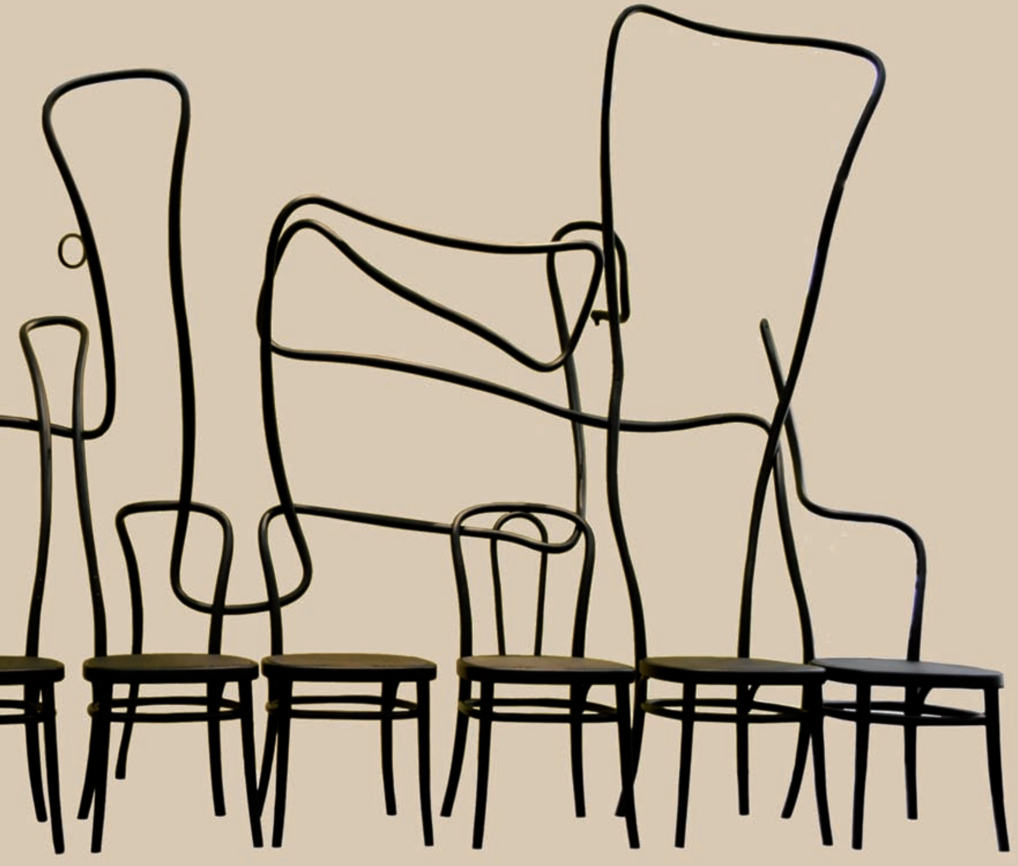
Engineering Sciences *Materials*

THERMO-HYDRO-MECHANICAL PROCESSING OF WOOD

Parviz Navi and Dick Sandberg



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EPFL Press
A Swiss academic publisher distributed by CRC Press

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20120201

International Standard Book Number-13: 978-1-4398-6043-4 (eBook - PDF)

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http://www.crcpress.com

PREFACE

The fabrication of wood-derived products is widespread and growing, thanks to its unique advantages: widespread availability, natural renewability, favorable ecological assessment, and flexibility of implementation. Moreover, the polymeric components of wood, together with its porous structure, confer upon it a faculty for transformation exceeding that of other materials.

Since the dawn of civilization wood has been used in its natural state. Only recently has wood been developed to form a range of products that are increasingly functional, based on a combination of performance and sustainability requirements. Indeed, since the beginning of the last century, knowledge on this topic has advanced constantly, mainly through the efforts of systematic scientific research and new types of applications.

The early 1900s, preliminary work on the science and technology of wood was first published. Our current understanding of the material properties, chemistry, and physics of wood – coupled with advances in materials science and modeling techniques – has provided the tools to allow engineers and researchers to fully exploit wood as a material and to produce new components and products under controlled processing conditions.

In order to overcome the inherent difficulties in wood-processing technologies, an interdisciplinary approach is required. Close co-operation between scientific disciplines – such as the anatomy of wood, physics, chemistry and mechanics – allows for mutual and constructive progress to be made. Thus the wood-treatment technology evolves with our understanding of the basic science in such areas as conservation, drying, machining, shaping and joining, etc.

One of the emerging eco-friendly treatment methods is the combined use of temperature, moisture and mechanical action – the so-called Thermo-Hydro-Mechanical (THM) treatment. THM processing is implemented to improve the intrinsic properties of wood, to produce new kinds of materials, and to acquire a form and functionality desired by engineers without changing the eco-friendly nature of the material. These processes can be divided into two major categories; Thermo-Hydro (TH) treatments and Thermo-Hydro-Mechanical (THM) treatments.

As mentioned, wood consists of natural polymeric chains, connecting to each other by hydrogen bonds and, in other zones, by covalent bonds. The hydrogen bond is at the origin of its transformation properties. For example, when wood is put under thermo-hydrous conditions, allowing for the softening of its amorphous components, it can easily deform, making it possible to apply a range of industrial processes such as molding, densification, surface densification, bending, shaping, and drying at high temperature. However, the application of high temperature – with or without moisture – can mechanically damage or chemically modify the polymeric components of wood.

In this book, we bring together the key elements of the chemical degradation of wood constituents under TH and THM processing; the behavior of wood under these conditions; as well as a selection of the principal technologies that can be considered

TH/THM treatments. This work is intended for researchers, professionals of timber construction, as well as students in the fields of material science, wood technology and processing, civil engineering, and architecture. Our goal is not to provide exhaustive coverage of the subject, but rather to highlight the scientific disciplines necessary to comprehend THM technologies, as well as the behavior of wood during treatment and later in product application.

This book consists of 11 chapters. The first is devoted to the justification for TH/THM processing. Ancient treatments of wood by THM processing are discussed in the second chapter. It is shown that different heat-treatment processes were already in use thousands of years ago in order to improve the performance of wood. The description of the structure and the chemical composition of the components of wood are given in the third chapter. In the fourth chapter, the explanation and modeling of certain THM behavior of wood is presented. In the first part, the small and large deformations of wood are described, and the constitutive equations of elastic linear and elastic nonlinear behavior of wood, are derived. In the second part the viscoelastic behavior of wood under ambient temperature, constant and variable humidity is described. In the chapter five, the behavior of THM of wood under variable moisture and temperatures (as high as 200 °C), is examined by considering that during the processing, at high temperatures, the components of wood undergo certain chemical modifications. In this chapter the effects of the processing parameters – temperature, moisture content and time – on the THM wood characteristics are discussed. The sixth chapter is devoted to the process of wood densification by THM treatment. In the first part of this chapter, various THM wood-densification processing methods are discussed, with illustrations of the machines developed in different countries corresponding to open, closed, and mixed processing. Later in the chapter, the origin and mechanisms of shape memory and elimination of the compression-set recovery by THM treatment are discussed. Chapters seven and eight are devoted to techniques of wood welding by friction and wood-surface densification. In each of these chapters, different techniques are discussed and the problems related to these different ‘open systems’ are explained.

