Surface Charring of Silver Fir Wood Cladding Using an Enhanced Traditional Japanese Yakisugi Method

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The aim of this work was to better understand the ignition method of timber charring in order to improve the industrial process. Three silver fir boards were tied together to make a triangular prism, which acted as a chimney. To start the charring process, the traditional Yakisugi method uses an ignitor paper ball. This ignitor paper ball was in this research replaced with a gas burner. The gas burner supplies the required energy in an even level and provides airflow in the upward direction. The surface temperature of the samples increased from 10 to 500 °C in approximately 40 to 80 s at all recorded positions, which is considerably faster than when using a traditional method. The thickness of the charred layer and the resulting cupping effect were investigated as an indicator of the quality of the process. The charred layer produced by the gas burner method was not as thick as was achieved with the traditional method, which can be attributed to a shorter charring time. Approximately half the specimens showed cupping to the charred side, which may be related not only to a shorter charring time than previous studies, but also to the annual ring orientation of the timber. Further research should be performed on the charred layer thickness and cupping to define all relevant parameters.

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INTRODUCTION

Wooden cladding has the task of protecting a building from environmental influences. It is advantageous if the wooden boards employed are pre-treated so that they can offer this protection for longer compared to untreated boards. Nowadays, there is a strong demand for environmentally friendly and sustainable treatment processes (Hill 2006; Sandberg *et al.* 2017). One-sided surface charred wood, with a rich, deep black colour, is becoming more and more established and used by architects and designers (Hasburgh *et al.* 2021). The surface charred wood is mostly used outside as a cladding, siding, or fences. Nowadays, interior applications of charred boards as walls and ceilings have become popular as well. Users seeking a modern style of architecture find that this type of surface treatment appears natural and is visually appealing. In addition, surface-charred boards are advertised as long-lasting and maintenance-free, even though evidence for this in terms of scientific studies is limited (Kymäläinen *et al*. 2020). One way of meeting this demand is a method that has been used in Japan for centuries, *i.e.*, the traditional charring technique, yakisugi. Timber boards are charred on one surface by tightening three planks together to create a triangular prism that performs as a chimney. The starting energy comes from a handcrafted paper ignition ball. After lighting this ball at the bottom, the draught in the chimney helps to increase the internal temperature until the wood starts to burn on the inner side. The fire rises from the bottom to the top, at which point the charring process is complete (Ebner *et al.* 2021). In theory, this is a simple process. However, in practice, the ignition process causes great difficulties because other factors, such as ambient temperature, wind condition, and wood moisture content, play a key role. If the paper ball is not expertly prepared, it produces fire more or less randomly. In addition, as the ball is lit at the bottom, flames spread more or less without control. The difficulty of making and attaching the ignition ball makes it difficult to achieve a consistent result.

After several attempts to handcraft the ignitor ball in a proper way according to the traditional Japanese standard failed, an alternative starting of ignition was sought by the authors. Understanding the ignition process and the spread of the flames could help to develop an easier and faster way of generating a homogeneous charred surface over the length, width, and edges of timber (White 2000). Wood is considered a porous material and does not burn directly. However, when exposed to high heat fluxes, it goes through pyrolysis. Extreme temperatures cause the primary wood polymers to decompose to a mixture of volatiles, tar, and carbonaceous char (Friquin 2011). When an appropriate volatile fuel to air concentration has been reached, the oxidation of the pyrolysis gases leads to flaming combustion (Lowden and Hull 2013). Thermal decomposition generates fuel vapours, which in turn catch fire. To make this process self-sustaining, the burning gases must return sufficient heat to the material to continue the production of the fuel vapours (Hirschler and Morgan 2008). The ignition of wood is the start of sustained combustion fueled by wood pyrolysis. Therefore, the flow of energy or heat flux from a fire is a necessary condition of ignition. Sufficient conditions for flaming ignition are the mixing together of combustible volatiles and air in the right proportions (White and Dietenberger 2001).

