Recent Progress in the Industrial Implementation of Thermo-Hydro (TH) and Thermo-Hydro-Mechanical (THM) Processes

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ABSTRACT

The implementation of thermo-hydro (TH) and thermo-hydro-mechanical (THM) techniques on an industrial scale dates back to 1850, when Michael Thonêt introduced his invention for the bending of solid wood. The development and commercialization of processes for the softening of wood and for the kiln drying of sawn wood followed. More recently, several thermal wood treatments have reached an industrial scale and the markets, and new thermal processing techniques are continuously being developed and introduced onto the market. As a result, the volumes of thermal-treated wood for interior and exterior use are continuously growing. This paper presents the latest developments in the field of TH and THM processing with a focus on processes that are in an implementation phase for industrial production or have the potential for such development. Challenges faced during the commercialization of TH and THM processes are also discussed. In this paper, the following TH/THM treatments are presented:

- Densified engineered wood products (EWP)
- Moulding for two-directional or three-directional shaping of veneer
- Ageing of wood
- Frictional wood welding and wood surface fusion
- Laser treatment for the TH processing of wood surfaces

INTRODUCTION

One of the emerging treatments involves the combined use of temperature and moisture, and force can be added, so that one speaks of thermo-hydro (TH) and thermo-hydro-mechanical (THM) methods, Figure 1. TH/THM processing is implemented to improve the intrinsic properties of wood, to produce new materials, and to acquire the form and functionality desired by engineers without changing the eco-friendly nature of the material.

Researchers have discussed whether the term “hydro” or “hygro” should be used to describe the influence of water during the processing of wood. Hydro comes from Greek hudór and is a prefix that means water. Hygro comes from Greek hugróś and is a prefix that means wet or moist. Depending on which processes are in focus, one of the two prefixes is more suitable than the other. For simplicity, in this article, we use only the prefix hydro.
Figure 1: Classification of thermo-hydro (TH) and thermo-hydro-mechanical (THM) processes

TH/THM processing has been used by humans for thousands of years. A 5200-year-old find of a pair of skis shows that the front tips of the skis were bent with the help of THM action. The ancient Egyptians also used this technique for the manufacture of tools, weapons, and utility equipment (Navi and Sandberg 2012). Nevertheless, it was not before 1849, when the inventor of the Vienna Chair, Michael Thonét, started a workshop for the production of bent solid wood furniture, that the first step was taken towards the industrialization of a TH/THM process intended for mass production. In the 1850s, the Thonét method was developed for bending thick, solid pieces of beech wood on a large scale. This method involved wood plasticization by treatment in hot steam, bending in a special mould and drying in a fixed position. Before 1900, the Thonét Bros factory had already produced over 50 million of their famous café chair No. 14 and the chair was being delivered in six parts as the world's first "knock-down" piece of furniture, Figure 2. At the time of Michael Thonét's death in 1871, the company had 4000 employees and an annual production of 450,000 items of furniture. Twenty years after Michael Thonét's death, there were 60 factories, mostly within the Austro-Hungarian Empire.

Figure 2: The famous Thonét café chair No. 14; left - ready for delivery in parts from a factory (36 chairs in 1 m³), and right - finally assembled
In the beginning of the twentieth century, the use of heat and moisture into wood processing came in focus. It had been observed that wood dried at a high temperature changes colour, and has a greater dimensional stability and a lower hygroscopicity (Tiemann 1915, Koehler and Pillow 1925). After the First World War, comprehensive studies were made on the effect of the kiln drying temperature on the strength of wood for the aviation industry in the United States (Wilsson 1920). In 1946, Stamm et al. reported the first systematic experiments of wood heat treatment, illustrating an increase in dimensional stability and in the decay resistance of wood treated at a temperature between 120 and 320°C, but their results did not come into industrialization before the mid of 1990s when several thermal-treatment processes were commercialized; the Finish ThermoWood process one of the best known.

In recent decades, scientists have raised concerns about urgent and complex problems impacting our environment. As threats to the Earth's ozone layer mount, the planet warms, agricultural lands turn to deserts, and the threat of carbon dioxide emissions increase, our very survival may be at stake. One way of reducing the emission of carbon dioxide is to use more wood products and to increase the life of these products so that the carbon is bound over a longer period of time. Another possibility is to replace energy-intensive materials with wood and wood-based products. However, for timber as a material to be competitive against other materials, its environmental advantages alone are not enough. Wood must also be competitive for its technical qualities, show a high material utilisation during further processing and, not least, a competitive economic yield during usage. The TH/THM technology may be one way to strengthen the competitiveness of wood. In this context, there has since the 1990s been renewed interest in developing TH/THM products.

