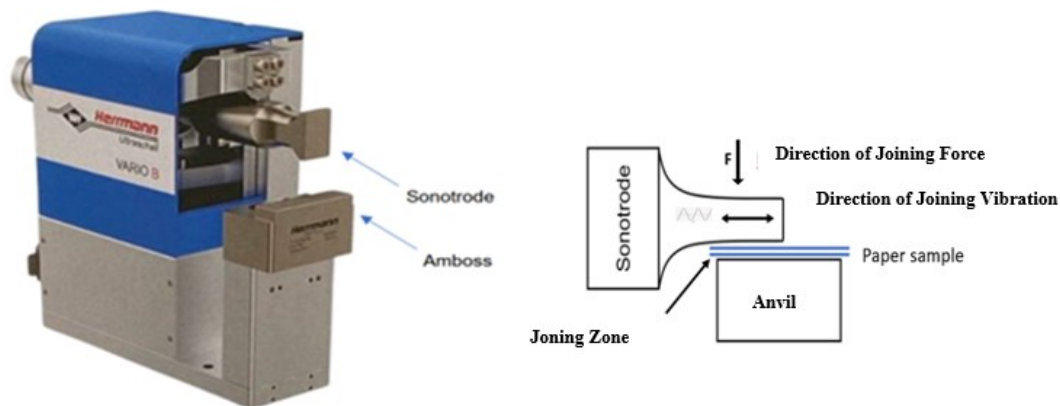


Fig. 2. Basic structure of the ultrasonic test stand

The test stand generated ultrasonic vibrations with a nominal frequency of 20 kHz and a maximum vibration amplitude of 31.9 μm . Process parameters, joining force, and input energy can be directly adjusted on the device. The surface contours and two anvil surface contours can be used interchangeably. A finely textured waffle sonotrode surface measuring $1.0 \times 0.4 \text{ mm}$ was applied to one surface at an angle of 45° , together with a waffle-textured anvil surface measuring $0.5 \times 0.175 \text{ mm}$, also at an angle of 45° (Fig. 3).

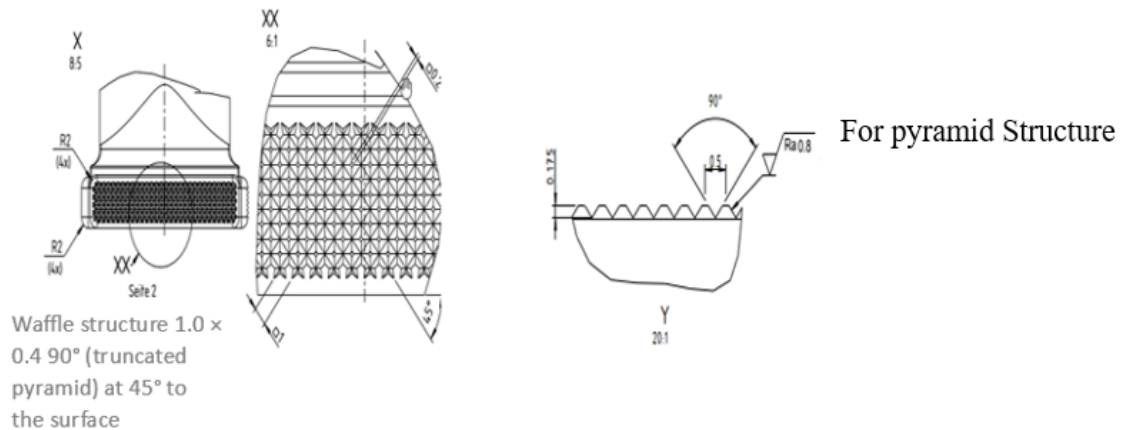


Fig. 3. Waffle sonotrode surface on the left, waffle anvil surface on the right. (Herrmann Ultraschalltechnik GmbH & Co.)

Immediately before joining the samples, one of the two samples was moistened in the defined area. Unless otherwise specified in the test protocol, demineralized water was applied using a piston-operated pipette. The applied water was then distributed evenly over the entire marked area using a glass rod, avoiding the application of pressure. The second sample strip was placed flush on the moistened sample strip without moistening. When joining without moistening, the two upper sides of the paper strips were placed directly on top of each other without further pre-treatment. The samples were then placed in the ultrasonic welding device so that the mark on the outside (screen side) was aligned with the outer edge of the sonotrode. This ensured that the full surface of the joining tools acted on the moistened joining surface.

Once the samples had been positioned correctly between the anvil and sonotrode, the joining process could be started. The sonotrode moved towards the anvil with a defined force. As soon as the trigger point was reached, ultrasonic vibrations are introduced into the joining partners, which continued until the pre-defined amount of energy is reached.