To achieve the proper charring of wood, four temperature phases should be achieved. The first is drying the wood surface, at a temperature of approximately 100 to 240 °C to reach a moisture content (MC) of 0%. During this first phase, bound water is removed from the cell walls, the wood dries, and the cell walls shrink, which may cause microcracks and compressions in the weakest regions between the S1 and S2 cell wall layers (Fengel and Wegener 1989). During the second phase, when the wood is dry and heated to a temperature of approximately 280 °C, it begins to spontaneously break down to produce charcoal plus mixed gases and vapours, in addition to some tar. The hemicellulose and lignin components are pyrolyzed at the temperature ranges of 150 to 300 °C and 225 to 450 °C, respectively (Gosselink *et al.* 2004; Kymäläinen *et al.* 2018). In the third phase, the intensive generation of flammable volatile extracts from the wood occurs at a temperature range of 300 to 450 °C. In this range, the depolymerization of cellulose starts at a temperature range of 300 to 350 °C. Finally, the carbon-carbon linkages between the lignin structural units are cleaved at a temperature range of 370 to 400 °C (White and Dietenberger 2001). The degeneration of the lignin is an exothermic reaction, which peaks at a temperature between 225 and 450 °C. All wood components end their volatile emissions at a temperature of approximately 450 °C. In phase four, which occurs at temperatures greater than 450 °C, the remaining wood residue is char (Beall and Eickner

1970; Shafizadeh 1984; White and Dietenberger 2001). During these four phases of surface charring, sufficient oxygen is the key to a proper charring effect.

In this study, the authors replaced the ignition ball with a gas burner to induce the pyrolysis conditions for ignition. As mentioned earlier, the ignition ball produces fire more or less randomly, and, as ignition occurs from the bottom, it spreads more or less without control. However, by using a gas burner, the ignition process might be more easily controlled and made sufficiently homogeneous to be the basis for a flaming combustion until self-sustained pyrolysis prevails. An increased oxygen concentration might allow the greater oxidation of char and the combustion of pyrolysis gases. The procedure enhanced with gas could also enhance the heat flux to provide more energy for the pyrolysis reactions (Yang *et al.* 2006; Bartlett *et al.* 2015). Therefore, this study set out to find whether propane gas support could enhance the industrial wood-charring process based on the traditional yakisugi method. The measurement data obtained would be compared with the data from the study previously published by Ebner *et al.* (2021), to see whether similar results can be achieved with this enhanced process while keeping all other parameters the same. More specifically, the following questions were to be addressed: (1) is this method faster or better in terms of the surface charring combustion process compared to using a paper ignition ball; (2) what is the structure of the charred layer at points from the bottom to the top of the timber; and (3) is the cupping effect the same as in previous attempts or is it less pronounced due to the faster expected burn-up process?

EXPERIMENTAL

Material and Methods

Silver fir (*Abies alba* Mill.) wood, collected from an Upper Austrian lumber mill (Holz Reisecker, Roßbach), was studied. The plain sawn boards were graded class III to IV according to Austrian standards and pre-dried. Timber boards with dimensions of 24 mm ×170 mm × 4000 mm were used for the experiment. The boards were in general without defect but showed small and spike knots but no dead or loose knots. All tests were carried out under winter conditions, *i.e.*, at a temperature of -1 °C to +4 °C. Overall, five test runs were completed (5 tests × 3 boards). Before the experiment, the average MC of the boards was 12% and the average density was 441 kg/m³.

The Process of Timber Charring *via* the Yakisugi Technique, Enhanced by Gas-Supported Ignition

Three wood boards were tied together using wet ropes to create a triangular prism and form a chimney. The starting energy was provided by a conventional gas burner (RoMaxi, Rothenberger Industrial, Germany), as illustrated in Fig. 1A.

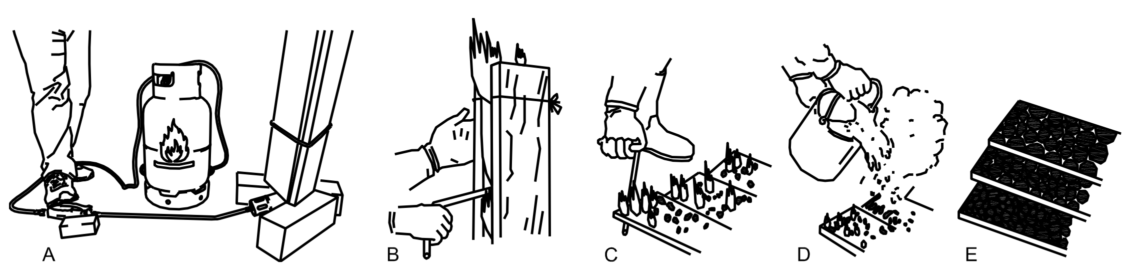

Fig. 1. The methodology of one-sided surface charring *via* the traditional Japanese yakisugi technique enhanced with propane gas ignition