The purpose of this paper is to present the latest developments in the field of TH and THM processing with a focus on wood processes that are close to the implementation stage for industrial production or have the potential for such development.

**RECENT DEVELOPMENTS IN TH/THM PROCESSING**

Engineered densified wood products, moulded veneer products, and wood products modified through ageing, frictional welding or laser treatment are areas in which the development of TH/THM-technology is especially concentrated. This is especially true when we are looking at the modification of solid wood and veneer.

**Densified engineered wood products (EWP)**

Densification is an old modification method to improve wood properties such as hardness and resistance to abrasion. A major problem with densified wood is, however, its ability to retain its original dimensions under the influence of moisture. Recent developments in the compression of wood in the transverse direction have focused on limiting the shape memory of compressed wood with the help of a TH action or by mechanically “locking” the compressed wood within the structure (Inoue et al. 1993, Dwianto et al. 1997, Nilsson et al. 2011). Applications of “densified and shape memory fixed wood” in different EWPs include panels, beams, columns, and other 3D-shaped components used mainly for interiors and furniture. The developments are aiming either (1) to increase the strength and usability of wood for structural purposes, or (2) to increase the potential for using wood in free 3D-shapes for non-structural purposes.
With the aim of providing engineered wood products for structural applications, tubes or columns of densified glued laminated timber boards of spruce have been developed by Haller et al. (2004). The tube has a much larger load-bearing capacity than solid wood. The THM-formed tubes can be optionally reinforced with technical fibres and/or textiles laminated to the outer wood surface to strengthen and protect the construction against decay, Figure 3. Besides structural applications in civil engineering, the tubes can also be used as water pipes (Putzger et al. 2011). This invention is now productized and is close to being ready for introduction onto the market.

Increasing the density of the surface only, to improve surface hardness rather than modifying the whole material, could be an advantage in applications where it is desirable to maintain the low bulk density of wood but improve the surface properties (Rautkari 2010). In surface densification, only the first few millimetres beneath the wood surface are compressed, in effect just the first few cell layers. Inoue et al. (1990) have developed the THM technique for surface densification to improve abrasion resistance and hardness. The surface was saturated with water through narrow grooves (2 mm wide and 5 mm deep) before the surface was heated irradiated by microwaves, followed by compressing in the radial direction and drying under restraint to fix the compressive deformation. Densified wood from different densifications method has been introduced in commercial wood flooring products, but these products have had difficulty in competing with high-density hardwoods.

The free 3D-shaping of solid wood for non-structural purposes has not achieved any significant commercial success, except in the traditional solid wood bending technique and the forming of veneers (see below). Densification of wood in the transverse and/or longitudinal direction makes the wood more flexible in these directions (see e.g. Navi and Sandberg 2012, pp. 290, 320). 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 the compressive moulding of solid wood can be overcome. Recently, the Olympus Corporation presented wood products, such as the outer casings of electronic products, manufactured in a three-dimensional compression moulding process for wooden materials (Tatsuya, 2007). In the USA, commercial interest in low density species has driven the wood-research community to investigate the possibility of employing densified wood products in the structure of composite materials (Kamke 2004, 2006, Kutnar et al. 2009). To densify small low-density hybrid poplar specimens, Kamke and Sizemore (2008) have developed the continuous viscoelastic thermal compression (VTC) process.

Only few wood THM-densification applications have been industrialized to some extent and there are several reasons for this relatively low transfer of research results to a full up-scaled industrial production. Initially the reason was a lack of adequate consideration of the plasticization or stability of the products. The latter issue was solved by development of resin-impregnated laminated THM products during the first half of the 20th century and such products are today commercially produced, e.g. Panzerholz and Dehonit (Germany), Permawood (France), Ranprex (Italy), Permali (USA), Insulcul (Australia), Surendra (India), and MyWood (Japan).
Moulding for two-directional or three-directional shaping of veneer

Veneers have been used for a long time for the production of complex forms in wood, i.e. laminated veneer products. Although formability is significantly better when using veneer than when using solid wood of thicker dimensions, there is still a problem with the lower strength in the transverse than in the longitudinal direction. A major problem in laminated moulding is the stretching of the veneers and the risk that the veneers can crack if they are subjected to large three-dimensional deformations. The bending direction of the construction is therefore normally in the longitudinal direction of the external veneers.

