From Nano- to Macromechanical Properties of Wood via the Hierarchy of Its Structural Units and Size Effects (A Review)

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Abstract—A review presents the results of current studies of wood’s hierarchical structure using modern physical means on the nano- to the macro scales. Relationships between structure and mechanical properties at these levels are discussed. It is shown that size effects in wood strength obey the Hall—Petch relationship in a range of around six orders of magnitude of structural unit characteristic sizes.

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INTRODUCTION

By the beginning of the 21st century, it had become obvious that the continuously growing amounts of extracted mineral resources (especially different ores, nonmetallic minerals, coal, oil, and gas) and open-loop technologies for their processing increase the amount of industrial and domestic waste. This poses a threat to the biosphere, due to the environmental pollution and an increase in the concentration of carbon dioxide in the atmosphere. The low proportion of materials that are recycled exacerbates the situation. Added to this is the accelerated growth in the production of packaging polymeric materials, the lion’s share of which are not biodegradable and a considerable amount is not recycled. The growing pressure on the environment requires more and more efforts and ways of neutralizing it.

One promising solution is to replace traditional materials with ones that contain cellulose—primarily modified wood, vegetable waste from agriculture, and especially the nanocellulose inside them. Cellulose is the most widespread natural linear polymer in the biosphere, polysaccharide \((\text{C}_6\text{H}_{10}\text{O}_5)_n\). Materials based on it have many advantages:

- Unlike the vast majority of mined minerals, cellulose-containing materials have renewable, stable sources of raw materials: forests, field crops, and aquatic resources.
- These materials are multifunctional and can be used in construction and many other industries \([1–6]\), medicine \([7–9]\), and everyday life \([1, 2]\).
- They are technological and non-toxic.
- An attractive feature of biocomposites (the role of which is growing every year) is their biodegradability—self-destruction after the end of their service life without the formation of toxic products \([1–6]\).
- They can be used to organize a closed carbon cycle that does not increase the content of carbon dioxide in the atmosphere and greenhouse effect that raises the average annual temperature on Earth.
- Nano- and microstructural components in the structure of wood (nanocrystals, nanofibrils, and cellulose microfibers) have mechanical characteristics comparable to or exceeding those of high-strength structural materials (steels, titanium and aluminum alloys). The specific strength of nano- and microcellulose can be an order of magnitude or more greater than in steels (allowing for 80% lower density \(\rho \sim 1.5\ \text{g/cm}^3\) versus \(\sim 8\ \text{g/cm}^3\) in steel).

Of course, wood and other cellulose-containing materials also have a number of disadvantages. Without additional processing, they are combustible and hygroscopic. They lose some of their strength as humidity rises, and are prone to decay and biodamage. In addition, the mechanical properties of wood of any species depends strongly on the conditions of growth, testing, and operation: humidity, the structure of cell walls and annual growth rings, the proportion of early and late wood, the stress state, sample or loaded area size, load application rate, duration and direction. This makes it difficult to identify the broadest patterns of the mechanical properties of wood of different species. However, the literature data and accumulated experience allow us to make some generalizations, which are outlined below.
This review considers the means and results from a multiscale study of the structure and mechanical properties of wood of different species, allowing for the nano-, micro-, and mesoscale structural levels of its structure. At the end of our analysis of the literature data, it is shown that in a huge range of the characteristic dimensions of a structure (about six orders of magnitude), the mechanical properties of wood generally follow the Hall–Petch relationship familiar to metallurgists.

**Fig. 1.** Scale-hierarchical levels of wood structure. (1) polymer cellulose molecule, (2) elementary nanofibrils, (3) hemicellulose, (4) lignin, (5) nanocrystalline zone, (6) amorphous zone, (7) primary cell wall, (8, 9, 10) layers S1, S2, S3 of the secondary cell wall, (11) tracheid (capillary), (12) annual rings, (13) tree.

This review considers the means and results from a multiscale study of the structure and mechanical properties of wood of different species, allowing for the nano-, micro-, and mesoscale structural levels of its structure. At the end of our analysis of the literature data, it is shown that in a huge range of the characteristic dimensions of a structure (about six orders of magnitude), the mechanical properties of wood generally follow the Hall–Petch relationship familiar to metallurgists.