In the recent decades, heat-treatment techniques have advanced considerably. At present, many countries have developed their own national version of wood TH treatments. In chapter nine, most of these processing methods are presented and discussed. In chapter ten, a number of wood-bending processes – including bending of solid-wood, laminated-wood bending, green-wood bending and kerfing – are presented and different techniques discussed. In addition, the reader will find a presentation of the theory of solid-wood bending and a demonstration of solid-wood bending in the laboratory and at industrial levels. Finally, the eleventh chapter provides a selection of technologies on the fabrication of reconstituted wood, namely fiberboards, particle boards and panels made of veneers.

For the benefit of wood engineers and others with an interest in this fascinating industry, we hope that the convenient availability of this material will lead to a deeper understanding of some of the fundamentals involved in TH and THM processing of wood.

Parviz Navi & Dick Sandberg

Acknowledgements

The authors wish particularly to thank Dr. Brenhard Stamm (wood circular friction welding), Lauri Rautkari (surface densification), Professor Preben Hoffmayer (creep and mechano-sorption), Professor Alain Curnier (on large nonlinear deformations), Fred Girardet (conception of THM closed reactor), Professor Frederick Kamke (conception of THM mixed reactor), David Anguish and Professor Ove Söderström for his constructive remarks.

The financial support of the Swiss National Foundation on the field of wood THM processing is gratefully acknowledged.

A special thank is directed to the Swedish Knowledge Foundation and Ikea of Sweden for their long-term support in the areas of solid wood bending and laminated bending.

The authors would also express their thanks to the Editor, Dr. Frederick Fenter, as well as to the entire helpful team of the Presses polytechniques et universitaires romandes (PPUR) for dealing with all the numerous details through the book's final production.

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CHAPTER 1

WOOD MODIFICATION

1.1 INTRODUCTION

Wood is the ultimate renewable material. It possesses qualities that have made it a material of choice for millennia and these qualities are further enhanced by its recognized carbon sequestration. Moreover, the polymeric components of wood and its porous structure confer on it a noble, versatile and general-purpose character and a faculty for transformation exceeding that of all other materials. The unique advantages of this material, its widespread availability, sustainable renewal, favorable ecological assessment and its flexibility of implementation, give this worthy material its letters patent of nobility in the eyes of scientists and engineers. Nevertheless, the fact that wood is a natural product originating from different individual trees imposes limits on its use. This natural material may need to be transformed in order to acquire the desired functionality.

There are ways in which the properties of wood can be enhanced by modification through eco-friendly methods. One emerging eco-friendly method is the combined use of temperature, moisture and mechanical action, the so-called thermo-hydro-mechanical treatment. There are numerous thermo-hydro-mechanical processing techniques and the number of these processes is growing continuously. Thermo-hydro-mechanical processing is implemented to improve the intrinsic properties of wood, to produce new materials and to acquire a form and functionality desired by engineers without changing the eco-friendly characteristics of the material. These processes can be divided into two major categories; Thermo-Hydro treatments (TH) and Thermo-Hydro-Mechanical (THM) treatments.

Craftsmen have modified wood for centuries by TH/THM treatments, but it was in the 19th century, with the construction of the Vienna Chair by Michael Thonét (1796-1871), that the industrialized process of wood molding technology was born, allowing its products to be commercialized all over the world. Besides greatly improving the understanding of basic material properties, chemistry and physics as well as giving rise to advances in materials and wood science, modeling techniques provided the means for engineers and researchers to engineer wood as a material and produce new materials under controlled processing conditions.

1.2 REASONS FOR THERMO-HYDRO-MECHANICAL PROCESSING

Never before have the forestry and forestry-related industries been so sharply in the focus of discussions concerning the major challenges for the future. The challenges being discussed are of great significance: instead of consuming the Earth's non-renewable resources, the use of renewable materials is being encouraged in all quarters; fossil fuels must be phased out and human consumption must increasingly reflect a concern for the climate and the environment. Whilst in service, the carbon having been fixed in wood by photosynthesis can act as a long-term carbon store. Wood-based products such as solid wood can also act as short-term carbon stores. Carbon accounts for about half of the mass of a wood product. For example, with a wood product stock of about 60 million tonnes in Europe alone, the carbon storage effect of wood products plays a significant role in mitigating ecological and societal effects. The forest industry uses renewable raw materials and manufactures eco-friendly products. Carbon is stored in the forests and in their products. This means that both forests and forest products are part of the answer to the climate challenge.

Concern for the environment and the climate has put pressure on wood researchers and the wood industry. The demand for investigations and the development of new treatments for eco-friendly products, for improving wood properties and finding alternatives to tropical hardwoods as well as to energy-consuming material processes and fossil-fuel-based materials is greater than ever before, and this is the reason why some new modification technologies are being commercialized.

The TH process is based on wood, water and heat, and the THM treatment incorporates an additional mechanical force. This is an environment-friendly process that uses a recyclable and renewable natural resource that decreases the CO_2 in the atmosphere. At the same time, TH/THM processes consume relatively little energy. The result of studies in different fields of TH/THM processing also indicates that the properties of wood such as its dimensional stability, strength, surface hardness and durability are improved.

Enhancing the competitiveness of timber by using an innovative upgrading method with a low environmental impact can increase the use of local materials instead of imported rare tropical hardwoods, creating added-value for local timber resources, increasing profitability, providing regional income and providing employment in regional/convergence areas. People are also starting to recognize the advantages of combining renewable sources such as wood with an environmentally acceptable processing technique in order to achieve new high-quality materials. Thermo-hydro-mechanical processing as a base for product improvement and the development of new product-market combinations is now of significant interest in the industry. Potential areas of application for the thermo-hydro-mechanical processing include the building industry, furniture manufacture, improving service lives of wood products through increased durability and stability, wood-finish compatibility and in new market areas now being identified.

1.3 MODIFICATION OF WOOD

The purpose of any technological development involving wood is to standardize, homogenize and produce new wood-based materials with dimensions that are independent of those of the tree, to decrease anisotropy, overcome the problems of dimensional instability and improve the material's durability and resistance to fire. In order to obtain semi-finished and finished products with or without added value, wood can be transformed

- by transformation, i.e., sawing, chipping, pulping;
- by reconstitution, i.e., in the manufacture of engineered wood products from wood, wood chips and particles; and
- by modification.

This book presents the principal tools and instruments used in the TH/THM wood modification, the rich experience gained during several millennia of wood TH/THM treatment and especially the role of wood science, chemistry, mechanics and physics on the recent techniques of wood thermo-hydro-mechanical processing.

To modify wood, two treatment types are implemented: chemical treatments and TH/THM treatments. The former are much more numerous and the range of chemical agents is very broad, whereas for the TH/THM treatments, only heat, water and mechanical forces are employed. Figure 1.1 displays a simplified synoptic diagram of the current chemical and THM treatments.