After completion of the joining process, the samples were acclimatized for at least approx. two hours in a standard climate at a temperature of 23 ± 1 °C to ensure defined drying before the joint strength was determined. During this acclimatization, slight water evaporation may occur, which can promote additional hydrogen bonding between the adjacent fibers.

To evaluate the joint strength, a peel test was carried out in accordance with DIN 55529 (Deutsches Institut für Normung e.V. 2012). The tests were performed using a testing machine from the manufacturer ZwickRoell GmbH & Co. KG (model Xforce HP 1 kN, Z016 with BT1-FR010TM.A50). The joined paper strips were clamped in a tensile testing machine so that they were positioned perpendicular to the tensile direction and a peel angle of 90° was created. The samples were clamped in the center of the tensile axis with a free clamping length of 50 mm (Fig. 4). The pull-off speed was constant at 100 mm/min during the measuring process. The test took place in a standardized climate chamber.

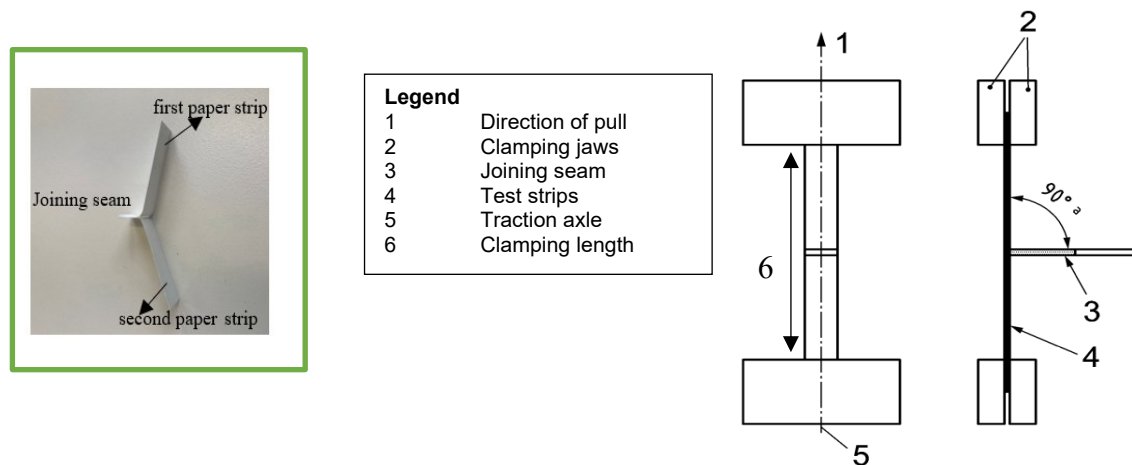


Fig. 4. Schematic diagram of the test arrangement according to DIN 55529

A force-displacement diagram was recorded for each measurement process, from which the maximum force ($F_{\max}$) could be determined. The average value of the maximum forces was calculated from a series of five test samples. This describes the joint strength of a series of samples.

In addition to determining the joint strength, the joint was also assessed based on visual criteria. If too much energy is introduced, the joining process can lead to signs of burns in the samples. To enable quantitative comparison, the signs of burns are expressed as a percentage. This considers both the proportion of the total joining area that is affected by burning (Fig. 5) and the intensity of the burn, which can range from light yellow-brown to dark brown-black. Burns occurring outside the marked joining area were not considered, as the samples were only moistened and subjected to load within the marked region. Figure 5 illustrates the different gradations of burn marks on the joining surfaces. It should be noted that differences of 10% to 20% points in the measurement results across different series were negligible, as the assessment was subjective. Categorically, the burn marks could be divided into weak burns (10% to 30%), medium burns (40% to 70%), and strong burns (80% to 100%).

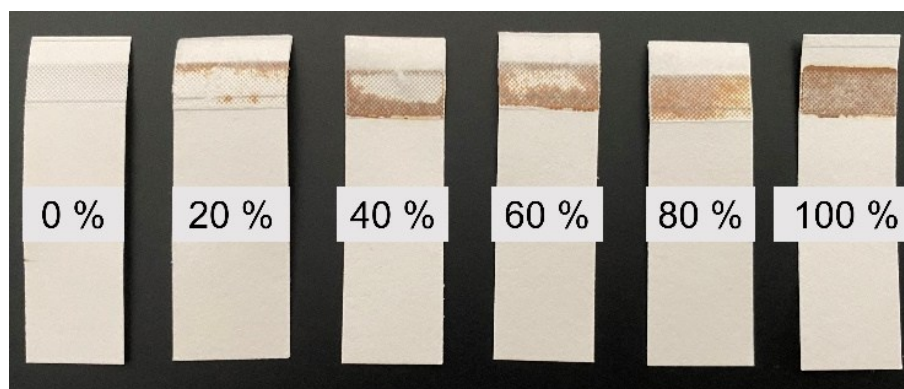


Fig. 5. Illustration of burn phenomena on the joining surface: from no burn marks (0%) to severe burn (100%)

The factors and parameters analyzed in this study are systematically presented in Table 2 below. In addition, it is indicated for each factor and parameter whether they are continuous or categorical variables. Continuous factors are quantitative and have a fixed order, while categorical factors represent qualitative data without a natural order.