**HIERARCHICAL STRUCTURE OF WOOD**

From the viewpoint of physical materials science, wood is a hierarchically complex structured natural composite material with pronounced heterogeneity and anisotropy of all properties, along with the ability to regenerate [10–13]. Several scale-hierarchical levels can be distinguished loosely in the structure of wood (Fig. 1): atomic/molecular, nano- (nanocrystals, nanofibrils), micro- (microfibers, cell walls), meso- (cells, large vessels), and macro- (e.g., annual rings, structural macrodefects, and cracks). Each of these contributes to the set of wood physicochemical and mechanical properties. The wide range of characteristic sizes of the structural components of wood (6–8 orders of magnitude), and the wide range of tasks and problems that arise in studying it, require an arsenal of research techniques and tools for their implementation. They are briefly analyzed in the next section.

The most important aspect of wood science is the roles of nano-, micro-, meso- and macrostructures in the formation of wood macroscopic properties. There are many reasons for this interest in the relationships between the macromechanical properties of wood and its nano- and microstructure. First, such patterns clarify the nature and mechanisms of the most important practical physical and mechanical properties of wood on the macroscale. Second, nanomechanical strength characteristics, being appreciably greater than those on the micro- and macrolevels, testify to the potential for strengthening close to the theoretical limit of nanocrystalline cellulose (~10 GPa). Third, the growing use of composite materials in different fields of technology, construction, and medicine allows us to replace traditional metals and alloys with lighter and more environmentally friendly composites. The fuse-lages of the latest models of Boeing and Airbus aircraft are already more than 50% reinforced composites by weight. They are gaining popularity in other fields as well, e.g., the automotive industry, shipbuilding, and sports equipment. However, glass or basalt fiber (not to mention micro- and nanocarbon) used for reinforcement is very expensive and still cannot claim a
Cellulose fiber is around an order of magnitude cheaper than glass fiber and not necessarily inferior to it in terms of mechanical characteristics. It is therefore highly relevant to deepen our understanding of the strength and mechanisms of the fracture of microcellulose fibers, fabrics, and non-woven materials made from them, and to find ways of improving their durability. Finally, many tree species growing for several hundred and sometimes thousands of years (e.g., sequoia) accumulate large amounts of information about the climatic conditions of growth and environmental disasters in their nano-, micro-, meso- and macrostructures. This natural archive can serve as a source of information for climatology and the dating of different events in the history of the Earth (dendrochronology).

PHYSICAL WAYS OF STUDYING THE STRUCTURE AND PROPERTIES OF WOOD AT DIFFERENT HIERARCHICAL LEVELS

The classical materials science of wood focuses on identifying and describing the dependence of its macromechanical, physicochemical, and other service properties on internal structural characteristics and external thermodynamic factors [14–21]. Over the last 20 years, growing attention has been given to the fine structure of wood at the nanolevel. This was made easier by both the development of nanotechnology and nanometerology, and the realization that untapped reserves lie at the nanolevel.

In the two decades, modern procedures and tools used in solid state physics and physical material science have been increasingly involved in studying the microstructure and properties of wood [2, 3, 22–24]. Microstructure is studied via transmission and scanning electron microscopy, scanning probes (mainly atomic force), and confocal laser and optical microscopy in a variety of modes [2, 3, 25–27]. A wide range of X-ray techniques are used to determine the composition and microstructure of wood down to the atomic level. The character and degree of ordering of cellulose molecules in nanofibers, and the angle between microfibers and the long axes of cells, are determined by means of X-ray diffractometry [2, 3, 28–30], microtomography [31, 32], synchrotron X-ray radiation [33], and small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) [2, 3]. Elemental and molecular composition is determined by various spectroscopic means. These include X-ray fluorescence [34], infrared (IR) and Fourier transform IR (FTIR) spectroscopy [35–39], Raman spectroscopy [39–42], Brillouin spectroscopy [43], nuclear magnetic resonance (NMR) spectroscopy [44], and other types of analysis. Together, they cover a huge spatio-temporal range of structures and the processes in them (Fig. 2a) [45]. Comparative analyses of the capabilities of the most common physical means of studying the molecular, subcellular, and cellular structure of wood can be found in [14, 45].