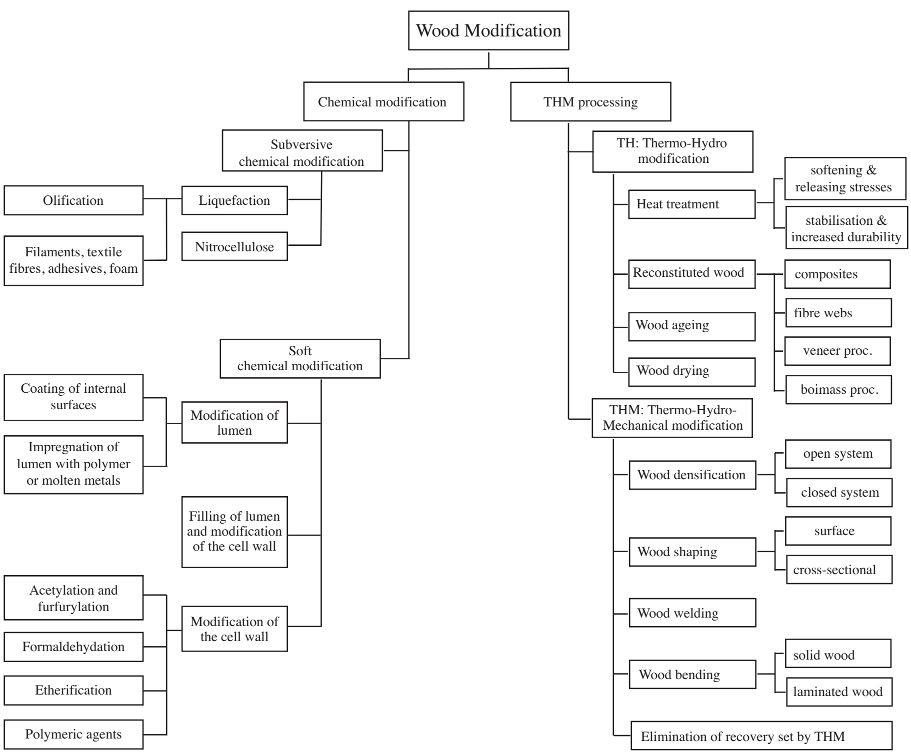


Fig. 1.1 A diagram of the various processes of chemical modification and thermo-hydro-mechanical processing of wood.

1.3.1 Chemical modification

Chemical modification of wood is defined as any chemical reaction between a reactive wood cell component and a chemical reagent, with or without a catalyst, giving rise to a covalent bond between the two components (Hon & Shiraishi, 1991; Hill, 2006). The most promising application of this technology is developed in the area of reconstituted wood products, e.g., particle boards, plywood and veneer-based products and in the enhancement of the dimensional instability, resistance to biological degradation (durability) and resistance to fire of the wood.

In Figure 1.1, two classes of chemical treatments can be distinguished: subversive and soft. The subversive treatments are those that enter into the core of the cellulose fibrils. They break down the crystalline structure of cellulose and eliminate the multilevel and hierarchical structure of wood. These treatments radically modify the chemical components of the wood, and consequently the material produced lacks practically all the intrinsic characteristics of untreated natural wood. Examples of subversive treatments are liquefaction and olification of lignocelluloses (Yao *et al.*, 1994), where liquefaction is adopted mainly to produce oil from biomass under very severe conditions. Appel *et al.* (1969, 1975) converted celluloses to oil using reactive chemicals, under high temperature and high pressure. This type of liquefaction is called olification of lignocelluloses. Other recent types of liquefaction involve the dissolution of chemically modified wood or even untreated wood in a solvent. Applications of these types of liquefaction have been developed in the preparation of adhesives, moldings, foams etc. Nitrocellulose (cellulose nitrate) is prepared by treating cellulose with a mixture of nitric acid and sulfuric acid. It is employed as a propellant or low-order explosive (guncotton) and as a film-forming resin in the inks and coatings market.

The soft chemical treatments, on the other hand, leave the crystalline structure of wood intact and touch only the amorphous part and the side groups (functional groups) of the wood components at the molecular level. These treatments allow the microstructure of the modified wood to remain more or less unchanged. In this category, some typical treatments include: formaldehydation, acetylation, etherification, impregnation by carbinol and maleic acid, impregnation by vinyl resins, impregnation by polyethylene glycol (PEG), impregnation by phenol formaldehyde resin, filling by metal alloys of low melting point, etc. These treatments can lead to improvements in certain physical and mechanical properties of wood, such as hygroscopicity, resistance to micro-organisms, and fire resistance, as well as in its mechanical behavior with respect to the moisture variations. Norimoto and Grill (1993) have investigated the influence of various soft chemical treatments on the mechanical and physical charachteristics of wood, and they have shown that some treatments improve certain properties of wood but are likely to lead to deterioration in others. For example, the impregnation of wood with a polyethylene glycol (PEG) resin reducees the hygroscopicity of wood but at the same time increases the mechano-sorptive creep deformation. In contrast, acetylation can simultaneously reduce both the hygroscopicity and the mechano-sorptive creep behavior of wood.

The chemical treatments that involve a radical modification of the wood structure, i.e., subversive chemical wood treatment, constitute a delicate field, which requires a detailed study of the organic chemistry. The soft chemical treatments of wood are mainly implemented to reduce the hygroscopicity and mechano-sorptive creep and increase the resistance to micro-organisms.

1.3.2 Thermo-hydro and thermo-hydro-mechanical modification of wood

The TH/THM treatments have an important advantage over the chemical treatments since the products of the TH/THM wood are particularly environment-friendly. During thermo-hydro-mechanical processing, no chemical agents are introduced into the wood and no subversive chemical degradation affects any of its components. Under TH/THM treatments, many types of processes are developed to produce different products. Some of the results achieved at the laboratory level or in industrialized-commercialized processes are shown in Figure 1.1. The TH treatments include many types of processes, such as those to

- improve dimensional stability and reduce the wood hygroscopicity;
- enhance the resistance to micro-organisms;
- achieve an accelerated aging of the wood; and
- release internal stresses (reduce the recovery set) and to soften the wood through wet heating.

One can also perform a TH treatment of reconstituted wood products, e.g., wooden composites, paper, fiber-boards, plywood and wood plastic composites. The THM treatments include

- densification, i.e., THM densification in a closed or open system;
- wood shaping by surface densification and embossing;
- wood shaping by wood cross-sectional transformation;
- wood welding;
- wood bending, i.e., solid wood bending and laminated bending; and
- THM treatments to eliminate the shape memory of densified wood.

The fact that wet wood can be shaped under the action of mechanical and thermal loads has been known for a very long time. Figure 1.2 shows the principles used in the construction of a canoe by an elementary and ancient THM process. The various stages of the construction include the preparation of the hull starting from a trunk, heating of the hull of humidified wood, giving the desired shape to the canoe and mechanical fixing to maintain the given shape.

The shaping of steamed wood has been employed since antiquity and has been carried out in numerous ways. Plasticization of the solid wood in order to make it possible to bend the piece without fracture is the most common way of shaping, e.g., for furniture-making and ship-construction. The bending can be achieved in one or in two planes as well as in different directions in the same plane. Wood is normally bent after pre-steaming in various types of strapping devices that minimize the effect of tension on the convex surface and maximize the compressive yield on the concave surface, thus limiting the risk of breakage.

Another process involving the shaping of wood is the technique of laminated bending that is primarily directed towards the bending of veneers for other than

(a)

(b)

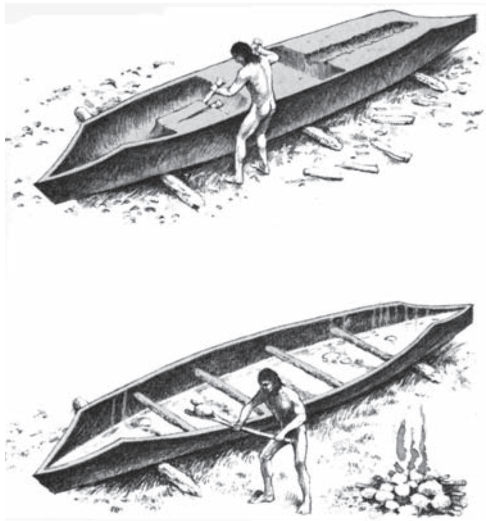
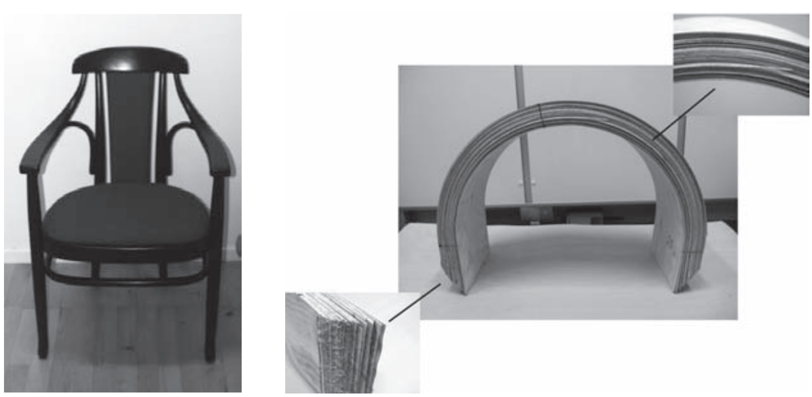


