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ISBN: 978-91-89821-99-6

Transparent Trä som laminat i Glas

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SMART HOUSING SMÅLAND

SHS rapportnr: 30101

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Sammanfattning

Transparent wood and glass were laminated to provide a sandwich structure that can be used in building applications such as windows. In this project, a novel transparent wood/glass laminated composite material was developed with attractive optical properties, thermal insulation and mechanical performance. The objectives of this project were to gain understanding on the processing of sandwich structures combining glass with wood materials, evaluate the adhesion properties between the glass and wood layers, and finally to design a prototype demonstrator of transparent wood/glass laminates as energy-efficient and robust materials for structural applications. The functionalization of the transparent wood with functional nanoparticles was also investigated to provide added functionality such as UV and temperature response for smart windows. We expect that this novel transparent wood/glass laminated composite will be attractive for smart housing design.

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Bakgrund

The building sector accounts for 37% of global CO_2 emissions, and glass windows are responsible for around 15% of energy loss in buildings. Therefore, lowering the carbon footprint of window building materials during their production and use phase is needed for sustainable development. This can be achieved via the design of novel multifunctional hybrid components for energy-efficient windows. Wood is a renewable material that has been used in buildings for millenniums owing to its robustness combined with thermal insulation properties. The development of advanced engineered transparent wood/glass composite materials for window applications could revolutionize the building sector toward smart and energy-saving housing.

Wood is a sophisticated bio-based material with a natural hierarchical, anisotropic, and porous structure. The wood cellular structure can be functionalized at the micro and nanostructural level for the design of advanced functional materials. In recent years, the development of transparent wood biocomposites derived from delignified wood substrates has gained interest because they combine attractive structural properties with optical functionality. Dr Céline Montanari has played an essential role in the development of transparent wood together with the team of researchers at KTH since it was first developed in 2016.[1,2] Structural tailoring of transparent wood biocomposites is required to improve optical transmittance, mechanical performance, and to add new functionalities. The aesthetic and optical properties of transparent wood make it attractive for various applications where transparent wood can bring added value and provide unique optical features. In this project, transparent wood/glass laminates will be investigated as energy-efficient and robust materials for smart windows. Glass is commonly laminated into a sandwich structure with fossil-based polymer interlayers to improve its mechanical properties and reduce safety hazards when the glass is broken. Here we suggest using sustainable transparent wood as a lamination layer to replace commonly used fossil-based ethylene-vinyl acetate (EVA) or polyvinyl butyral (PVB) lamination foils.

The combination of wood and glass in new innovative ways has been the driving force in many prototypes. Wood has been combined with glass in different ways and the latest prototype of that kind laminated together different kinds of wood with glass. These have been tested as both interior walls and exterior details such as facade material Several prototypes that demonstrate different areas of use are intended to be developed in this project. The optimal product and the visionary goal is a laminated product where the laminating film itself is replaced with just transparent wood. It would provide a bio-based laminating foil that challenges current polymer-based PVB and EVA foils. Such a prototype would be the final marriage between wood and glass. The objectives of this project were to gain an understanding of the processing of sandwich structures combining glass with wood materials and evaluate the adhesion properties between these layers. We also expect that this novel transparent wood/glass laminated composite will be attractive for smart housing design.

Viktigaste resultat

Wood is an anisotropic cellular material with a defined organization at various structural levels.[3] The wood hierarchical structure extends from the macroscale (stem level), to the microscale with the tissue structure (growth rings), and down to the nanoscale with the assembly of the cell wall layers and biopolymers (cellulose, hemicellulose, lignin). The structure of the wood tissue differs among species – softwoods *versus* hardwoods – and among individual trees since wood is produced by a natural growth process and adapts to the environment in which it develops.[4] Hardwoods feature a more complex microstructure than softwoods with specialized cells. At the tissue level, hardwoods mainly contain vessel elements (100-200 μm wide) and fiber cells (20-30 μm wide) extending in the longitudinal direction, the cell wall thickness is about 3 μm. Hardwoods are interesting wood species because of their unique microstructural features that can provide opportunities for functionalization and the development of new sustainable and high-performance materials. In this project, veneers from birch, beech and ash hardwood species were used as starting materials for the transparent wood composite fabrication (**Figure 1**).