Mechanical properties on the nano- and microscales are studied by means of nano/micromechanical testing (SSMT, or small scale mechanical testing) [46–49], most often using atomic force microscopes (AFMs) [50–53] and nanoindentometers (NIs) [54–62] (Fig. 2b). Their structural schemes and capabilities are similar [55–57]. In both cases, a probe with a radius of curvature of units (in AFM) to tens (in NI) of nanometers is brought to the tested surface by precision drives and begin to interact with it. Force \( P \) and depth of penetration \( h \) of the probe are measured continuously, and the kinetics of their
changes is recorded throughout test cycle. A $P$–$h$ diagram (an analog of the $\sigma$–$e$ diagram during macro-tests) is then plotted on the basis of these data, and standardized algorithms are used to obtain around a dozen different mechanical characteristics of the material (e.g., Young’s modulus, hardness, fracture toughness, and the creep rate) on the nano- and microscales. NI uses a trihedral Berkovich diamond pyramid, which is superior to AFM in terms of actual vertex geometry and provides more accurate and reliable data.

The mechanical properties of individual cellulose nanofibrils and microfibers [63–67], cell walls [45, 68–74], and annual rings of wood of different species have been studied via SSMT, yielding a great deal of interesting information. However, it was largely for specific locations in a structure and did not involve scanning or mapping the mechanical properties of a region covering several annual growth rings. This prevents us from tracing the relationship between the properties of individual nano- and microstructure elements of wood and its macromechanical properties.

In contrast to microstructural and physicochemical studies of wood, the main tool for studying and analyzing annual growth rings from the view point of dendrochronology, dendroclimatology, and predicting strength and other useful properties are simple optical means in which the raw data are based on the difference between the reflectivity of early and late wood (EW and LW, respectively) [75]. Purely geometric and morphological characteristics of an object can be obtained (e.g., the thickness of annual growth rings, the fraction of EW and LW in them, and their variation from ring to ring). Data obtained by different means were compared and analyzed in [76]. Numerous attempts have been made to improve the traditional means of dendrochronology, mainly by modifying procedures of sample preparation and using blue instead of white light, technologies of visualization, and mathematical data processing [27, 77–85]. Despite this, the capabilities of the approach based on photographic recording and analysis of the images of cross sections remain very limited, since the reflective optical properties of wood vary greatly and are unclearly or weakly related to its other physical characteristics, especially its mechanical properties.

In [31–33, 86, 87], attempts were made to apply modern physical means to dendrochronology, where information must be obtained not at one point but along the radial coordinate at least. Two-dimensional mapping of properties on a cross section of a tree trunk, and 3D X-ray [31, 32] and NMR tomography [43] have also been used. They were briefly described and compared in [58]. However, they are time-consuming, difficult to employ, and require expensive or unique equipment. They are therefore used only sporadically. A simpler technique is X-ray densitometry [88], but it requires bilateral access to a flat sample cut that is strictly perpendicular to the long axes of the cells.

Note that the mechanical properties of cellulose-containing materials depend strongly on the rate of monotonic loading, the frequency of an oscillating load, and the duration of applying force. They can vary from sample to sample and change during operation over a much broader range than in architecturally similar technogenic composites (e.g., in reinforced glass and carbon fiber reinforced plastics) [6, 7, 89]. Such variability of properties further complicates identifying general patterns of their formation.

Cross-cutting relationships between properties at all scale-hierarchical levels, from cellulose nanocrystals to macrosamples, have yet to be fully studied. However, there is a great deal of information on each of these levels separately. It is considered below in the order of the increasing characteristic scale of a structure.

### NANOCELLULOSE AND ELEMENTARY NANOFIBRILES

The main material of which wood, the stems of cereals, reeds, bamboo, and other load-bearing plants are made is cellulose, the most common natural polymer. Cellulose is a high molecular weight polysaccharide ($C_{6n}H_{10n}O_{5n}$), in which glucose molecules are bound by $\beta-(1 \rightarrow 4)$ bonds into linear unbranched chains from several hundred to many thousands of $n$ in length [23] (Fig. 1). Cellulose can be of two origins, plant or bacterial [7, 9, 23]. Cellulose molecules easily form nanocrystals with diameters of 3–10 nm and typical lengths of 100–300 nm (Fig. 3a), from which nanofibrils 5–20 nm in diameter and up to thousands of nanometers long are formed (Fig. 3b). Cellulose in a nanofibril is in an amorphous-crystalline state in the form of alternating domains. The amorphous phase weakens the nanofibril somewhat, but it also makes it more flexible and plastic. Table 1 shows typical morphological characteristics of nanocellulose formations.

