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REVIEW ARTICLE

Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products

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Abstract
This state-of-the-art report presents the basic concepts of some of the thermo-hydro (TH) and thermo-hydro-mechanical (THM) wood processes that are in use today, i.e. heat treatment, compression of wood in the longitudinal or transverse direction and wood welding. The reasons for the growing interest in TH and THM techniques are discussed, and the development of the different concepts, from first ideas to current status, is briefly presented. The physical and chemical changes that occur in wood during TH and THM processing according to the latest research are also presented. Finally, developments that are close to or already have an industrial application are presented, and the challenges for further development of the heat treatment, compression and wood welding processes are discussed. The TH processing of wood is based entirely on water and heat, and a THM process incorporates an additional mechanical force. The purpose of wood transformation by a TH or a THM process is to improve the intrinsic wood properties, to acquire a form and functionality desired by engineers without changing its eco-friendly characteristics or hindering its further use in the total material life cycle. Only a few of the recently developed techniques, e.g. heat treatment, wood welding and various densification applications, have been industrialized to some extent. There are many reasons for this relatively low transfer of the research results to a full up-scaled industrial production. Some of them are related to unsolved problems at the laboratory level on small-sized samples and others are related to the scaling-up processes in industry. Furthermore, the ageing of heated wood leads to deterioration with time, in some cases there is an unpleasant odour, the strength of the wood decreases substantially and the wood becomes more brittle. These are new challenges which need to be resolved by the collaboration of researchers from the different scientific domains of academia, research institutes and industry.

Keywords: *Ageing, bending, densification, heat treatment, value added, welding, modification.*

Reasons for thermo-hydro-mechanical (THM) processing

Today, forestry and forestry-related industries are sharply in the focus of discussions concerning the major challenges for the future. A great challenge for humankind is to develop a sustainable society. Such a society requires the use of renewable materials, a large reduction in the use of non-renewable natural resources and a large reduction in environmental impacts, including a drastic reduction of greenhouse gas emissions. One way of reducing the emission of carbon dioxide is to use a larger portion of wood products and to increase the life time of these products so that the carbon is stored over a longer period of time. Another possibility is to replace energy-intensive materials with wood and wood-based products (Mahapatra and Gustavsson 2008). Forest resources and wood products can, therefore, play an important role in a long-term strategy for sustainable development and lessen man's impact on environment. Replacing non-renewable materials with wood-based ones is hence crucial for the development of a sustainable society, and new knowledge is required to show how resource-efficient processes for wood products with a low environmental impact can be designed and implemented. In the future, wood products also have to be refined so that all the life cycle phases – production, operation, retrofitting and end-of-life – are considered and optimized as a whole, including the energy and material chains from forest to final services. The development of thermo-hydro (TH) and THM

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techniques and processes for wood can be a key factor in this context.

For the recycling of wood and wood fibres it is important that the components, i.e. chemicals or other materials, added to wood in the different process stages do not prevent the use of the wood in the next cycle or prevent the return of the ash to the natural life cycle. In this respect, the TH and THM processes have great advantages in adding only energy and water to the process.

For wood to be competitive against other materials in a broad sense, the environmental advantages of wood alone are not enough, i.e. that wood shows low emissions of carbon dioxide according to calculations based on life-cycle assessment (LCA) criteria (see Ekvall 2006, Gustavsson and Sathre 2011). Wood must also be competitive for its technical properties and show not only a high material utilisation while providing a competitive economic yield during usage. Some TH or THM processes (e.g. wood bending) have a high material yield and consume little energy, and thus are economically advantageous compared to the processing of other materials (Navi and Sandberg 2012). However, the technical and environmental performance of TH or THM processed wood products is not always competitive with products for other materials and it must therefore be improved.

The results of studies in different fields of TH or THM processing indicate that the properties of wood such as its shape stability, strength, surface hardness (in THM process only) and durability can be improved (Navi and Sandberg 2012). Potential areas of application for TH or THM products are now being identified in the building industry, furniture manufacture, with longer service lives of wood products through increased durability and stability. TH and THM processing as a base for improving intrinsic wood properties and developing new product-market combinations are now of great interest in the industry.

The concepts of TH and THM processing

TH is used on wood to enhance wood properties, to dissipate internal stresses, to dry and to soften (plasticize) the wood. Common TH processes are for example heat treatment, the drying of wood under high temperature and of wood-based composites or veneer products. THM processes, on the other hand, are employed in wood shaping and moulding, welding of wood by friction, improving wood quality through densification, embossing and wood bending. A number of these techniques have been known for a long time. The result of the TH or THM processing depends on whether the process is open or closed. It is not possible to adequately control the process parameters, e.g. the moisture content of the elements, during processing in an open system. In a closed system, all the process parameters involved, such as type of medium, time, temperature and humidity can be controlled accurately throughout the treatment. A traditional example is the *thermal degradation of wood* which leads to totally different results depending on whether air is present or not. Generally, heating without air is called pyrolysis, e.g. producing charcoal in a closed system. Heating with access to air is called combustion where the combustion may be complete (e.g. burning in a fireplace, i.e. an open system) or incomplete (e.g. the production of producer gas or charring in a charcoal stack). The different TH and THM processes can be performed in either an open or a closed process and generally with totally different results.

Heat treatment and the accelerated ageing of wood

Heat-treatment processes have been known for a very long time and they include several different methods. In ancient Africa, natives hardened wooden spears by placing a sharpened straight wooden stick into glowing coals and then pounding the burned end with a rock, repeating this process many times until the end was sharp and hard (Rowell 2009). The heat-treatment process can also give changes in acoustic properties of wood and that may be particularly of interest in musical instruments (CEN 2008). In most industrialized processes today, heat treatment involves temperatures between 150 and 260°C for times ranging from a few minutes to several hours. The goal when treating wood is to achieve increased dimensional stability and resistance to biological degradation. The heat-treatment process can also be followed by compression in the axial or transverse direction of the wood, and this is discussed in the next two sections. The heat-treatment process is in most cases performed in a vacuum, in air or with an inert gas such as nitrogen. Pre-heated oil can also be used, in which case the oil acts as a heat-transfer medium and also excludes oxygen from the wood. The heat treatment of wood above 300°C is of limited practical value due to the severe degradation of the wood material (Hill 2006). Accelerated ageing of wood is a heat-treatment process using a mild temperature, i.e. a treatment temperature in the range of 100–150°C, in most cases under controlled relative humidity and pressure.

During the twentieth century, there have been several reports of wood heat treatment (see Stingl *et al.* 2002, Navi and Sandberg 2012). These studies began particularly after it had been observed that wood dried at a high temperature changes colour, has a greater dimensional stability and less hygroscopicity (Tiemann 1915, Koehler and Pillow 1925,

Pillow 1929, Stamm and Hansen 1937). After the First World War, comprehensive studies were made on the effect of the kiln drying temperatures on the strength of wood for the aviation industry in the USA (Tiemann 1920, Wilson 1920). Stamm *et al.* (1946) reported the first systematic experiments on wood heat treatment illustrating an increase in dimensional stability and in the decay resistance of wood treated at temperature between 120 and 320°C. To minimize the oxidation and its effect on strength and to make possible rapid heat transfer, a method of heating wood beneath the surface of molten metal was adopted (Stamm 1942). It was also found that the loss in strength per unit anti-shrink efficiency (for definition see Ibach 2010) obtained was greater when the wood was heated in the presence of air than when air was excluded (Stamm 1956). From this, they developed a product called *Staybwood*. However, Stamm (1964) later reported that although the dimensional stability as well as the elimination of shape memory of com-pressed wood was improved by heating, other important properties such as wood strength were reduced to an unacceptable level and the product was never commercialized. Maclean (1951, 1953) studied the influence of the heat-treatment condi-tions on wood properties and found that wood degrades faster when heated in either steam or water than when heated under dry conditions.

In the 1970s, Burmester studied the effects of temperature, pressure, moisture content and time in order to empirically optimize conditions for the heat stabilization of oak, beech, spruce and pine wood, and a heat-treatment method called Feuchte–Wärme–Druck was developed. Within this frame-work, the optimum conditions for pine wood were found to be a moisture content of 20–30% and a temperature of 160°C for 15 hours in a closed vessel (Burmester 1973, 1974a,b). Under such conditions, the development of considerable resistance to brown-rot fungus was reported, and the strength reduction was stated to be insignificant.

Heat treatment significantly influences the proper-ties of the wood, e.g. its hygroscopicity, decay resistance, durability, strength and dimensional sta-bility. To increase the knowledge of the chemical changes occurring in heat-treated wood, numerous investigations were started to clarify the chemical degradation of wood constituents during heat treat-ment. There are a number of difficulties in des-cribing the changes that take place when wood is heated. A range of chemical reactions take place simultaneously, and these are both endothermic and exothermic reactions, making the determination of the onset temperatures for the different reactions nearly impossible. The analysis is complicated further by interactions between reactions involving

different constituents. This means that an analysis of the reactions involving an isolated derivative of one of the components can be very different from what actually takes place inside the wood. There are not only interactions between the components inside the wood but also interactions between the wood and the treatment atmosphere. The rate of thermal degrada-tion is different for the different constituents of wood: it is highest for hemicelluloses, much lower for cellulose and lowest for lignin (Stamm 1956, Bourgois and Guyonnet 1988, Yildiz *et al.* 2006, Esteves *et al.* 2008b). In general, hardwoods are less thermally stable than softwoods, and this is attribu-table to differences in the hemicellulose content and composition (Hill 2006).

Because of the loss of hygroscopic hemicellulose sugars and their conversion to less hygroscopic furan-based polymers (predominantly furfural and hydroxymethylfurfural) during heat treatment, the equilibrium moisture content is reduced to about half the value of the untreated wood (see Teichgräber 1966, Giebeler 1983, Esteves *et al.* 2006, Tjeerdsma 2006). Table I shows the results of a sugar analysis before and after treating aspen with high-pressure steam at 220°C for 8 minutes, presented by Rowell *et al.* (2009). The data show that at a very early stage of weight loss, the hemicellulose polymers (rhamnan, arabinan) are breaking down while the cellulose remains unchanged.

In the heat treatment of wood, the chemical structure is transformed by autocatalytic reactions of the cell-wall constituents. It is known that during the heat treatment of wood under moist conditions, carbonic acids, mainly acetic acid, are initially formed as a result of cleavage of the acetyl groups particularly of hemicelluloses (Kollmann and Fengel 1965, Dietrichs *et al.* 1978, Bourgois and Guyonnet 1988). Depending on the acid concentration and on the temperature, hemicelluloses are hydrolysed into oligomeric and monomeric structures (Klauditz and Stegmann 1955, Bobleter and Binder 1980, Carras-co and Roy 1992). The weight loss from hardwoods

Table I. Sugar analysis of aspen before and after heat treatment with saturated steam at 220°C in a closed system for 8 minutes (Rowell *et al.* 2009).