Fig. 1.2 The construction of a canoe (Freed & Baby, 1983). (a) Mallets and wedges are used to hollow out the interior of the trunk. The trunk is then scraped to give it the desired thickness; one finger thickness for the upper part and two fingers for the bottom. (b) In order to widen the canoe and give it the final shape, it is filled with water to humidify the wood. The water is then heated to boiling by heated stones. The fire lit at the side also heats the outside of the canoe. Once the wood has been softened by the hot water and fire, the wooden beams are set up to widen the hull, fixing and maintaining the desired shape.

structural purposes, such as in sports goods, furnishing details etc. (Stevens & Turner, 1970). The need to increase the efficiency of the process of manufacturing wood veneer products and the increasing importance of laminated bends in structural applications have led to an increasing interest in a basic understanding of the wood material and the process (Ormarsson & Sandberg, 2007). The fundamental mechanisms that



(a) (b)

Fig. 1.3 Examples of products made by (a) solid wood bending (chair) and (b) laminated bending (window frame).

must be understood and developed for bending laminated wood for structural purposes and for non-structural members are however similar, especially when the radius of curvature is small. Figure 1.3 shows examples of products made by solid wood bending and laminated bending.

Wood can be densified and its properties modified not only by filling its void volume with polymers, molten natural resins, waxes, sulphur and even low fusion metals, but also by compressing it under conditions such that the structure does not become fractured. Densification is the process whereby the wood density is increased by reducing the void volume of the lumens in the wood material.

In wood shaping, the wood can be processed either at the surface or in the cross-section of the wood. Embossment is a process where the surface of the wood is partially densified, normally by a steel tool, to create a decorative pattern in the surface, as exemplified Figure 1.4. This process is comparable with the methods of densification of wood, but its main purpose is not to increase the density of the wood, but only to shape the wood surface. Embossment has a long tradition. For example, the art of pressing, engraving and fretting patterns into wood has been a part of Iran's ancient history and goes as far back as 5000 years when it comes to the interior design of palaces, boxes laid over tombstones, pulpits and book-racks (Khamouski, 1999).

Fig. 1.4 Example of embossment work.

The advances achieved during the 20th century in wood material science and engineering provided the means for the engineers and researchers to develop new eco-friendly materials from wood. One of the most interesting areas is wood processed in a closed system under controlled processing conditions. The most remarkable examples of science-based technologies in thermo-hydro-mechanical processing are briefly described in the next section.

Thermo-hydro wood processing

The thermo-hydro treatment of wood constitues a modification technique since the wood constituents undergo chemical changes during the treatment. The reason for heat-treating the wood is to improve some of its intrinsic properties such as the dimensional stability, resistance to micro-organisms, stress relaxation during the forming of wood-based composites, veneer production, wood cutting and wood fracture resistance. Currently, this technique is implemented to make artificially aged wood, so-called accelerated wood ageing.

Stamm *et al.* (1946) investigated the effect of heat and processing time on the dimensional stability of wood. Wood was immersed in baths of molten metal at temperatures between 140 and 320 °C, and it was reported that heating for seven hours at 260 °C reduced the swelling of Sitka spruce by 60%. However, Stamm (1964) reported that, although the dimensional stability and set recovery of compressed wood were improved by heating, certain parameters related to strength were reduced to an unacceptable level, particularly the surface strength. Hence, it was predicted that the dimensional stabilization of wood by heat had no future.

In the 1970s, Burmester (1973) studied the effects of temperature, pressure and moisture content to find the optimum conditions for the heat-stabilization of different species of wood, and a heat-treatment method called FWD (Feuchte-Wärme-Druck) was launched. The optimum conditions for pine wood for instance were stated to be a moisture content of 20-30%, a temperature of 160 °C and a pressure of 0.7 MPa. A considerable resistance towards brown rot fungus was reported, and the strength reduction was stated to be insignificant.

During the 1980s, French and Japanese industries began to study the heat treatment of wood in a closed system in order to increase the microbial durability. Since then, the interest for heat treatment has increased all over the world. The process essentially involves a controlled degradation of wood, primarily resulting in the destruction of hemicelluloses. Several different methods are included. The basic diversity of the different processes is indicated by their oxygen-excluding and heat-transporting media. A substantial similarity is that these processes run in a temperature range between 180 and 240 °C to change the chemical composition of the cell wall. Due to a severe loss of strength, TH treatments of wood at elevated temperatures above 300 °C are limited (Hill, 2006). The temperature is achieved with superheated steam in vacuum, or with an inert gas such as nitrogen. Pre-heated oil can also be used in the process. A simplified picture of the results obtained from the heat-treatment methods indicates that heat treatment increases the stability and durability but also the brittleness of wood and leads to a loss of certain strength properties including impact toughness, modulus of rupture and the work to failure.

The commercializing of industrial heat-treated wood products is a recent advance. This type of industry aims at improving the biological durability of less durable wood species and enhancing the dimensional stability of wood or wood-based products, e.g., particle boards. The properties of industrially produced heat-treated wood in general have been intensively investigated in recent years.

On the European market, several industrial heat-treatment processes have during the last few years been introduced using closed systems. Figure 1.5 shows one heat-treatment chamber for controlling the temperature and humidity of a two-stage treatment plant.

The most wide-spread industrial heat-treatment process of wood is the seasoning sawn wood in kilns. This process is performed at temperatures below 100 °C, i.e., low-temperature convective drying, or above 100 °C, i.e., high-temperature drying. Thermal modification of wood may be viewed as an extended seasoning process,

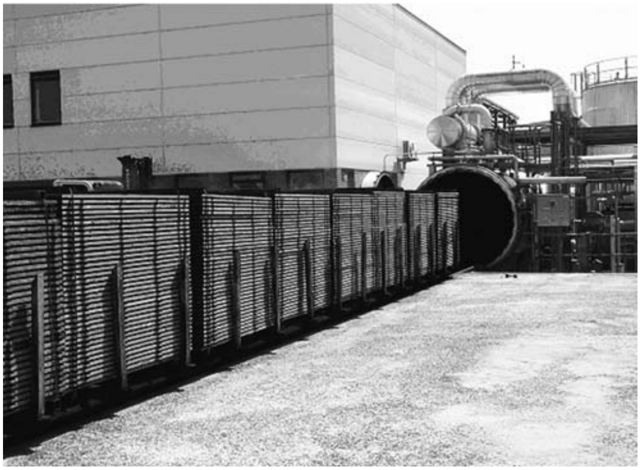


Fig. 1.5 Heat treatment according to the Plato process in a thermo-hydro vessel, 20 m long and 2.4 m in diameter, with a controlled temperature and humidity (by courtesy of the Plato International BV, the Netherlands).

which ends with an increased temperature period when all the water in the wood has vaporized.