The mechanical properties of nanocrystalline cellulose (Table 2) have been determined by a variety of means that include calculating the strength of bonds in a macromolecule, computer modeling, IR and Raman spectroscopy, AFM, and WAXS. The scatter of the data is due to features of the calculating schemes, models and algorithms for processing primary data, and difficulties in directly measuring mechanical properties on the nanoscale. Differences between the age, structure, and origin of wood are also important in the second case.

### NANO- AND MICROFIBER CELLULOSE

A typical high-level wood structure hierarchy includes nano- and microfibers. These form as a result of interaction between elementary nanofibrils (mainly
through hydrogen bonds). Nanofibrils form bundles immersed in a matrix that consists mainly of lignin (the aromatic polymer polyphenol), hemicellulose (a low molecular weight branched polysaccharide),pectin (a gel-forming polysaccharide), and water [23]. The content of cellulose in fibers varies from 40 to 60% in different types of wood (it can be more than 96% in cotton fibers) [7, 9, 23].

Table 1. Structural characteristics of nanocrystals and elementary cellulose nanofibrils [67]

| Characteristics                        | Nanocrystals       | Nanofibers       |
|----------------------------------------|--------------------|------------------|
| Length of nanoparticles, nm           | 100–500            | ≥10³              |
| Transverse size of nanoparticles, nm  | 5–30               | 10–40            |
| Aspect ratio of nanoparticles          | 10–50              | 60–100           |
| Length of nanocrystallites, nm        | 70–200             | 60–150           |
| Transverse size of nanocrystallites, nm| 5–10              | 3–7              |
| Crystallinity, %                       | 72–80              | 50–65            |
| Fraction of the amorphous phase, %    | 20–28              | 35–50            |
| Density, g cm⁻³                        | 1.57–1.59          | 1.54–1.56        |
| Porosity, cm³ g⁻¹                      | 0.01–0.05          | 0.1–0.2          |
The nano- and microstructures of cellulose materials depend strongly on the nature of the interaction between nanocrystals and elementary nanofibrils, and on the degree of their ordering in nano- and microfibers. The properties of such materials do so as well. As in most other materials, the mechanical characteristics (strength in particular) of cellulose nano- and microstructures are sensitive to structure. The morphology and internal structure are determined in turn by the raw material’s origin, its degree of structural order, and the technology of cellulose isolation [23, 90–93]. A key role in the formation of a fiber’s properties is played by the degree of crystallinity and fraction of cellulose in the nanofiber, and the character of their bonding in the material. An important role in the formation of mechanical properties is played by the angle $\mu$ between the axis of nanofibrils and the axis of the fiber or cell.

The authors of [90] gave a variety of information on the morphology, microstructure, and mechanical properties of nanocellulose fibers of different origins (Fig. 4a), along with examples of using them as reinforcing components for strengthening polymer composites. The strongest of them have Young’s moduli $E$ of 75–85 GPa and tensile strengths $\sigma_b$ of 1.6–1.7 GPa ($E/\sigma_b \approx 50$) [66]. Such strong mechanical characteristics were a result of the ordering and crosslinking of nanofibers (Fig. 4b). According to fundamental concepts, the theoretical strength of any defect-free material should be about 0.1$E$, while the strongest microcellulose fibers described above have strengths of 0.015–0.020$E$. It follows that even the strongest tested cellulose microfibers have the potential for at least a 300–500% increase in strength.

It should also be noted that the data on the mechanical properties of cellulose microfibers obtained in different ways differ considerably (Table 3) [90]. Results obtained with AFM and NI agree with one another within the accuracy of measuring, even though they are determined by different instruments and probes. They therefore can be trusted in the same way as those obtained via indisputable means of uniaxial tension. There is usually a 100–200% excess of tensile strength over compressive strength or hardness [93–96], while in solid materials their ratio is reversed (e.g., the Tabor relationship holds in metals, where hardness exceeds the yield strength by around 200%). In our opinion, this difference is due to the specific behavior of nanofibrils in tensile and compression tests or measuring hardness. In the first case, molecu-

### Table 2. Mechanical characteristics of nanocrystals and elementary cellulose nanofibrils [67]

| Characteristics                        | Nanocrystals | Nanofibers |
|----------------------------------------|--------------|------------|
| Young’s modulus longitudinal, GPa      | 140–160      | 30–40      |
| Young’s modulus transverse, GPa        | 15–30        | 10–15      |
| Tensile strength along the fibers, GPa | 8–10         | 0.8–1      |
| Tensile strength across fibers, GPa    | −1           | −0.1       |