	Before heat treatment	After heat treatment
Weight loss (%)	0	2.2
Arabinan (%)	0.56	0.20
Galactan (%)	0.68	0.58
Rhamnan (%)	0.30	0.14
Glucan (%)	42.4	42.2
Xylan (%)	16.3	14.6
Mannan (%)	1.6	1.5
Total carbohydrate (%)	61.8	59.2

is greater than that from softwoods, probably due to the greater content of acetyl groups in hardwoods which release acetic acid during heat treatment which contributes to the acid hydrolysis (MacLean 1951, 1953, Millett and Gerhards 1972, Hillis 1975). Subsequently, the monomeric sugar units are dehydrated to aldehydes, furfural being formed from pentoses and hydroxymethylfurfural from the dehydration of hexose sugar units (Burtscher *et al.* 1987, Kaar *et al.* 1991, Ellis and Paszner 1994).

Several other investigators like Burmester (1973, 1975), Popper *et al.* (2005), Boonstra *et al.* (2007), Welzbacher *et al.* (2007) and Pfriem *et al.* (2010) have shown that the reduced hygroscopicity accompanies increased dimensional stability and increased durability. The modification also leads to colour changes (Bekhta and Niemz 2003) and the development of an intense odour (Peters *et al.* 2008).

In the heat treatment of wood above 150°C, the strength is reduced and the mode of failure of heat-treated wood in mechanical tests is in most cases brittle. The density of wood is decreased by 5–15% during heat treatment, and this of course affects the strength, but it does not explain the entire reduction in strength (see Welzbacher *et al.* 2007, Esteves *et al.* 2008a). The loss in strength is due to a degradation of the cell-wall matrix due to a degradation of the hemicellulose polymer. General guidelines for the reduction in strength are: hardness 5–10%, bending strength 10–20%, modulus of elasticity 5–20% and impact bending 30–80%. This means that heat-treated wood in its current form is not suitable for load-bearing uses (Jämsä and Viitaniemi 2001, Militz and Tjeerdsma 2001, Rapp and Sailer 2001, Vernois 2001).

Heat-treated wood may be suitable for outdoor applications above ground due to its greater durability and dimensional stability. Nevertheless, the brown colour of heat-treated wood fades quite quickly when the wood is outdoors and it eventually becomes grey (Jämsä *et al.* 2000), indicating photodegradation and a loss of lignin at the exposed wood surfaces. Heat treatment gives no or a very poor protection against blue stain. There are discrepancies in the literature as to whether or not heat treatment reduces the susceptibility of wood to surface cracking when it is exposed outdoors. Vernois (2001) stated that 'cracking due to dimensional movement is reduced in comparison with natural wood'. In contrast, Jämsä *et al.* (2000) found that heat-treated pine and spruce surfaces cracked to the same extent as unmodified wood when exposed outdoors. However, Sandberg (1999) and Sandberg and Söderström (2006) have shown that the tendency of wood to crack during weathering is strongly related to the annual ring orientation in the cross section of the wood. To avoid cracks occurring on wood used outdoors, wood should be selected with the annual ring orientation perpendicular to the exposed wood surface. Differences in the annual ring orientation in the wood used for different studies of heat-treated wood are probably the main reason for the disagreement in the literature as to whether or not heat treatment reduces the tendency of wood to crack when exposed outdoors.

It is not recommended to use heat-treated wood in ground contact (Jämsä and Viitaniemi 1998, Kamdem *et al.* 1999, Wienhaus 1999, Rapp *et al.* 2000, Westin *et al.* 2004). Due to the low-equilibrium moisture content and partial degradation of the wood components, i.e. a large portion of the hemicelluloses are depolymerized, the susceptibility to biological degradation by brown-rot is reduced. Because of low-lignin degradation during heat treatment, there is a poor protection against white-rot that mainly attacks the lignin in wood.

Many artisans suggest that ageing improves the stability of wood and that aged wood has better acoustic properties than fresh wood. Many attempts have been made to clarify the effects of ageing on the wood properties. *Natural aging of wood* refers to the structural and chemical changes occurring in the wood over time when wood is subjected to unexceptional changes in the climate, UV irradiation, etc., and is not subjected to biodegradation. In general, the stiffness and strength of wood are enhanced by ageing for several hundreds of years, but the wood becomes more fragile and less ductile (Obataya 2007). On the other hand, little information is available regarding the acoustic properties of aged wood. All the results available indicate that the acoustic quality of wood is enhanced by ageing, and that such changes are qualitatively different from those due to chemical and thermal treatments.

The effect of natural ageing of wood at low temperatures, i.e. less than 50°, on the physical, mechanical and chemical degradation has been studied by Kohara (1952, 1953), and more recently by Erhardt and Mecklenburg (1995), Erhardt *et al.* (1996), Obataya (2007, 2009) and Froidevaux *et al.* (2012). The results show no or small changes in the mechanical properties during ageing. However, Erhardt *et al.* (1996) found some chemical changes during ageing. Ganne-Chédeville *et al.* (2012a,b) have used FTIR-ATR and UV resonance Raman (UVRR) spectroscopy to study chemical changes in naturally aged wood (200–500 years) and accelerated aged wood. They concluded that time alone does not affect the chemistry of wood during ageing. Additional factors such as UV-light, humidity, insects or fungal attack and the origin of the wood influence the changes.

Attempts have been made to reduce the negative effects of heat treatment at high temperatures, such reduced strength and odour, by treating wood at moderate temperatures, i.e. 100–150°C. The main task is to reach the required properties without too long a processing time. In general, most drying treatments, even at mild temperatures, decrease the hygroscopicity of wood, although this effect may be eliminated by saturation with water (Tiemann 1941a,b,c). Millett and Gerhards (1972) tested six different species in air at temperatures of 115, 235, 155 and 175°C for periods from 1 to 255 days. They found decreases in weight, in moduli of rupture and in elasticity in bending with continuing exposure at each of the four temperature levels. As expected, the rate of loss of these properties was very sensitive to temperature. The experimental data were summarized in Arrhenius-type graphs to enable properties values to be estimated under other exposure conditions. Ganne-Chédeville *et al.* (2012b) also found that artificial ageing at 160°C led to a significant change in the lignin structure, a well-known effect in the thermal treatment of wood, whereas treatment at 130°C did not alter the wood structure to any significant extent. Principal component analysis of the UVRR spectra confirmed that the spectrum of wood artificially aged up to 160°C is dissimilar to that of naturally aged wood and also dissimilar to that of unaged wood. Heat-treated wood is very similar to aged wood with respect to its fragile nature and improved stability. However, different effects of dry heating (oven heating) and steaming suggest that careful moisture conditioning is required for 'true' accelerated ageing (Obataya 2009). To clarify the differences between heat treatment and accelerated ageing it is important to show the effects of humidity on the viscoelastic properties of heat-treated and aged wood.

A pre-study at Linnaeus University in Sweden during 2010 showed that pine heat-treated at 105°C exhibited colour changes to the same degree as that processed at higher temperatures but no appreciable odour and strength reduction. The process time was very long (one year), and this probably affects the economic value of such a process. The result, however, indicates that it is possible to reduce the unwanted odour from heat-treated wood and thus to increase the potential for indoor use. Recently, a international company for interior design stopped the sale of traditional heat-treated wood for indoor use as a result of its odour.

Compression in the fibre direction of wood–wood bending

The concept of changing the shape of wet wood by heating and applying an axial compression force is old. The origins of the technique of wood bending have been the subject of some dispute among experts, but it is clear that wood bending was known in Egypt around 1000 B.C. (Rivers and Umney 2005) and probable already as early as 2800 B.C. (Aldred 1954). More immediate evidence that the process of bending wood was known to the Egyptians is provided by the paintings in the tomb of the Amenemhat at Beni Hasan, 1971–1928 B.C. It contains an illustration, Figure 1, of a bowmaker who holds a rod over a receptacle that possibly contains hot water, while straight rods and completed bows are displayed nearby (Ostergard 1987).

In about 1850, Michael Thonet (1796–1871) developed and applied techniques of bending beech wood treated by steam for furniture manufacture. His invention of the bentwood process and his design of the famous 'Vienna No. 14 chair' led his company to become the largest furniture manufacturer in the world. The technique was industrialized quickly in many countries and is still in general use.

The main reason for the difficulty in bending solid wood is the low strain to failure (about 1–2%) in tension. However, when wood is plasticized it becomes more plastic or semi-plastic, and this means that it can be softened and formed so that it keeps its shape after it cools. Wood contains areas of crystalline molecular structure that are difficult to plasticize and it is therefore also called semi-plastic. Its compressibility in the longitudinal direction is then greatly increased, as much as 30–40%, although its ability to elongate under tension is not appreciably affected, Figure 2. After plasticization, compression parallel to the fibres and bending causes a combination of tensile and compression stresses in the bentwood. Because the compression strain to failure is many times larger than that in tension a curvature, even sharp, can be obtained. The ability of the plasticized wood to be compressed without damage is then being fully utilized. In practice, this means that one has to control the length of the pieces during bending with the help of some type of end

Figure 1. Bending of bows from a facsimile of a *wall painting* in the tomb of the nomarch Amenemhat at Beni Hasan, ca. 1971–1928 B.C. A nomarch was the semi-feudal ruler of an Ancient Egyptian province (Newberry 1893)
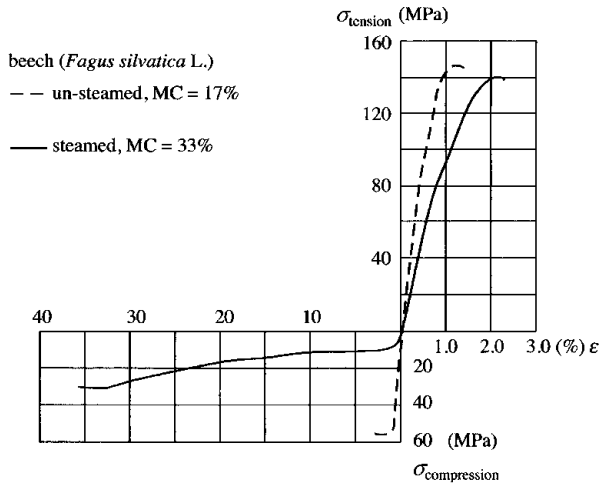
Figure 2. Stress-strain (σ–ε) diagrams for air-dried non-plasticized beech and plasticized beech. Note that the strain axis has different scales to the right and to the left of the origin (after Prodehl 1931a,b). MC, moisture content

stop (strap-and-stop) on the tensile side of the pieces being bent to prevent them from being elongated by more than 1–2%.

