

Research Article

Open Access

Atomic Force Microscopy: A Powerful Tool for Surface Analysis of Nanostructured Materials

Usha Shukla

Amity School of Applied Sciences, Amity University Lucknow Campus, India

ABSTRACT

Atomic Force Microscopy (AFM) has emerged as a leading technique for the high-resolution characterization of nanostructured surfaces. Its ability to generate three-dimensional topographical maps at the nanoscale enables detailed analysis of surface roughness, texture, morphology, and other critical features that influence the behavior and functionality of advanced materials. This review highlights AFM's capabilities in measuring nanoscale mechanical properties such as elasticity, adhesion, stiffness, and viscoelasticity using advanced imaging modes like nanomechanical mapping and phase imaging. Recent advancements including the integration of machine learning algorithms for automated image analysis and the use of chemically functionalized probes for site-specific surface interactions are also discussed. Compared to other microscopy techniques, AFM offers distinct advantages, including minimal sample preparation, ambient condition operability, and versatility across material types. This review aims to provide a comprehensive understanding of AFM's role as a powerful and adaptable tool for surface analysis in nanotechnology and materials science.

*Corresponding author

Usha Shukla, Amity School of Applied Sciences, Amity University Lucknow Campus, India.

Received: September 02, 2025; Accepted: September 12, 2025; Published: September 29, 2025

Keywords: Atomic Force Microscopy (AFM), Nanostructured Materials, Surface Characterization Nanomechanical Mapping, Phase Imaging, High-Resolution Imaging

Introduction

The growing demand for nanoscale materials, particularly nanoparticles, stems from their remarkable properties, driving their widespread use across industries. Accurate characterization of these materials is crucial to unlocking their full potential in both scientific and industrial applications. Atomic Force Microscopy (AFM) is a highly versatile, nondestructive tool capable of imaging a diverse range of materials—such as polymers, composites, and biological samples—in various environments (air, liquid, or vacuum). Many industries now incorporate nanosized materials to leverage their unique attributes, making proper characterization essential [1,2].

The foundations of nanotechnology were established by Feynman in 1990, who foresaw its immense possibilities long before the necessary tools were available. Electron and scanning probe microscopy, including AFM, revolutionized material analysis by enabling atomic- and nanoscale observation and manipulation. SPM techniques, especially AFM, employ a fine probe to measure surface properties with extraordinary precision, producing high-resolution images that reveal not only surface topography but also material characteristics. In this method, a nanoscale probe interacts with the surface to detect local properties, generating detailed images by scanning a predefined grid. While topography is the most common output, other properties can also be mapped. Additionally, if the probe-sample interaction is sufficiently strong, nanoscale modifications to the substrate are possible [3].

Since topography imaging alone is often insufficient, advanced AFM modes have been developed to quantify various surface

properties. Modern AFM techniques can measure friction, electrical and magnetic forces, capacitance, conductivity, viscoelasticity, surface potential, and resistance. Unlike conventional microscopy, AFM provides 3D imaging at atomic resolution and directly assesses mechanical, electrical, and chemical properties at the nanoscale. It is widely used in polymer nanocomposite research to analyze morphology, mechanical behavior, phase distribution, and interfacial properties—all without extensive sample preparation that might alter the material [4].

AFM's nanomechanical capabilities offer deep insights into properties like elastic modulus, adhesion, and deformation. By examining force-deformation curves at the nanoscale, AFM helps elucidate interaction mechanisms in polymer blends and composites, significantly enhancing material characterization.

Operating under native conditions with minimal (often nondestructive) sample preparation, AFM detects interactions between a probe and the sample surface. It can precisely measure exosome quantity, biomolecular content, biomechanics, and structure. However, a key limitation is that AFM characterization is conducted externally, subject to variable conditions such as temperature, pressure, scanning speed, and probe-sample force. Despite this, AFM reveals substructural details beyond the reach of traditional electron microscopy. Functioning like a “blind microscope,” AFM senses micro- and nano-objects, making it indispensable for exploring nanoscale morphology. The cantilever, acting as a force transducer, is also widely used to study surface and molecular interactions [5,6].