Table 2. Overview of the Factors and Parameters Analyzed

Factor	Unit	Variable Type
Amplitude	%	Continuous
Joining Force	N	Continuous
Joining Energy	J	Continuous
Humidification		Categorical ¹
Material Type		Categorical

Unmoistened or moistened sample

The experiments in this investigation were planned and analyzed using the data analysis software Cornerstone 7.1 (Camline GmbH 2018). Statistical test planning was based on the principle of D-optimality, which aims to obtain maximum information with a reduced number of tests and thus save time and resources. To analyze the test series, regression models were created that relate the target variables to the varying factors. The goodness of fitness of the model was evaluated using the adjusted coefficient of determination (Adj. R-square). In addition to numerical analysis, the software was also used for the graphical visualization of the test results to facilitate the interpretation and communication of the results.

RESULTS AND DISCUSSION

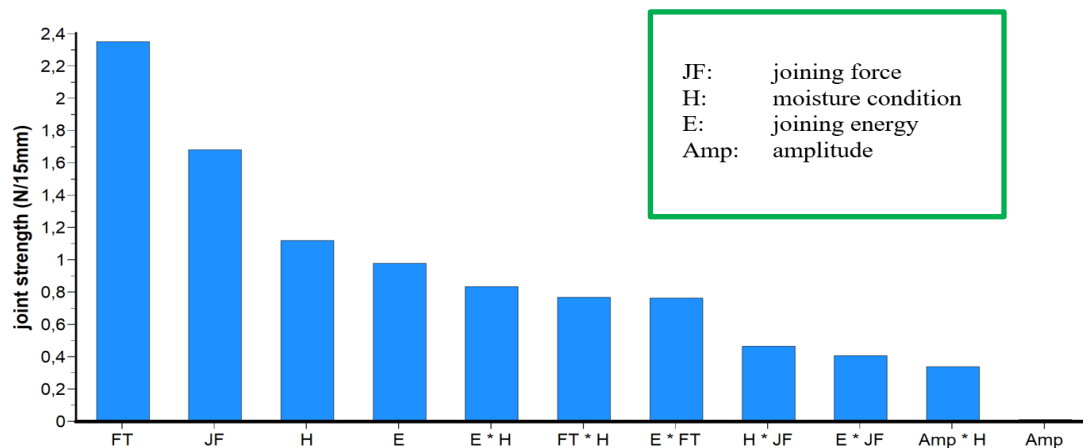
To investigate the relationships between the process parameters, the material properties and the joint strength during ultrasonic joining, a full-factorial test plan was created using the data analysis software Cornerstone 7.1 (Camline). This comprised 20 test points with different combinations of joining parameters for each material (Table 3).

Each test section was repeated five times to ensure statistically reliable results. The evaluation of the joined samples showed that the joint strength was significantly influenced by the material properties and the process parameters.

The Pareto diagram shown in Fig. 6 illustrates the dominant factors influencing the joint strength and reveals the effective strengths of the individual variables in descending order, with the most significant factors positioned on the left-hand side. The analysis shows that the fiber type had the strongest influence on the joint strength. In addition, the joining force (JF) was another key factor. The moisture condition (H) and the joining energy (E) also had a significant effect on the joint strength, while the amplitude (Amp) only had a minor influence.

Table 3. Experimental Design

No.	Amplitude (%)	Joining Force (N)	Energy (J)	Moisture (μ L)
1	70	400	10	0
2	70	1400	10	0
3	100	1400	40	3
4	100	1400	10	0
5	70	400	40	0
6	70	400	10	3
7	100	400	10	0
8	100	400	10	3
9	70	400	40	3
10	85	1067	10	3
11	85	1400	40	0
12	100	1067	30	0
13	100	1400	10	3
14	100	400	30	3
15	100	400	40	0
16	85	733	40	3
17	70	1400	40	3
18	85	400	20	0
19	70	1067	40	0
20	70	1400	20	3

**Fig. 6.** Effects Pareto - Influence of the individual factors on the joint Strength (N/15 mm)

In addition to these main effects, interactions between various influencing variables were also identified, in particular between the joining energy and the fiber type (E *Fiber type) as well as the joining energy and the moistening state of the joining energy (H * E). However, since the experiments were conducted in energy mode on the test bench, joining energy was not varied independently. Instead, at constant Amp and JF, the energy input was achieved *via* the resulting ultrasonic duration. The observed energy-related effects are therefore indirectly time-dependent and should be interpreted because of changes in welding time.