Hanemann (1917, 1928) plasticized wood by heating it in low-pressure steam or in hot water, after which the wood was compressed along the fibre direction. In order to avoid bending during compression, the wood was set up in a fixture. The compressed wood was then bent in a cold state and set in the desired curved shape by heating to 80°C. The idea of compressing the wood in the longitudinal direction to improve the bending properties

was further developed in the 1930s under the name Patentbiegholz (Kollmann 1936). No industrial application came until the 1990s (Morsing 2000).

In general, the application of a compressive load in the longitudinal direction of softened wood may lead to the following:

(a) plastic deformation of the cell wall with the formation of slip planes;
(b) cell wall buckling;
(c) localised shear-band deformation (at the macro-level); and
(d) diffuse shear-band deformation (homogeneous).

These deformations are shown diagrammatically in Figure 3.

Each type of deformation that is developed is also dependent on the density of the wood. The deformation at the macro level may be explained by various physical mechanisms taking part at the cellular level. Many researchers have observed this behaviour in different kinds of wood. In wood of low density (<300 kg/m^3), Easterling *et al.* (1982) showed that the cause of the local large deformation is the collapse of fibres by rupture at the ends of the cells. This mechanism is shown schematically in Figure 4b. Kučera and Bariska (1982) have shown that in wood of higher density the local large deformation of wood can be due to a local Euler type buckling in the walls of the cells, illustrated in Figure 4c, which generally leads to the formation of a shear band as shown in Figure 3c on the wood macro-level.
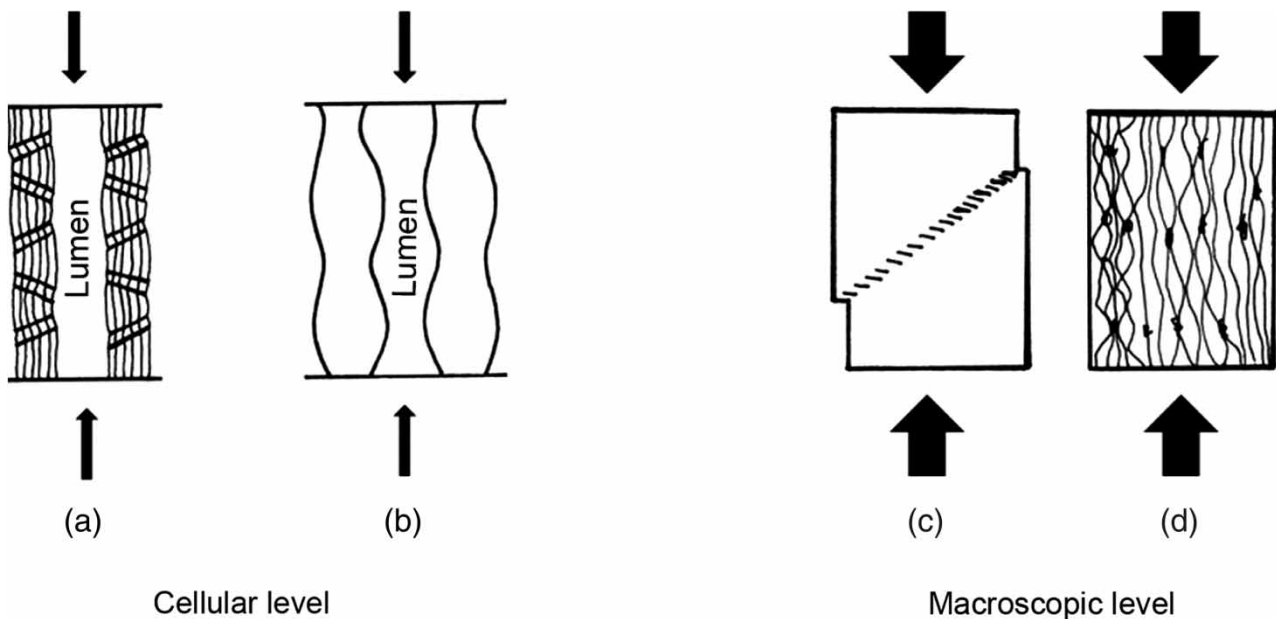

Figure 3. Various modes of deformation of the cell walls of wood under compression in the longitudinal direction; (a) plastic deformation of the cell wall (formation of slip planes), (b) lateral buckling of the cell walls, (c) localised shearing band, (d) diffuse buckling of the cell walls
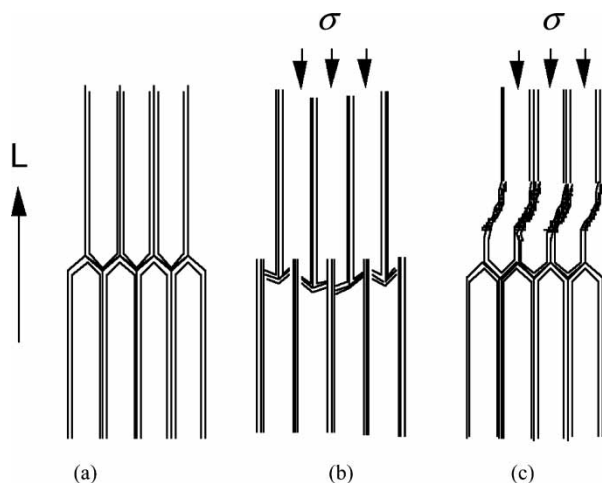
Figure 4. Diagrammatic representation of the mechanisms of local deformation of wood cells under a longitudinal compression force; (a) wood before the application of the force, (b) collapse of fibre by rupture, (c) collapse by the buckling of cell walls

Compression in the transverse direction of wood–wood densification

Compressing wood in the transverse direction reduces the void volume of the lumens in the wood material and increases the wood density. This process is commonly called densification, i.e. the untreated wood has been compressed under conditions that do not cause flow of the lignin. Initially, the main aim of wood densification was to improve the mechanical behaviour of wood by eliminating its porosity (Kollmann 1955). It is well known that many of the properties of solid wood correlate with its density and can thus be enhanced by increasing the density. Vorreiter (1942) reported that in 1886 the idea of densification of massive wood by applying a compression force was patented by Robert Stöckhart. In the USA, Sears (1900) patented a method for densifying wood for use as matrix-block for character-impressions. Around 1915, the Pfleumer brothers in Austria incidentally found a method for the densification of wood through impregnation with rubber. They developed the idea to an industrialized process for wood densification (Pfleumer and Pfleumer 1915, Pfleumer 1922). This type of densified wood was used in the aviation industry until 1945, after which it was replaced by aluminium. During the 1920s and 1930s several patents were issued for compressed wood products, e.g. Walsh and Watts (1923), Ollesheimer (1929, 1930), Brossman (1931), Olsen (1934) and Esselen (1934).

There are two principal ways of achieving densification in the transverse direction; densification of the whole volume of wood (uniform densification or bulk compression) or densification of a surface layer of the wood (surface densification). The uniform densification process is used during the shaping of wood. One negative effect of compressing the whole wood is, however, the loss in volume. To circumvent this problem, an alternative approach is to laminate bulk compressed wood onto uncompressed wood or other material using an adhesive (Kifetew and Wiklund 1999, Kutnar *et al.* 2008, Nilsson *et al.* 2011). The purpose of surface densification is to increase the abrasion resistance and hardness of a wood surface, by compressing only the surfaces of solid wood to a depth of 1–5 mm or only a few cell layers. For decades, many attempts have been made to invent new techniques for producing a form-stable densified wood surface. The main motivation of this work is to utilize low-density woods for flooring where the wood surfaces are exposed to excessive wear. Figure 5 shows micrographs of uniform densification and of a densified surface. Rautkari (2012) has investigated three different methods of surface densification; a lamination technique, where low-density wood was laminated to a high-density compressed wood surface, surface modification where densification was accomplished using a single-sided heated press and with a single-sided heated press assisted by frictional heating. With the lamination technique, it proved easy to generate the desired hard surface, but an adhesive is needed. The difference between compression with and without friction is that when friction is used the process temperature is rather difficult to control, but an even layer of extractives is formed on the surface. Without friction, however, extractive spots are seen on the surface.

Wood can be densified without a pre-treatment or softening. However, to avoid damage to the wood (buckling of latewood annual rings) it is then very important that the compression is in the radial direction of the wood. Nilsson *et al.* (2011) have presented a simple solid wood densification technique based on compressing a solid piece of softwood with vertical annual rings and without knots in the radial direction by restraining the tangential expansion. They also suggested a method to mechanically hinder the compression-set recovery. To avoid macro-cracking of untreated wood during compression, semi-isostatic densification has been tested with success (Lindhe 1993, Sandberg 1998, Blomberg 2006). In this method, however, the compression deformation is mainly in the radial direction, which results in a deformed shape of the specimen if the annual rings in the cross section are not parallel to the sides of the specimen. In most of the transverse densification methods presented in the literature, the wood has been softened by steam or chemicals before densification.
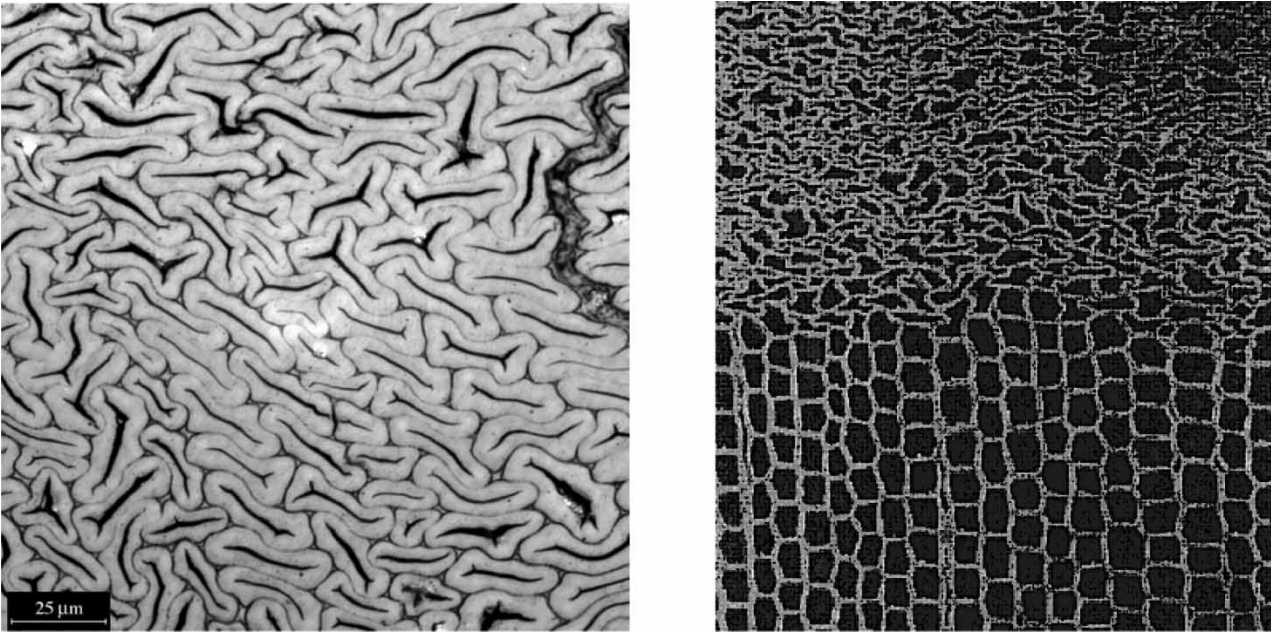
Figure 5. Micrograph of uniformly densified spruce latewood cells after compression at 140°C under saturated moisture conditions (Navi and Heger 2005). Micrograph of the boundary between the compressed surface and uncompressed regions of wood (Inoue *et al.* 1990)

