Original scientific paper
Received:01.08.2023
Accepted: 04.10.2023
UDK: 684.4.053-035.31

PROCEDURE OF OPTIMIZING SOLID OAK WOOD (*Quercus robur* L.) BENDING PROCESS IN FURNITURE MANUFACTURE

Mislav Mikšik[1], Stjepan Pervan[1], Silvana Prekrat[1], Mladen Brezović[1]

[1]University of Zagreb, Zagreb, Republic of Croatia,
Faculty of Forestry and Wood Technology,
e-mail: mmiksik@sumfak.unizg.hr; pervan@sumfak.unizg.hr;
sprekrat@sumfak.unizg.hr; mbrezovic@sumfak.unizg.hr

ABSTRACT

Solid wood bending is a type of processing with certain levels of mechanical destruction. Higher material utilization, small investments in technology, high strength and stiffness of bent wood elements, and uniformity of structure in furniture parts are some advantages of wood bending. Sawn elements have their grain slope cut off in certain parts, which lowers the strength and load-bearing capacity of the final piece of furniture, contrary to the continuous grain slope in bent counterparts.
In this research, the procedure for optimizing the solid oak wood bending (Quercus robur L.) process in furniture manufacture will be explained. All the challenges encountered while attempting to optimize the bending process by using a combination of steaming and drying with high frequency (HF) will be described and explained. Utilization comparisons at the beginning of the process and after optimizing it, including the current state, will be presented.

Key words: oak (*Quercus robur* L.), solid wood, bending, high frequency, steaming

1. INTRODUCTION

Solid wood bending is a type of wood processing that has been known for thousands of years. Earlier, it was mostly used for bending bows by using green wood. Later and nowadays, it is mostly used in manufacturing ships and boats, sports equipment, fishing rods and bows, tool equipment, and furniture. The most recognizable and significant advantage of wood bending is the higher utilization of used materials. Lesser-known advantages are the higher strength and stiffness of bent wood parts when compared to the same parts that are sawn due to continuous grain slope.

When bent, wood compresses on the concave side and stretches on the convex side. After bending, the convex side becomes longer than the concave side, which results in the accumulation of stresses, which results in the well-known phenomenon of the spring-back effect, which tends to force wood to return to its original shape. Before bending, wood is commonly softened by a combination of heat and moisture or with chemicals, which causes lower stress development. The reason why wood is softened prior to bending is because wood cannot be stretched significantly even after softening, which is why the concave side is forced to absorb all the compressive deformation and stresses. This is done by using metal strips on the convex side, which prevent elongation on the convex side. Sandberg et al. (2013) stated that after plasticizing, wood compressibility in the longitudinal direction is increased up to 30–40%, which is suitable when bending wood. If the end force is too small, it causes longitudinal tensile failure; on the other hand, an excessively large end force causes premature longitudinal compressive failure. Because of those reasons, Stevens and Turner (1970) suggested that controlling the length and longitudinal tensile strain in the vicinity of the convex surface of a wood specimen during a bending process is a very important feature. Báder et al. (2019) stated that compression in the longitudinal direction causes changes in wood tissue, which result in better bendability. After plasticizing, wood is formed, and after cooling and drying, it keeps its bent shape.

Báder and Németh (2019) and Taylor (2008) suggest that the best flexibility for bending is achieved when the moisture content (MC) of wood is close to its fiber saturation point, or around 25-30 %. This statement has been shown to be true, but after conducting many experiments and bending tests, it was concluded that MC can and should be lower in most of the cases, which will be explained later.

Navi and Sandberg (2012) and Taylor (2008), along with many others, suggest that around 2 minutes of steaming per millimeter of width is optimal for bending, and it turned out to be correct. Liquid ammonia can also be used for the plasticization of wood, which results in bent wood without the spring-back effect, but this method will not be described here because it is not used in the manufacturing process. Softening of wood is mostly done by steaming, but many companies use a combination of steaming and high-frequency (HF) processes. In that way, heating, plasticizing, bending, and drying are done in succession. Although bent pieces are partially dried in an HF press, they still need to be air dried or conventionally dried afterwards to the desired MC while being fixed with metal straps or wood slats (which are mostly used to prevent the spring-back effect during drying).