The gas burner, with the gas bottle and gas burner valve fully open, provided enough energy to raise the internal temperature to inflame the wood boards. In this series of tests, the gas burner was set to the same position each time and replaced the traditional ignition ball. In contrast to the orthodox yakisugi method, where the chimney is set at a 70° angle from horizontal, in this test the chimney was fixed vertically at 90° from the start. The gas burner sucks in air and releases it upwards. This hot air flow supports the drying process, which takes place from bottom to top (Ebner *et al.* 2021). This draught determines the direction of the air in the chimney. It is not necessary for the chimney to be initially tilted, as in the traditional method. When the right internal temperature is reached (phase 1, MC = 0%), the wood starts to burn on the inner side. The fire rises from the bottom to the top of the wood. After 40 to 60 sec, the gas was switched off. During the first period of burning, the edges of the narrow side need to be switched. For this task, a rim-iron was used to give the narrow side of the board the chance to get charred right up to the edge (Fig. 1B). When the fire reached the top and flames appear in the gaps where the edges of the wood meet, the charring process was regarded as complete. After approximately 3 min (160 to 200 s) the burning process was terminated by flipping the chimney to the horizontal position. When the ropes were released, the fire in the chimney stopped immediately (Fig. 1C). The last glowing embers inside the open chimney were extinguished with a soft water hand spray (Fig. 1D). As a result of this process, the inner surface of the wood was covered by a thick charred layer (Fig. 1E), preferably uniform from one edge to the other, and from the bottom to the top (Ebner *et al.* 2021).

Temperature and Time Measurements

During the charring process, the temperature inside the chimney was monitored by placing three NiCr-Ni thermocouples (Type K) in one of the three boards inside 8 mm holes drilled perpendicular to the surface. The thermocouples were located on the midline of the samples at heights of 500, 2000, and 3500 mm, measured from the bottom of the chimney, as depicted in Fig. 2A.

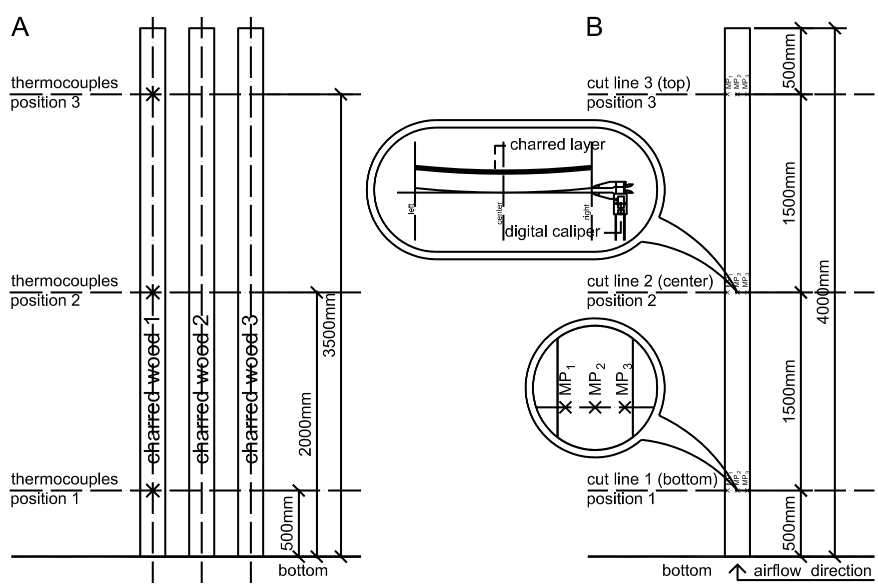

Fig. 2. Positions of the thermocouples at different heights in the wood chimney (A); and cut lines for the charred layer thickness (measurement points MP1, MP2, and MP3) and cupping measurements (B)

Each of the thermocouples continuously displayed the temperature during the charring process on the digital display of an EMPlus 600 acquisition system (Eliwell, Italy). Simultaneously, a camera recorded the charring process, the development of smoke, and the increase in temperature over time. The information about time is essential to determine the temperature increase inside the chimney in each section. The duration of each test was approximately 3 min (160 to 200 s). The measuring method corresponds to the sequence previously used by Ebner *et al.* (2021). The measurements were taken five times.