Figure 1. Wood species evaluated in this project for the preparation of transparent wood composites.

Besides its natural anisotropy and cell wall nanostructure, wood features a hierarchical porosity. However, the low permeability of the dense wood cell wall remains a major challenge for wood functionalization, and improving cell wall accessibility is needed to allow functionalization of the cell wall at the nanoscale. An efficient approach to improve the wood cell wall accessibility in wood substrates is the partial and selective removal of wood components. Delignification treatments enable the full or partial removal of lignin while preserving the anisotropic wood cellular structure and cell wall nanostructure.[5–7] For wood substrates, structure-retaining delignification can be applied to selectively remove lignin while retaining cellulose and hemicelluloses. Partial lignin removal generates porosity, both at the microscale in the middle lamella/cell corner regions and at the nanoscale inside the cell wall. Transparent wood biocomposites are obtained from wood substrates by a two-step procedure, which consists of 1) a delignification treatment to remove the light-absorbing chemical groups from wood and increasing porosity, followed by 2) monomer filling and in-situ polymerization to form a polymer with a refractive index close to that of the wood cell wall.

In this project, a sodium chlorite delignification treatment was applied to selectively remove lignin and associated chromophores from native wood veneers (birch and ash), resulting in white delignified wood substrates of high porosity. After delignification, the lignin content is reduced to less than 2%, while most of the hemicelluloses (28%) are retained and the cellulose content is high (70%).[8] The wood cellular morphology and microstructure are preserved after delignification, and porosity is generated at the micro and nanoscale in the cell wall (**Figure 2**).

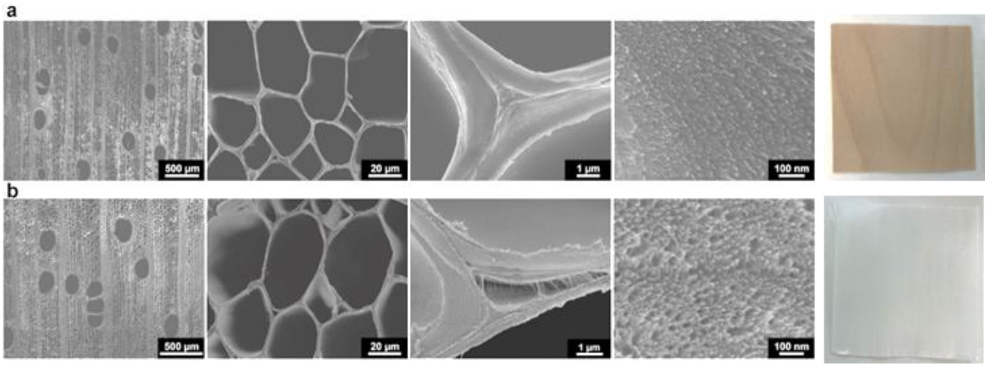

Figure 2. a) High-resolution SEM micrographs of native wood (a) and delignified wood (b), with increasing magnification from left to right (adapted from [8]).

Transparent wood biocomposites and glass laminates were then prepared by 1) impregnating the delignified wood veneers with methyl methacrylate (MMA) monomer, 2) laminating the impregnated wood between two glass slides, followed by 3) polymerization of the monomer to polymethyl methacrylate (PMMA), see **Figure 3**. The final product is a transparent wood/glass laminate, where the transparent wood acts as the adhesion layer and reinforcement for improved toughness. The glass slides enable the protection of the transparent wood against humidity exposure.

Figure 3. Schematic of the preparation procedure of the transparent wood/glass laminates.