This makes it clear that the interaction between material and process parameters played a significant role and that an isolated consideration of individual factors may not be sufficient to optimize Joint strength.

While the Pareto diagram illustrated the strength of the influencing factors on the joint strength, it did not provide any detailed information on how these factors influence the strength. To analyze the specific influence of the fiber type on the joint strength in more detail, a boxplot diagram was therefore also used. The boxplots shown in Fig. 7 enable a statistically sound analysis of the joint strength (F) of various materials under systematically varied process parameters.

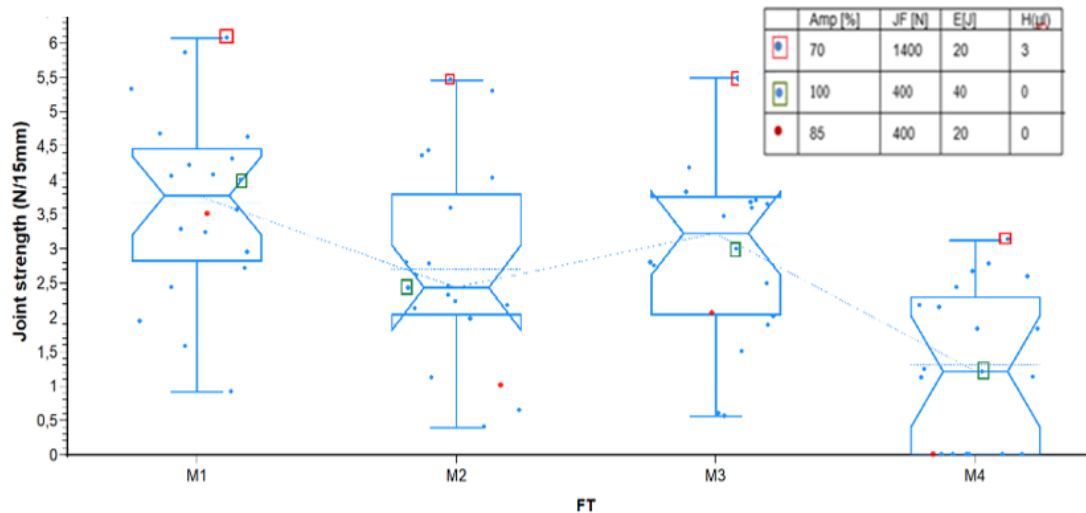


Fig. 7. Comparison of the joint strength of different fiber types using box plots (see Table 1 for the description of M1–M4)

The underlying parameter combinations correspond to the 20 trials of a standardized experimental design that was applied uniformly to all investigated materials. The visualization includes key distribution metrics—such as the median, quartiles, and potential outliers—thus allowing a differentiated assessment of the materials' joining suitability. The variation within a single material reflects the influence of different parameter combinations on the resulting joint strength. In contrast, differences in the distributions between materials under identical parameter settings provide insights into material-specific effects.

The diagram in Fig. 7 shows that M4 had the lowest joint strength overall, with a maximum achieved value of around 3.2 N/15 mm, as highlighted by the points marked in the red square. This was significantly lower compared to the other materials. More than 60% of the values were below 2.5 N/15 mm, and numerous tests resulted in an inadequate joint. The median value of less than 1.5 N/15 mm was significantly lower than for the other fiber types. Sufficient strength is not achieved in many parameter combinations.

The sample M2 exhibited a greater spread of joint strength values than softwood pulps, with a maximum strength of approx. 5.6 N/15 mm. The median was around 2.7 N/15 mm, and around 65% of the values exceeded 2.5 N/15 mm, which indicates good overall joinability. However, the distribution of values was more uneven than for M1, which suggests that certain parameter combinations can lead to lower strength values.

The fiber type M1 had a high joint strength overall. The median was around 3.6 at the upper end of the scale, and around 80% of the values exceeded 2.5. The distribution was homogeneous, and only a few parameter combinations led to insufficient strength

values. The highest measured value was 6.0, which represents the best joinability among the materials analyzed.

The unbleached material M3 had a lower Joint strength compared to the bleached material M1. The median was below that of M1 and is approx. 3 N/15 mm, with around 70% the values exceeding 2.5 N/15 mm. The maximum measured strength was around 5.5 N/15 mm. This shows that the bleaching process caused a structural modification that positively influenced the joinability.

The comparison of pulp from softwoods M1 and hardwoods M2 showed that spruce/pine pulp had a higher joint strength. On average, joints were achieved with long-fiber papers that were around 0.9 N stronger than those made from eucalyptus fibers. This indicates that the specific properties of the fiber type, in particular the fiber structure and fiber length, play a decisive role in the strength of the joint. Softwoods have longer fibers, and a denser structure compared to hardwoods (see table 1), while at the same time they are softer and have lower transverse compressive strength and higher deformability (Rug 2021). These material properties could promote improved mechanical interlocking in the joint area and enable more efficient fiber adaptation, which would potentially have a positive effect on the strength of the joint.