Measuring the Thickness of the Charred Layer

The thickness of the charred surface layer was determined to evaluate the intensity of the charring process. The board was cut into four pieces (Fig. 2B). The cut lines were set at the locations of the temperature thermocouples (Fig. 2A) so that the temperature values could be compared with the thickness of the charred layer at the same points. For cutting, the charred boards were turned over to avoid any charred layer damage. The thickness of the charred layer was measured with a digital caliper (PRECISE PS 7215 - with an accuracy of 0.01 mm, Burg Wächter, Germany). At each section line, the thickness was measured three times at points MP1, MP2, and MP3 (Fig. 2B). The measuring method corresponded to the sequence used by Ebner *et al.* (2021).

Measuring the Level of Cupping

After charring, the cupping of the samples was measured with a digital caliper (Fig. 2B). The measurements were carried out at the same points used to measure the thickness of the charred layer. The deformation was measured on the left and right sides of the sample while placed on a plane surface. The charred layer was on the upper side during these measurements. The measuring method corresponded to the sequence used by Ebner *et al.* (2021), though the measurements in this study were taken in the middle as well as from the right and left, as cupping had also deformed boards against the charred side.

RESULTS AND DISCUSSION

All of the results of this study were compared with the results published by Ebner *et al.* (2021) to test the efficiency of using a gas burner for ignition instead of a paper ball. While Ebner *et al.* (2021) took measurements when smoke appeared at the upper end of the chimney, the recordings in this study were started immediately after lighting up the gas burner. In addition, in the previous work, the temperature was taken every 30 s, while in the present experiment the temperature was recorded every 10 s, which should provide more accurate data.

Charring Process – Temperature and Time

Figure 3 shows the charring process as a function of time and temperature. Data from the gas burner method is compared with the data previously reported by Ebner *et al.* (2021).

The temperature first increased at position 1, reaching an average temperature (with standard deviation) of 863 °C (103 °C) for 10 s, at its maximum, and slowly decreasing afterwards, before remaining relatively stable (a temperature greater than 800 °C) for another 60 s. The temperature at position 2 did not increase as quickly as it did at position

1; however, it overtook the maximum temperature after 130 s and reached a peak temperature of 905 °C (79 °C) after 170 s before slowly flattening out.

The simple explanation for the temperature rising first at position 1 is that position 1 was close to the ignition source and therefore phase 1 (reaching a MC of 0%) was the first to be fulfilled before the self-ignition started at a temperature range of 200 to 300 °C (Lowden and Hull 2013). To ignite the wood, chemical compounds first have to break down. To create a self-sustaining reaction, the combustion of these gases must generate enough heat to keep the production of volatile gases going (Hirschler and Morgan 2008). Polymers present in the wood are broken down and produce inert and flammable gases, which enable the charring process. Dehydration and pyrolysis can occur simultaneously; moisture content typically slows the temperature increase until it reaches a temperature of 115 °C. The bound water is evaporated later at temperatures of approximately 240 °C (Bartlett *et al.* 2018).