During the densification process, wood is generally heated with high-temperature steam at 110°C, under saturated conditions to reach a softened state. After the wood has been plasticized, it is compressed in the transverse direction and undergoes elastic-visco-plastic deformation, before it is cooled and dried. When the compressed sample is moistened and heated in the absence of any external force, it generally returns to its original shape, to a degree depending on the process parameters, i.e. temperature, moisture content and time, during compression of the wood. The thermo-hydro-plasticity of wood under these conditions of densification is thus only apparent. The phenomenon is known as 'shape memory' or 'compression-set recovery'. The origin of the shape memory is to be found at the level of the cell-wall ultrastructure and molecular structure and an explanation of the phenomenon has been formulated by Norimoto *et al.* (1993).

There are in principle several ways to prevent the compression-set recovery of densified wood:

- by hindering the compression-set recovery by mechanically fixing the movements of the wood;
- by preventing the compressed wood from being re-softened by avoiding re-humidification of the cell walls and thus making the cell wall inaccessible to water;
- by forming covalent cross-links between the wood components in the deformed state by chemical modification; or

- by releasing the elastic stresses and strains stored in the microfibrils and matrix during the compression through:
  - hydrolysis of hemicelluloses under the effect of water and high temperature; or
  - a THM treatment. During drying, the mechano-sorptive effect plays a large role in reducing the internal stresses in the wood.

Figure 6 illustrates the four stages in the densification of wood at the cellular level of compression in the radial direction and fixation of the shape memory.

After the early work on wood densification in Europe, much of the research in wood modification, especially within the area of adhesive impregnation, was performed by Alfred Stamm and co-workers at the Forest Products Laboratory in Madison. To overcome the problem of the recovery from compression, Stamm and Seborg (1941) impregnated thin veneers (in the green or dried state) with an aqueous solution of a phenol–formaldehyde pre-polymer (polymer precursor) whose molecules were small enough to penetrate the cell wall together with the water. The pre-polymer swells the cell wall up to 25% more than the swelling in water. After curing, the composite has a final volume roughly equal that of the water-swollen wood. The veneer is dried, but the pre-polymer is not polymerized, and the desired thickness can then be assembled from layers of
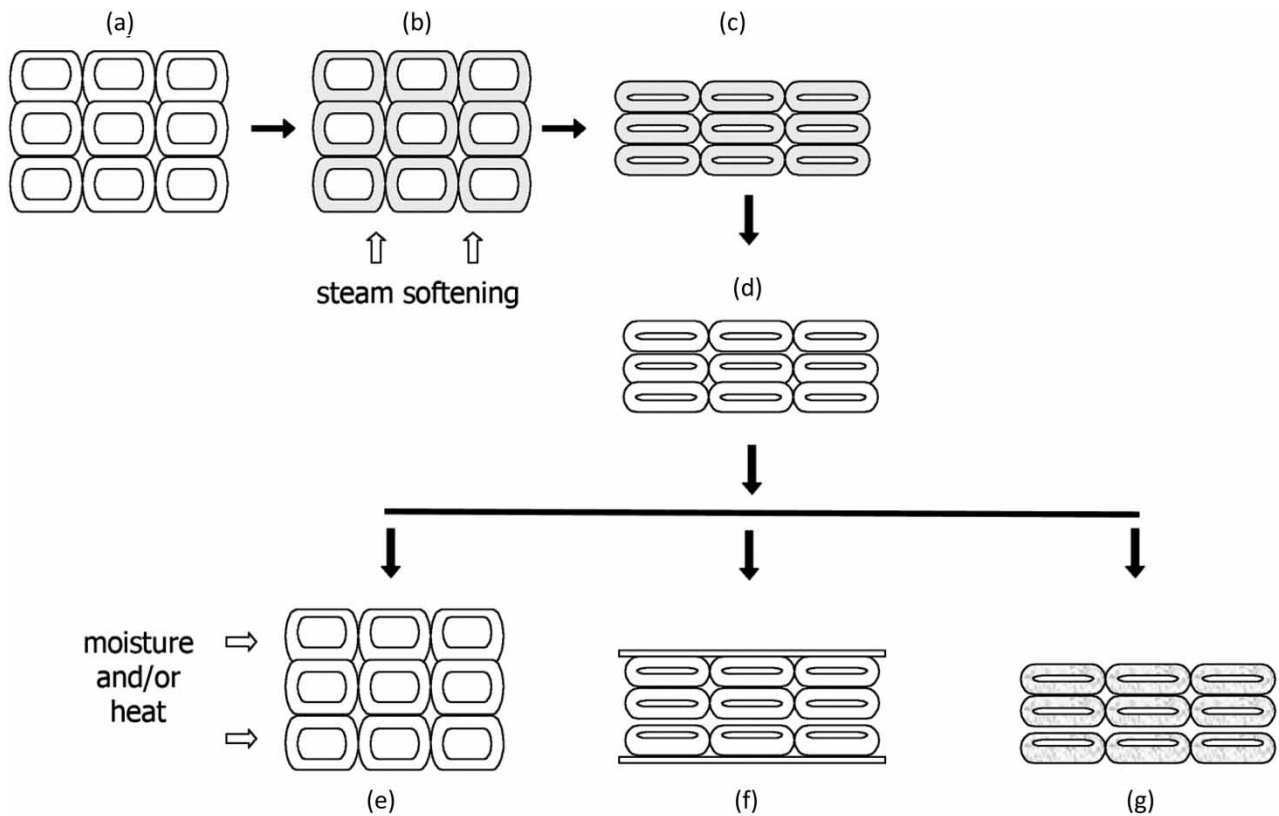
Figure 6. Schematic illustration of wood densification in the transverse direction at the cell level, recovery and different methods of fixation of the compression set: (a) initial undeformed state, (b) softening of the wood by steam, (c) densification, (d) cooling, (e) total set recovery, (f) mechanical fixation, (g) chemical fixation or fixation by a THM treatment

veneer. Under heat and pressure, the impregnant is polymerized to yield a cohesive composite with an anti-shrink efficiency of 70–75%. Stamm and Seborg called this product *Impreg*.

Instead of merely gluing the impregnated veneers together, the stack of veneers can be placed in a press with heated platens and, as the composite material is heated, a pressure of up to about 7 MPa can be applied to compress the wood and collapse the cell structure. Heating at about 150°C for 15 to 30 minutes per 25 mm of thickness polymerizes the adhesive. The result was a high-density (up to 1460 kg/m^3) product with very low-volume swelling (<4%) when soaked in water. This material has been given the generic name of *Compreg*. Compreg is an adhesive-treated and compressed wood which is stabilized in its densified form by the presence of an adhesive. Haygreen and Daniels (1969) developed a method of densifying and drying green sapwood. When the product was soaked in water for three weeks, the recovery of the product was found to be between 10 and 15%. To reduce the water absorption, they impregnated the green wood with phenol–formaldehyde. The recovery of the resin-treated wood was then only 1–2%. In the same way, Gabrielli and Kamke (2008) report the

greater shape stability of phenol–formaldehyde treated and also acetylated densified wood. In this case, the wood was densified by the viscoelastic thermal compression process (Kamke and Size-more 2005, Kamke 2006). Westin *et al.* (2009) have tested Compreg-type products impregnated by furfurylation or waterborne furan during hot-pressing. The products had hardness higher than any known wood species, high-dimensional stability and decay resistance.

Seborg and Stamm (1941) also succeeded in partially eliminating the shape memory of densified wood by thermo-hydrous treatments. Thin plates of hickory (12 mm thick and 106 mm in diameter) were densified at different moisture contents (6, 12, 20 and 26%) and at temperatures up to 170°C for 20 minutes. Seborg and Stamm showed that after densification at 170°C, the compression-set recovery was about 10%. An essential part of this process was the need to press the wood at a sufficiently high temperature and moisture content to ensure that the lignin flowed during processing, to relieve internal stresses during compression. Later, they improved the process and further decreased the recovery, and they called this product *Staypak* (Seborg *et al.* 1945, Stamm *et al.* 1948). Staypak is heat-stabilized,

compressed wood that has been heated, during the pressing process under conditions such that the compression is not lost when the wood is subsequently swollen. Although it can swell appreciably, it returns to practically the original compressed thickness on drying to the original moisture content. It is thus wood that 'stays compressed' (Seborg and Stamm 1941). The advantages of Staypak over Compreg lie, however, in its strength characteristics. Although the shear strength parallel to the grain and in a plane perpendicular to the direction of compression of the wood is appreciably lower for Staypak than for Compreg, the impact strength is about double, and the tensile and bending strengths are approximately 25% higher than those of Compreg.

To obtain a stable densified wood (i.e. a densified wood with no shape memory), a post-treatment process involving a THM treatment in two steps can also be used. The transverse densification of the wood (first step) is followed by a second post-treatment step to eliminate the shape memory. The fixation of the compressive deformation of densified wood has been investigated using saturated steam (Tanahashi 1990, Inoue et al. 1993, Dwianto et al. 1997, Ito et al. 1998a,b, Navi et al. 2000, Navi and Heger 2005), by dry heating (Dwianto et al. 1997) and also under non-saturated conditions by Heger (2004). These investigations have shown that higher temperature and moisture content greatly reduce the post-treatment time necessary to eliminate the shape memory. For instance, it is necessary to keep the samples in a dryer for two weeks at a temperature of 40°C, for 30 hours at 140°C or for 12 hours at 180°C (see Navi and Sandberg 2012). A THM post-treatment of thin densified wood specimens at 200°C with saturated steam for 4 minutes is sufficient to eliminate the shape memory. The hydrolysis of hemicelluloses during THM post-treatment plays an important role in the elimination of shape memory through the dissipation of the stresses stored in the microfibrils and matrix. It should, nevertheless, be noted that to achieve a total elimination of the shape memory, it is necessary for the lignin to be in its rubbery state during the THM treatment.