AFM is particularly valuable in polymer research due to its lower maintenance costs compared to electron microscopes. Polymer surfaces often contain microscopic inhomogeneities that affect

adhesion, wettability, abrasion resistance, and environmental degradation, making their identification and mapping scientifically and technologically important. Recent years have highlighted material characterization as a major challenge in polymer nanocomposite synthesis. Despite numerous available techniques, no single method can fully characterize their structure [7].

In scanning probe microscopy, an image is produced by raster-scanning a probe across the sample while recording local properties. AFM employs a unique non-optical approach based on SPM principles, using a physical probe to achieve atomic-level resolution in lateral and height measurements. However, its resolving power is limited to features no smaller than ~100 nm, a constraint that has become more evident with the rise of advanced imaging technologies like SEM and AFM [8,9].

AFM’s three primary functions are force measurement, topographic imaging, and nanomanipulation. Developed to overcome the limitations of early techniques like scanning tunneling microscopy (STM)-which only worked on conductive surfaces-AFM eliminates the need for conductive coatings, preserving the sample’s natural state. Recently, AFM-based nanomechanical analysis has emerged as a powerful tool in polymer science, biology, and medicine. In force mode, a nanoscale tip presses against the material to measure micromechanical properties, with data visualized through 2D image processing. Recent advancements have improved AFM’s fast imaging, tip durability, and quantitative mechanical measurements for multifrequency analysis. Established modes like amplitude modulation and peak-force tapping have also seen significant refinements [10-12].

AFM can image polymers, ceramics, composites, glass, and biological samples while assessing properties such as friction, electrical/magnetic forces, capacitance, conductivity, viscoelasticity, surface potential, and resistance. This paper explores AFM’s fundamental principles and reviews recent research developments, emphasizing its applications across multiple fields.

Comparison of AFM with other Microscopy Techniques

AFM offers several key benefits compared to conventional techniques such as SEM and TEM. A comparative analysis (see Table) highlights AFM’s superior advantages, including significantly lower capital and operating costs. Unlike SEM and TEM, AFM employs cost-effective silicon or silicon nitride probes, which are critical for high-resolution topographical imaging. Sharper AFM tips further enhance performance by minimizing contact area and reducing long-range forces.

Resolution is a critical factor in microscopy performance. As illustrated in Fig. 1, different microscopy techniques vary in their resolution and imaging ranges. The human eye can distinguish features as small as 0.01 mm, while conventional optical microscopy (excluding super-resolution methods) is limited by light wavelength constraints to just under 1 μm . SEM achieves resolutions of around 1 nm, whereas both TEM and scanning probe microscopy (including AFM) can reach atomic-scale resolution [1,13].

Beyond resolution, AFM’s versatility-coupled with its cost efficiency and adaptability to various environments-makes it an ideal choice for polymer research.

Parameter	SEM	TEM	AFM
Imaging Advantage	High Depth of Field	High Resolution and High Magnification	High Contrast
Dimensions	2-D	2-D	3-D
Measurements	Chemical Composition	Structure and Properties	Physical Properties
Environment	Vacuum	Vacuum	Air, liquids, vacuum
Surface Height	Not possible	Not possible	Possible
Size of Equipment	Large	Large	Very Small
Cost	Expensive	Expensive	Cheap
Usage	Skilled operator required	Skilled operator required	Easy to use
Measurement speed	Fast	Fast	Slow

Table: Imaging Ranges for Different Microscopy Techniques in Comparison. Source [1].

History and Background

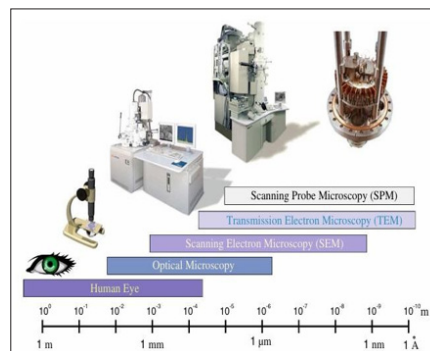


Figure 1: The Resolution of Microscopy Source [1].

The scanning tunneling microscope (STM), developed by Gerd Binnig and Heinrich Rohrer in the early 1980s, marked the birth of scanning probe microscopy and earned its creators the 1986 Nobel Prize in Physics. Building on this breakthrough, Binnig collaborated with Calvin Quate and Christoph Gerber the same year to create the atomic force microscope (AFM), a transformative advancement that has redefined nanoscale characterization .The original AFM design utilized an innovative approach: a diamond tip attached to a gold foil cantilever made direct contact with samples, with interatomic van der Waals forces providing the measurement mechanism. The system detected cantilever deflection using an STM positioned above it [14].

The development of AFM addressed a critical limitation of STM technology - the requirement for conductive samples. While STM could only examine conducting or semiconducting surfaces, AFM’s revolutionary design enabled imaging of virtually any material, including polymers, ceramics, composites, glass, and biological specimens. This breakthrough dramatically expanded the scope of nanoscale investigation.

Like STM, AFM operates by raster-scanning a sharp probe across a surface while maintaining precise control through feedback mechanisms. However, AFM fundamentally differs by measuring atomic-scale forces rather than tunneling current. This principle allows AFM to characterize diverse interactions including van der Waals, electrical, magnetic, and thermal forces. Certain advanced AFM applications do require specialized probes and custom software configurations.

As a premier scanning probe microscopy (SPM) technique, AFM integrates two critical measurement capabilities: deflection detection and force quantification. When combined with Angstrom-level positioning precision and sophisticated feedback systems, these features enable unparalleled surface characterization

across numerous material systems. The evolution from STM to AFM represents more than just technical progress - it embodies the expansion of our ability to interrogate matter at the most fundamental scales [9].

Basic Components of Atomic Force Microscope

In materials engineering and related fields, AFM serves as an indispensable tool for three-dimensional characterization of surface imperfections including scratches, gouges, scribe marks, and corrosion pits. As illustrated in Figure 2, the atomic force microscope combines compact dimensions with user-friendly operation, while delivering unparalleled nanoscale resolution - making it uniquely capable of analyzing surface properties at microscopic features

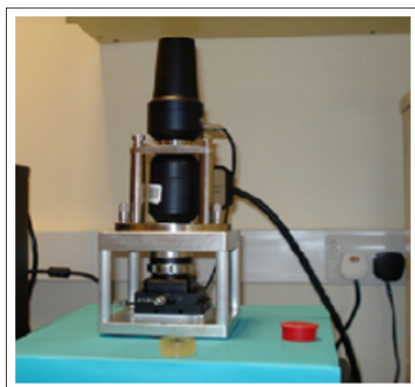


Figure 2: A Typical Atomic Force Microscope (AFM) Source [5].

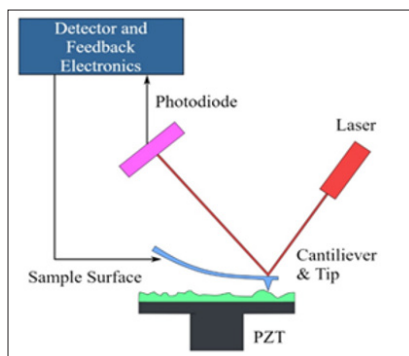


Figure 3: Schematic Representation of an Atomic Force Microscope, Illustrating Components Like the Cantilever, Probe Tip, and Laser Detection System Source [7].

The instrument's architecture, depicted in Figure 3, comprises several critical subsystems that enable its advanced functionality [7].

Specialized Probe Tips: Engineered tips interact with sample surfaces, detecting topographical variations through measurable deflections.

Advanced Data Processing: Sophisticated software transforms raw measurement data into high-resolution sample images.