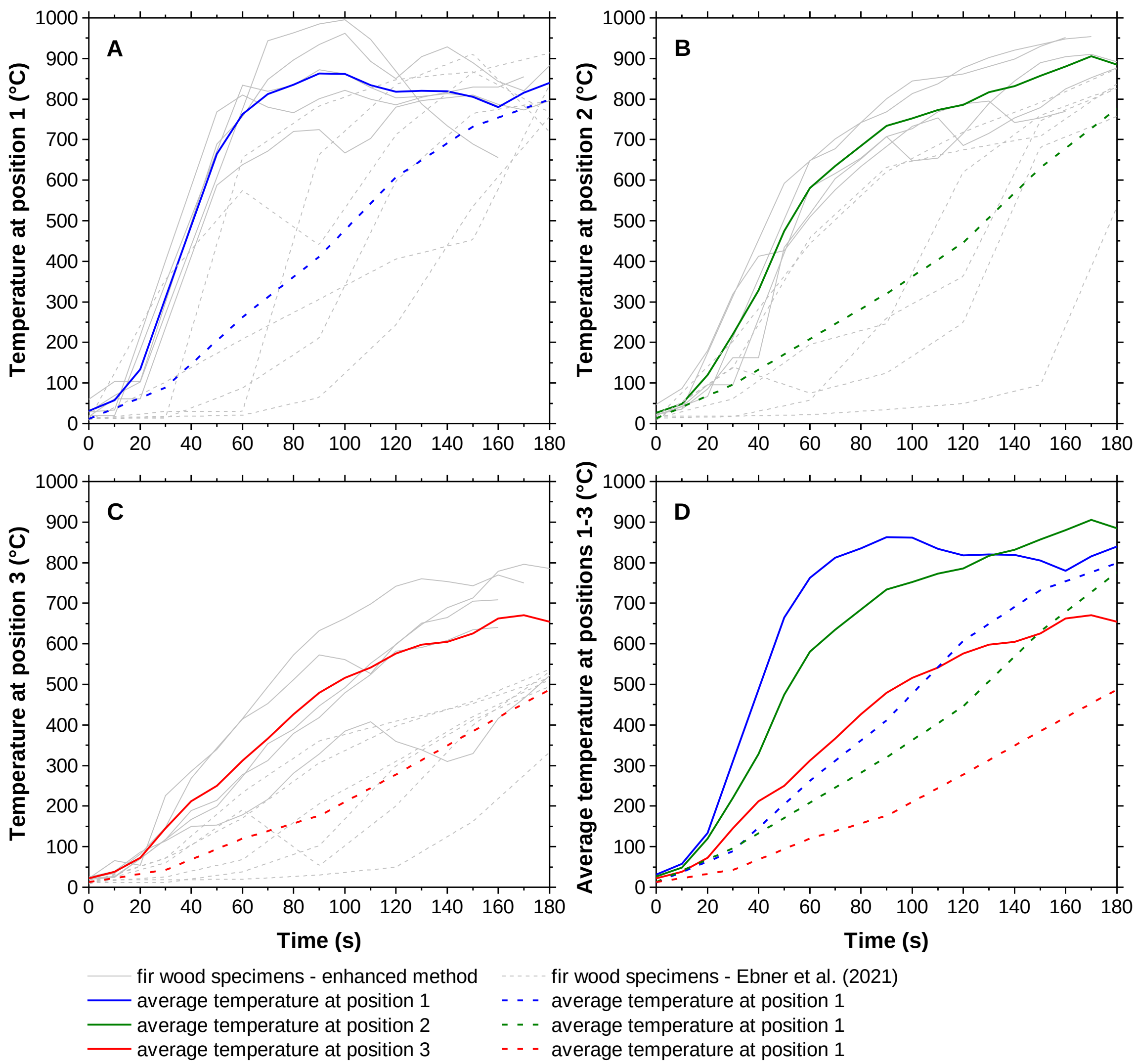

Fig. 3. Temperature-time diagram for the fir samples measured at positions 1, 2 and 3 (A through C) and the average temperature data (D). Solid line depicts values obtained by enhanced method, while dotted line stands for values recorded by Ebner *et al.* (2021).

By comparing the two charring methods using the temperature and time diagrams, it is obvious that the gas-enhanced method delivers more homogeneous data based on the temperature curves. However, all repetitions (enhanced with gas) were immediately stopped after 160 to 180 s by moving the chimney from the vertical to the horizontal position. Even though the previous research indicated that it was the proper time, perhaps the process was stopped too early in this series of tests. A closer look at the temperature curves (Fig. 3D) offers the clue that it could be that the temperature at position 3 also rose to 800 °C and reached nearly the same charring thickness at the positions below it (1 and 2). This could be an approach for the hypothesized optimal charring process based on the three optimal temperature curves (Fig. 4), which will be discussed later in the text.