The analysis of bleached and unbleached pulps showed that the bleaching process influenced and tended to improve joint strength, albeit to a limited extent. Studies on the distribution of hemicelluloses across the fiber cross-section of a fully bleached sulphate pulp have shown an increased xylan content in the primary wall (Bleichschmidt 2013). In addition, the data provided by the PTS Institute show that the lignin content of the produced pulp was about 6.7% in unbleached material, while it was reduced to less than 1% by the bleaching process. These structural changes could explain the higher joint strength of bleached pulp. An increased xylan content could strengthen the intermolecular interactions between the fibers and thus increase the efficiency of cross-linking in the joining process. Due to the hydrophilic properties of xylan, an increased number of hydrogen bonds would be formed and could therefore enable more efficient crosslinking during the joining process (De Paula Castanheira *et al.* 2025). At the same time, the reduction in lignin content leads to increased flexibility of the fibers, which would favor fiber interlacing in the joining zone. This is consistent with the observed difference in joint strength between pulp M1 and mechanical pulp M4. In the mechanical pulping process, the lignin content remains largely unchanged, which leads to a stiffer and more stable fiber structure (Luca Motoc *et al.* 2018). However, this reduced flexibility of the fibers could impair the quality of the joint in the joining process. In addition, lignin is hydrophobic, which could inhibit the formation of hydrogen bonds between the fibers (Gruber 2012).

In contrast, Regazzi *et al.* (2019) reported increased joint strength in thermo-mechanically processed (TMP) papers with high lignin content. The authors attributed this effect to the reaching of the glass transition temperature of amorphous wood polymers (lignin, hemicelluloses), which soften and begin to flow during the joining process, thereby acting as a matrix material by encapsulating fibers and filling voids. The apparent discrepancy with the comparatively low joint strength observed for PTS 63 (lignin content: 28.4%) in the present study may, however, be due to significantly different process conditions. While Regazzi *et al.* (2019) applied welding times of up to 15 s (including hold time), the joining times used in this study were below one second. It is therefore assumed that under such short-time conditions, the lignin does not sufficiently soften to develop its potential matrix function.

Another possible reason for the lower suitability of mechanical pulp papers in the joining process could be the paper thickness, which has a significant influence on the joining process. Mechanical pulp papers are bulkier and are two to three times thicker than cellulose papers with the same grammage. This high thickness makes it difficult to achieve sufficient compression in the joining zone, which could have a negative impact on the quality of the joint. In addition, the fibers are greatly shortened during mechanical pulping, further reducing flexibility, which could also have a detrimental effect on the joining process. Reducing the lignin content in the pulp, on the other hand, could increase flexibility, which could enable better fiber cross-linking and thus a more stable joint in the joining process.

The combined influence of paper thickness and high lignin content may overlap and thus reduce the weld joint strength of groundwood papers compared to chemical pulp papers, thereby limiting their suitability for ultrasonic joining.

To determine whether the high lignin content was a decisive factor for the lower weld strength independently of paper thickness, a comparative study was conducted on M4 paper in two conditions: in its original (uncalendered) form and after calendering, which reduced the paper thickness by approximately 40%. Both variants were tested under identical joining conditions, with the joining force incrementally increased up to the maximum applicable value of 3000 N to maximize paper compression. The samples were pre-moistened with 5 microliters of water, the amplitude was set to 70%, and the joining energy to 40 J.

The results shown in Fig. 8 illustrate the joint strength of M4 and calendered M4 as a function of different joining force levels. No clear trend can be observed, indicating a continuous increase in joint strength with increasing joining force. Despite enhanced mechanical compression—achieved both through higher joining forces and by reducing the paper thickness *via* calendaring, the resulting joint strengths in both cases remained at a comparable level. This suggests that under the applied joining conditions, the structural properties of the material particularly the high lignin content played a limiting and potentially detrimental role. The comparison of both material variants thus highlights the importance of chemical composition over purely physical adjustments in determining the achievable joint quality.