![Fig. 4](image-url) Strength $\sigma_b$ as a function of Young’s modulus $E$ of (a) different natural cellulose-containing microfibers [90] and loading diagrams $\sigma$–$\varepsilon$ of (b) highly oriented cellulose microfibers in (1) uncrosslinked and (2) crosslinked states [66]. (a) (1) Poplar (cottonwood), (2) cotton, (3) jute (hemp hibiscus), (4) cannabis (hemp), (5) wood, (6) Rami (Chinese nettle), (7) bamboo, (8) flax, (9) feather grass stretching. (b) (1) before and (2) after the cross-linking of cellulose nanofibrils with lignin molecules. The insets show the structural molecular schemes: (3) cellulose, (4) lignin, (5) cross-linking.
lar chains are strengthened by stretching and being partially oriented along the fiber axis. Compressive stresses predominate during indentation (with both NI and AFM). Under their influence, microfibrils bend and lose stability much earlier than they break under uniaxial tension.

**CELLS AND CELL WALLS**

Cellulose microfibers form cell walls as a result of interacting with other components (e.g., lignin, hemicellulose, pectin, and water) (Fig. 1). There is a primary wall and a multilayered secondary wall, the latter of which makes the main contribution to the rigidity and strength of the cell. The cells get smaller upon moving from EW to LW, the cell walls grow thicker, and the internal cross section of the capillaries shrinks.

The results obtained via NI can be illustrated by several examples. The authors of [73] analyzed the dependences of longitudinal Young’s modulus $E$ and nanohardness $H$ of cell walls on the cell’s position in two annual rings of Scotch pine ($Pinus sylvestris$ L.) corresponding to ages of 7 and 74 years. It follows from Fig. 5a that $E$ grows by approximately 50% upon moving from EW to LW, while $H$ rises by only 6–7% (Fig. 5b). Similar data were presented in a number of other works, indicating the nanohardness of cell walls does not differ very much in different layers and annual rings, and even in different types of wood. In [97], the nanohardness of the cell walls in pine ($Pinus massoniana$ Lamb.) varied in the range of 0.35–0.42 GPa. The authors of [98] found that the hardness of the cell walls in Masson pine wood was 0.41–0.53 GPa and did not differ within the scatter of results for EW and LW. The authors of [99] found that $H = 0.34–0.54$ GPa in frankincense pine ($Pinus taeda$) (without differentiating between EW and LW).

In [100, 101], the maximum load $P_{\text{max}}$ applied to the indenter was set at 2 mN, ensuring indentations with depth $h$ several times greater than roughness parameter $R_a \sim 200$ nm of the sample’s surface prepared by mechanical grinding, and the lateral size of the zone of deformation, which is on the order of the cell diameter. The values of $E_e$ and $H_e$ measured in this way can be considered effective for a given layer of wood (along with those determined in macrotests of porous bodies, especially wood), due to the above ratio between the size of an imprint and the transverse size of a cell. The main experimental results from determining the radial dependence of $E_e$ and $H_e$ in English oak ($Quercus robur$) are presented in Fig. 6a, and in small-leaved linden ($Tilia cordata$) in Fig. 6b. Each point on the plots is a result from averaging 10 to 20 individual measurements. The transition from the EW to LW structure can be abrupt, as in oak (Fig. 6a), or smooth, as in linden (Fig. 6b). The difference between the mechanical properties at the end of the

![Fig. 5. Dependences of (a) elastic modulus $E_e$ and (b) nanohardness $H_n$ of a cell wall on the number of cells in an annual layer for two annual rings corresponding to ages of 7 years (blue symbols) and 74 years (red symbols) [73].](image-url)
growth stage and the beginning of the next year’s growth was several hundred percent. This allowed us to determine the thickness of the rings and the mechanical properties in each one very accurately, and then associate them with the conditions of growth not only over years, but within the growth season as well, which cannot be done using traditional optical ways of studying annual rings.