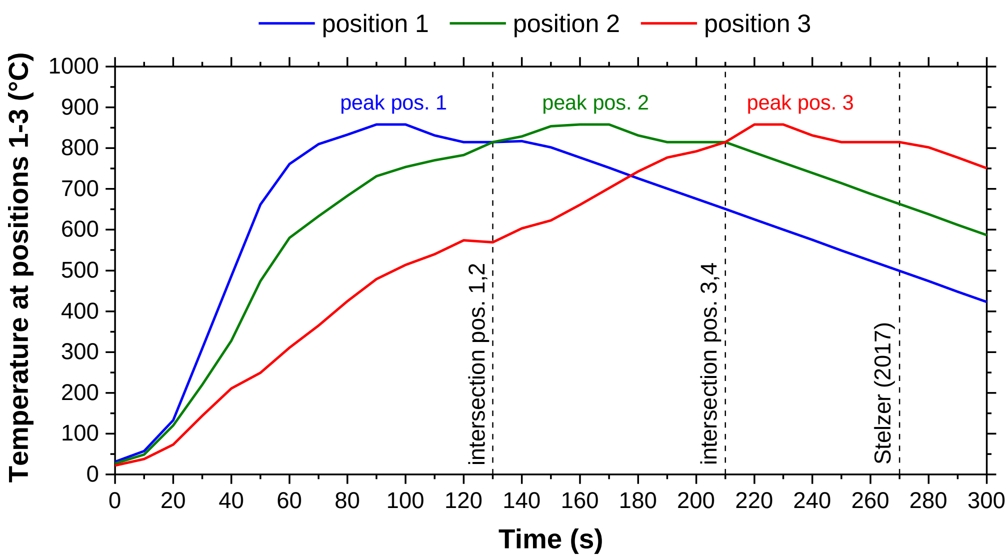

Fig. 4. Hypothesized temperature-time diagram for the three optimal temperature curves

Kymäläinen *et al.* (2020) describes the traditional knowledge that is well guarded in Japan, but there has also been an important statement from Stelzer (2017), who witnessed the traditional Yakisugi charring process taking place in Japan, recording a time of 270 s from ignition until the fire stopped. This statement was in agreement with the theory of the optimal temperature curves, *i.e.*, each temperature curve rises to a peak of approximately 800 to 900 °C, though at different times. Lowden and Hull (2013) summarized the research work of wood pyrolysis: whilst the charred surface of wood can have a temperature of 800 °C, primary pyrolysis begins at temperatures greater than 225 °C and ends at temperatures lower than 500 °C. After reaching a temperature of 800 to 900 °C, the temperature decreases because the charred surface acts as an insulating layer, which increases the thermal resistance between the underlying wood and the pyrolysis front (Friquin 2011). This results in a decrease in the heat release rate and acts as a mass transport barrier for volatiles released from the fuel and oxygen from the air (Tran 1992; Lowden and Hull 2013). These temperatures also referred by Friquin (2011), who wrote that natural fires initially have a rapid growth phase, a phase when the fire is fully developed and the temperature rise is slow, and a decay phase when the temperature decreases. Xu *et al.* (2015) reported that the thermal conductivity of the charring layer is much lower than the thermal conductivity of unburnt wood, which reduces the amount of heat transferred by the burning surface to the unburnt wood beneath.

The Thickness of the Charred Layer

The charred layer is generally thicker at the lower part of the chimney, which has been previously confirmed. As the high temperatures prevail in this area longest, this is where the carbon layer is thickest. Stelzer (2017) described that the thickness of the charred layer applied on Japanese cedar (*Cryptomeria japonica*) produced with the traditional yakisugi method, was approximately 3 to 5 mm, which was in agreement with the results presented by Ebner *et al.* (2021). Šeda *et al.* (2021) also found a thicker charred layer, *i.e.*, greater than 2 mm, at temperatures that prevailed longer than 4 min, when charring was performed using a contact heating system at lower temperatures (up to 400 °C).