In a TH process, wood is heated in water to soften it and to release its internal stresses. A common industrial TH process is steaming and boiling logs before slicing or rotary peeling them to veener. Actually, the boiling temperature of water is seldom reached. Almost always, the temperature is lower than 100 °C. TH processes have also been extensively studied as a technology for the processing of biomass for the production of sugars (Garrote *et al*., 1999).

For several decades, friction welding has found broad applications in many metal and plastic industries. Suthoff *et al*. (1996) made the first attempts to join wood by means of pressure and frictional movement. They stated that two pieces of wood can be welded by means of an oscillating or linear frictional movement.

Early work in joining pieces of wood by friction welding was carried out by Gfeller *et al*. (2004), Stamm *et al*. (2005) and Stamm (2006). It was demonstrated that during the welding process the contact zones between two wooden pieces were joined together by "molten wood" through the heat produced during the frictional movement. The movement causes a thermal alteration of the wood cells, which leads to the formation of a viscous layer or "molten wood". After stopping the friction movement and cooling, the material in the contact zone forms the connection between the pieces, as displayed in Figure 1.6.

Investigations of the welded wood show that the strength achieved by this method is close to that obtained using conventional glues, but that the strength of friction-welded joints decreases at high humidity. The development of a relatively high initial resistance also permits for instance the continuous welding of multilayered laminates. In this technique, the temperature of the wood between the welded surfaces may rise to more than 400 °C during welding. Moreover, the total welding processing time is short, about 10-20 seconds. These techniques have attracted industrial interest.

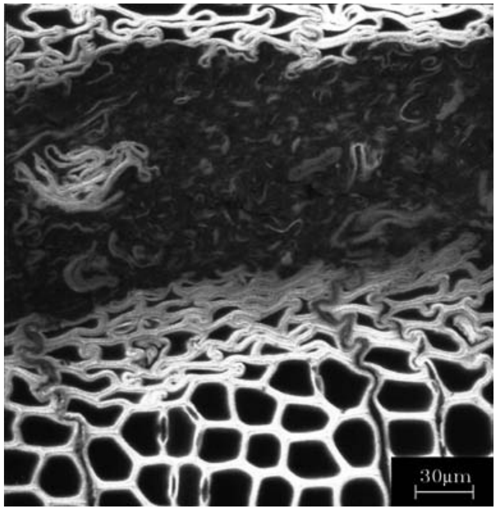


Fig. 1.6 Cross-sectional view of a confocal laser-scanning micrograph picture of the heat-affected zone and the adjacent regions of friction-welded Norway spruce (Stamm *et al.*, 2005).

Mechanically induced vibration wood-welding techniques can also be utilized to obtain wood surface finishes with a greater surface hardness and performance in the presence of polymerizing unsaturated oils, such as sunflower oil or other polymerizing finishes (Pizzi *et al.*, 2005).

Thermo-hydro-mechanical wood processing

Compressing wood in the transverse direction reduces the void volume of the lumens in the wood material and increases its density. This process is commonly called densification. In 1886, the idea of wood densification by compressing the wood in its radial direction existed (Vorreiter, 1949). In Austria, the Plumfes brothers developed a method in 1922 for densifying wood by impregnation with rubber. This type of wood was used in the aviation industry until 1945 when it was replaced by aluminum. Compressed solid wood has also been made in Germany since the early 1930s and commercialized under the trade name of Lignostone, a corresponding laminated compressed wood under the trade name of Lignofol, and a resin-treated laminated compressed wood under the name of Kunstharzschichtholz (Kollmann, 1936; Stamm, 1964). The first aim of the densification was to improve the mechanical behavior and moisture sorption of wood. At present, the objective of wood densification is manifold and includes numerous processes, such as wood shaping, enhancing the intrinsic mechanical, physical properties of the wood, producing high-quality wood, wood surface densification. One of the reasons for densifying wood in the transverse direction is to produce high quality timber from timbers of low quality. A process developed in Japan called “Compressed Lumber Processing System” transfers a local timber with a low density of about 300 kg/m^3 to a timber with a density greater than 900 kg/m^3. Figure 1.7 shows two elements fabricated by this THM process at a temperature of 180 °C.

Fig. 1.7 Photograph of two elements of densified wood fabricated by the "Compressed Lumber Processing System" from low-density wood.

However, densified wood shows an undesired behavior, i.e., a tendency to recover all or part of its compression-set and return to its initial dimensions when subjected to heat and humidity. This phenomenon is called "shape memory" or "compression-set recovery". Various wood products (bent wood, densified wood, wood surface densified wood, molded wood and compressed wood fibers) suffer from shape memory. To overcome this issue, Stamm and Seaborg (1941) impregnated the wood after compression with a phenol formaldehyde resin. The wood was then heated for 10 to 20 minutes to polymerize the resin. This type of compressed and impregnated wood was called "Compreg". Stamm *et al.* (1946) had thus succeeded in partially eliminating the shape memory of densified wood by a TH treatment.

Advanced investigations of the densified wood treatment in THM processing have been reported by Tanahashi (1990), Inoue *et al.* (1993), and Ito *et al.* (1998a). They have shown that the THM post-treatment of densified thin wood specimens at 200 °C for only 4 minutes was sufficient to eliminate almost totally the shape memory of densified wood. On the other hand, the thermal treatment of wood was limited to 300 °C, due to severe degradation of the strength of the material (Hon & Shiraishi, 1991; Hon, 1996; Navi & Heger, 2005; Hill, 2006).

The purpose of recent research into molding and wood densification as well as the development of new techniques for THM post-treatment (to eliminate set recovery) is to implement wooden elements with large dimensions. Currently, in Japan, various investigations into the THM densification of wood are being carried out. These processes are based on a two-directional transverse densification of wood elements and involve four stages: wood plasticization by high temperature steam, compressive molding, THM post-treatment and cooling. Two techniques are being developed: one by Ito *et al.* (1998b), in which small trunks of wood with a circular sections are transformed into trunks with square sections; and one known as the "Compressed Lumber Processing System". The differences between the two technique lies in the stage of post-treatment. In the first technique, the molding and post-treatment form a continuous process, whereas in the second technique these two stages are separated. The problems related to the dimension of the wood elements (size effects), such as the development of cracks and exfoliation during shaping, cooling and drying have apparently yet to be completely solved. Shigematsu *et al*. (1998), Kyomori *et al*. (2000), and Tanahashi *et al*. (2001) have reported that to overcome the problems of "compressive molding of wood under a high-pressure steam technique" requires much fundamental knowledge on wood THM behavior is required.

From the 1990s, as in Japan, various investigations and research studies on the molding, densification of wood and THM post-treatments as well as on the thermal heat treatment of wood were started in Europe, in the United States and recently in Canada. For example, in Denmark, besides the work of Morsing (2000), a machine was developed for pre-compression of wood in the longitudinal direction. The procedure involves:

1. compressing the steamed softened wood element longitudinally about 20%;
2. releasing the applied compression, after which the wood partially recovers the compressed set, so that the residual deformation is about 4-5%; and
3. then allowing the wood to cool at room temperature and dry to a moisture content of 12%. This type of densified wood element can be bent without steaming and jigs.