Transparent wood/glass laminates were prepared using glass slides of various thicknesses and with transparent wood prepared either from birch wood or ash wood species. The resulting transparent wood/glass laminates of various thicknesses are displayed in **Figure 4**.

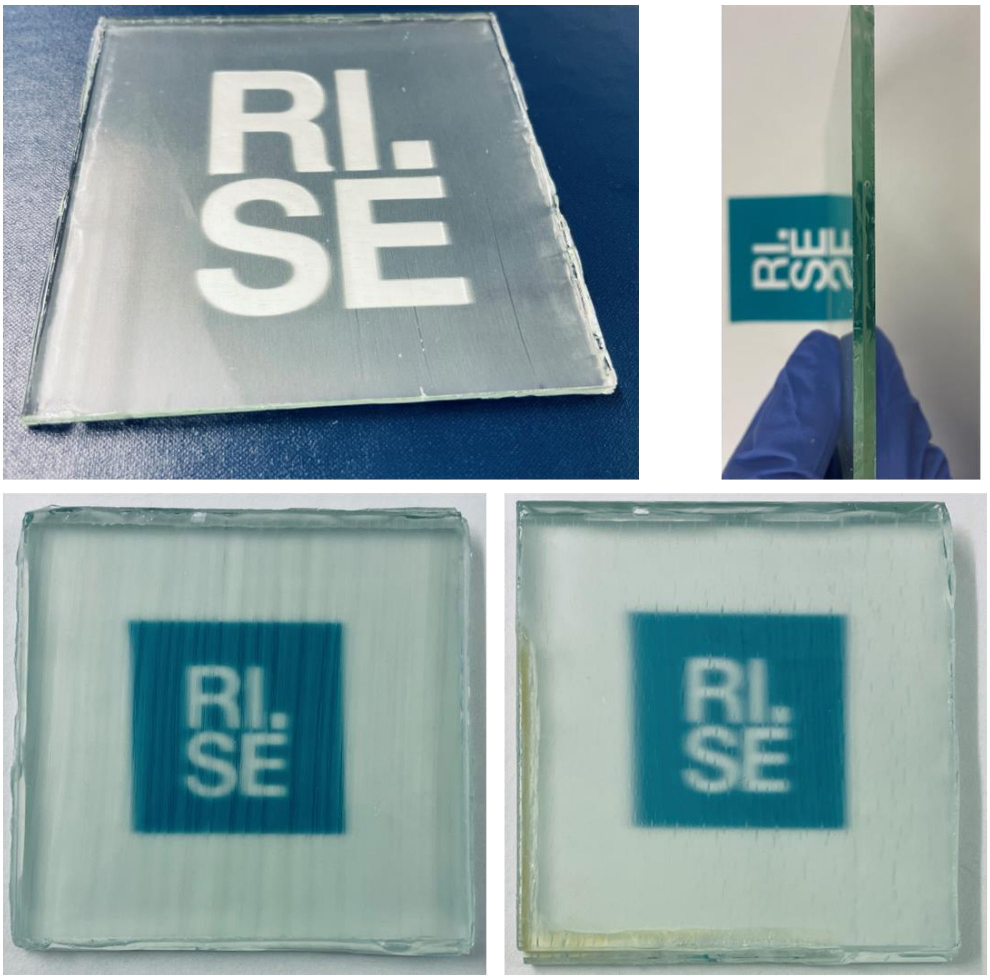

Figure 4. Photographs of the 5 mm thick (top) and 10 mm thick (bottom) transparent wood/glass laminates produced using birch and ash wood species respectively.