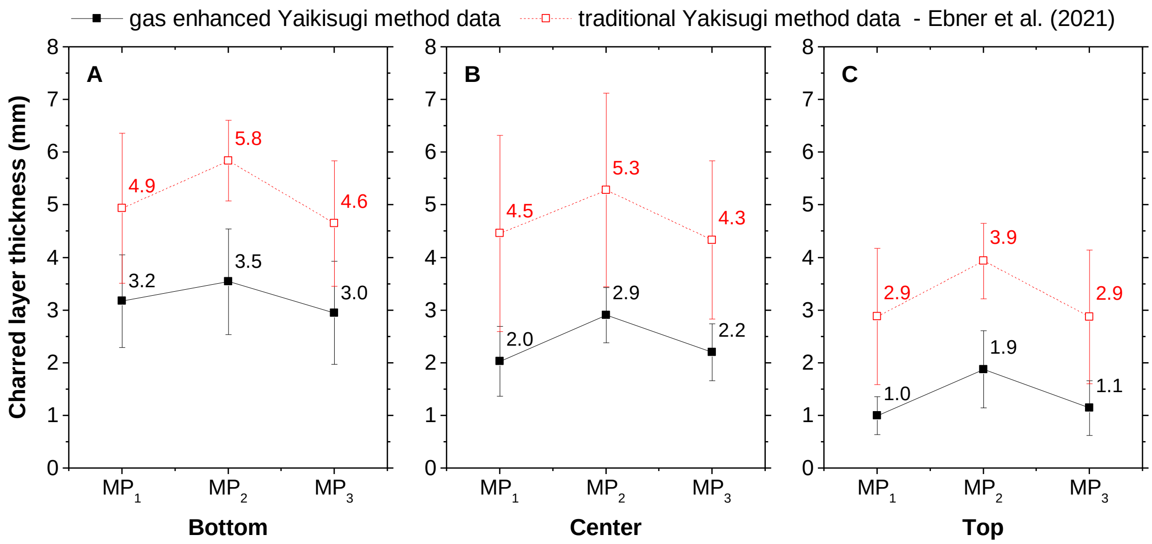

Fig. 5. The charred layer thickness at: cut line 1 – bottom (A); cut line 2 – middle (B); and cut line 3 - top (C) compared with previously measured data by Ebner *et al.* (2021) (Note: the error bars represent the standard deviation)

The method using gas did not produce charring as thick as was achieved with the ignition ball; however, it was more even with lower variation. The average values reached at measuring points MP2 were 3.5, 2.9, and 1.9 mm, measured at the bottom, center, and top, respectively, which were 40% to 50% lower than those previously observed. An explanation for this is the shorter treatment duration of 160 to 180 s, as Ebner *et al.* (2021) used a considerably longer charring time (250 to 300 s). The charring rate is related to the density, and, for fir wood, is approximately 0.8 mm per 60 s, suggesting that the repetitions carried out with the gas burner were stopped too early (Bartlett *et al.* 2015; Bartlett *et al.* 2018). According to Friquin (2011), the char layer acts as thermal insulation between the exposed surface and the pyrolysis front, decreasing the char rate during the first stage of the fire. The steeper temperature increase chars the surface layer faster, which inhibits the thermal conductance and therefore thinner char layer may occur. If the process had lasted 270 s, the carbon layer would have been 3.4 mm thick. This assumption would support the hypothesis shown in Fig. 4, with an intended treatment duration of 270 s. Even though longer time at high temperature cracks the surface and thus may improve char thickness, concomitant ash formation and consumption of carbon decrease the surface charred layer. Therefore, this hypothesis would need to be validated be further measurements. The char depth can vary considerably within one cross-section, and as well as from one cross-section to another in the same specimen. The rounding off of the corners also complicates the measurement process.

Level of Cupping Caused by Charring

All charred samples from Ebner *et al.* (2021) showed a cupping effect towards the charred side, no matter the orientation of the annual rings in relation to the charred surface, while the repetitions enhanced with a gas burner did not show such clear results. Only approximately half of the specimens in this study showed a cupping effect to the charred side (Fig. 6), and the data variability was much lower than in the original study. Time and temperature effect cupping, as described by Ebner *et al.* (2021). A longer exposure time results in a thicker charred layer and therefore a greater cupping effect. In the previous discussion, Ebner *et al.* (2021) concluded that the surface charring led to structural changes, such as increased porosity, decreased density, and decreased volume, and consequently it did not exhibit swelling. Therefore, the charred wood cupping remains after conditioning to the ambient relative humidity. To prove this hypothesis, the specimens were remeasured after 18 months and the results were just as clear as the measurements immediately after the charring process; therefore, the hypothesis was confirmed.