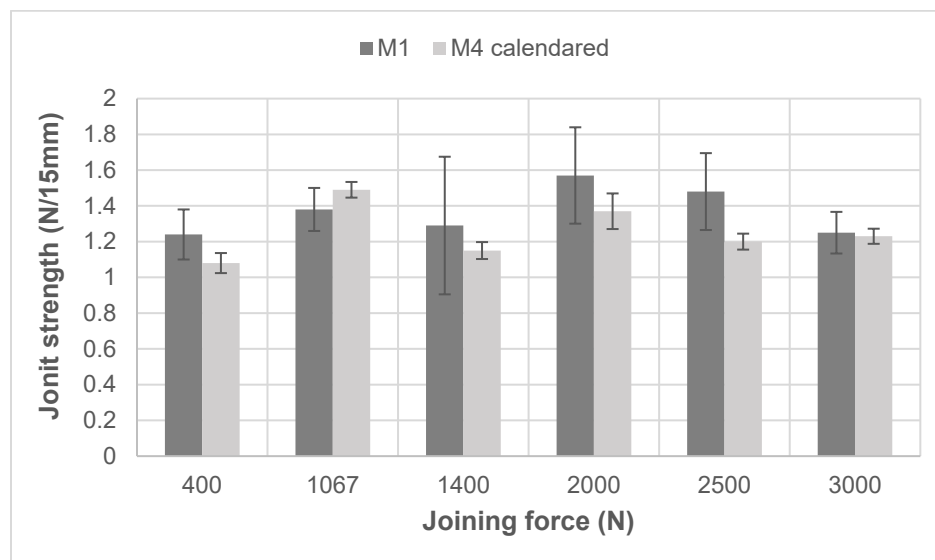


Fig. 8. Weld seam strength of M4 and M4 (calendered) under increased joining force

The interaction diagram was therefore used for further analysis. This diagram in Fig. 9 makes it possible to visualize the mutual dependencies between the process parameters under consideration and shows how various factors jointly influenced the joint strength.

The analysis of the interaction diagrams shows that both the fiber type and a few process parameters had a significant influence on joint strength. While the amplitude within the analyzed range (70, 85, 100) only had a minor influence on the strength, there were significant effects of the moisture content, the joining energy, and the joining force on the mechanical stability of the seam. For moistened samples in particular, no significant change in the joint strength could be determined by increasing the amplitude. In contrast, a higher amplitude led to a slight increase in the joint strength for non-moistened samples.

One possible explanation for the limited influence of amplitude variation on the joint strength could lie in the specific oscillation direction of the sonotrode. Vibration did not occur orthogonally to the material specimen, but primarily in a transverse direction (see Fig. 2). As a result, mainly transverse compression was generated between the workpieces. The effective oscillation amplitude reached a maximum of 5 μm at 100% generator output. Under the conditions used in this study (70% generator setting), the amplitude was accordingly reduced to approximately 3.5 μm . Given this relatively narrow range of variation, it appears plausible that amplitude changes under the given conditions had only a limited effect on the resulting joint quality.

Additionally, it can be speculated that the specific damping behavior of paper as compared to denser materials such as plastics may influence the transmission of ultrasonic energy. According to the literature, paper is considered to have relatively high damping characteristics due to its fibrous structure and porous morphology (Richter 2007). This may lead to a portion of the introduced vibrational energy being dissipated within the material before reaching the joining interface. However, the present results do not allow for direct conclusions about the actual damping effect, so further investigations are required to validate this hypothesis.

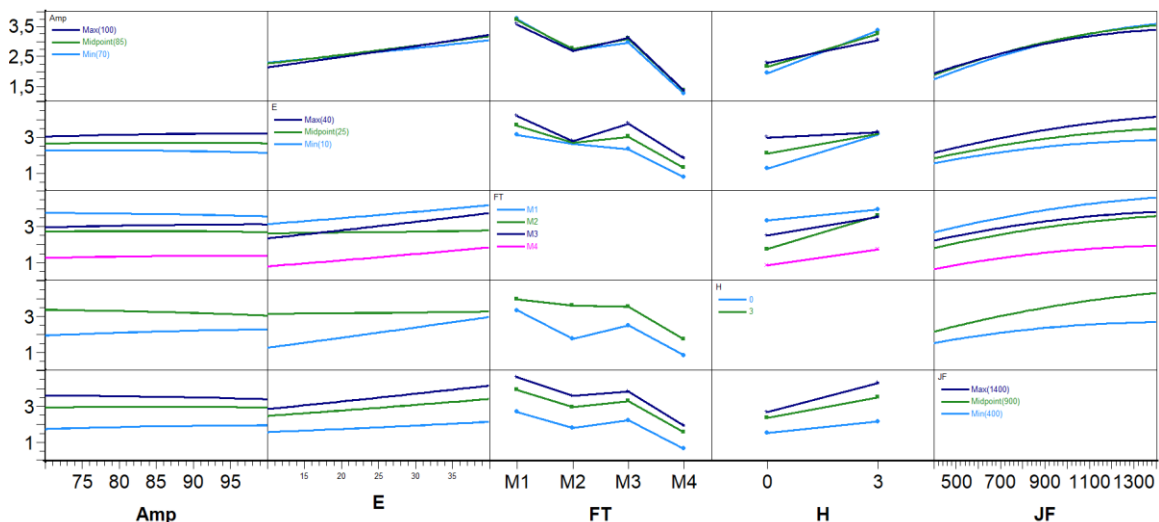


Fig. 9. Interaction graph for joint strength

Increasing the moisture content generally leads to improved joint strength but also influences the effect of other process parameters. It has been shown that the joining energy is highly dependent on the moisture content of the samples. Dry samples react more

sensitively to increasing energy than moist samples. The material M2 showed a particularly low sensitivity.