Transparent wood biocomposites demonstrate high optical transmittance (80-90%), tunable haze (30-70%), high toughness and low thermal conductivity. Hence, the sustainable transparent wood layer in the glass sandwich structure has for function to improve toughness and thermal insulation properties and to provide unique optical and aesthetic properties. Transparent wood composites exhibit favorable anisotropic mechanical properties with tensile strength up to 270 MPa and elastic modulus of 20 GPa in the longitudinal direction (parallel to the fiber).[9] The tensile properties are dependent on the wood volume fraction,[1] and high-density wood species such as birch and beech are desired for improved mechanical performance. The optical properties of TW are attractive because it provides both high transmittance (90% for 1.5 mm thick)[10] and high haze (80% for 1 mm thick).[11] The haze can be controlled by replacing the PMMA matrix with other polymers, such as bio-based limonene acrylate, reducing the haze down to 30% only. TW biocomposites demonstrate attractive insulating properties with low thermal conductivity of 0.3 W m^{-1} K^{-1} along the fiber direction which is 5 times lower than glass.[11]

The impact energy of the transparent wood/glass laminate obtained via hammer impact tests is much higher than normal glass and reaches up to 1.3 J for 5 mm thick samples. In addition, the laminated samples did not shatter upon impact but only cracked while retaining their integrity because of the wood fibers. Therefore, the transparent wood layer provides safety and prevents dangerous glass-shattering effects.

The compatibility between the glass and transparent wood layer is favorable, with PMMA acting as an interface layer between the glass and transparent wood. Indeed, the confocal Raman microscopy images in **Figure 5** demonstrate excellent adhesion between the various interfaces in the transparent wood/glass laminates, i.e. glass/PMMA and PMMA/wood interfaces.

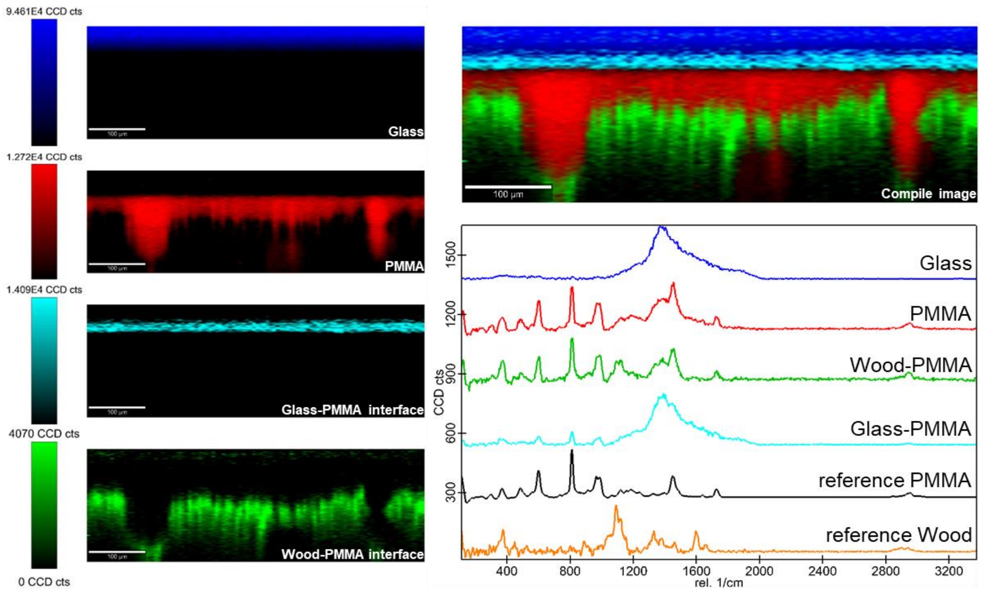

Figure 5. Confocal Raman microscopy images and Raman Spectra showing the various layers and interfaces in the transparent wood/glass laminates.

Further functionalization of transparent wood biocomposites by active molecules or inorganic nanoparticles is interesting to extend the concept for engineering applications. The wood structure can be functionalized in various ways at the nanoscale to provide added functionality to the bulk material. Multifunctional transparent wood layers combining optical transmittance with other functions can be designed by the addition of a functional third-phase component to the polymer matrix and/or the cell wall (**Figure 6**).[12] For example, quantum dots were added to the polymer matrix to obtain TW with luminescent properties,[13,14] while heat-shielding properties could be obtained by the inclusion of near-infrared absorbing nanoparticles.[15,16] The main challenge when designing multifunctional composites is to achieve component diffusion inside the cell wall to fully utilize the wood structure and create a nanomaterial effect to maximize performance.