In this paper, the optimization of the oak wood bending process will be explained. In general, oak wood is a desired species for the manufacture of furniture, which is why it was decided to try and bend it. In the literature, most of the data on wood bending that was found was about beech wood. To optimize the process, the data about steaming temperature and duration, initial MC of wood, and press parameters were taken as if beech wood were bent. It was used as a starting point due to a lack of knowledge in general about oak wood bending. Later, it was optimized and adapted to oak wood bending by the trial-and-error method and by further study of available literature and data. Niemiec and Brown (1995) noted many other factors that also affect wood bending, such as the radius of bending, wood species, moisture content, thickness, width of wood, steaming time, fiber direction, and wood defects. Wood selected for bending should be defect-free with straight fibers, but in practice it was observed that this is not the case since wood parts with knots and interlocked or wavy fibers can also be bent properly depending on the final use.

Wood can also be bent in a cold state, in contrast to the other methods, with the pre-compressed method. First, wood is compressed in a longitudinal direction after plasticizing it with steam. It is fixed to avoid deflection during compression. According to Navi and Sandberg (2012), wood is longitudinally compressed by approximately 20%, then allowed to cool to room temperature, and finally dried to a moisture content of 12%. After that, the wood is processed to the desired cross-sectional shape, and it can be bent in a cold state.

2. BEGINNINGS OF OAK WOOD BENDING PROCESS EXPERIMENT

All bending experiments conducted were done as part of a project on which the faculty was partnered with a manufacturing company.

When we first started conducting bending experiments, little to no knowledge was possessed about the whole process. The only information we possessed was from the machine seller. Steaming chambers, steam boilers, presses, and high-frequency (HF) generators were bought in order to conduct test bends and to be implemented in production later. During the period of 2.5 years, a lot of field work has been done where the process of bending was monitored and attempts were made to optimize it. The first challenge was to get the raw materials that had the optimal moisture content (MC), which ranged from 16 to 25 %. It became a problem due to the manufacturer's usual kiln drying programs, which dried all the goods to a MC of 8 – 10 %, but in this case had to be stopped halfway through to take out the material for bending. For those reasons, material was often overdried, and it would be 11 – 15 % MC, which was shown to be too low for greater bends with a large cross section. Smaller bends for chair legs with a smaller cross-section could handle MC as low as 13% but not lower than that. A small experiment was conducted to see if, in any way, wood with MC ranging from 8 - 10% can be used as bending material because, in that way, drying would not have to be stopped midway to take out raw material for bending. Results suggested that no amount of steaming can soften wood enough not to break after it is kiln dried to such a low MC. Perhaps if wood pieces were immersed in water prior to bending, they could be softened later with a sufficient amount of steaming, but the whole process would be too complicated and time-consuming. The best drying method for bending material would be air drying, but it requires a lot of material in advance and is time-consuming.

When it first started, the overpressure in the steam boiler was 3.2 bar, which amounted to a temperature of 145 °C. It was quickly realized that the temperature was too high because it resulted in a high number of checks and cracks on bent pieces. When taken out of the steaming chamber, the wood dimension parts were very hot but not moistened at all. A higher temperature can heat the wood faster, but if it is too high, it only makes the wood more brittle. High-temperature steam also possesses a lower amount of moisture, which otherwise helps to soften the wood pieces. The overpressure when steaming the chamber was 0.8 bar. According to Peck (1957), steaming at high pressure causes wood to become plastic in a shorter time, but wood treated with high-pressure steam does not generally bend as successfully as wood treated at atmospheric or low pressure.

During the project, technology sellers in Italy were visited a few times to obtain more information about the steaming. It was seen there that they also steam their material at atmospheric pressure, which produced good bends. It was also noticed that their steam was slowly circulating and passing through the steaming chamber. In that way, fresh, wet steam enters the whole system at all times and is better at moistening and keeping the desired temperature inside.

Figure 1: *Steaming chambers*

Figure 2: *Mechanical press during bending*

Due to the above-mentioned reasons, it was decided that the process would try to be imitated as much as possible to see if, that way, good bent parts could be produced. The steaming chambers used can be seen in Figure 1. On top of it was a manual valve, which was opened in order to gradually eject the steam. The chamber needs to be under constant pressure because its lid cannot be closed otherwise. It is equipped with sensors that automatically add more steam when pressure gets too low, but pressure is kept at minimum levels in order to get as close as possible to atmospheric pressure. In that way, steam is constantly and gradually released, while at the same time, fresh steam enters the system. Figure 2 shows the mechanical press during the bending of the “U"-shaped back of the semi-armchair.