Numerical simulation of the wood-moulding process is complex and is currently at an early stage of development. Nairn (2006) has carried out an extensive numerical modelling on both softwood and hardwood in transverse compression with good results. He used the material point method which can handle large deformations, can model elastic-plastic cell-wall properties, and automatically takes into account contact between cell walls. It is also easy to discretize micrographs of wood specimens into a numerical model. Ormarsson and Sandberg (2007) have successfully studied deformations in the laminated bending of veneers using finite element analysis.

Wood welding

Wood welding is a mechanical friction process allowing two pieces of wood to be assembled by fusion of the surfaces in contact. The time required for the welding process is short, taking less than a few minutes. The mechanical performance of the pieces joined by friction welding can be as good as that achieved by gluing with conventional adhesives, but it is highly dependent on the process parameters and on the wood species. Furthermore, the welded joint is sensitive to moisture, i.e. there are problems with the water resistance of the joint.

Bevington (1891) invented a rotary welding process to form tubes and to weld the ends of two tubes together. The first connections with plastics were made in the 1940s by Henning (1942). In the 1950s, the friction welding process was also developed in the Soviet Union and Czechoslovakia and, using different techniques, friction welding was developed and applied to numerous materials (Vill and Shternin 1957, Vill 1959). With these techniques, it is even possible to join different materials, e.g. steel and aluminium. Not until the 1990s were the first attempts made to join wood by means of friction (Suthoff et al. 1996, Suthoff and Kutzer 1997). The first work on the frictional welding of wood was documented and the process patented by Suthoff et al. (1996) in Germany. This patent and a subsequent one (Suthoff and Kutzer 1997) have reported that pieces of wood can be joined together through an oscillatory frictional movement. It has also been suggested that it may be possible to join pieces of timber with a wood dowel using rotary frictional welding. This patent also includes the welding of wood under an inert atmosphere or vacuum. The heat generated during the welding process depends on various parameters such as the welding machine setting (frequency, amplitude, welding pressure) and the wood properties (wood species, surface conditions, moisture content, etc.). These parameters have an important influence on the heat generation rate and consequently on the processing time and on the bond quality. Four different types of oscillatory friction movement are usually used for the welding, as shown in Figure 7.

Linear welding is characterized by a linear oscillatory movement. The movement stops and changes direction when reaching the maximum amplitude of the oscillation. In this movement, the velocity and its corresponding frictional force (parallel to the surface) are sinusoidal, as shown in Figure 7a. The frictional

74   *D. Sandberg et al.*

movements in orbital and circular welding are similar. In orbital friction welding, the movement is elliptical so that the force and velocity are sinusoidal, as shown in Figure 7b. In circular welding, the movement is circular and the velocity and frictional force are constant during the processing, as shown in Figure 7c. In rotary friction welding, the connection between the pieces is made by dowels and the method is usually called 'dowel rotary friction welding', as shown in Figure 7d. In this method, a cylindrical (or conical) dowel is pressed into predrilled holes while rotating around its axis.

In 2002, the first attempt to weld wood by a linear vibration movement was carried out in Switzerland. Some of the research results are given by Gfeller *et al.* (2003), Pizzi *et al.* (2004), Leban *et al.* (2004, 2005), Ganne-Chédeville *et al.* (2005, 2006a,b, 2007, 2008a,b,c), Stamm (2005), Stamm *et al.* (2005a,b,c), Boonstra *et al.* (2006), Stamm *et al.* (2006). Most of the wood welded by friction is Norway spruce (*Picea abies* (L.) Karst.) and beech (*Fagus sylvatica* L.), and the work has mostly been carried out on small samples with dimensions of about $150 \times 20 \times 15$ mm, but specimens as large as $1600 \times 40 \times 20$ mm have also been welded.

Rotary friction welding was first developed by Pizzi *et al.* (2004) to join two wood pieces by wooden dowels, and it was shown that the method leads to an effective ligno-bonding between the wooden dowel and the predrilled wood. Figure 8 shows a photograph of cross-sections of a dowel rotary weld.

Figure 9 shows interphase of a welded joint of two spruce pieces achieved by circular friction, observed in a confocal microscope. This figure shows that the connected interfacial zone consists of two parts: a middle part of a dense amorphous material 'fused' with fragments of densified wood fibres and melted material and a second part of densified fibres surrounding the middle part. The densification of the second part gradually decreases until the undeformed wood fibres are reached. The total thickness of the middle and second zones is less than 1 mm.

The chemical and physical changes induced by the welding process have been intensively investigated. The thermal energy generated by friction is used to soften the wood constituents, mainly lignin and hemicelluloses. This leads to the detachment of wood cells and the formation of an entangled network of fibres immersed in a matrix of molten material which then solidifies and yields significant adhesion in the interphase of the weld. To understand the thermal reactions, thermal decomposition and alteration of the wood constituents during the welding process, between 140 and 440°C, Stamm *et al.* (2005c, 2006) have studied the formation of the 'melted' material by chemical and spectroscopic methods. Their results have shown that the hemicelluloses were degraded to a great extent while the
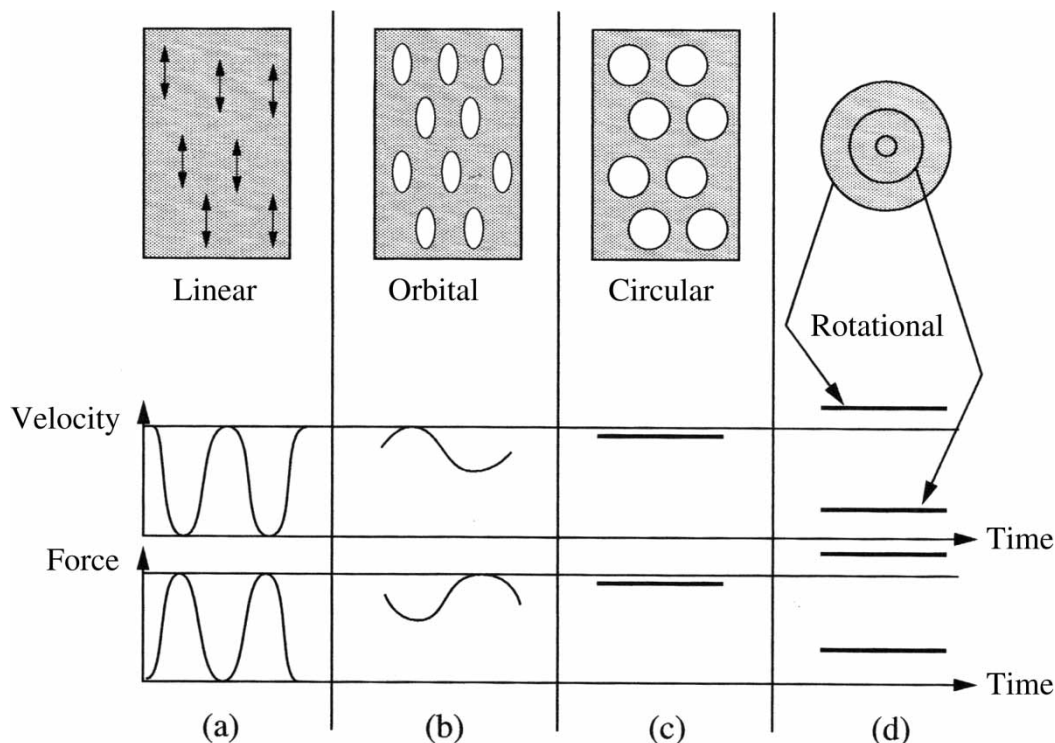

Figure 7. Movements, velocities and forces in four different types of frictional welding; (a) linear friction, (b) orbital friction, (c) circular friction and (d) rotary friction welding (Stamm 2005)

Figure 8. Cross-sectional profile of a dowel ligno-bonded by rotary friction welding (Ganne-Chédeville *et al.* 2005)

Figure 9. Micrograph of a zone of joined and adjacent areas between two pieces of spruce welded by circular friction (Stamm *et al.* 2005a)

cellulose remained relatively stable. The lignin also underwent distinct changes, as demonstrated by an increase in the number of free phenolic groups and a decrease in the typical bonds between the phenol propane units. They also detected furan derivatives within the volatiles of the smoke gas, arising mainly from hemicelluloses. They concluded that reactions between furfural and other furan derivatives with lignin are the main reactions in the friction zone leading to cross-linking of the 'melted' contact material. This material has also been examined by Gfeller *et al.* (2004), Ganne-Chédeville *et al.* (2005) and Kanazawa *et al.* (2005) and it has been shown that the essential chemical modifications involving the polymeric constituents of wood in friction welding occur in the first five to six seconds and that they slow down or even stop afterwards. Analysis by FTIR and CP-MAS ^{13}C NMR of the welded area of wood has shown dehydration and an apparent increase in the crystallinity of the cellulose. Certain hemicellulose degradation has occurred, accompanied by the generation of furfural. Cellulose degradation is very slight. Both analytical techniques
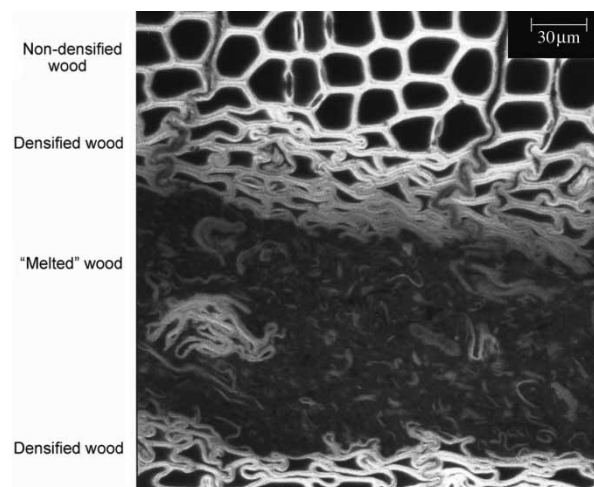
show an increase in the proportion of lignin in the welded interphase. Self-condensation of lignin occurs by internal rearrangement, and this continues throughout the welding process. After six seconds of welding, the wood begins to carbonize, and an increase in cross-linking of the lignin network is observed. Ganne-Chédeville *et al.* (2005) have suggested that to produce the frictional energy necessary for the reaction between furfural and other furan derivatives with lignin and to achive good adhesion between the two wood pieces, the variation in temperature at the interface has to be monitored (Ganne-Chédeville *et al.* 2006a,b). During the welding process, the interface of the wood heats up and creates a 'melted' material. After the frictional movement has stopped and during the cooling phase, the 'melted' layer solidifies forming a continuous joint between two wood pieces. Pizzi (2012) has suggested that the mechanism of mechanically induced wood vibration welding is due mainly to the melting and flowing of wood intercellular polymer material. This causes the 'ungluing' of long wood fibres, and the formation of an entangled network of fibres in the matrix of solidified molten cell-interconnecting material. Thus, a high-density, high-strength wood cell/fibre entanglement network composite with a molten lignin polymer matrix is formed.

