Nanomaterials in the forest products industry

Nanotechnology is the study and engineering of matter at the dimensions of 1–100 nm where physical, chemical, or biological properties are fundamentally different from those of the bulk material. The nanotechnology paradigm is to modify bulk properties and functionality by controlled manipulations at the nanoscale. Nanotechnology research has dramatically grown within the past 10 years because of recent developments in nanoscale characterization techniques, processes, and understanding of material behavior at the nanoscale. By expanding our understanding and control of matter at such levels, new avenues in product development can be opened. Nano-based science has applications across nearly all economic sectors and allows the development of new technologies with broad commercial potential within the forest products industry.

Forest products industry. Wood has been widely used as an engineering material for thousands of years because of its availability and unusual ability to provide high mechanical strength and high strength-to-weight ratio while retaining its toughness. Wood has also been used as a material source for a variety of composite products based on wood chips and flakes, wood sawdust (wood flour), wood fiber (individual wood cells), and recently cellulose nanomaterials. The forest products industry produces many items, such as solid wood lumber, wood-based composites (plywood, oriented strandboard. fiberboard, three-dimensional engineered fiberboard), engineered structural members (I beam, finger-jointed wood), wood-plastic composites (decking), paper products (paper, filters,

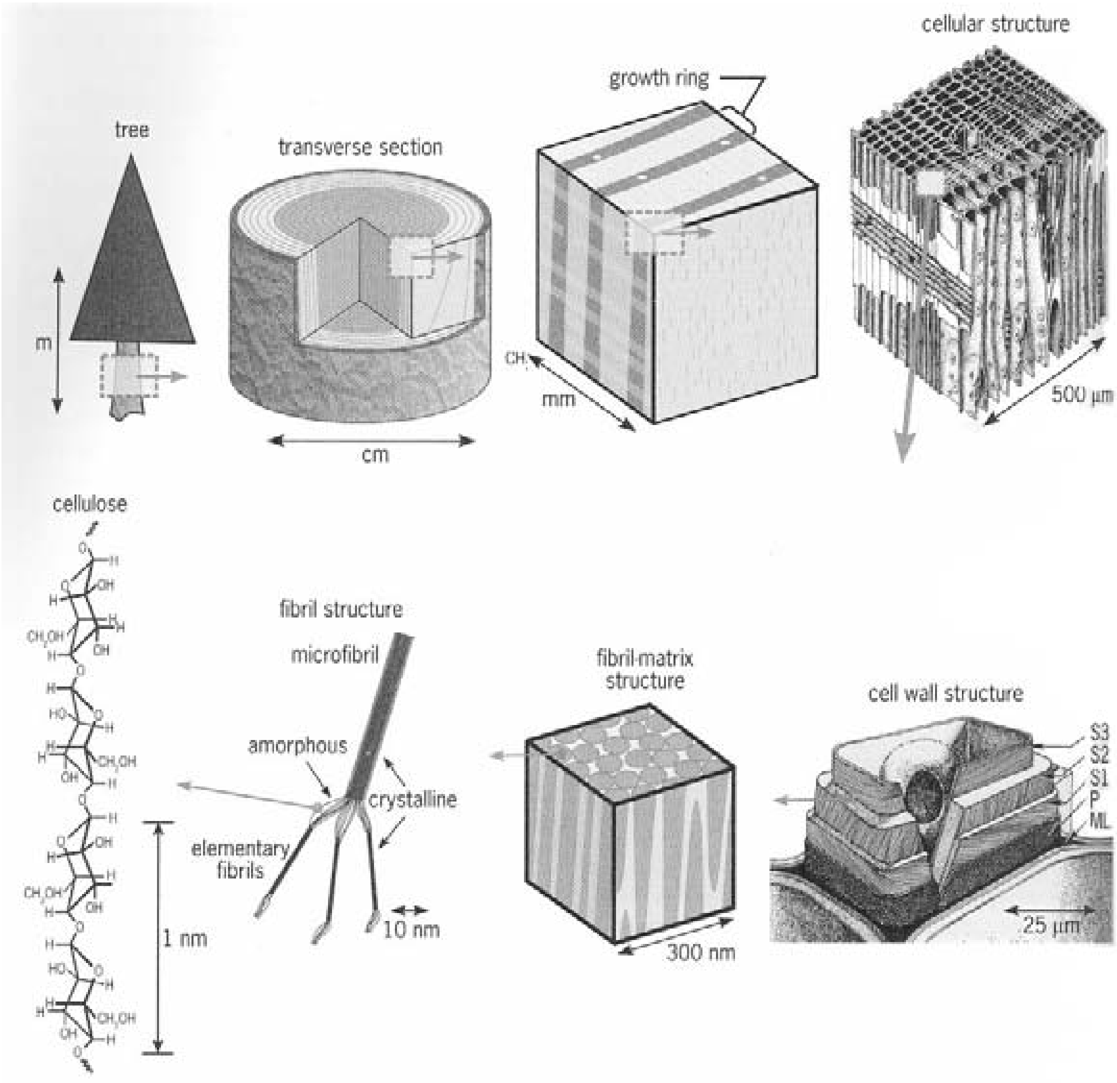

Fig. 1. Hierarchical structure of wood, showing the size scale of each structural feature within wood. The linear polymer chains of cellulose (30% of wood by weight) arrange to form cellulose fibrils, which are the base strengthening component within wood. ***(Adapted from R. J. Moon, C. R. Frihart, and T. Wegner, Nanotechnology applications in the forest products industry, Forest Prod. J., 56(5):4–10,2006)***

corrugated containers), and products that are used in conjunction with wood (adhesives, coatings/paints, stains, stabilizers).

Nanotechnology offers the potential to transform the forest products industry in virtually all aspects, including production processes (raw materials, engineered wood and wood-based materials), improved energy efficiencies, new applications for composite and paper products, and composites made from cellulose nanomaterials. Additionally, there are opportunities to use new products in conjunction with wood-based materials to improve a particular function. For example, an array of built-in nanosensors within wood- and paper-based products can be used to monitor force, moisture level, temperature, pressure, chemical concentrations, and attack by wood decay fungi. More traditionally, nanofillers can be used within wood or wood composites, offering new opportunities to improve durability (with regard to wear, ultraviolet or biological decay, fire, and dimensional stability) or to improve chemical bonding with paints, sealants, and adhesives. Also, by building functionality onto the surfaces of cellulose nanomaterials, new opportunities for products such as pharmaceuticals, chemical sensors, self-sterilizing surfaces, and electronic wood-based devices may be achieved.