3. HIGH FREQUENCY HEATING PROCESS

The second problem encountered was HF heating during bending. After steaming, wood is mechanically bent and heated with HF to dry it sufficiently to keep its form. Presses are equipped with a 20 kW, 10 MHz HF generator. This type of generator is intended for bending beech wood and has specifications made for it. For that reason, a high-power ceramic disc capacitor needs to be used when bending oak wood to store excess electrical energy in order not to overheat the wood too fast when heating. A ceramic capacitor added to the press can be seen in Figure 5. Heating was done in cycles of 2 minutes, 3 to 7 times, depending on the size of the cross-section, bending radius, and MC. It has been shown that it is easier to dry and maintain the shape of specimens with smaller bending radii (greater curvature) than those with greater bending radii (smaller curvature). The reason for this is that when curvature is too small, wood still remains in its elastic state, which makes it harder to retain it.

When heating bent wood using HF, it is essential to exercise caution to avoid overheating, even when utilizing capacitors. Some smaller tests were conducted with thermal cameras to see how temperature is spread in the press and in the specimens individually. It was noticed that the specimens with higher MC are heating much faster than those with lower MC, which is logical due to the way HF heating functions. For those reasons, specimens of individual loads were paired in groups with similar MC to avoid large differences in temperature. Figures 3 and 4 show what happens when wood is heated excessively and too fast. Wood for bending still contains a lot of bound water and, in some cases, small amounts of free water. When heated quickly and at high temperatures (above 100 °C), water starts to evaporate rapidly and steam expands. Since the whole system is very closed off and specimens are trapped in the press, as can be seen in Figure 2, vapor cannot exit the specimen fast enough, and water vapor erupts, which destroys wood tissue completely and renders parts unusable.


Figure 3 and 4: *Cracks and gapes in wood tissue due to excessive HF heating*

During bending, wood adjusts and starts creaking regularly because of its resistance. As nonstandard a procedure as it sounds, it is really important to listen to the wood during bending and heating. It gives a sound as a warning to adjust parameters, such as to lower longitudinal pressure or reduce or turn off HF heating. Specimens will start to crackle, and steam will start bursting rapidly from certain places if the temperature is too high. Heating should be turned off immediately in order not to destroy parts. That is why heating is done in cycles of 2 minutes to heat them gradually, with pauses in between lasting 1 to 5 minutes, depending on which cycle repetition it is. The last few cycles when wood is already close to 100 °C pauses are longer to allow wood to cool itself a bit in order not to overheat them. Longitudinal pressure should be put to the maximum by the presses when the bend starts, but later in the bend, when the press is almost completely closed, that pressure should be lowered a little bit so that specimens can adjust better to the mold.

Figure 5: *Heating specimens and capacitors can be seen added to the press*

After heating, the wood is left for an additional 10 minutes to rest at a heated temperature. After those 10 minutes, cooling fans are turned on, which are placed underneath the press. Fans are used to cool down mold and specimens faster to retain their shape. The whole bending cycle, which includes loading the press, bending, heating, and cooling specimens, lasts 90 ± 15 minutes, depending on the desired shape and cross-section of the wood.

4. TYPES OF PRESSES AND METHODS OF BENDING

During bending, two types of presses were used. One type is the mechanical press, which uses a mold on top and steel strips with end stops at the bottom that adjust to the shape accordingly. Steel strip also benefits the convex side, keeps it in place, and prevents specimens from elongating. Preventing wood from lengthening is a very important feature (as already mentioned in the introduction), which is why additional metal sheet is used on top of iron strips to further reinforce the convex side. Oak wood in contact with iron will cause black coloring, but it is not important since it will be removed in further processing. This type of press uses hydraulic cylinders to provide longitudinal pressure. Longitudinal pressure at the same time prevents specimens from elongating and slightly compresses them, which favors their bendability, as mentioned by Báder et al. (2019).

Figure 6: *Chair legs in different types of presses*

Figure 7: *Chair backs after bending*

This type of press is also connected to the HF generator. Two presses of each type are currently located in the factory. A smaller press is mostly used for bending more demanding curves, such as chair backs and aprons for chairs, tables, etc. The chair back and aprons are bent completely in this type of press, as all operations are done in one place, which includes bending and heating. The chair legs and backs with lower curvature are done on a larger press, which operates a bit differently and cannot make such demanding curvatures. A larger press is used only to mechanically bend specimens. After that, they are transferred into a second type of presses, which use male and female bending forms as molds, as shown in Figure 6.

That type of press uses high pressure combined with HF heating to dry and keep the specimens in shape. Because curvatures are small, high pressure up to 300 bars is used to press specimens from both sides. The second type of press is slightly larger and can bend more specimens at once. One of the reasons why the combination of two types of presses is used is because it speeds up a process a bit as certain operations overlap. In earlier stages, bending specimens were left in the first press for 60 minutes but would often get too cold and lose a lot of moisture. For that reason, the time was reduced to 30 minutes, and in that way, specimens would still remain warm and moist. After that period, bent specimens are quickly moved to another press and put under pressure. Heating is also done in cycles of 2 minutes, but this time the pressure is also increased.

