History of Pleating

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Pleating is basically the process of compressing high-quality hardwood along the grain after plasticization by supporting the sides of the wood to avoid buckling. Many treatment variations can be used with a wide range of parameters. Pleated wood can be bent into small curves in any direction. Industrial pleating is still done today in some parts of the world and its success is influenced by many factors, such as wood species, wood quality, moisture content, compression ratio, fixation time, etc. The treatment significantly changes the physical, mechanical and anatomical parameters of the wood. The first written record of the procedure dates back to 1917, and since then many patents, articles, and books on this subject have been published.

cell structure | fibre softening | hardwood | longitudinal compression | mechanical properties | physical properties | pleating | wood bending | wood modification

1. Introduction

Nowadays, curved wood constituents are usually made of glued or glued-laminated solid wood or wood-based composite materials [1]. These technologies require a lot of wood, tools, glue, and precise work. It follows that the properties of wood must be modified so that it can be shaped by simple tools using little force. This is possible with wood compressed along its grain. The cell walls of the wood become wavy as a result of this thermo-hydromechanical (THM) wood modification process, similarly to a plisse shade, which is why Báder and Németh [2] proposed the term “pleating” to describe the phenomenon and to briefly name the modification process. Pleating is basically the process of compressing high-quality hardwood along the grain after plasticization by supporting the sides of the wood to avoid buckling. Many treatment variations can be used with a wide range of parameters, but the final result is always a timber free from harmful substances and highly bendable in the cold state.

Through pleating, it became possible to create pliable, springy, and light furniture made of bent wood [3]. Pleated wood bent to the proper shape can be mechanically fixed as a handrail or fixed by glue as an edge closure without cracking or breaking of the material [4][5]. Veneer can also be made of it, which can be used for 3D curved surfaces where some elongation of the veneer is required [3][6]. The shape of wooden spiral springs corresponds to those used in mechanical engineering. At the same size, the energy stored in a wooden spring is smaller compared to a metal spring, but it can be used in many areas of life as a bio-product due to its low weight and the fact that it is non-magnetizable [7]. Segesdy [8] investigated the usability of pleated wood for kitchen furniture. He found that it primarily contributes to the aesthetic functions of the kitchen, such as fittings, decorative and design accessories, and supplementary devices. It can also be used for other furniture in the apartment, e.g., chair legs, armrests, backrests, and table legs [9]. Sőregi [10] used pleated wood to design the interior of a boat cabin, which is ideal to produce unique curved equipment as safe furniture for ships and aircraft, or to produce reinforcing ribs [11]. Kollmann [9] also described its use as a raw material for certain parts of a wide variety of vehicles. Because it can be individually manufactured, it is also very useful in restoration, where it is not necessary to rebuild the contemporary technology to reproduce one bent constituent but it is sufficient to bend and dry the pre-compressed wood. Tokodi [12] used this modified wood in her thesis to design clothes and clothing accessories. Pleated wood can be used for vibration-dampening tool shafts and custom-shaped tools, picture frames, modeling, and saddles and other horse equipment. It can be used for furniture, interior design applications, construction, vehicle manufacturing, toys and sports equipment, musical instrument manufacturing, fine arts, and medical aids [2][9][11][13][14][15].

Pleated wood, which can be bent in any direction, can be subjected to large deformation and can be processed with low waste [3][16]. No large manufacturing oversize is required, and the structure of wood remains intact [4] because the fibre direction always follows the arc. Its appearance is the same as that of untreated wood, but there is always some discoloration depending on the method and the duration of fibre softening. Due to its stockability and pliability, it is an outstanding raw material for series-produced bent constituents. It has a great advantage in the preparation of individual works, too [16]. Pleated wood is an excellent product from the point of view of aesthetics, material saving, and machining. However, even today there is still little awareness of the technology and its products. With expected future shortages of wood and labour worldwide, its role could become more important because it can be used quickly and with little loss of material for curved solid wood elements.

2. History of Pleating

The technology of wood bending using steam was already known by the ancient Egyptians, as evidenced by a tomb painting nearly two millennia before Christ [17]. Wood bending within the use of wood is about the same age as the culture of humanity. The demand for bent wood for different purposes has existed throughout history. Examples include the Greek klismos chair from the 5th century BC [18] and the British Windsor chair from the 18th century [19]. In 1808, Samuel Gragg in the USA patented a wooden chair containing bent parts [20]. There are also typically chemical fibre softening modes, such as cooking the wood in aluminous or ammonia solutions [9]. Impregnation with glycerin also improves the bendability of wood, but high temperatures are always required to achieve the desired result [9]. As an example, the advantage of ammonia treatment against classic water steaming is that the treated wood remains plasticized even after the wood has cooled down until the toxic ammonia evaporates [21]. The German Michael Thonet was the first who bent wood by steaming in serial production in the Austro-Hungarian Monarchy from the mid-19th century. Initially, he experimented with thin-layered adhesive-based products, and then discovered the potential of heating wood in wet media. He reduced the structure of the chairs to a few components, making it possible to produce them in large series with cheap, unskilled workers [22]. In addition, the variation of the elements can be used to produce unique constructions on demand; in this way, Thonet reformed the furniture industry. His first patent was published in 1842, while the most important patent in terms of the manufacture of bent furniture was published on 7 October 1856 with the title “For the production of chairs and table legs made of bent wood, the bending of which is accomplished by the use of steam or boiling liquids” [23]. Steaming is only economical in large-scale production and it is difficult to carry out [9]. After the steamed wood has cooled down, it cannot be bent further [9][24]. For example, the raw material of the back legs of a Thonet No. 14 Vienna chair must be bent within a half-minute after the raw material has been taken out from the oven [25].