Recently, considerable work has been carried out to investigate the potential of wood joining by different frictional techniques. The mechanical performance, particularly the resistance to fracture propagation and the influence of water on fracture toughness has been examined by various tests developed for adhesive joints. Joining by frictional methods still involves certain inconveniences, which

need to be overcome before they can be applied in timber construction. Water absorption by friction-welded wood joints lowers the strength of the joints. This is one of the greatest weaknesses of wood welding and its use for constructional purposes. However, Pizzi (2012) has shown that dowel welding can be used for protected exterior joints due to the combination of rosin waterproofing and joint geometry. Welded dowel joints hold together for longer than 500 days on immersion in water. Vaziri (2011) studied the water resistance of welded Scots pine (*Pinus sylvestris* L.) and found that the water resistance was greater when heartwood was used, due to the higher content of extractives in heartwood. The water resistance was not, however, sufficient to classify the joint as an unprotected exterior grade. In an attempt to explain the behaviour of a welded joint to water, Rhême *et al.* (2011, 2012) have investigated the characteristics of mode I and mode II fracture propagation at various moisture contents. They have shown that the critical energy release rate in both mode I and mode II is a function of the moisture content of the specimen. Figure 10 shows a multi-layer wooden element consisting of eight 6 mm thick lamellae of alternating spruce and beech manufactured by circular friction welding . This welded wooden element could be used instead of a laminated wooden beam or a wooden wall element made of glued boards (Stamm 2005).

Recently, more studies have concentrated on improving the strength of wood joints by optimizing the welding machine parameters (frequency, amplitude and welding displacement or welding process time), to solve up-scaling problems and improve the quality of large welded joints for application in timber construction. An attempt to use linear friction welding to produce an adhesive-free strand-board of spruce has been described by Bianchi *et al.* (2012). The method represents an interesting alternative to standard adhesive-bonded hot-pressing technology, but is affected by limitations such as the large amount of volatiles derived from the thermal degradation of wood, and that the maximum reachable mechanical properties are lower than those of the existing standards.

The phenomena that arise on the micro-level of wood during friction welding have an interesting relation to the rather unexplored area of laser treatment of wood. Laser treatment, depending on irradiation parameters, is a form of heat treatment which is very concentrated in space and time and exhibits interesting effects such as a molten surface. This type of molten surface was observed by Sandberg (1999) and Johansson and Sandberg (2007) during preparation of weathered samples of pine and spruce with the help of UV-laser ablation (Seltman

1995a,b). Haller *et al.* (2001) have investigated the effect of laser irradiation on wood with respect to changes in structural, chemical and physical properties, and they have identified the laser parameters which guarantee melting of wood without pyrolysis.

Industrialization of TH/THM concepts

Several TH/THM processes have been industrialized during the last 150 years. Examples are the bending of solid wood, i.e. the Thonet process, laminated bending, softening of logs or sawn wood before veneer slicing, kiln drying of sawn wood and various concepts in board manufacture. Today, there are still advances in these concepts, e.g. to increase productivity or for developing more environment-friendly processes. The following is a presentation of some TH/THM concepts where great progress has been made during recent years and where that progress has in some cases resulted in new or improved industrialized processes.

Heat treatment

The heat treatment of wood has been investigated for many years without any break-through in commercialization. The general discussion about the use of tropical hardwood, the toxicity of wood preservatives, and especially the willingness of sawmills and the wood industry to broaden their product range has led to the industrial development of several heat-treatment processes since the early 2000s.

On the European market, several industrial heat-treatment processes have been introduced. The most common processes are: the Thermowood process, the Plato process, the retification process, le Bois Perdure, the oil-heat treatment (OHT) process. The total capacity of heat-treated wood in Europe is about 200,000 m^3/year and Finland alone has a production of 100,000 m^3/year. The heat-treatment plants have a capacity between 1000 and 30,000 m^3/year. Several different species are used in the process, but spruce is dominant.

Industrial heat-treatment processes typically aim at improving the biological durability of less-durable wood species and at 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 by Viitaniemi and Jämsä (1996), Leithoff and Peek (1998), Sailer *et al.* (2000), Jämsä and Viitaniemi (2001), Rapp and Sailer (2001), Boonstra and Tjeerdsma (2006), and for OSB-strands particularly, Del Menezzi and Tomaselli (2006) and Paul *et al.* (2006, 2007).

Figure 10. A wooden multi-layer element made of alternate layers of spruce and beech bonded by circular friction welding (Stamm 2005)

The basic difference between these different processes is in their choice of oxygen-excluding and heat-transporting media. The Thermowood process uses steam, and in the Plato process the wood is heated to 150–180°C in an aqueous environment at superatmospheric pressure (including saturated steam as the heating medium) in a first step followed by a drying and heating once again to 150–190°C, but under dry and atmospheric conditions; and finally a conditioning phase. The retification process uses nitrogen and the OHT process use vegetable oils, e.g. rape seed oil, linseed oil or sunflower oil (Rapp and Sailer 2001, Rapp *et al.* 2006). However, the treatment conditions are very similar in these processes which operate between 160 and 240°C to modify the chemical composition of the cell wall. Modified heat-treatment processes are also emerging in Denmark, the Wood Treatment Technology (WTT) process working at 160–180°C, and in Austria, the Huber Holz process working at 170–230°C. Both processes have heated steam as medium, but the WTT process can also add oil in the process. Only a few processes, like Plato, have used relatively mild heat treatment to improve dimensional stability and at the same time avoid a deterioration in the mechanical properties of the heat-treated wood. These different heat-treatment processes are covered in detail in Navi and Sandberg (2012).

Advances in wood bending

The industrial production of bent wood for furniture production had its peak in produced volume around 1900. Even then, machinery for bending could make a large number of bends in one operation, and production rates were considerably increased. The development of machines for higher productivity has proceeded throughout the twentieth century. However, these machines are seldom used for the production of multiple (bi-planar) bends.

There has been considerable interest in finding ways to shorten the long processing times for heating (plasticizing) the wood before bending and drying it after bending. Dielectric heating, i.e. radio-wave heating (or high-frequency heating) and microwave heating technologies are the most common techniques developed for this purpose. Plasticizing wood with through dielectric heating has been studied for several years by Norimoto (1979), Norimoto *et al.* (1980), Mori *et al.* (1984), Norimoto and Hasegawa (1984), Norimoto and Gril (1989) and Eggert (1995). The literature indicates that there have been problems with uneven heating, but with today's knowledge of dielectric methods it should be fully possible to achieve a uniform heating. In Navi and Sandberg (2012), an automatic process for plasticizing, bending and drying solid wood is presented in detail. This technique is now being introduced in industrial applications for in plane bending.

Being able to bend wood in a cold state is especially desirable in small product series and in workshops where it is not possible to provide equipment for conventional bending. The Compwood AS company in Denmark, emanating from the work of Morsing (2000), has developed a machine for the pre-compression of wood in the longitudinal direction to make it bendable in a cold state, as shown in Figure 11. The procedure consists of three distinct stages: (1) the steamed, softened wood element is longitudinally compressed by about 20%, (2) the applied pressure is then released, after which the wood partially recovers from the compression-set so that the residual deformation is 4–5% and (3) the wood is then allowed to cool at room temperature and dry to a moisture content of 12%. The wood piece can then be polished and processed to the desired cross-sectional shape and surface-finished as a straight piece of material. The advantage of this process is that the wood element can be subsequently bent in a cold state without the application of steaming or jigs. The smallest radius of curvature for 25 mm beech is ca. 230 mm, which may be compared with the value of 330 mm for plasticized beech without any restraining band.
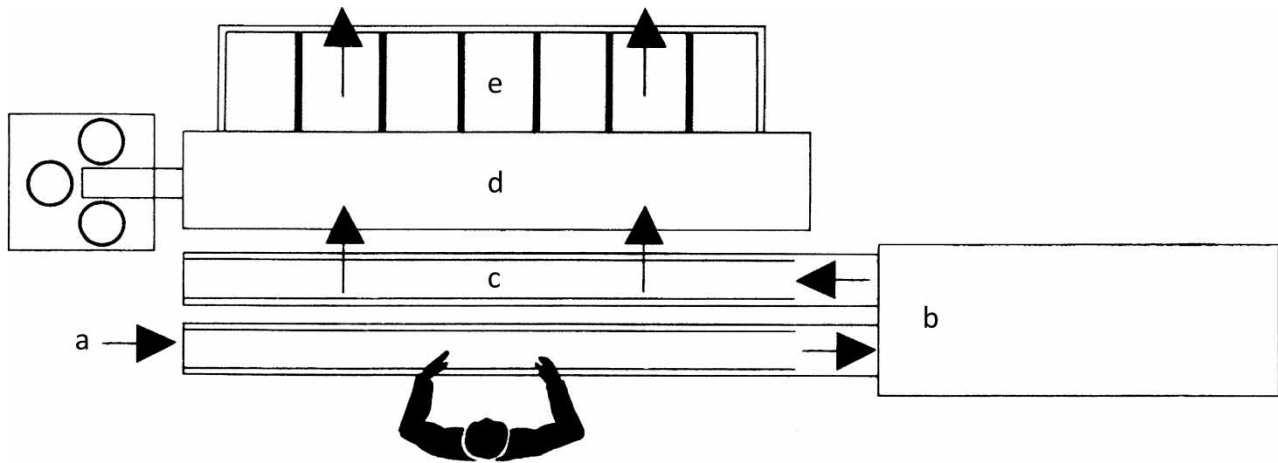
Figure 11. Compwood machine for pre-compression of wood in the longitudinal direction to make it bendable in a cold state (view from above). The operations are: (a) loading, (b) autoclave for plasticizing the wood, (c) automatic input, (d) machine for longitudinal compression, and (e) output of densified wood

The bendability of the wood can be further increased if, after having been pre-compressed and dried until item 3 in the above list, the material is subjected to a further compression of 20% in the cold state. After the pressure has been released, there is a residual deformation of about 15%. A piece of beech which has been processed in this way can be bent in the cold state to a radius of curvature as little as 100 mm.