After heating, specimens are left to cool down. The whole operation lasts for 90 minutes, including both presses, heating, and cooling. After taking out specimens from the press, they are left at room temperature to condition themselves a bit before grading them. Grading is done in such a way that bent specimens are compared to the final sample, which passed through all parts of the processing. The overmeasure of each individual specimen is monitored to check if it can handle all upcoming processes. Steaming and grading the specimens are processes that overlap with bending, which is favorable for the whole process because no additional time is spent on those operations.

Figure 7 shows bent chair backs. All the specimens are from one cycle of bending, and they all passed the grading. This grading is slightly different because specimens are compared to thin mold samples made of plywood, which provide a check of bending radius and shape.

Figure 8: *Chair legs after further processing*

Figure 9: *Framework after further processing*

After the shape is checked, specimens are additionally tightened to fit the mold with clamps because there is always a slight spring-back effect that tends to return specimens to their original shape. Specimens are fixed with metal straps and wooden sticks and nails from both sides in order to stop them from returning to their original shape. Those straps and sticks should be kept on until the very end of kiln drying. Only when they are fully dried to the desired MC and cooled down will the specimens stop returning to their original shape. Figures 8 and 9 display bent specimens for chair legs and various frameworks following additional processing.

5. CURRENT STATE OF THE ART OF WOOD OAK BENDING

The spring-back effect is a big problem when bending wood, but what was encountered when it first started was a completely reversed situation. Bent shapes tend to go more inward as they are cooling and drying. The initial response from bent specimens is spring-back, but it is only normal after releasing it from the press. After some time, when specimens start drying and cooling down, they tend to bend inward. The reason for this is that wood is compressed on the concave side, and it is well known that the shrinkage and swelling of densified wood are twice the normal values. This phenomenon shows that the shrinkage of densified wood is stronger than the spring-back effect. This actually favors the whole process when bending leg chairs and specimens with small curvature and a small cross-section because the forces of shrinkage and springback will mostly equalize and keep them in place. The problem arises when chair backs and frameworks are bent with demanding curvatures and large cross-sections. Larger cross-sections and larger curvatures result in more intensely compressed wood on the concave side of the specimen. More compressed wood means more shrinkage. This problem must be treated the same as springback, and specimens need to be banded with straps and sticks. If not attended, specimens will go far too inward after drying and will be deemed defective. Figures 10 and 11 depict the collapsed structure of the specimens, attributed to the small bending radius and potentially excessive longitudinal pressure.

When the experiment was first started, the percentage of utilization of the whole process was very low, around 50 %. With a lot of trials and new information gathered from all the possible sources, utilization improved significantly. Nowadays, if the specimens have optimal MC utilization, it goes up to 95 % and even more in some cases. When bending chair legs, one cycle of bending can have up to 25 specimens. A problem may occur if the whole cycle is faulty, because that way, most of those 25 will be deemed defective. That is why, when bending solid wood, one should always be aware of what is happening in presses, and if there are problems, one should adjust accordingly.

Figure 10 and 11: *Collapsed structure of specimens in places of small bending radius*

One of the missions in the future is to find an optimal ration between the overmeasure of specimens and the need for overmeasures due to the further processing on CNC machines. So far, overmeasures were maybe too great and were causing a lot of collapses of structure on the concave side of thick specimens. Those specimens could still be further processed and prove to be satisfactory due to the great overmeasures. But collapses of structure are also causing problems for CNC tools due to great densification. Bending chair legs and small curvature chair backs at the moment is satisfactory, and high utilization rates are proof of that. Now, it only remains to develop an optimal drying process to speed it up; so far, 2 to 3 weeks of drying after bending, depending on MC, have been shown to be adequate. If the drying step is skipped, a whole lot of problems can appear.

Specimens will not stick properly if they need to be glued; they will tend to spring back or move inwards during further processing; and CNC machines will make rough cuts if the tools are not new and sharp. On figure 12, a stack of bent chair backs banded with sticks and ready for drying can be seen.

Figure 12: *A stack of chair backs banded with wooden sticks*

Figure 13: *Turned chair pieces bent in two planes*

According to Sandberg et al. (2013), straight-grained, knot-free wood materials should be used for bending work, especially if the bend is to be of a small radius. Practice has shown somewhat different cases. Knots should be avoided on the side where tension is mandatory, but smaller knots can be tolerated on the concave side, especially if they are not in the bending zone. Cracks and all other defects should be avoided at all costs since cracks are only increasing in number and size after steaming and especially after bending, and all those specimens will be graded as defective. Straight-grain, on the other hand, has not turned out to be such a big problem. All kinds of grain angles and shapes were bent properly, even when it was expected for them to fail.

During the visit to the manufacturer in Italy, an attempt was made to bend oak wood in two planes. When bending in two planes, a significantly more demanding bend should be made across the radial section, and a smaller bend should be made across the tangential section. First, specimens were bent in a “U” shape, then heated with HF and left to cool. After that, only straight parts of specimens were steamed again in specially constructed steaming chambers because if whole specimens were steamed, they would straighten out. After a second steaming, specimens were placed in a press with a special mold to bend them in different lanes. When cooled, the specimens were turned and sanded. Test specimens are shown in Figure 13.

The type of process in Italy includes a lot of handwork, which is not suitable in manufacturing where serial production is done. The problem will be further processing of specimens bent in two planes. It is impossible to tighten a specimen bent like that onto the worktable of a CNC machine. Figure 13 shows a mold made of plywood with a specimen tightened in it. It turned out to be the only possible option, but it was decided to be too complex. All the specimens would have to be perfect in order to fit mold that is tight by itself, which is almost impossible. Specimens would have to always be in perfect position when drilling holes in order for them not to go outside the given dimensions. Another idea that occurred was to bend specimens in one plane with great width, then imitate the second bend by routing on a CNC machine.

The idea of bending oak wood in two planes has been abandoned for now. The focus will be directed towards further optimizing and speeding up the process for all bending types and shapes. Bending on the press with male and female bending forms initially should be learned as well. This type of press does not have longitudinal pressure and end stops, which makes it difficult to bend. Some small chair backs with minimum curvatures have been done that way so far, but more demanding curves are still not an option. Without end stops, wood tends to break on the convex side. For that reason, it has to be slowly heated with HF and slowly adjusted to shape without breaking. In the future, that technique will also be learned and implemented into the process.

6. CONCLUSIONS

Wood bending techniques have been around for a long time and are still used today. Bending wood can result in innovative shapes with improved mechanical properties. To bend wood at all, if it is not in a green state, it needs to be plasticized. Plasticization can be done with high temperatures and moisture or with chemicals. The most important parameters when bending wood are the initial MC of the specimens, steam temperature and pressure, thickness of the wood, steaming time, proper HF heating, longitudinal pressure, use of metal straps, and end stops on the convex side. Without metal straps and end stops, more demanding bends of wood with big cross-sections cannot be produced. Only slight curves with smaller dimensions can be done that way. For further studies, the focus will be on finding even better drying schedules and even better bending parameters to speed up the whole process. There is a possibility of implementing even more different bending techniques and obtaining more machinery to experiment on.

REFERENCES

[1] Báder, M., Németh, R., Konnerth, J. (2019): Micromechanical properties of longitudinally compressed wood, European Journal of Wood and Wood Products, 77:341–351

[2] Báder, M., Németh, R. (2019): Moisture dependent mechanical properties of longitudinally compressed wood, European Journal of Wood and Wood Products, 77:1009–1019

[3] Navi, P., Sandberg, D. (2012): Thermo-hydro-mechanical processing of wood. Presses polytechniques et universitaires romandes, Lausanne, ISBN 978-2-940222-41-1

[4] Niemiec, S.S., Brown, T.D. (1995): Steam Bending Red Alder. In: Green D, von Segen W, Willits S, editors. Western hardwoods-value-added research and demonstration program. Gen. tech. rep. FPL-GTR-85. Madison (WI): U.S. Department of Agriculture, Forest Service, Forest Products Laboratory

[5] Peck, E.C. (1957): Bending solid wood to form. U.S. Department of Agriculture, Forest Service, Agriculture Handbook No. 125.

[6] Sandberg, D., Haller, P., Navi, P., (2013): Thermo-hydro and thermos-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products, Wood Material Science & Engineering, 8:1, 64-88

[7] Stevens, W.C., Turner, N. (1970): Wood bending handbook. Parkersburg: Woodcraft & Supply Corp.

[8] Taylor, Z., (2008): Wood Bender's Handbook; Sterling Publishing Co., Inc New York.

Acknowledgements

The article was published as part of the project "Development of innovative products from modified Slavonian oak" by Spin Valis d.d. and partner University of Zagreb Faculty of Forestry and Wood Technology. The total value of the project is HRK 55,064,343.84, while the amount co-financed by the EU is HRK 23,941,527.32. The project was co-financed by the European Union from the Operational Programme Competitiveness and Cohesion 2014–2020, European Fund for Regional Development.