With the further evolution of industrial technology, it was possible to develop a process that provides flexible wood even at room temperature. This process is wood compression along the grain, first patented in the German Empire in 1917 [26]. The development brought new opportunities because it results in a highly flexible material that uses much less bending force than uncompressed wood, mainly in its wet condition but occasionally in its dry condition as well. Moreover, unlike steam-bent wood, compressed wood along the grain does not need heat during the actual shaping. By the end of the 20th century, it had become common practice to adjust the shape of curved elements on site [27]. According to Hanemann [26], large pieces of wood should first be cooked or steamed and then placed in a press in their hot and humid state, where they are surrounded by a cover during the process to prevent buckling. With the press plates, the wood is compressed in the longitudinal direction, then cooled and dried so the wood can be further processed (cut into boards or machined) and easily bent. With the same content, the Danish Pedersen was granted patents in several countries in 1918. The second patent of Max Hanemann [28] presents a more productive version of pleating.

Using a suitable device, the compressed length of the wood must be fixed and removed from the press in its compressed state and then cooled and dried. The latter operations can thus be carried out faster while the press can continue the production process. In the absence of adequate technological solutions, the method had not yet become known and spread. A few years later, in 1926, Holzveredelung Ltd. (Essen, Ruhr, Germany) [29] was the first to introduce industrial compression equipment, supplemented with technical drawings. The machine is designed to be able to compress a wood piece along its grain. The wood is pressed to the side wall during compression but it may move longitudinally along the wall. The clamping device lies under the press plate of the workpiece, can be fastened to the workpiece after compression, and keeps the wood in its compressed state. Taking the clamped wood out of the machine, drying will be easier and faster and production accelerates because the next workpiece can be compressed in the machine.

Magyar–Amerikai Plc in 1927 (Budapest, Hungary) [30] further developed the technology to be able to ensure an equal compression ratio along the entire length of long wood pieces by reducing friction between the wood and the side walls of the machine. During compression, high friction occurs on the side walls of the press, which hyperbolically reduces the compression force towards the center of the wood [9], i.e., consumes a large portion of the applied compression force. This is avoided by the support plates covering the inside of the press mould because the plates can move in the mould following the wood. It is also possible during compression to move tooth-surfaced support plates in the direction of the compression force. In this way, these plates transfer compression force to sections further away from the ends of the wood. The disadvantage of this solution is that due to its design, the tooth-surfaced support plate damages the surface of the workpiece. However, during the next manufacturing steps after pleating, the damaged surface is removed. Additionally, using the angle irons and fasteners on the corners, the compressed length of the wood can be fixed.

In the second half of the 1920s, the British Anglo-European Company Ltd. (London, UK) received numerous patents across Europe that are essentially identical to the wording and drawings of previous patents of Pedersen [31], Holzveredelung [29], and Magyar–Amerikai Plc [30], translated into the language of the country where the patent was made.

According to August Thurn [32], the production of defect-free pleated wood with a rectangular cross-section results in a great loss of material because good-quality parts falling from the logs become waste. Using wood with a cylindrical cross-section, the quality of pleating is less affected by the defects in the fibre structure. The raw material must be placed in a support case, which prevents it from buckling, in which logs of various diameters can be compressed with an appropriate space-filling casing. Fibre softening and subsequent drying can be accelerated by removing the pith. During compression, this should be replaced by a pressure-resistant metal core. In order to speed up the drying process, hot compressed air can be circulated in the hole that remains after the pith is removed. According to the description, the production costs of the pleated wood are reduced to one-quarter and it becomes possible to produce peeled veneer of pleated wood. The technological details have not been patented and the method has never been used.

Thurn and Thurn [33] said that the greatest available flexibility is not always necessary, but using a lower compression ratio has not been a suitable solution. The authors have probably come to this conclusion because wood that has been less compressed results in both less equal compression along the length and in a less uniform pliability. It was known that after pleating, the wood can be cooled and dried in its compressed state, resulting in a very flexible material, whereas if the wood is allowed to spring back after pleating, it will be less pliable. By regulating the spring back, it is therefore possible to produce wood with a desired uniform pliability along the length according to its intended use. This will speed up the manufacturing process and reduce the costs of production.