It is important to note that the proposed scanning technique aimed at cell walls with no preliminary selection of indentation points, a chosen value of \( P_{\text{max}} = 2 \, \text{mN} \), and a simplified procedure for preparing a sample’s surface for measurements that leaves some of the ground microfibers in the capillaries, does not interfere with determining the effective \( E_e \) and \( H_e \) values. It also has a number of advantages over the ways described earlier of measuring \( E \) and \( H \) in individual cell walls at lower \( P_{\text{max}} \) (see, e.g., [16, 73], where NI was done at \( P_{\text{max}} = 0.2–0.8 \, \text{mN} \)). It allows us to inspect large areas (\( \sim 10^4 \, \text{mm}^2 \) and more) efficiently instead of units of \( \text{mm}^2 \) when preparing them with a microtome; the ratio of \( E_e \) to \( H_e \) in LW and EW is much higher than that of \( E \) to \( H \) in cell walls; and finally, determining the effective \( E_e \) and \( H_e \) values with allowance for porosity \( p \), brings them closer to the macro characteristics of wood and allows us to predict the latter (if necessary) with no independent determination of \( p \). This means that measuring the effective values of \( E_e \) and \( H_e \) can be a much more sensitive means of dendrochronology and dendroclimatology than determining the local values of \( E_e \) and \( H_e \) in cell walls and measuring variations in the width of growth rings.

The presented data on the values of \( E \) and \( H \) on the nanoscale thus testify to the similarity between the structures of cell walls in different layers and types of wood. Their values are higher than those measured in [100, 101] for the effective microscopic values of \( E_e \) and \( H_e \), and even more so for the tabled macroscopic characteristics in [102–104]. This can formally be regarded as a manifestation of the size effect (SE) in the mechanical properties of wood. However, the question of which parts of the SE can be attributed to solid wood material and which can be attributed to pores requires separate study.

**SIZE EFFECTS IN WOOD**

There is little information about SEs in wood at different scale-hierarchical levels. Here we present the most interesting and typical data. The calculated and experimentally determined strength of elementary cellulose nanofibrils 3–15 nm in diameter is 4.9–10 GPa, which exceeds that of microfibers 8–12 μm in diameter by 500 to 1000%. Figures 6a and 6b show the effective values in the EW and LW layers were 2 to 4 times lower than the nanohardness of cell walls typically 2–5 μm thick [59, 65] and 5–10 times less than the strength of cellulose microfibers (0.8–1.57 GPa) with transverse dimensions of 8–20 μm. At the same time, the effective value of \( H \) was several times higher than Brinell macrohardness \( H_B \) and the uniaxial tensile strength obtained in macrotests [102–104].

It is clear that in addition to the internal factors caused by the molecular and supramolecular structure, the drop in the effective Young’s modulus and hardness at the meso- and macrolevels is also strongly affected by the nano- and microporosity of wood, due to the structure of any wood having pores, capillaries, and larger tracheids with high aspect ratios. These are responsible for several major differences in the mechanical behavior of wood from solid macrobodies. The first is that the Tabor rule, according to which the hardness of soft materials is around three times higher than the yield stress or strength, is almost never obeyed. On the contrary, the macrohardness in most types of wood is usually several times lower than the yield stress or tensile strength. The origin of all such phenomena is apparently the loss of stability of the wood’s cellular structure during indentation and uniaxial compression, which occurs much earlier than...
A detailed examination of the properties of wood in the nanoscale region is essential, as this region affects the mechanical characteristics of materials. The strength characteristics of nanocellulose are systematically lower by more than an order of magnitude than those of other known materials, such as metals, alloys, and structural steels. The density of nanocellulose is close to that of water, which makes it less dense than any other known materials. The tensile strength characteristics of single-walled carbon nanotubes and composites with natural fillers, such as cellulose microfibers, are vastly superior to those of the most common existing and promising structural materials. Interest in composites with natural fillers, such as cellulose microfibers, compared to those of the most common existing and promising structural materials. Shaded fields are absolute characteristics (Young's modulus $E$ and tensile strength $σ_b$); unshaded fields are specific strength characteristics of materials normalized to their density $ρ$. The mechanisms of softening and inelastic deformation and tensile failure. Due to the anisotropy of the mechanical properties of wood, these phenomena depend strongly on the direction in which the load is applied relative to the long axis of the cell. They are roughly an order of magnitude higher in the longitudinal direction than in the transverse direction. Anyway, as follows from the above, the SEs in wood are prominent, so that the strength/hardness drops from $~10$ GPa in nanocrystalline cellulose to $~0.1$ GPa in macrovolumes of wood. This means that all cellulose-containing materials have great strengthening potential that can be realized with optimally organized nano-, microstructure, and related technologies.

Specific mechanical characteristics, normalized to density $ρ$ of a material, are of key importance in many fields of application (e.g., aviation, astronautics, the automotive industry, and sports equipment). Defect-free nanocellulose can exceed the characteristics of aluminum alloys and structural steels by more than an order of magnitude in terms of $σ_bρ^{-1}$. They are inferior to them only in terms of deformation to fracturing and crack resistance. Only some polymeric microfibers (carbon and para-aramid Kevlar) can compete with nanocellulose in terms of specific strength characteristics. Single-walled carbon nanotubes (SWCNTs) and graphenes are vastly superior to any other known materials in terms of specific mechanical properties.

Presenting strength characteristics as a function of the characteristic dimensions of structure $R^*$ in double logarithmic coordinates yields a characteristic diagram in the form of a hockey stick (Fig. 8). The descending part of this dependence has a slope close to 0.5, making it similar to the Hall–Petch relationship known in physical materials science: $σ_y = σ_0 + A(R^*)^{-0.5}$, where $σ_y$ is the yield stress, and $σ_0$ and $A$ are constants of the material. Of course, the reasons for the drop in strength as $R^*$ rises can vary in different groups of materials, but there are common features. A size dependence can also be observed on the macroscale, but it is much weaker than in nano- and microscale regions. This is explained by an increase in the probability of large defects emerging when the volume of the object grows. This is described by Weibull’s statistical theory, consideration of which is beyond the scope of this review. The mechanisms of softening with rising $R^*$ require additional study of the relationship between nano-/microstructure and properties.

COMPOSITES WITH CELLULOSE REINFORCING FIBERS

More complex wood-polymer composites can also be created, especially ones reinforced with randomly arranged or oriented fibers with a layered or honeycomb structure and architecture. Materials consisting entirely of modified plant components are also gaining in popularity. Interest in composites with natural fillers and reinforcing elements has grown greatly in recent years, for a combination of reasons described.
above. Evidence of this is the large number of new materials and reviews published in the last year or two [105–114]. The main problems that must be solved when creating such composites are the choice of raw materials, the technology of their processing, the isolation and ordering of fibers, ensuring good adhesion to the matrix, and creating a planned architecture while meeting requirements for ecology, the safety of production, and subsequent use and disposal. These must be balanced with mechanical and other service properties, in addition to cost. Unfortunately, biodegradable polymer matrices by themselves have low strength, and they cannot be made strong even with high-strength fibers.

CONCLUSIONS

Even though wood of different species and its most important component (cellulose) have been serving mankind for many thousands of years, the nature of their properties remains unclear, and the potential of this unique natural material is far from being fully used. To predict the characteristics of wood, purposefully alter them as they grow, modify them with different types of treatments, and preserve them during operation, we must understand which elements of wood’s structure and defects of nano-, micro-, meso-, and macrostructures are responsible for certain macroscopic properties and how their state, orientation, interaction and evolution affect them. This requires knowledge of such properties for the most general and important elements of wood’s microstructure: the nanocrystalline and amorphous phases of cellulose, microfibrils, cell walls, and annual growth rings.

Along with scanning indentation at different maximum loads, a variety of modern means for studying nano- and microstructures allow us to obtain multiscale data on the mechanical properties of wood at different structural levels, from nano- to macrolevel. A comparison of macrocharacteristics and detailed information on the distribution of mechanical characteristics in an annual ring and in neighboring rings gives us a better understanding of the nature and mechanisms of the formation of the former. This can in turn yield new approaches to optimizing the conditions for growing wood with such predetermined mechanical properties as high strength and elasticity, required acoustic characteristics or slow creep rate, and physically grounded ways of strengthening wood. A multiscale study of the relationship between the structure and properties of cellulose-containing materials provides premises for finding new approaches to designing next-generation composite materials, and revealing the internal relationships of different properties (e.g., mechanical and thermal). The high specific strength of nanocellulose, which exceeds that of almost all modern structural materials except for nanocarbons, poses the problem of using this potential in preparing new high-strength, environmentally friendly materials. Results of scanning the nano- and micromechanical properties of wood over a successive series of annual growth rings create a basis for developing innovative procedures and tools for dendrochronology and dendroclimatology that complement traditional ones. Since the average size of cells in a cross section of wood is 30–50 μm, and the average thickness of an annual ring is 1–3 mm, it can contain 50–100 cells. Nanoindentation basically allows us to measure the mechanical characteristics of each cell, so the limit temporal resolution for the dendochronological use of NI could be around one week.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

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