Transverse densification or moulding

Densified wood has been produced in Germany since the early 1930s and marketed under the trade name of *Lignostone,* and a corresponding laminated compressed wood was produced under the trade name of *Lignofol*. A resin-treated laminated compressed wood under the name of *Kunstharzschichtholz* has also been in commercial production (Kollmann 1936, Stamm 1964). Lignostone is still being manufactured in Germany by the Röchling-Gruppe. The compressed and resin-impregnated wood *Compreg* presented by Stamm and Seborg (1941) is today being produced on an industrial scale in Germany and Poland. Compreg plywood with a density of 1250 kg/m^3 can also be found on the market.

The primary goal of recent research on existing wood densification techniques and of the development of new techniques in THM post-densification treatments is to extend them to wooden elements of larger dimensions than was previously considered feasible. Today, in Japan various investigations into the THM moulding of wood are going on. In summary, the processes investigated are commonly based on the two-directional transverse densification of wood elements which employs in four distinct

stages: (1) wood plasticization by high-temperature steam, (2) compressive moulding (two-directional shaping), (3) THM post-compression-treatment and (4) cooling. Ito *et al.* (1998a,b) have developed a system to transform small logs (maximum length and diameter of 340 and 200 mm, respectively) into beams with a square section by two-directional transverse densification, as shown in Figure 12.

Due to the decrease in availability of the Japanese high-strength hardwoods, Dwianto *et al.* (1997, 1998) have attempted to improve the properties of the more readily available low-density softwood Sugi for flooring and interior wall materials. The wood was compressed to 50% of its original thickness in the radial direction in a wet condition. It was then restrained and dried under heat and an almost complete fixation was achieved with about 4% weight loss of the heat-treated and compressed wood. The most important differences between these two processes reside in the post-treatment stage. In the first technique, the operations of moulding and post-densification are overlapping, whereas in the second technique these two stages occur separately. The problems related to the dimension of the wood elements (scale-related effects) such as the development of cracks and exfoliation of wood during shaping, cooling and drying have apparently not yet been solved. Shigematsu *et al.* (1998), Kyomori *et al* (2000) and Tanahashi *et al.* (2000) estimate that more fundamental knowledge on wood THM behaviour is required before the issues that currently stand in the way of developing a new manufacturing system for 'compressive moulding of wood under high-pressure steam techniques' can be overcome. Recently, the Olympus Corporation presented wood products, such as the outer casings of electronic
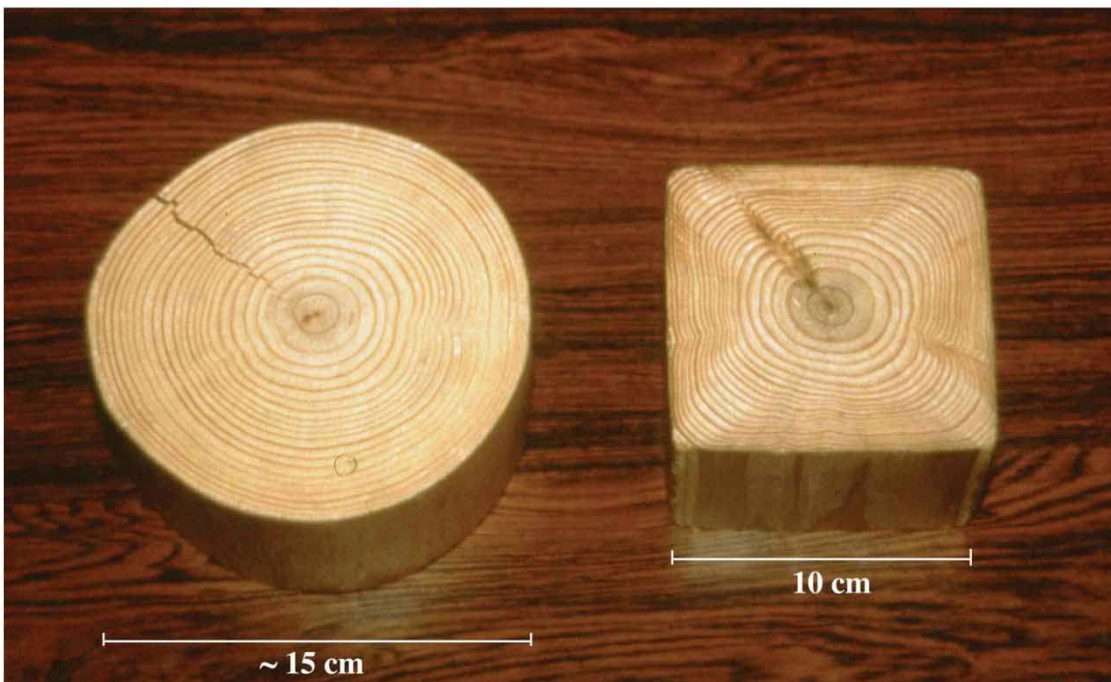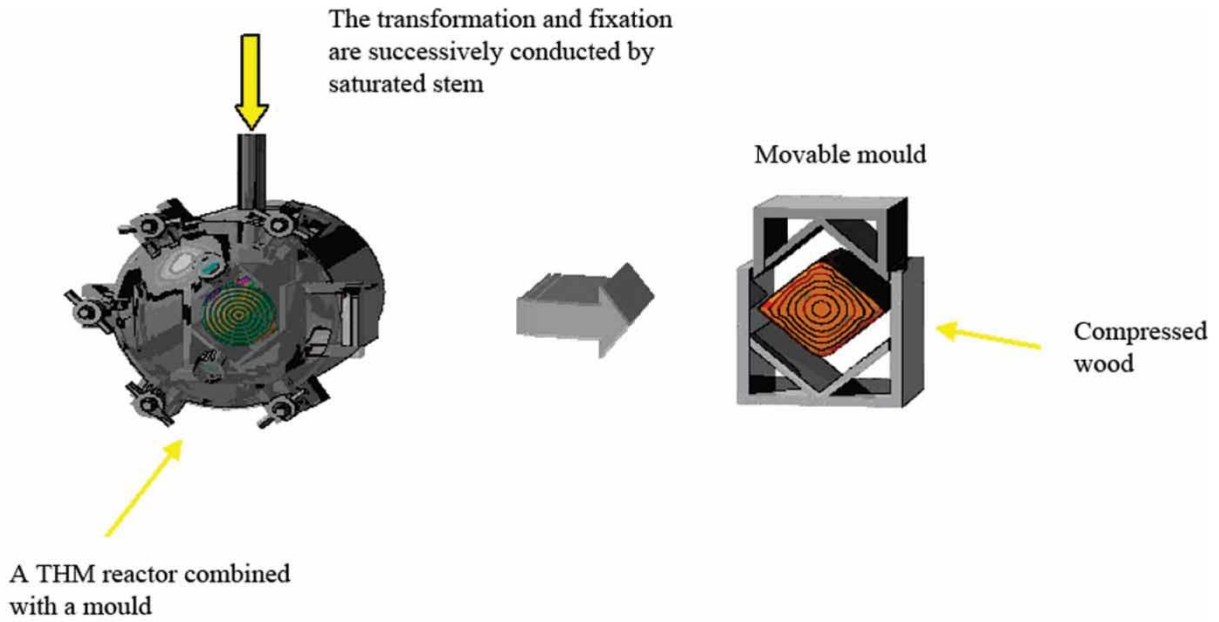
Figure 12. Thermo-hydro-mechanical apparatus and the internal moulding block (left) and transformation of a circular trunk to a square-section block by two-dimensional densification (right) (Ito *et al*. 1998a)

products, manufactured in a three-dimensional compression moulding process for wooden materials (Tatsuya 2007). The processed wood has the feel and grain pattern of natural wood, but is much harder than engineering plastics such as acrylonitrile–butadiene–styrene (ABS) and polycarbonate. The material is strong enough to be used to create the outer casings of electronic products, and it can enhance the aesthetic value and pleasure of ownership that these products provide.

In the USA, commercial interest in the harvesting of rapidly grown wood with an innate low density has driven the wood-research community to investigate possible opportunities of employing densified wood products in the structure of composite materials (Kamke 2004, Kutnar *et al*. 2009). To densify small low-density hybrid poplar specimens, Kamke and Sizemore (2005) have developed a semi-closed THM reactor. The process of densification and shape-recovery elimination consists of four stages:

(1) softening of the wood element through hot-steaming and densification, (2) transient release of steam pressure and mechanical compression for about 100 seconds, so that the specimen partially loses its temperature and moisture content, (3) reapplication of the compression load and increasing the temperature from 175 to 200°C and (4) cooling the specimen to 100°C while still under compression. This semi-closed system might have had some potential advantages over the closed systems developed in Japan and Switzerland, but unfortunately the dimensions of the specimens used for densification were very small. Scaling issues render it difficult to evaluate the interest of this system for wood elements of the size envisaged in building constructions without practical research on elements of a comparable size.

New ideas on tubes and column constructions

Next to material properties, the structural and economic performance of the cross section of a load-bearing structural component is the most important design issue. With the aim of providing engineered wood products for structural applications, tubes or columns of densified wood have been developed at the Institute of Steel and Timber Construction at the Technische Universität Dresden, Germany (Haller *et al.* 2004). The tube has a much larger load-bearing capacity than solid wood. The formed tubes can be optionally reinforced with technical fibres and/or textiles laminated to the outer wood surface, as shown in Figure 13. The purpose of such a composite confinement is to strengthen the relatively thin-walled sections and to protect the wood against environmentally induced damage. Besides structural applications in civil engineering, the tubes can also be used as water pipes (Putzger *et al.* 2012).

The columns are made from densified glued laminated timber boards of spruce and rolled to a wooden tube (Haller 2007). Figure 14 shows the different steps in the manufacture of a tube from sawn wood and from wood with a more or less circular cross section.

Sawn boards at a moisture content of about 12% are softened and densified in the transverse direction in an open system at 130–160°C for about 2 hours. After cooling, the densified boards are glued to a panel with a length which corresponds to the final length of the tube. The boards in the panel can be oriented at an angle α to the longitudinal direction of the tube to achieve a tube with a spiral grain according to the tree stem, which is expected to give a higher load-bearing capacity, although this has not yet been confirmed experimentally. Today, an angle α equal to 0° is used. The panel is heated to a

Figure 13. Wood tube of densified spruce (left) and filament winding of moulded tubes (right)

temperature of 80°C and the panel is formed in a mould, as shown in Figure 15.