Many written memories—such as the book by Graf published in 1932—provide evidence of the industrial production of pleated wood [34]. The book by Kollmann [35] on wood technology already introduces the characterization of pleated wood. Schneider [36] describes that pleated wood is used for aircraft components. Heisel and Eggert [37], Bátori [13], and Material Archive (Zürich, Switzerland) [38] link the first industrial production to Holzveredelung Ltd., so the industrial production of pleated pliable wood might have begun in the second half of the 1920s. For half a century after the 1940s, there does not appear to be any new patent or research in conjunction with pleating, only references to previous knowledge (Vorreiter [11], Blankenstein [39], König [40], Schietzel [41], and Heisel and Eggert [37], among others). According to the British Stevens and Turner [42], patents are already known for the production of pleated wood, but the technology is limited from a mechanical and economic point of view.

Chronologically, the next patent is owned by Sparke in 1989 [4] in Denmark, which deals with double compression. The author describes combinations of different process components (fibre softening, compression, quick or gradual release of the wood after compression while it dries, various repetitions of these processes, fractional compression, etc.) and the possibility of variable side pressure in describing the technology. In addition, the patent specifies a generally used 20% compression ratio relative to the original length, and that in some cases, the process makes the wood permanently close to the plastic state, which remains even in dry conditions.

Thomassen et al. in 1990 [43] assembled a wood compression device. The text of the patent is supplemented with technical drawings of the patent granted in Denmark in 1989, which uses both pre-patented inventions and new technological innovations. The side wall components are pushed against the wood by a hydraulic tube and thus the side pressure can be different along the length of the workpiece. Nowadays, electronically controlled compression equipment using the principles of this patent (manufactured by Compwood Machines Ltd., Slagelse, Denmark) are operating in Hungary and in the USA [44]. In addition, machines operating based on the patent of Magyar–Amerikai Plc [30] are used in Italy [13].

Bakos [45] describes an experimental device developed in Debrecen, Hungary. It used ball screw technology to compress rods made on turning lathe with a diameter of 22 mm. According to the description, this machine operated on the basic principles of the patent of Magyar-Amerikai Plc [30], but no further data on the equipment can be found, so the development was probably stopped. Chronologically, the following patent presents the usual process of preparation and pleating of wood, illustrated with a wood piece of 100 × 120 mm cross-section [5]. The advantages and possible uses of pleated wood are discussed. The machines for bending metals in wood bending also appear. Pleated wood can be used glued or mechanically fastened, and it is possible to make slight corrections of the bending radius during installation of the finished product. This patent does not introduce new technology or a new method, but it summarizes a lot of information.

Volkmer et al. [6] approached pleating from a new direction: a short free section of wood between two clamps is pre-compressed by about 5%. The free section always advances and another section is compressed until the entire length is pre-compressed. In the second cycle, using the technology described in earlier patents, the pre-compressed wood should be compressed up to half of its original length. If it is necessary to set the wood to an exact final length, it must be dried under pressure after compression. If the wood is compressed 10% shorter compared to its desired final length, the fastening devices required for drying under pressure can be omitted. A 5% longitudinal stretching of the longitudinally compressed and dried wood further reduces the stiffness, making bending even easier. Currently, no modified wood is produced under this patent.

A compressing device has been operating at the University of Sopron since 2015. The required pressure and continuous measurement data are provided by an Instron 4208 (Instron Corporation, Norwood, MA, USA) universal material testing machine. When the device is attached, specimens of 20 × 20 × 200 or 20 × 30 × 200 mm^3 can be compressed in the fibre direction up to 33% compared to their original length. The side walls of the semi-closed chamber are heated and able to move along with the specimen during the compression process if this is required [14][46].

It is worth mentioning additional patents loosely related to pleating. Curtis [47] cooked maple, beech, and birch raw materials with a moisture content of less than 12% for 2 h in crude oil, and then compressed them through a truncated mold after 2 days of drying. The thickness of the wood preheated to 100 °C was compressed to 84% in the heated press, and its length was also reduced while its width remained unchanged. He found that with longer cooking time, the wood becomes saturated and the required compression force increases. The purpose of this operation is to produce mechanical properties similar to dogwood (*Cornus*) in other wood species to produce a particular loom component, which is achieved by the combination of longitudinal and transverse compression after the softening of fibres. Jouko [48] discloses snap-on wooden constituents with reference to the original patent published in 1996 and identifies the pleated wood as a raw material, among others.

Szabó et al. [25] describe the main parameters of compression technology (moisture content, compression ratio, etc.) and a wooden spring made of pleated wood that can store and deliver energy. It can be used as part of mechanical, medical, furniture, or toy constructions. Eckardt [49] designed a means for demarcation of space using pleated wood for furniture parts, interior design elements, and decorative purposes. In a wood panel made of pleated wood there are several lines cut parallel and offset to each other and parallel to the fibre direction. Thanks to this, the wood can be laterally drawn out and made in a wide range of widths.

As is apparent from the patents presented, there have been numerous demands and technological problems over the past hundred years in the development of wood compression along the grain. Several solutions have been developed to overcome these problems, and nowadays, the production of high-quality pleated wood has been solved. It is possible to produce a variety of special products, primarily serving the needs of furniture and interior design, and further opportunities continue to arise.

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