Here, the development of smart transparent wood/glass laminates was also investigated by embedding functional nanoparticles inside the wood structure. Smart transparent wood/glass laminates with thermo-responsive and UV-responsive properties were prepared as demonstrated in Figure 6c. The Transparent wood/glass laminates turned black upon heating above 35 °C or exposure to UV. This can be used for energy-saving applications in smart housing.

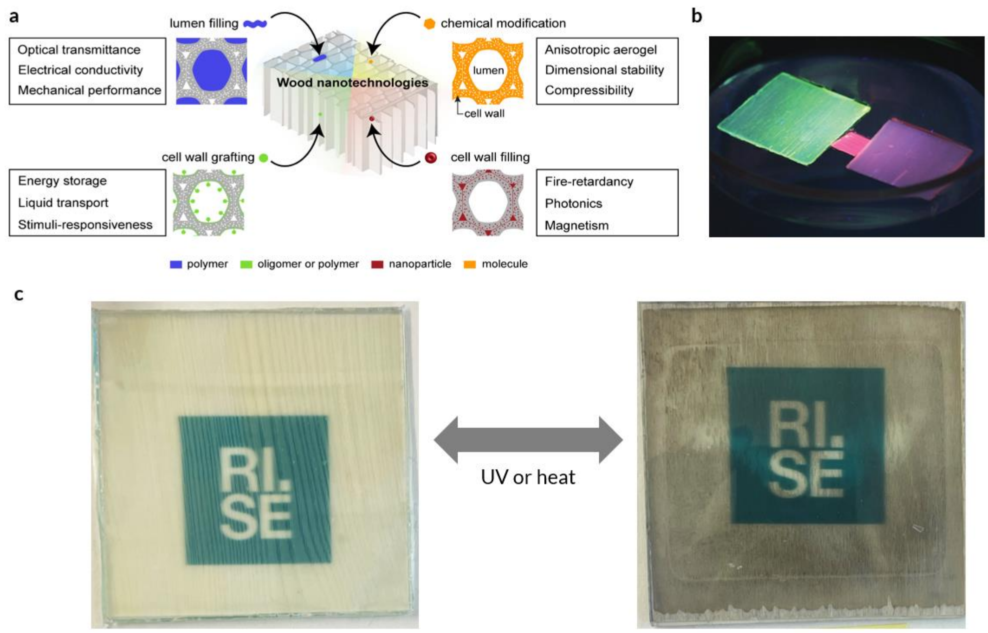

Figure 6. a) Functionalization of transparent wood by embedding nanoparticles inside the wood structure.[12] b) Luminescent transparent wood with embedded quantum dots.[13] Smart transparent wood/glass laminate with UV and thermo-responsive properties.

Fortsättning

The project results show the elegant assembly of glass and wood together in a laminated transparent wood/glass material. This novel material offers a wide range of attractive properties. To further improve the mechanical performance, the preparation of transparent wood plywood (0°, 90°)[17] would be interesting to further increase the mechanical performance of the transparent wood/glass laminates. The potential for the scalability of transparent wood is high,[10,18,19] which is promising for the scalability of the transparent wood/glass laminates.

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Genomförandeorganisationerna RISE, Linnéuniversitet, Jönköping University och Träcentrum i Nässjö i Smålandsregionen. I samverkan ingår förutom finansiärerna representanter från näringslivet genom OBOS, Tengbom, CBBT- Centrum för byggande och boende med trä, TMF – Trä och möbelföretagen, Sveriges Träbyggnadskansli, Glasbranschföreningen, Glasforskningsföreningen Glafo och dessutom de tre länens Länsstyrelser. Utöver detta sker samverkan med andra universitet, innovationsplattformar och samverkanskluster både nationellt och internationellt.

Finansieras av:

Koordineras av: