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Review Article

Mechanical Behaviour and Structural Dynamics of Nanomaterials

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Abstract

Nanomaterials exhibit distinctive mechanical and structural properties that arise from their nanoscale dimensions, high surface-to-volume ratios, and size-dependent interactions. These characteristics influence their elastic modulus, hardness, strength, plasticity, deformation behavior, and dynamic response, distinguishing nanomaterials from their bulk counterparts. This review summarizes the principal classes of nanomaterials and examines the experimental techniques commonly used to characterize their structural and mechanical properties, including atomic force microscopy, scanning and transmission electron microscopy, X-ray diffraction, and Fourier-transform infrared spectroscopy. Particular attention is given to size and shape effects, grain-boundary contributions, surface effects, and the mechanical behavior of nanowires, nanoplates, polymer nanocomposites, carbon-based nanomaterials, and metal nanoparticles. The review also discusses theoretical approaches used to describe nanoscale mechanical behavior, with emphasis on nonlocal elasticity, strain-gradient theories, couple-stress models, and stress-driven integral formulations. Wave propagation and vibration in nanobeams, nanotubes, and multilayer structures are considered in relation to their dynamic behavior and potential applications. Finally, current challenges and future research directions are outlined, emphasizing the development of reliable theoretical and computational frameworks for the design of advanced nano-enabled materials and devices.

Keywords: nanomaterials, mechanical properties, structural dynamics, size effects, nonlocal elasticity, strain-gradient theory, wave propagation, nanostructures, nanomechanics, mechanical characterization

1. Introduction

Over the past two decades, nanomaterials have become one of the most rapidly developing fields of materials science. Materials with structural features on the nanometer scale (approximately 1–100 nm) exhibit physical, chemical, and mechanical properties that differ markedly from their bulk counterparts. This divergence arises primarily from quantum size effects, a sharply increased surface-to-volume ratio, and altered interatomic interactions. As a result, nanomaterials can exhibit distinctive mechanical, electrical, optical, thermal, and catalytic properties compared with their bulk counterparts, making them attractive for applications ranging from medicine and electronics to aerospace engineering and energy storage [1], [2].

The rapid advancement of nanotechnology is driven not only by the discovery of new materials but also by the atomically controlled structuring of existing ones. The resulting nanomaterials exhibit mechanical strength, flexibility, and dynamic response characteristics that cannot be achieved under ordinary bulk conditions, which makes them appealing for both fundamental research and industrial application [2], [3].

The field of nanomaterials has also created an important research domain for applied mathematics and structural mechanics. Classical continuum mechanics may not adequately capture certain size-dependent phenomena observed in nanostructures, particularly when surface, nonlocal, and microstructural effects become significant. This review systematically examines the principal classes of nanomaterials, their mechanical properties, the structural-mechanical approaches used to describe these properties, and their practical fields of application.

2. Classification of Nanomaterials

Nanomaterials are commonly classified according to their chemical composition and morphology. Organic nanomaterials include micelles, dendrimers, polymersomes, and hydrogels, while inorganic nanomaterials consist of metal- and metal-oxide-based particles [1], [4]. Metal nanoparticles, for example, those based on gold, silver, copper, and zinc, display unusual optical, electrical, and catalytic properties owing to their quantum effects and high surface-to-volume ratio.

Carbon-based nanomaterials form a distinct class encompassing fullerenes, carbon nanotubes, graphene, and nanodiamonds. Owing to their sp^2-hybridized carbon structures, these materials exhibit high mechanical strength, electrical conductivity, and thermal conductivity [5]. Composite nanostructures arise from the combination of different classes of nanomaterials and frequently produce synergistic effects that exceed the properties of the individual components. Synthesis methods also significantly affect the ultimate properties of nanomaterials. Laser ablation, sputtering, chemical vapor deposition, the sol-gel method, and green synthesis based on plant extracts are among the most widely used approaches [1], [4]. Careful control of synthesis conditions, including temperature, reaction rate, and precursor concentration, determines particle size, shape, size distribution, and grain-boundary structure, which in turn influence mechanical behavior.

3. Characterization Methods

Accurate assessment of the structural and mechanical properties of nanomaterials relies on a range of modern characterization techniques. Atomic force microscopy (AFM) enables nanometer-precision mapping of the surface topography of nanostructures and is also used in resonant-contact mode to directly measure the elastic modulus. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) serve to visualize particle morphology, size distribution, and internal crystalline structure, while in-situ mechanical testing modes allow simultaneous recording of load-deformation curves [2], [3].

Ultraviolet-visible (UV–Vis) spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), and vibrating-sample magnetometry (VSM) are used to characterize the optical properties, functional groups, crystal structure, and magnetic properties of nanomaterials, respectively [1]. The combination of these methods allows researchers to characterize both the static structure and the dynamic mechanical response of a nanomaterial under external loading in a unified way, providing the experimental database necessary for validating theoretical models.

4. Mechanical Properties: General Trends

The mechanical properties of nanomaterials elastic modulus, hardness, strength, and plasticity undergo systematic changes as size decreases. The widely accepted 'smaller is stronger' trend indicates that strength increases as characteristic size decreases, whereas the size-dependence of elastic modulus is more complex and does not follow a single, unambiguous pattern [2], [6]. Some studies report an increase in elastic modulus with decreasing size, while others report a decrease, a divergence stemming from the interplay of surface tension, grain-boundary structure, and the geometric shape of the nanostructure.

In nanocrystalline materials, a decrease in grain size typically leaves the elastic modulus close to the bulk value down to a grain size of roughly 5 nanometers; below this threshold, however, the modulus changes sharply because the volume fraction of grain boundaries begins to dominate the overall structure [2], [3]. This is among the key empirical findings demonstrating the limitations of classical continuum approaches in describing the mechanical behavior of nanomaterials.

Experimental studies on nanowires and nanoplates further show that not only size but also the shape of a nanostructure significantly affects its elastic properties, a factor long neglected in the literature. In-situ electron microscopy tests on gold nanowires have confirmed that the combined effect of shape and size substantially alters the value of the Young's modulus. Similarly, in copper nanowires, an increased surface-to-volume ratio has been shown to link elastic properties directly to the proportion of surface atoms [6].

In polymer nanocomposites, elastic modulus and yield stress are modeled as functions of nanofiller content, temperature, loading rate, and porosity [7]. Such models typically relate porosity to elastic modulus through power-law approaches and allow the reliability of polymer-nanocomposite membranes to be assessed for applications such as water purification and bone tissue engineering.

In carbon-based nanomaterials, particularly multiwalled carbon nanotubes and graphene flakes, mechanical properties also play an important role in interactions with biological media. Atomic force microscopy measurements show that cells exposed to these materials undergo changes in actin cytoskeleton structure, which in turn is reflected in a decrease in the measured Young's modulus of the cell. These findings indicate that the mechanical properties of nanomaterials are relevant not only to structural applications but also to biosafety assessment, since changes in cell mechanics can serve as an indicator of potential cytotoxicity.

In metal nanoparticles, contact mechanics deviates from the classical Hertzian model, since atomic-scale surface steps and structural asymmetry during compression violate the assumptions of continuum models. Molecular dynamics simulations serve as a complementary tool in this area: studies of copper nanowires under tensile load, for example, have shown that elastic properties are directly related to the proportion of surface atoms among the total atoms. Similarly, orbital-free calculations based on density functional theory have shown that in large nanosystems, cohesive energy and bulk modulus gradually approach the known values for bulk material.

5. Structural Mechanics and Wave Propagation Aspects

The inability of classical elasticity theory to fully describe mechanical behavior in nanostructures has directed researchers toward nonlocal continuum models. Eringen's nonlocal elasticity theory is among the most widely used frameworks in this area; according to this theory, the stress at a given point depends not only on the strain at that point but on the strain field of the entire body [8], [9]. This approach has found broad application in modeling the bending, compression, vibration, and wave propagation behavior of nanoplates, nanotubes, and nanolayers.

Alongside nonlocal elasticity theory, strain-gradient models have also been developed, incorporating higher-order gradient terms in addition to the classical strain field [8], [9]. Lim and colleagues combined Eringen's nonlocal law with strain-gradient elasticity to study wave propagation problems in unbounded media, obtaining higher-order differential constitutive equations. Such combined models make it possible to describe both softening and hardening effects simultaneously, a result that purely nonlocal or purely gradient models cannot achieve on their own.

Wave propagation analysis is of particular importance in studying the mechanical properties of nanostructures, since it is computationally efficient and does not require large volumes of experimental data. In Timoshenko- and Rayleigh-type nanobeams, dispersion characteristics and the dependence of phase and group velocity on wavenumber have been studied while accounting for the nonlocal parameter, temperature effects, magnetic fields, and elastic foundations [10]. Stress-driven integral models have eliminated the ill-posed boundary-value problems arising from the Eringen-Wieghardt approach, offering more consistent solution strategies.

Nanotubes and multilayer nanostructures with eccentric (off-center) geometry are of particular importance for studying how initial stresses, geometric asymmetry, and material heterogeneity affect wave dispersion characteristics. Unlike classical concentric cylinder models, this class of problems requires additional mathematical complexity, asymmetric boundary conditions, and additional geometric parameters, making it an ongoing and active research direction in structural mechanics and applied mathematics.

Wave propagation in magneto-electro-elastic (MEE) nanotubes and nanobeams has also been the subject of intensive study in recent years [11]. Because these materials exhibit coupled mechanical, electrical, and magnetic field effects, their dynamic models require combining nonlocal stress theory with modified couple-stress theory. Such coupled models play a central role in the design of smart nano-devices, sensors, and actuators.

Because the analytical solution of wave propagation problems becomes difficult under complex boundary conditions, researchers also turn to semi-analytical and numerical methods. The wave-based method is used to determine the wave characteristics of nanobeams with arbitrary boundary conditions: boundary conditions are incorporated into the construction of the system's total matrix, and the points where the determinant of this matrix vanishes are sought to determine natural frequencies. Similarly, numerical approaches such as the generalized differential quadrature (GDQ) method and the nonlocal operator method offer cost-effective alternatives for complex-geometry and heterogeneous nanostructures where analytical solutions are not feasible, eliminating the need to compute shape functions and their derivatives and thereby improving both accuracy and computational speed.

6. Applications

The practical outcomes of research into the mechanical properties of nanomaterials are evident across a wide range of industrial and medical fields. In medicine, nanoparticles are used for drug delivery, tissue engineering, bioimaging, and biosensing; in these applications, the mechanical stiffness of particles directly determines their interaction with cell membranes and their rate of biodegradation.

In structural engineering, polymer composites reinforced with graphene oxide and carbon nanotubes substantially increase elastic modulus and tensile strength; some studies have reported an increase in elastic modulus of up to 150% with the addition of a small amount of graphene oxide. This property is widely used in the development of lightweight yet high-strength construction materials.

In electronics, nanowires and nanoplates have a broad application spectrum, ranging from flexible displays to high-frequency nano-resonators. Reliable operation of these devices requires precise mathematical modeling of their dynamic behavior, particularly wave dispersion and vibration characteristics, since classical engineering approaches do not provide sufficient accuracy at the nanoscale.

In environmental applications, nanomaterials are used in processes such as pollutant adsorption from water, air purification, and soil remediation, where high surface area enhances adsorption efficiency. In the energy sector, nanostructured electrode materials are being investigated to increase the capacity of batteries and supercapacitors, making the mechanical stability of nanomaterials a critical factor for long-term operation.

In agriculture and the food industry, nanomaterials are used to improve the barrier properties of packaging materials, create antimicrobial coatings, and extend the shelf life of food products. In these applications, the mechanical elasticity and crack resistance of nanolayers are key parameters ensuring product resistance to damage during transport. In catalytic processes, the high surface energy of metal and metal-oxide nanoparticles significantly increases reaction rates, making them valuable across fields ranging from the petrochemical industry to environmental remediation.

In sensor technologies, the combination of mechanical flexibility and electrical conductivity in nanomaterials has enabled the development of wearable devices, biosensor chips, and structural health monitoring systems. In such sensors, the sensitivity of the nanostructure to small deformations, which depends directly on its elastic modulus and wave propagation characteristics, is a primary factor determining measurement accuracy, once again highlighting the connection between theoretical mechanics and applied engineering.

7. Conclusion and Future Directions

Owing to their unique size-dependent mechanical, electrical, and optical properties, nanomaterials have become one of the central research subjects of modern materials science. As shown in this review, the classification of nanomaterials, their synthesis methods, the size-dependence of their mechanical properties, and the mathematical modeling of these properties within the frameworks of nonlocal elasticity and strain-gradient theories constitute closely interrelated research directions.

One of the principal challenges for future research is unifying the various theoretical models, nonlocal, strain-gradient, and couple-stress, within a single, computationally efficient framework. Furthermore, the accurate description of wave dispersion and dynamic behavior in nanostructures with complex geometries, including eccentric and multilayer cylindrical structures, remains an ongoing and active research direction, both theoretically and experimentally. Progress in this area will lay the groundwork for more reliable and effective application of nanotechnologies in medicine, energy, electronics, and structural engineering.

Author Contributions

The author conceived, prepared, reviewed, and approved the final version of the manuscript.

Conflict of Interest

The author declares no conflict of interest.

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Abbreviations

Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Fourier-Transform Infrared Spectroscopy (FTIR), X-Ray Diffraction (XRD), Magneto-Electro-Elastic (MEE), Generalized Differential Quadrature (GDQ), Ultraviolet-Visible spectroscopy (UV–Vis), Vibrating-Sample Magnetometry (VSM).

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