In Switzerland, Schrepfer and Schweingruber (1998) have studied the deformation of wood cells during densification. Navi and Girardet (2000), Heger (2004), Navi and Heger (2005) and Navi *et al*. (2007) have investigated the origin of set recovery and have shown that the hydrolysis of wood hemicelluloses is sufficient to almost totally eliminate the shape memory through relaxation of the stored strain energy. In Germany, Rapp and Sailer (2001), Rapp *et al*. (2006), have developed a system for wood heat treatment based on oil at a high temperature (OHT). In this open system, rape-seed oil is used as a medium as it can be heated above 200 °C. The same system was investigated by Haller and Wehsener (2004) and Welzbacher *et al*. (2008) for eliminating the set-recovery of large industrial densified wood elements. The results have shown that oil-heating at a temperature above 200 °C can completely eliminate the compression-set recovery of large densified spruce panels. Such a product has shown improved resistance against micro-organisms. Because of its improved durability and the impregnation of densified wood by oil during the post-treatment, this type of product can be used for outdoor purposes.

In USA, due to the harvesting of rapidly grown wood with low density, wood researchers have shown an interest in the possible opportunities of using densified wood in the production of composite layered materials (Kamke, 2004; Kutnar *et al*., 2008a,b). To densify small low-density hybrid poplar specimens, Kamke and Sizemore (2005) have developed a semi-closed THM reactor. This system might have had some advantages for the closed system developed in Japan or in Switzerland, but unfortunately the dimensions of specimens used for densification are small and it would be difficult to evaluate the interest of this system when employed for large-sized wood elements for building and construction purposes.

At the present time, the technology of TH wood treatments has been industrialized and their products are being commercialized. The research in the field of wood THM molding and wood densification as well as the post-treatment of compressed wood by THM actions aims to widen this field to large-sized wood elements for applications in the building industry. Moreover, many other THM treatments are advancing at the laboratory level. However, the main characteristics of all recent TH/THM treatments are based on scientific knowledge, wood physics, chemistry, mechanics, material and wood sciences. Understanding these treatments clearly requires the appropriate scientific knowledge related to wood. It is essential to know the structure and composition of wood, the elasto-viscoplastic behavior of the wood according to the temperature and the wood moisture content, the effects of TH/THM processing parameters (heat, humidity and processing time) on the mechanical properties, the chemical kinetics of reaction and degradation of wood, heat and mass transfer in wood during TH/THM processing and the mechanisms of eliminating recovery-set in THM woods.

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CHAPTER 2

ANCIENT USES OF THERMO-HYDRO-MECHANICAL PROCESSES

2.1 INTRODUCTION

Our prehistory is usually divided into eras having received their names from the particular material that characterized the period, e.g., stone, bronze and iron. This division is based on archaeological finds, and since wood is rare in such contexts, it is easy to forget that there was also a “wooden age”. This age began when humans came to our country and it continues yet today.

For thousands of years, wood has been used by man for the manufacture of tools, weapons, utility equipment and instruments, in addition to as a building material. With the collected experience of numerous generations, consideration has consciously been given to wood properties in many areas of processing and usage. A very early example of a product made of wood that has survived until today is the Kalvträsk ski which can be seen in Figure 2.1. Such skis were used ca 5200 years ago and have been preserved by lying embedded in a swamp in northern Sweden (Åström, 1993). The wood for the ski was cut with vertical annual rings and the front tip of the ski was probably bent into a curved shape with the help of heat from an open fire in order to improve the performance of the ski. The use of heat and water to give skis the right shape was practised by the Saami (Insulander, 1998) and may be the oldest evidence for the use of THM processes.

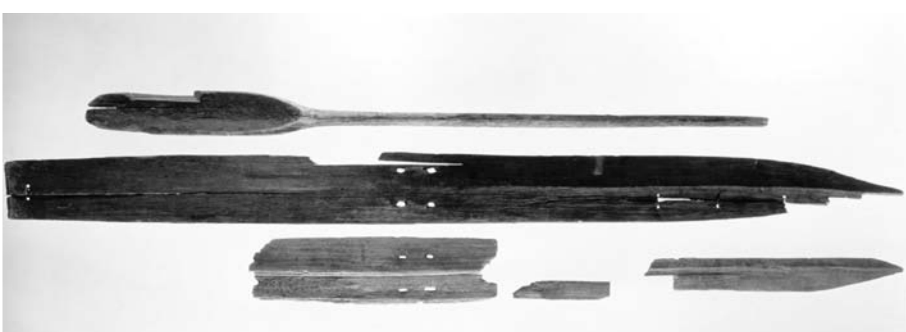

Fig. 2.1 5200 year old ski made of wood with vertical annual rings and formed by a THM process (photo by Sune Jonsson, Västerbotten Museum).

The simplest and in most cases also the strongest woodwork takes advantage of the natural shape of the timber. Bends, forks and holes can all be exploited in many ways. Even on a large scale, such as the building of houses or wooden ships, greater structural integrity can be achieved by using a single piece of timber having grown into the right shape rather than by joining several smaller pieces together. The building of wooden ships and stave churches in old times as well as of utility goods in the old farmer community exemplifies that it has traditionally been common to use naturally shaped timber, see for instance Halldin (1963); Holan, (1990), p.179.

One of the most graceful chair designs is the horseshoe armchair, which originated more than 500 years ago in the time of the Ming Dynasty. The back rail and arms of the chair form a continuous semicircle, gently descending toward the front with the terminals of the arms bent slightly back in a rhythmic yet reserved curve. Often coupled with tapered, S-shaped side posts, the effect is of a spherical void being gently cradled, simultaneously giving a sense of emptiness and wholeness. These inspired forms grew out of the rich tradition of Chinese craftsmanship, and integrating of aesthetic preferences with the science of joinery.

Of the existing horseshoe armchairs, most of the curved armrests are made of three to five segments with joints that fit so snugly that no nails or glue are required. In making the curved arm-rest of the horseshoe chair, craftsman selected wood with a naturally curved grain that would follow the curvature of the rail, ensuring that the grain would be straight and strong at the joint. This way of joining naturally grown curved sections has for example been practised in traditional Japanese wooden buildings. During the fourteenth century, the carpenter's square became popular in Japan. Its skilful use made possible the precise construction of complicated joints used in house building (Bramwell, 1976). In Norwegian stave churches, the longer construction elements, such as the nave's quadrant arches, consisted of curved wood elements made out of several pieces so precisely joined that even today it is difficult to detect the connection points (Bugge, 1953; Holan, 1990).

Egyptian workmen, whether they built vast temples or manufactured furniture, inspire both awe and admiration. But who were these people? How did they practise their different craftsmanships? Did they use techniques based on THM-processes or were such processes unknown? Were they well rewarded for their skilled work, or were they exploited? In order to answer such questions we need contemporary written texts, preferably written by and for the ancient workers themselves. So far, such documents have been found in very few archaeological sites (Lesko, 1994). However, the works settlement of Deir el Medina is among the most thoroughly documented and best-known communities from the ancient world.

The earliest evidence of true wooden furniture is found in the Egyptian society that existed some five thousand years ago. The exceptional conditions for survival in royal tombs have given us famous examples of furniture and other utility equipment. It is apparent that different pieces of furniture had been created by 3000 B.C., and there is no doubt that a skilled work force existed in Egypt. The origins of the technique of wood bending have been the subject of some dispute among experts, but it is probable that wood bending was known in Egypt around 1000 B.C. (Rivers & Umney, 2005). Unsubstantiated evidence suggests that some furnishing may have been fabricated by wood bending as early as 2500 B.C.

Egyptian tomb-drawings of Nebamen at Thebes (ca. 1400 B.C.) provide evidence of manufacturing processes where it is probable that the Egyptian carpenters used heat and moisture to bend wood, as depicted in Figure 2.2. The reliefs in the tomb of the scribe Hesire at Saqqara, dated ca. 2800 B.C., contain representations of furniture, including a chair whose seat has been described by Aldred (1954) in Singer (1954) as "strengthened by bent wood supports, in hard- and softwoods" and a stool "with bent wood reinforcements".