To overcome the problem with low formability of the veneers in the transverse direction, the so-called “3D-veneer” has been developed. This veneer can be formed extremely three-dimensionally. This special veneer was developed by the company Reholz GmbH and has now been successfully introduced onto the market (Müller, 2006). During the production of 3D veneers, narrow grooves spaced 0.1 to 1 mm apart and through the thickness of the veneer are introduced into an ordinary veneer along the fibre direction. To keep the wooden strips together, lines of glue are spread on the rear of the veneer, Figure 4. Other type of 3D-veneer also occurs in various products.
**Ageing of wood**

Wood ageing is a further development of classical thermal-treatment processes currently used industrially at temperatures between 150 and 260°C. Compared to these thermal-treatment processes, wood is aged at lower temperatures (100-150°C). The negative effects that a classical thermal treatment normally has on the strength and brittleness of wood are therefore reduced. The main purpose of this development is to increase the use of thermally treated wood in construction, enabling its use for load-bearing construction elements. Obataya et al. (2000) have studied the effect of artificial ageing on the mechanical properties of wood for use in the repair of ancient Japanese wooden constructions and in musical instruments. During the last year, this work has been continued in Europe by Froidevaux et al. (2012). No industrial process for ageing wood is however known today, but with all the knowledge built up during the development of the thermal treatment, it should not take long to reach an industrial implementation.

**Frictional wood welding and wood surface fusion**

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. It is stated that two pieces of wood can be welded by means of an oscillating or linear frictional movement. The time required for the welding process is short, taking less than a few minutes, and 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. Frictional welding techniques have also been shown to be viable for increasing the hardness of wood surfaces in the presence of oils (Pizzi et al. 2005).

Friction welded products still present several challenges which need to be overcome before the process can be applied on an industrial level. One weakness is that the absorption of water lowers the strength of friction-welded joints and limits their use in construction, but there is ongoing research to overcome this problem (Vasiri, 2011).

**Laser treatment for the TH processing of wood surfaces**

The phenomena that arise in wood at the micro-level during friction welding have an interesting relation to the laser treatment of wood. Laser treatment, depending on irradiation parameters, is a form of thermal treatment which is concentrated in space and time and exhibits effects such as a molten surface. Studies on the effect of laser irradiation on wood with respect to changes in structural, chemical and physical properties have led to the identification of laser parameters which guarantee melting wood without pyrolysis. This type of molten surface was observed by e.g. Sandberg (1999) during the preparation of weathered samples of pine and spruce with the help of UV-laser ablation (Seltman 1995). Haller et al. (2001) have investigated the effect of laser irradiation on wood with regard to changes in structural, chemical and physical properties, and they have identified the laser parameters which guarantee the melting of wood without pyrolysis. These laser treatments can be used to modify wood surfaces and to improve their mechanical or water-related properties. The technique is not well developed and further research is needed before the commercial potential can be evaluated.

Laser has also been used for engraving of wood, which is one of the most promising technologies for use in wood carver operations (Leone et al. 2009). In this method, a laser beam is used to ablate a solid piece of wood, following predetermined patterns. The sculpture is obtained by repeating this process on each successive thin layer.
CONCLUSIONS

The TH/THM processing techniques discussed in this presentation can be utilised to enhance wood properties, to produce new materials and to develop new products with a low environmental impact. These processes are at various stages of development, and the challenges that must be overcome in scaling up to industrial applications differ among them. The benefit of THM treatments are that several process parameters may be manipulated to create intermediate or final products with a broad range of applications and the treatments should be used for high-value product applications. Understanding these treatments requires, however, the appropriate scientific knowledge of the wood.

At the present time, the technology of several TH/THM wood processes has been industrialized and their products are being commercialized, and ongoing research in the field of wood THM moulding 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 TH/THM treatments are advancing at the laboratory level, e.g. wood welding and the ageing of wood. However, one challenge that all TH/THM developments need to consider is the economic viability of the industrial scale production.

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