Structure of wood. Nanoscale manipulation of wood occurs near its smallest structural scale **(Fig. 1).** Wood is a hierarchical structured composite, in which several unique structures span several length scales: growth ring structure (each ring represents one growth year), cellular tissue structure, multilayer cell wall structure, fibril-matrix struc ture within each cell wall layer, cellulose microfibril structure, and the structure of the three main polymer components (cellulose, hemicellulose, and lignin). Bulk properties of wood result from the culmination of interactions within and between each structural scale. The last three structural scales mentioned above are the realm of nanotechnology research of wood, which occurs in two general categories: (1) controlled manipulation of the three main polymer components through various treatment processes (chemical or genetic modification) to modify bulk properties, and (2) removal of the polymer components and processes to make new materials based on these starting materials (such as cellulose nanowhiskers).

Cellulose nanowhiskers. Cellulose is the world's most abundant biopolymer and is present in virtually all plants. Its main function is to act as a reiinforcement material. Cellulose is a linear chain of ringed glucose monomers (10,000 to 15,000) linked together. Multiple cellulose chains arrange to form cellulose microfibrils having regions that are disordered (amorphous regions) or highly ordered (crystalline regions). Microfibrils have diameters of 3–20 nm and lengths that can reach several micrometers, depending on the source of the cellulose (plant, wood, or bacteria). Cellulose nanocrys tals are obtained by acid hydrolysis of microcrystalline cellulose, in which the more chemically reactive amorphous regions within microcrystalline cellulose are dissolved. The remaining crystalline cellulose is nano-sized and has a rod or whisker shape (length: 100–300 nm, diameter: 3–5 nm, for wood cellulose source) **[Fig. 2].** The tensile modulus (the ratio of stress to elastic strain in tension) of these crystalline particles is estimated to be 150 GPa [(10^9 kg/m^2)], which is greater than that of Kevlar® (130 GPa; Kevlar® brand fiber is an innovative technology combining high strength with light weight).

Not all cellulose nanocrystals are the same; aspect ratio and surface chemistry are different depending on the cellulose source (wood, plants, bacteria) and the production process (type of acid used during the acid hydrolysis, or any additional chemical reaction used to intentionally modify the cellulose nanocrystal surface chemistry). Research is being conducted on several aspects of cellulose nanocrys tal processing science, including (1) characterization of nanowhisker properties from various sources and various production routes, (2) development of new low-cost, large-scale production routes (enzymes, cow-digested fiber, and as a by-product of other industrial wood processes), and (3) new chemical treatments for modifying the nanowhisker surface chemistry.