In addition, the influence of fiber length was strongly dependent on the moistening of the samples. A significant difference in the joint strength was found for unmoistened samples, with long-fiber papers exhibiting an average 0.8 N higher strength. In contrast, increased moisture content led to an equalization of the strength values, regardless of the fiber length. This indicates that the fiber length had no significant influence on the strength of the bond in moistened samples.

One possible explanation for this is the ratio of fiber length to fiber diameter, which was around 100:1 for softwoods and around 50:1 for hardwoods (Naujock and Blechschmidt 2021). Due to their longer and slimmer structure, softwood fibers can assume a denser and more stable alignment in the joining area, which leads to increased mechanical interlocking and thus to a stronger joint. When the samples are moistened, the fibers absorb water, causing them to swell more radially than longitudinally. This swelling process leads to an equalization of the length-to-thickness ratio of the fibers, which reduces the influence of the fiber length on the joint strength.

The joint strength was Sonotrode Side influenced by the joining force, whereby an almost linear increase was observed in the analyzed range. An increased joining force led to a denser and more stable fiber cross-linking, which improved the mechanical stability of the joint. Microscopic analyses of the joint cross-sections in Fig. 10 illustrate this effect. While a sample joined under low joining force exhibited low strength and visible gaps at the interface of the joining partners, Fig. 10 (at left) shows a sample joined under high joining force, resulting in a significantly higher joint strength, as illustrated in Fig. 10 at right. There were clear constrictions in the joint seam, which indicate greater compression and more intensive fiber cross-linking, which led to improved mechanical stability of the joint. The constrictions were caused by the structure of the joining tools. Regardless of the material used, an increase in the joining force led to a significant increase in the joint strength. Specifically, an increase in the joining force from 400 N to 1400 N resulted in an overall average increase in strength of around 2 N/15 mm.

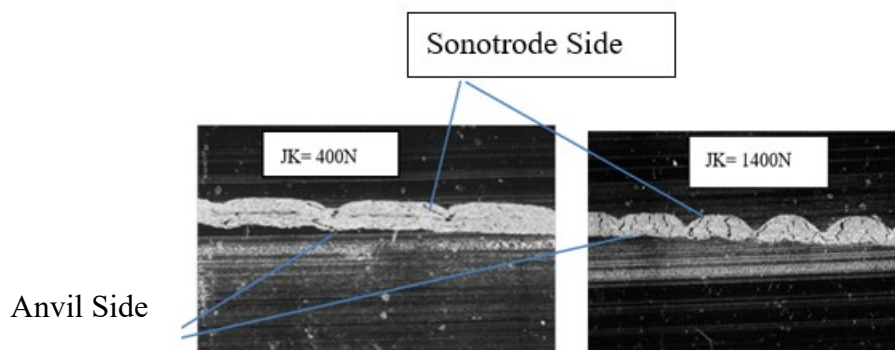


Fig. 10. Cross-section of joining strength (low joining force on the left, high joining force on the right)

The analysis of the factors influencing the combustion phenomena was carried out in the same way as the investigation of joint strength. An interaction diagram in Fig. 11

was used to quantify the relative influence of the process parameters and material properties.