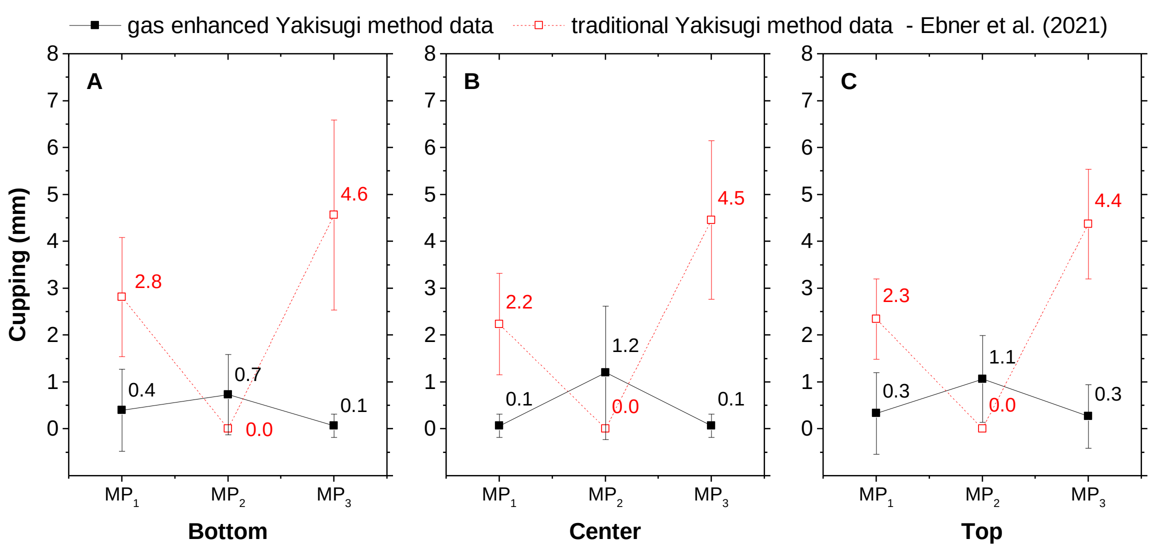

Fig. 6. The cupping at: cut line 1 – bottom (A); cut line 2 – middle (B); and cut line 3 - top (C)

There seems to be no analogy when the data observed from the gas enhanced method is compared with the previous study. The new data show a more-or-less random cupping effect, which can be explained by the shorter time exposure, resulting in a thinner charred layer as well as a tendency for cupping by its nature, rather than due to high temperature gradients, *etc*. The cupping of wood generally can result from both inherent characteristics of wood as well as number of introduced (process-related) variables. The cupping occurs when one face of a board shrinks more than an opposite face, as a result of different grain patterns on the two surfaces, *e.g.*, plain sawn wood. Another reason could be uneven drying process, *i.e.*, different MC of wood surfaces. However, from a total of 45 specimens measured, only 20 showed a cupping effect towards the charred side. A noticeable feature emerged when the authors took a closer look at the individual heights (sections) of the chimney. In the lower area (position 1) cupping towards the charred side was visible in 8 of the 15 boards. In the middle (position 2), 7 of the 15 and, at the top (position 3), 5 of the 15 showed cupping towards the charred side. It can be deduced that in the areas where the temperature acted over a longer period, there was a tendency towards the charred side.

Fig. 7. Visual comparison of boards showing the varied charred layer thickness and cupping effect

A visual comparison of the charred boards from the gas enhanced process, showing varied surface quality, *i.e.*, the charred layer thickness and cupping effect, can be seen in Fig. 7. Assuming that uniform cupping is preferred when using the charred wood as cladding, this would speak for the possible establishment of ideal temperature curves. The maximum temperature (800 to 900 °C) would be then reached at all 3 positions for a certain period of time (Fig. 4) and therefore provide more uniform cupping over the board length.

CONCLUSIONS

1. The time-temperature data of the previous work varied greatly, while the results of the enhanced method were more equal and had less variation. The charring time to reach the required temperature in the upper part of the chimney for a specified time was considerably shorter than using the original method.
2. However, the shorter duration resulted in a thinner charred layer. At this point, further investigations are necessary to determine which carbon layer thickness actually best protects the wood over the long term, when deployed as cladding. The burning process can now be adapted with the new findings. The charred layer still was thicker in the lower areas and decreased towards the top, which may indicate that the charring time needed further fine-tuning.
3. The previous results showed cupping towards to the charred side; the annual ring orientation did not influence this effect. The new tests showed more or less random cupping, which can be explained by the shorter exposure time, as well as the affinity of the wood for cupping by its nature, rather than by high temperature gradients or other factors.
4. It can be concluded that enhancement with gas burner ignition simplifies the entire process considerably (no requirement for experience, and a shorter time) and provides more consistent results. Based on the hypothesized optimal three temperature curves, further tests should be carried out to fully optimize charring time to achieve uniform charred thickness over the board length as well as to determine how thick the layer of charring should be to maximize the life of the wooden cladding.

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