Precision Feedback System

- Utilizes a laser deflection mechanism to monitor and control tip-sample interactions
- A precisely aligned laser reflects off the cantilever onto a photodetector
- Continuous feedback adjustment maintains optimal scanning parameters

Optical Detection System:

- Incorporates a Sensitive Laser Beam Deflection Arrangement
- Silicon-Based Cantilevers With ~10 Nm Tip Radius Enable

Ultra-Fine Measurements

- Reflected Laser Position is Tracked for Nanoscale Displacement Detection
- Force Quantification:
- Imaging Relies on Precise Measurement of Tip-Sample Interactions
- Cantilever Deflection (with Known Spring Constant) Provides Force Data
- Enables Quantitative Analysis of Surface Mechanical Properties

This integrated system architecture allows AFM to deliver comprehensive surface characterization while maintaining exceptional measurement precision across diverse material systems.

Working Principle of AFM

The Atomic Force Microscope (AFM) functions by precisely measuring intermolecular forces to generate nanoscale surface topography and property characterization. The system operates through three fundamental mechanisms: surface sensing, deflection detection, and image formation [7].

Core Operational Mechanism

AFM employs a microfabricated cantilever with a nanoscale tip that mechanically probes the sample surface. As the tip interacts with surface features, atomic forces induce cantilever deflection. This displacement is monitored through an optical lever system where a laser beam reflects off the cantilever onto a position-sensitive photodetector, enabling precise force measurement [3].

Additional AFM Microscope Principles

Beyond topography, AFM provides comprehensive material characterization including:

- Mechanical Properties (Elasticity, Adhesion)
- Electrical characteristics (Conductivity, Surface Potential)
- Functional properties (Ferroelectric, Piezoelectric Response)
- Magnetic and Thermal Attributes

Specialized techniques like Piezoresponse Force Microscopy (PFM) utilize conductive probes to evaluate electromechanical behavior through applied electrical stimulation. While dynamic modes dominate modern applications, contact mode remains valuable for specific electrical property measurements.

Modes of AFM

Contact Mode

The original AFM imaging technique maintains continuous tip-surface contact during scanning, primarily used for rigid materials (metals, ceramics). Cantilever deflection varies with surface topography, with two distinct measurement approaches:

- Constant Force Mode: Actively maintains fixed cantilever deflection through feedback adjustment, using correction signals to construct the surface image
- Constant Height Mode: Maintains fixed probe elevation for high-speed atomic resolution imaging of flat surfaces

Contact mode requires cantilevers with spring constants (typically <1 N/m) below the effective atomic bond stiffness (1-10 N/nm) to prevent surface damage.

Tapping Mode

As shown in Figure 4, this advanced technique oscillates the cantilever near its resonance frequency while monitoring amplitude reduction from tip-surface interactions. Suitable for both hard and soft materials, it minimizes lateral forces while maintaining high

resolution [14].

Friction Force Mode

It is referred to as lateral force microscopy (LFM), this specialized mode quantifies surface friction characteristics by measuring cantilever torsion rather than vertical deflection. The resulting data maps nanoscale variations in surface tribological properties.

Scanning Modes

AFM achieves 3D surface reconstruction through two scanning configurations:

- **Tip-Scanning:** Probe moves across stationary samples (common for large specimens)
- **Sample-Scanning:** Stage moves under fixed probe (typical for high-resolution systems)

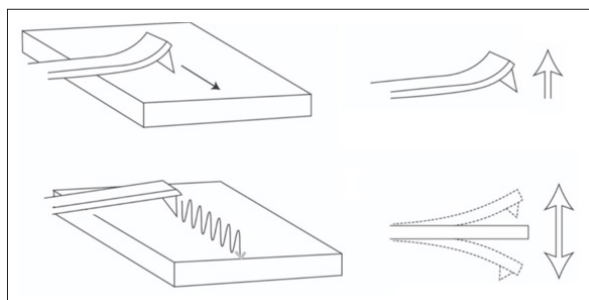


Figure 4: Illustrates the Operational Principles of Both Contact and Vibrating Modes Source [14].

AFM Operational Procedure

The standard workflow for Atomic Force Microscopy involves seven key steps:

- Sample Mounting on the AFM Stage
- Probe Installation in the Microscope Head
- Laser Beam Alignment
- Photodetector Calibration for Optimal Reflection Detection
- Controlled Probe Approach to Sample Surface
- Systematic Surface Scanning
- Safe Probe Retraction Post-Imaging [9,14]

Probe replacement is highly efficient, typically completed within two minutes.

Image Acquisition Process

During scanning, the probe's precise movements across the surface are recorded and reconstructed computationally, generating high-resolution topographic maps line-by-line. Unlike STM which requires conductive samples and measures quantum tunneling effects, AFM detects various atomic-scale interactions (van der Waals, electromagnetic, and thermal forces) through specialized probe tips and customized software algorithms.

Diverse Applications of AFM

Mineralogical Studies

AFM's unique lens-free design, incorporating a cantilever-tip system with laser detection and piezoelectric control, enables comprehensive mineral characterization. It provides 3D morphological data, surface roughness quantification, and crystal structure analysis in various environments, including aqueous conditions [16].

Bone Tissue Research

AFM's nanoscale resolution makes it indispensable for studying bone's hierarchical architecture, from macroscopic cortical/trabecular structures to nanoscopic collagen-mineral organization. This capability facilitates:

- Mechanical Property Mapping at Multiple Scales
- Investigation of Bone Remodeling Dynamics
- Analysis of Mechanotransduction Pathways
- Development of Biomimetic Materials [17].

Biomedical Investigations

Beyond basic topography, AFM offers advanced characterization modes:

- Phase-Contrast Imaging for Stiffness/Adhesion Mapping
- True 3D Reconstruction with 0.05 nm Lateral Resolution
- Single-Molecule Imaging Capabilities
- Bacterial Adhesion Studies
- Surface Property Analysis of Biomaterials [18].

Food Science Applications

AFM Provides Distinct Advantages over Electron Microscopy

- Minimal Sample Preparation Requirements
- Liquid Environment Compatibility
- True 3D Imaging Capability
- Mechanical Property Assessment

Applications Span

- Nanostructure Analysis of Food Components
- Quality Control Assessments
- Microbial-Surface Interactions [6]

Advances in AFM Technology

Modern AFM systems have achieved significant improvements in:

- Imaging Throughput and Speed
- Probe Longevity and Performance
- Multifrequency Measurement Capabilities
- The development of chemically-functionalized probes has further enhanced the technique's specificity, particularly for analyzing polymer compatibility in advanced electronic applications.

Conclusion

Atomic force microscopy has revolutionized nanoscale material analysis by seamlessly combining high-resolution imaging with detailed mechanical property evaluation. Its adaptability and non-destructive nature have made it a cornerstone for advancements in polymer research and nanotechnology. Continued innovations promise to broaden its applications, particularly in sustainable and high-performance material development. AFM's impact is evident across diverse fields such as mineralogy, biology, and food science, where it provides critical insights into the structure, mechanical properties, and interactions of materials at the nanoscale. The continued advancements in AFM technology and methodologies promise to further expand its applications and enhance our understanding of complex systems, making it a cornerstone of future scientific research and technological development.

Funding Declaration Statement: I declare that I have not received any funding or grants for this work.

Competing Interest Declaration: I declare that I have no competing interests related to this work.

References

1. Nanoscience Instruments (2024) Atomic force microscopy (AFM) techniques <https://www.nanoscience.com/techniques/atomic-force-microscopy/>.
2. Shukla U (2025) Fourier Transform Infrared Spectroscopy: A Powerful Method for Creating Fingerprint of Molecules of Nanomaterials. Journal of Molecular Structure 1322: 140454.

3. Voigtländer B (2019) Atomic Force Microscopy Berlin, Germany. Springer 137-147.
4. Otsuki A, Jose S, Mohan M, Thomas S (2023) Non-Destructive Material Characterization Methods. Elsevier <https://www.sciencedirect.com/book/9780323911504/non-destructive-material-characterization-methods>.
5. Ishida N (2024) Atomic Force Microscopy. In Non-Destructive Material Characterization Methods Elsevier 89-125.
6. Sousa FDBD, Scuracchio CH (2014) The Use of Atomic Force Microscopy as an Important Technique to Analyze the Dispersion of Nanometric Fillers and Morphology in Nanocomposites and Polymer Blends Based on Elastomers. *Polímeros* 24: 661-672.
7. Sinha Ray S (2013) Techniques for Characterizing the Structure and Properties of Polymer Nanocomposites. *Environmentally Friendly Polymer Nanocomposites* 74-88.
8. Microbe Notes (2024) Atomic force microscope (AFM) <https://microbenotes.com/atomic-force-microscope-afm/>.
9. AFM Microscope Basics: <https://afm.oxinst.com/outreach/how-does-an-afm-microscope-work>.
10. Nanoscience Instruments (2024) Atomic force microscopy (AFM) techniques <https://www.nanoscience.com/techniques/atomic-force-microscopy/>.
11. Liang X (2023) Visualization of Nanomechanical Properties of Polymer Composites Using Atomic Force Microscopy. *Polymer Journal* 55: 913-920.
12. Stan G, King SW (2020) Atomic Force Microscopy for Nanoscale Mechanical Property Characterization. *Journal of Vacuum Science & Technology B* 38: 060801.
13. AFM Workshop (2024) Atomic force microscopy <https://www.afmworkshop.com/learning-center/atomic-force-microscopy>.
14. Quantum Design Inc (2022) History and Background of Atomic Force Microscopy <https://qd-europe.com/it/en/news/latest-updates/newsdetails/history-and-background-of-atomic-force-microscopy--1807/>.
15. Khan MK, Wang QY, Fitzpatrick ME (2016) Atomic Force Microscopy (AFM) For Materials Characterization. In *Materials Characterization Using Nondestructive Evaluation (NDE) Methods* Woodhead Publishing 1-16.
16. Liu Q, Fu Y, Qin Z, Wang Y, Zhang S, et al. (2023) Progress in the Applications of Atomic Force Microscope (AFM) For Mineralogical Research. *Micron* 170: 103460-103460.
17. Zhou Y, Du J (2022) Atomic Force Microscopy (AFM) And Its Applications to Bone-Related Research. *Progress in Biophysics and Molecular Biology/Progress in Biophysics and Molecular Biology* 176: 52-66.
18. Burgo Thiago AL, Kalil G, Bernardo Almeida Iglesias, Moreira KS, Luiz Felipe Valandro (2022) AFM Advanced Modes for Dental and Biomedical Applications. *Journal of the Mechanical Behavior of Biomedical Materials/Journal of Mechanical Behavior of Biomedical Materials* 136: 105475.
19. Alsteens D, Gaub HE, Newton R, Pfreundschuh M, Gerber C, et al. (2017) Atomic Force Microscopy-Based Characterization and Design of Biointerfaces. *Nature Reviews Materials* 2: 1-16.
20. Gowri S, Umasankareswari T, Rathish RJ, Prabha SS, Rajendran S, et al. (2023) Atomic Force Microscopy Technique for Corrosion Measurement. In *Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring* Elsevier 121-140.
21. Paruchuri A, Wang Y, Gu X, Jayaraman A (2024) Machine Learning for Analyzing Atomic Force Microscopy (AFM) Images Generated from Polymer Blends. *Digital Discovery* 3: 2533-2550.
22. Nanomagnetics Instruments (2024) Polymer Science Using Atomic Force Microscopy <https://www.nanomagnetics-inst.com/post/polymer-science-using-atomic-force-microscopy>.
23. Rahmat M, Hubert P (2019) Polymer-Polymer Interaction at the Nanoscale: An Atomic Force Microscopy Study of Interaction Stress. *Polymer Testing* 77: 105902.
24. Sousa FDBD, Scuracchio CH (2014) The Use of Atomic Force Microscopy as an Important Technique to Analyze the Dispersion of Nanometric Fillers and Morphology in Nanocomposites and Polymer Blends Based on Elastomers. *Polímeros* 24: 661-672.
25. Liu S, Wang Y (2011) A Review of the Application of Atomic Force Microscopy (AFM) in Food Science and Technology. *Advances in Food and Nutrition Research* 201-240.
26. Shukla Usha (2023) Carbon Nanotubes: Potentially Revolutionary Impact of Nanomaterials. *Journal of Nanoscience & Reports* 5: 2-7.