When the process begins with a log, the log is densified in transverse directions to yield a more or less rectangular cross-section. The pith is then sawn away and the pieces are glued together to a panel that has wood with the lowest degree of compression on one side of the panel and wood with the highest degree of compression on the other side of the panel. When the panel is shaped to a tube, the high-density side will be on the outer surface of the tube.

The maximum possible bending radius for the moulding operation is primarily dependent upon the degree of compression and upon the thickness of the panel.

Haller and Wehsener (2004) and Welzbacher *et al.* (2008) have tested heat treatment (the OHT process) for eliminating the compression-set recovery of large, industrial-scale densified woods. This study showed that oil heated at a temperature above 200°C can completely eliminate compression-set recovery of large densified spruce panels. The resulting product
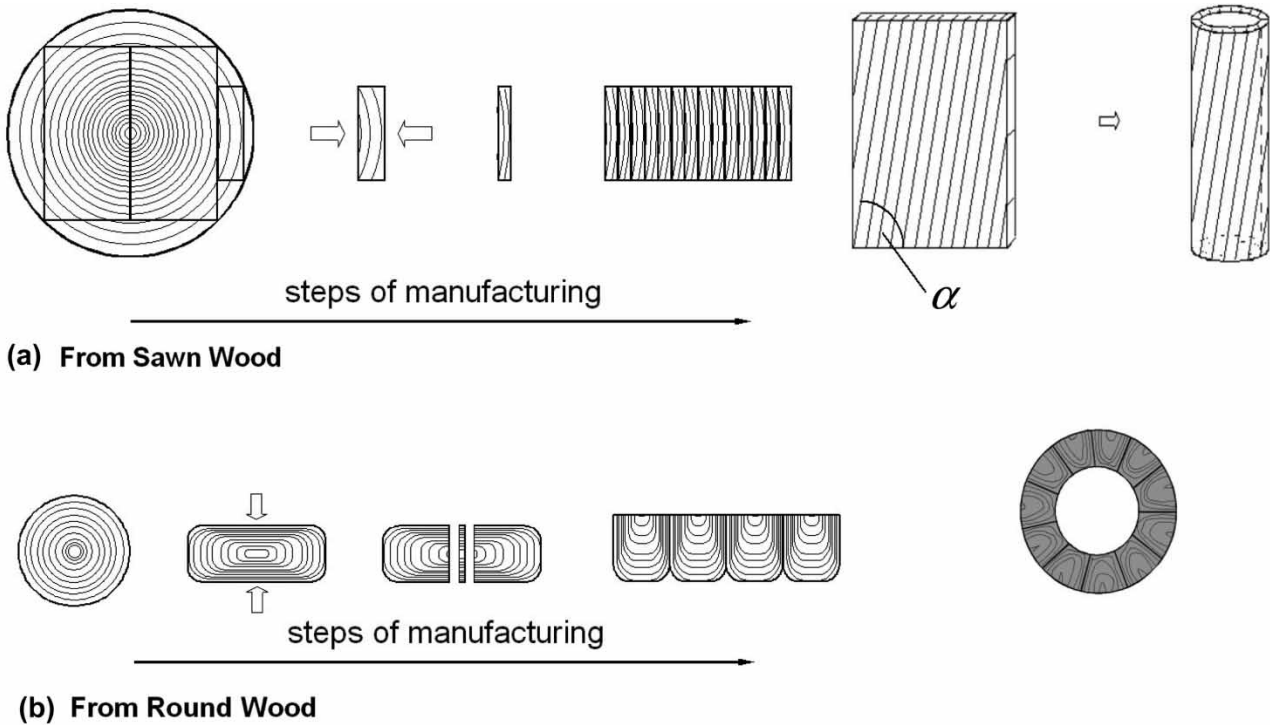
Figure 14. Manufacture of wooden tubes from (a) sawn wood and (b) a log

has also shown greater resistance to micro-organism degradation. Because of the greater durability than existing commercial products and the impregnation of densified wood by oil during post-treatment, this type of product is predicted to have potential for outdoor service.

Challenges for the TH and THM processing techniques

Various types of TH/THM processing technique can be utilised to enhance wood properties, to produce eco-friendly new materials and to develop new

Figure 15. Moulding of a densified wood panel to a tube of diameter 450 mm; (a) charging, (b) closing, (c) forming. The thickness of the tube wall is 100 mm

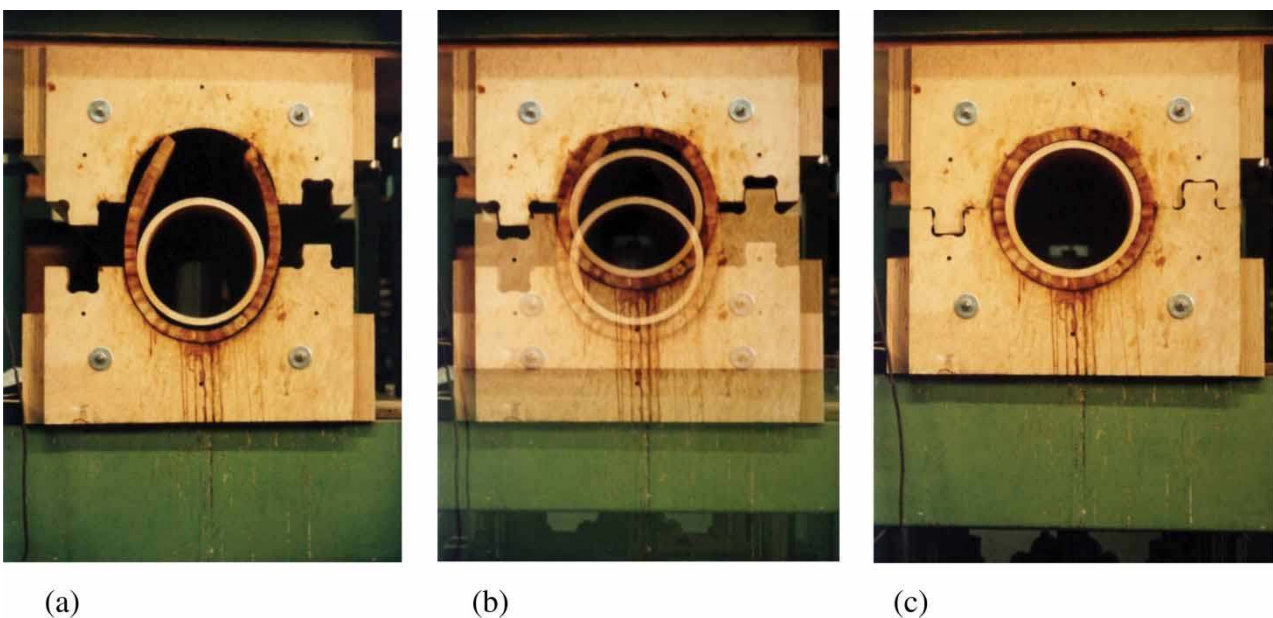products. However, altering the way in which wood is treated is known to dramatically alter the way it performs. As an example, an unsuitable high-temperature TH/THM treatment can chemically degrade wood, and lead to structural and mechanical damage, loss of strength and greater brittleness. Another inconvenient feature of high-temperature-heated wood is its rapid ageing. Heat-treatment methods are knowledge-based processes. The modification of mechanical properties, dimensional stability, resistance to micro-organisms, change of the colour and odour are functions of the process parameters and consequences of wood chemical degradation. Any investigation of the combined effects of temperature, humidity, oxygen and time on wood chemical degradation and the corresponding modification of wood properties requires a multidisciplinary approach and sophisticated chemical and mechanical analyses and studies of resistance to micro-organisms. The changes in wood properties have their origin in the chemical reactions of the wood cell constituents produced during processing. There is a need to better understand the chemical degradation of wood to optimize the processing conditions and thereby ensure that treatments meet product needs. The environmental impact of the TH and THM processes is also an area that is not well explored. A life cycle and system perspective study of the different TH and THM processing techniques is necessary so that all the life cycle phases i.e. production, operation, retrofitting and end-of-life are considered and optimized as a whole, including the energy and material chains from natural resources to final services. Establishing a greater understanding through knowledge exchange will promote the effective processing of wood. This is particularly the case in transferring knowledge and experience from the research and development sector to the industrial sector and vice versa.

Heat treatment, densification and wood welding by friction have been in focus in this state-of-the-art review. These processes are at various stages on the way to industrial implementation and therefore they have also different needs with regard to further development. From a technical and industrial point of view, the following areas have been identified as focus areas for the present on-going research or industrialization projects.

For heat-treatment processes:

- fast methods for quality and process control;
- processing techniques to withstand the heat-treated wood brittleness and the presence of dust during, e.g. mechanical processing due to its low moisture content;

- adhesive and paint systems adapted to the low moisture content of heat-treated wood;
- new material properties of the heat-treated wood such as UV instability, weak surface (low hardness and fibre–fibre failure), corrosion, bleeding new chemicals through the coating (phenols), low screw-withdrawal burglar resistance, cracks in annual ring orientation, etc.; and
- new TH treatments, in contrast to heat-treated wood at high temperature, with fewer undesired effects, to produce heat-treated wood suitable for load-bearing elements and for indoor application.

Heat and mass transfer are involved in almost all TH and THM wood treatments. The transfer phenomena are at the heart of the size effect during up-scaling.

For compression processes:

- the primary focus of current research in the domain of wood-moulding and wood densification as well as in post-compression treatment of moulded wood by THM is to overcome the challenges being faced in up-scaling. This becomes highly important while the current aims are to broaden the range of densified wood to encompass large-size wood elements for structural application in the construction industry; and
- Ingenuity and creativity for implementing the compressed wood elements with shape memory for developing new wood products.

For wood welding processes:

- up-scaling laboratory experiments to an industrial scale;
- methods to increase the moisture resistance of the welded joint;
- methods to decrease the odour of the welded wood material; and
- rapid methods for quality/process development.

During TH and THM treatment, wood undergoes mechano-chemical transformations which depend upon the process parameters, material properties and element size. An investigation of these phenomena requires collaboration between groups from different wood disciplines. An interdisciplinary approach requires the interaction of researchers from scientific domains such as wood mechanics, wood chemistry, physics, material sciences and numerical analysis. This will help to overcome the challenges being faced in scaling-up research findings, as well

improving full industrial production and processes, enhancing product properties and developing new wood products.

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