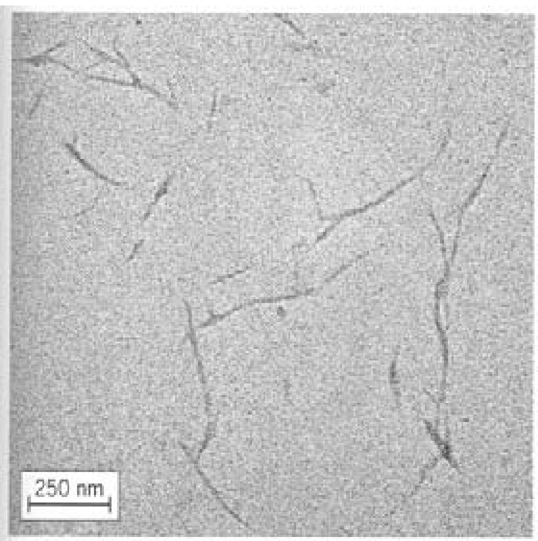

Fig. 2. Transmission electron microscope image of a cellulose nanocrystal. ***(Courtesy of James Beecher, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin)***

Strength and stiffness of reinforcement materials*

Material	Tensile strength, GPa	Modulus, GPa
Cellulose nanocrystals	7.5	150
Glass fiber	4.8	86
Steel wire	4.1	207
Kevlar	3.8	130
Graphite whisker	21	410
Carbon nanotubes	11–73	270–970

***Data taken from <http://woodscience.oregonstate.edu/faculty/simonsen>.**

Cellulose nanowhiskers offer several advantages as a reinforcement particle. They have a high aspect ratio, high stiffness, and a unique surface chemistry. The reinforcement efficiency is enhanced by this high surface area and aspect ratio, resulting in better reinforcement with less material than is possible with larger sized particles (such as wood fibers). The specialized surface chemistry offers new applications that exploit this chemistry (for example, dispersion in new matrix polymers, self-assembly, chemical sensors). Additionally, cellulose nanowhiskers can be considered as a green technology because they are naturally produced, are biodegradable, and are likely to have lower health risks if ingested or inhaled than those associated with other reinforcement materials. Cellulose nanowhiskers also have comparably low production costs. These advantages make up for some of the shortcomings in properties as compared to other reinforcement nanoparticles, such as carbon nanotubes (see **table**). Interestingly, some researchers are coating carbon nanotubes with cellulose nanowhiskers to change the surface chemistry of the carbon nanotubes while retaining their mechanical properties.

Cellulose nanowhisker composites. The addition of cellulose nanowhiskers to bulk composites, panels, or thin films has been demonstrated to improve composite thermal stability, mechanical strength, toughness, and flexibility. The arrangement of cellulose nanowhiskers within composites and films has a major effect on the final properties. Recent research has focused on new chemical treatments to tailor the surface chemistry of the nanowhiskers for controlling the degree of dispersion within the matrix material and to control the bonding strength between the nanocrystalline particles and the matrix material, both of which strongly influence the resulting composite properties. A major challenge is in minimizing nanocrystal particle agglomeration (that is, grouping together large numbers of particles) so that the desired level of reinforcement particles can be added while still achieving a uniform dispersion within the polymer matrix. Researchers are also investigating the optimum nanocrystal structural organization within composites for a desired property and developing assembly techniques necessary to produce these desired structures. Electric fields, magnetic fields, and shear deformation have been used to improve the nanowhisker alignment. For more complex nanowhisker arrangements, techniques using self-assembly and nanomotors are being investigated.

Some potential consumer applications for cellulose nanowhiskers will be in the production of biodegradable, lightweight, and high-strength composite panels in the electronics, automotive, and aerospace industries. Additionally, cellulose nanowhiskers have been used as the reinforcement network structure in the development of robust, flexible, durable, lightweight, and dimensionally stable films. These reinforcement films are seeing applications in razor-thin flexible display screens, polymeric fuel cell membranes, and barrier applications. For barrier applications, the surface chemistry, high surface area, high aspect ratio, and small pore size of the nanowhisker network assembly are used to filter a number of toxic industrial chemicals. By modifymg the surface chemistry and the spacing of the nanowhiskers, different toxins can be selectively filtered.

Outlook. Nanotechnology has the means to revolutionize the forest products industry, both by providing new opportunities for current product improvements and by developing new applications of cellulose in a wider consumer products realm that is outside the scope of the traditional forest products industry. Cellulose nanowhiskers are a unique particle that can be manipulated for the development of specified properties in various applications such as reinforcement for polymers and specialized barrier films.

For background information *see* CELL WALLS PLANT); CELLULOSE; NANOSTRUCTURE; NANOTECHNOLOGY; WOOD ANATOMY; WOOD COMPOSITES; WOOD ENGINEERING DESIGN; WOOD PROCESSING; WOOD PRODUCTS; WOOD PROPERTIES in the McGraw-Hill Encyclopedia of Science & Technology.

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