More immediate evidence that the process of bending wood was known to the Egyptians is provided by the paintings in the tomb of the nomarch Amenemhat at Beni Hasan, ca. 1971-1928 B.C. It contains an illustration, cf. Figure 2.3, of a bowmaker who holds a rod over a receptacle that possibly contains hot water, while straight rods

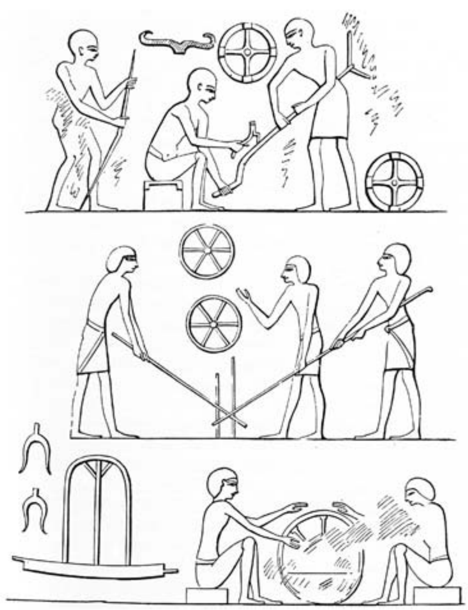

Fig. 2.2 Section of tomb-drawing of Nebamen at Thebes showing various operations on different parts of a chariot. In the upper picture, the carpenters are bending poles, and the drawing at the bottom to the left shows a wooden chariot-yoke that may have been THM-processed (from Latham, 1957).

Fig. 2.3 Bending of bows from a facsimile of a wall painting in the tomb of Amenemhat at Beni Hasan, ca. 1971-1928 B.C. (from Newberry, 1893).

and completed bows are displayed nearby (Ostergard, 1987). Only green and unseasoned wood could be bent by this method; seasoned wood of large cross-sectional dimension can only be bent by softening with the use of a steam chest and there is no evidence that this apparatus was used in ancient Egypt (Killen, 2000). Montet (1946) construed Egyptian paintings showing bowmakers as meaning that the heating and bending of the wood was carried out before debarking and that it may thus be understood that the wood was green.

The technique of laminating thin sheets of wood, with the grain of one sheet perpendicular to that of the next, i.e., plywood, was known to Egyptian carpenters at least from the period of the Third Dynasty, 2686-2613 B.C. (Killen, 1994).

Nearly two thousand years after some furnishing may have been fabricated by wood bending in Egypt, the classic Greek Klismos chair was introduced as a form of furniture. Some scholars believe that the graceful shape of the chair's sabre legs was achieved through a bending process (Ostergard, 1987). The Klismos chair is a light and elegant chair developed by the ancient Greeks, and presented in Figure 2.4. Perfected by the 5th century B.C. and popular throughout the 4th century B.C., the chair had four curving, splayed "saber" legs and curved back rails with a narrow concave backrest between them. In spite of the fact that the chair is familiar in different variants from frequent representations in vase paintings and reliefs, no original specimens have come down to us. In the pictures, the Klismos chair always has the same primary shape, but there is no unequivocal design of the construction of the chair and how it has been manufactured. The dramatic, concave sweep of its distinctive legs has led to the conclusion that the form was probably achieved by steam bending (Richter, 1966).

The outward legs of the chair, which at the back are transformed into a comfortable inclined back-support, make very high demands on both material and design. That fact that the shape must bear the extremely large loads to which the legs are

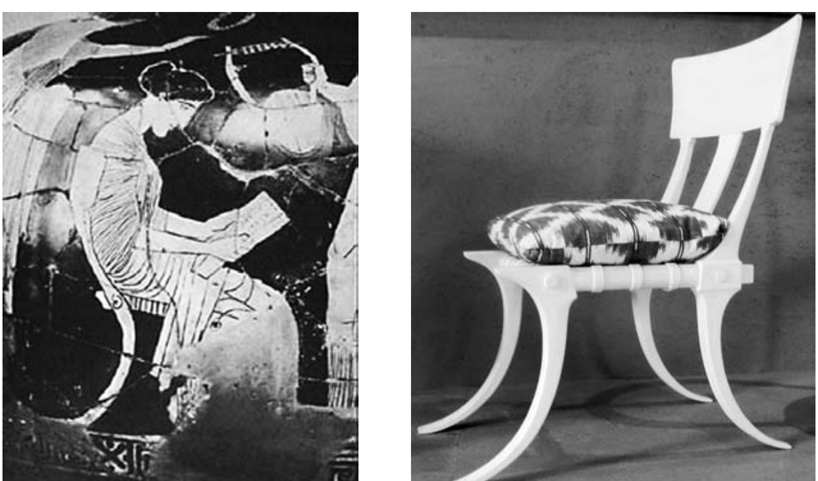

Fig. 2.4 Detail from a hydria found at Vári, Greece, showing the poet Sappho seated on a Klismos chair, ca. 420-440 B.C., in the National Archaeological Museum, Athens (left). A contemporary interpretation of the Klismos chair made by architect Åke Axelsson (right).

subjected supports the theory that the Greeks, already in the 5th century B.C., must have understood the technology of bending solid wood through heating and steaming. This hypothesis is corroborated by the Greek philosopher and scientist Theophrastus (372-287 B.C.). In his book, *Enquiry into Plants*, he states "In general those woods which are tough are easy to bend. The mulberry and the wild fig seem to be specially so; wherefore they make of these theatre-seats, the hoops of garlands, and, in general, things for ornament" and later "The work of bentwood for vessels is made of mulberry manna-ash elm or plane; for it must be tough and strong (Hort, 1916).

Another characteristic part of the chair is the broad upper rail at the back. In the 5th century B.C., it had a fairly weakly rounded flat shape, which can have been sawn and processed out of a single piece of solid wood. Later, in the 4th-3rd centuries B.C., the shape becomes strongly rounded and this development was probably achieved either by using a steamed and bent piece of solid wood or alternatively by the lamination of thin glued veneers.

2.2 WOODLAND CRAFTS

In older times, craftsmen in general had a profound, empirical insight into the subtle and diversified qualities of their materials. Knowledge handed down from generation to generation meant that they had a detailed understanding of how the properties of different kinds of wood could be used in an optimal way in various articles, whether for everyday use, for transport by means of carriages and boats, or for building purposes. An illustrative example within the furniture sphere is the so-called Windsor chair, depicted in Figure 2.5. The seat was traditionally made of durable hard-to-split elm (*Ulmus glabra*), the rear pins of tough and elastic yew (*Taxus baccata*) and the round-shaped back-piece of flexible ash (*Fraxinus excelsior*). The types of wood used in such old, solid wood furniture have in many cases probably been chosen on the basis of the physical properties of the particular wood species. In simple utility goods,

Fig. 2.5 A classic Windsor chair.

provincial furniture and interior decorations, the carpenter's choice has been limited to the species of wood growing locally. The species have been consciously used for various purposes depending on properties such as hardness, toughness and rot-resistance. An illustrative example of the provincial choice of different wood species is again the Windsor chair. When the tradition of manufacturing this type of chair spread to the USA, it was often made from other species of wood than those mentioned above (see for instance Dunbar, 1984; Abbott, 1989).

2.2.1 Bending of solid wood in woodland craft

Techniques for bending wood have, as already indicated, existed since prehistoric times, although early man used heat to help straighten rather than bend his arrows (Sentance, 2003).

Rigid pieces of wood may be rendered pliant by heating, steaming, or boiling, and these methods are used in such varied crafts as basketry, chair-making, and the shaping of tool handles and wooden hoops (Edlin, 1949). Thin rods will often bend satisfactorily without treatment, if the wood is handled whilst it is still green and unseasoned, and in other instances water alone may suffice to restore its pliancy. For walking sticks, craftsmen have often bent and bound wood while it is still alive and green, so that it will grow into the desired shape without being weakened by the stress of stretching and compression (Edlin, 1949).

Sometimes the material is warmed over a naked fire or in damp sand. The softening treatment may be used for straightening curved rods as well as for bending straight ones. In either case, the wood retains the shape in which it is dried and "set", as shown in Figure 2.6.

Ash wood is a strong, tough and pliant material that is also light in weight, readily cloven and easily bent either in the green state or after steaming. Consequently, ash is a common material in woodland crafts in regions where this species is commonly grown. Edlin (1949) describes in detail how split ash and beech can be bent into

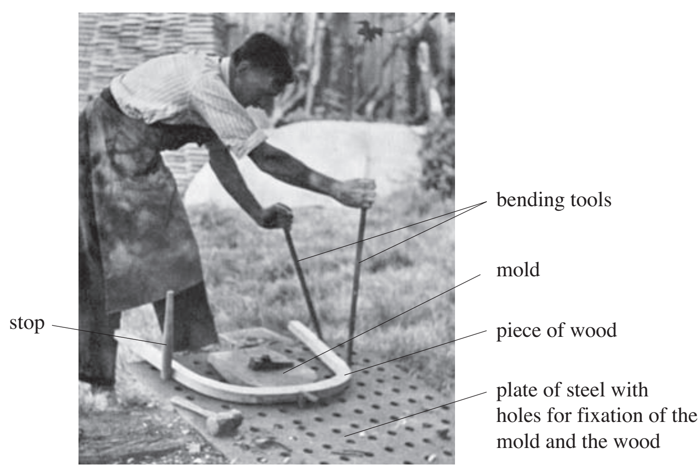

Fig. 2.6 Bending a length of steamed ash to form the back frame of a Windsor chair (from Edlin, 1949).

circular shapes to form hoops and rims. This craft was widespread in the countryside of Great Britain until about the 1950’s, and it has also been practised in many other parts of the world.

When making a hoop, a straight ash pole is first split into three or four segments with a froe (sort of knife), while being held in the angle of a stout three-legged break. The hoop-shaver then trims each piece to shape with his draw-knife, sitting astride his wooden shaving horse, which holds the wood in its vice-like grip. Each thin band is then warmed over a fire to render it pliable and then bent between two rollers or over a wooden frame. A more “modern”, and simpler method is to steam the band in a steam chest over a water boiler. This renders the band so pliant that it can be coiled without further treatment. The final coiling is done on a rigid wooden frame with four, six, or eight spokes. The hoop is formed and held in its circular shape by being forced against adjustable pegs set on the spokes, until its two ends can be nailed together. Hoops are made in sets of six, known as coils, and each is coiled in turn within the pegs or within the stronger shive or “master hoop” that forms the pattern. The strongest and largest ash hoops are those used by coopers to set up their barrels, but ash hoops have been used in a wide range of applications, such as runners holding the sails to the mast, sieve rims, rims of military drums, bushel measures for grain, seed-lips for sowing grain in open fields, and old-fashioned spinning-wheels. Bent ash wood has also traditionally been used for the handles of various tools employed by farmers, foresters, craftsman, carpenters etc.

Before the modern composite materials were developed, ash was the sportsman’s wood. Ash was found in the ordinary tennis racket, the frame of which may consist of a single piece of wood bent, after steaming, into a circular form with it ends extending down into the handle. Cleft ash is used, because its grain is unbroken throughout, which is not always the case with sawn material. Later, tennis rackets were made of laminated frames.

2.3 THM-PROCESSING IN THE CONSTRUCTION OF WOODEN VESSELS

Vessels of wood have been in use on water for thousands of years. Before ships or even boats, there must have been a long succession of floats and rafts used as aids to swimming. However, details of drawings, carvings, and models of Egyptian, Greek, Assyrian, and Minoan times, and even the work of Scandinavian Neolithic artists, representing early vessels do not suffice to show how they were constructed (Digby, 1954). It is even less possible to determine whether any part of the vessel construction was the result of a thermo-hydro-mechanical (THM) process.

In the introduction, the fabrication of a canoe from a log is presented. A logboat is carved out of a single log and then expanded over an open fire. Such a boat is light and has much more room than a regular logboat. Extra boards can be added to increase its size. This type of vessel belongs to the group of boats that are called primitive boat-types, i.e., boats built of skin, bark, reeds or hollowed-out tree trunks, that have been used by man for thousands of years. Dug-out canoes have been found wherever there are suitable forests. They vary in shape depending on local requirements and on the available material. The limiting factor is the tree diameter. The size of the hull was often increased during manufacture by filling the hull with wet and perhaps even heated sand, the weight of which forced the sides apart (Digby, 1954). Today such boats are used by different aboriginal groups, e.g., Greenlanders, Indians in Canada and the Punan Bah people in Borneo. The Punan Bah people use dugouts or longboats for transport on the many rivers that flow through the landscape of their great island. A special feature of these longboats is that the tree-trunk, after being hollowed out with an axe, is widened over a fire. This technique is also known from prehistoric times with regard to longboats in northern Europe. After widening, a plank is sewn to each side of the boat and we thus have the first step towards the development of the clinker-built ships with which we are familiar from the Viking period (Crumlin-Pedersen, 1970; Nicolaisen & Damgård-Sørensen, 1991).

Nicolaisen & Damgård-Sørensen (1991) have studied the technique for fabricating longboats in Borneo and they summarize the main steps of the boat-building process as

- selection and felling of the tree;
- preparation and cleaving of the trunk;
- preliminary shaping of the base;
- trimming of the base;
- expanding the hull by heat; and
- sewing.

The Punan Bah build their longboats of the same kind of species. Ideally they use meranti (Shorea gen.), but to save time during building softer species can also be employed. The Punan Bah select their wood on the basis of a variety of criteria, all associated with their beliefs in a shared destiny for the boat-builder and his boat, as well as taking into account the quality of the wood, its hardness, accessibility and size.

The boat-building process begins in the rain forest, where the tree has been felled. Here, the branches are cut off, and the bark removed. The length of the boat is then measured out on the bare trunk and the selected piece of the trunk is cut. Thereafter, a cleavage-line is drawn lengthwise, exactly following the fiber direction of the trunk. The trunk is cleaved into two halves with the help of wooden wedges. Both halves of the trunk can be used for longboats if small boats are to be built, whereas for large boats, only one part of the trunk is utilized.

The preliminary shaping of the base naturally involves following sub-phases: removing the sapwood, hollowing out the trunk, and shaping the base. The preliminary boat is then transported to the place were it will be finished.

After the preliminary shaping, the base has to be trimmed and smoothened, both externally and internally, to give the final shape and thickness. This is a time-consuming precision work done by hand with the help of adzes and axes.

The widening of the base takes place over a fire: the entire hull is placed over a large bonfire until the wood reaches a temperature at which it becomes flexible. The sides are then twisted outwards and downwards with the help of large forked branches so that the base is flattened and widened, while the ends lift themselves, and the sheer in the base increases. The widening is first and foremost designed to improve the