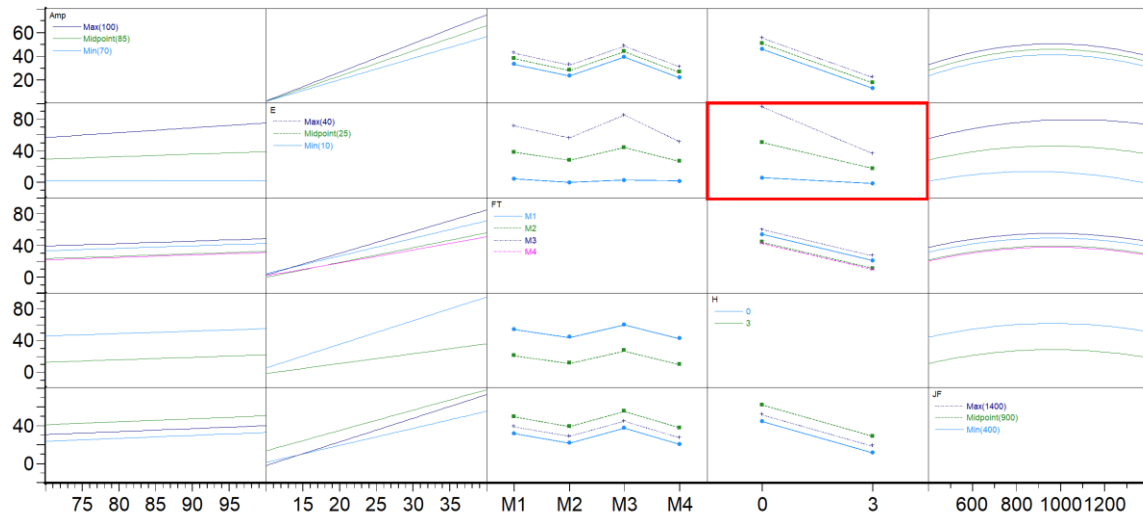


Fig. 11. Interaction graph of combustion level %

The investigations showed that the joining energy had the greatest influence on the occurrence of combustion phenomena during the ultrasonic joining of paper. A higher joining energy therefore resulted in a longer ultrasonic duration – and thus a prolonged friction phase between the paper layers. This extended mechanical friction led to increased heat generation, as the frictional energy produced by the ultrasonic vibrations was converted into thermal energy. As a result, the local temperature rises, promoting thermal decomposition processes of the cellulose and favoring the occurrence of combustion phenomena.

Moisturizing of the samples was identified as the second most important factor. Moisture has a temperature-regulating effect, as it absorbs some of the heat generated and dissipates it through evaporation. This considerably reduces combustion phenomena even at high energy levels. A significant interaction between joining energy and humidification was also observed. While non-humidified samples showed a strong increase in combustion phenomena with increasing joining energy, this effect remained comparatively low with humidified samples. This is shown in Fig. 11 using red-marked matrix field. Nevertheless, a limitation of the joining energy (or welding time) was more effective than simply moistening the samples in order to avoid burning.

According to the regression model, other process parameters such as amplitude and joining force had no significant influence on the combustion phenomena. Their effect was only about one fifth of the influence of the joining energy.

Regarding the material properties, paper made from bleached and unbleached spruce/pine pulp as well as mechanical pulp papers tended to exhibit more pronounced combustion phenomena compared to eucalyptus paper.

CONCLUSIONS

1. The investigation of the joint strength of different paper materials under varying process parameters showed that both the material properties and the process conditions had a decisive influence on the mechanical stability of the seam.
2. There were significant differences between pulp and mechanical pulp paper as well as between different fiber types and degrees of bleaching. Pulp papers made from softwood (spruce/pine) achieved the highest joint strength due to their longer and slimmer fibers.
3. The bleaching process improved the joinability by reducing the lignin content and increasing the xylan content, which promoted intermolecular interactions. Mechanical pulp papers, on the other hand, groundwood papers showed significantly reduced joint strength due to their higher stiffness and lower flexibility. These properties were attributed to the higher lignin content, which increased fiber stiffness and reduced the material's plasticity. Additionally, the greater thickness of mechanical pulp papers, relative to the effective oscillation amplitude of the sonotrode, made efficient compression in the joining area more difficult.
4. Since the ultrasonic vibration primarily occurred in a transverse direction, mainly transverse compression was generated. Due to the comparatively small amplitude range in relation to the material thickness, compression was less effective, which can impair the quality of the joint. In addition, the greater thickness of mechanical pulp papers, relative to the effective oscillation amplitude of the sonotrode, made efficient compression in the joining area more difficult.
5. The analysis of the process parameters made it clear that moisturizing and joining force contributed significantly to the mechanical stability of the seam, which can be further explained by the concept of surface activation and interdigitation of cellulosic fibrils, as better fiber interlocking enhances three-dimensional contact and hydrogen bonding between the paper sheets, contributing to stronger joints, while the amplitude of the ultrasonic vibration played a subordinate role. The influence of the fiber length on the joint strength was particularly pronounced with dry samples but decreased with increasing moisture content. The effect of the joining energy also depended significantly on the moisture content of the samples. Dry samples achieved a higher joint strength with increasing energy input but are more prone to burning phenomena. Such effects can be effectively minimized or completely prevented through controlled moistening and a limitation of energy input, for instance by shortening the joining duration.
6. The observed increase in joint strength at higher joining force and optimal moistening can be interpreted in part by the concept of surface activation and interdigitation of cellulosic fibrils. Better fiber interlocking enhances three-dimensional contact and hydrogen bonding between the paper sheets, contributing to stronger joints.
7. A potential mechanism for the observed effects at the joint may involve the combined influence of heat, moisture, pressure, and ultrasonic energy, which could facilitate molecular self-assembly of fibers into crystalline cellulose, similar to processes occurring during hornification in lignin-free fibers.

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