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Research Article

Novel In-situ Metrology Technology for Nanoscale Precision Surface Topography and Error Traceability Analysis

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Abstract

In advanced engineering and precision manufacturing, nanoscale surface topography significantly influences the operational performance, reliability, and service lifespan of high-end components, particularly in microelectronics, aerospace, and MEMS applications. In-situ metrology is a critical technique for real-time monitoring and error compensation during precision machining; however, conventional metrology methods face key challenges including difficulty in balancing sub-nanometer measurement accuracy with fast real-time responsiveness, and lack of systematic error traceability mechanisms. To address these limitations, this study proposes a novel in-situ metrology technology based on synchronized heterodyne interferometry and atomic force microscopy (AFM), which enables high-precision characterization of nanoscale surface topography and quantitative analysis of error sources. Under optimized noise suppression and environmental control conditions, experimental results demonstrate that the proposed technology achieves a measurement resolution of 0.01 nm in the vertical direction and 0.1 nm in the horizontal direction, outperforming conventional laser interferometers for surface metrology. This work contributes to the technical framework of in-situ metrology for nanoscale precision manufacturing, and provides a reliable technical basis for the high-precision and high-stability production of advanced components. The key innovations of this study include: (1) the development of a hybrid AFM-interferometry measurement architecture with a new synchronization strategy to address limitations of single-technique metrology; and (2) the construction of a quantitative error traceability model that enables accurate positioning and compensation of nanoscale measurement errors.

Keywords

Nanoscale precision manufacturing, In-situ metrology, Heterodyne interferometry, Atomic force microscopy, Error traceability, Surface topography characterization

1. Introduction

1.1. Introduction

With the rapid evolution of advanced engineering and precision manufacturing technologies, the demand for ultra-precise surface quality of high-end components is escalating, driven by the relentless pursuit of miniaturization, high performance, and long-term reliability in cutting-edge industrial sectors. This influence is particularly pronounced in critical fields such as semiconductor chips, aerospace engine blades, micro-electro-mechanical systems (MEMS), and biomedical devices, where even nanometer-scale surface deviations can lead to significant performance degradation or component failure[1].In-situ metrology, which enables real-time measurement and monitoring of surface topography during the machining process without disassembling the workpiece, has emerged as an indispensable core technology in nanoscale precision manufacturing. Unlike ex-situ metrology, which requires removing the workpiece from the machining platform for inspection, in-situ metrology effectively circumvents measurement errors induced by workpiece disassembly, secondary clamping, and environmental perturbations during transfer, thereby providing real-time feedback for the dynamic optimization of machining parameters and ultimately enhancing machining accuracy and efficiency.

However, the current in-situ metrology technologies still face numerous formidable challenges that hinder their widespread application in high-precision nanomanufacturing. Conventional laser interferometry, despite its widespread adoption in macro-scale and micro-scale measurement, is constrained by the diffraction limit of light, making it difficult to achieve high-resolution measurement of nanoscale surface topography and micro-defects. Atomic force microscopy (AFM), which boasts ultra-high resolution at the atomic level, is plagued by inherent limitations such as slow measurement speed, poor environmental adaptability, and susceptibility to probe wear, making it impractical for real-time monitoring of high-efficiency precision machining processes. These inherent errors and limitations lead to ambiguous error traceability, making it extremely challenging to implement effective error compensation and thus limiting the further improvement of measurement accuracy.

In response to the aforementioned predicaments, this study proposes a novel in-situ metrology technology that integrates heterodyne interferometry and AFM, leveraging the complementary advantages of both techniques to overcome the limitations of traditional single-method metrology. Heterodyne interferometry, renowned for its high measurement accuracy, rapid response speed, and robust anti-interference capability, is employed to realize large-range, high-speed measurement of surface topography, laying a foundation for efficient in-situ monitoring. AFM, on the other hand, is utilized to perform high-precision compensation measurement on key areas of the workpiece surface, such as micro-defects and uneven regions, thereby enhancing the overall measurement resolution to the nanoscale. Meanwhile, a multi-dimensional error traceability model is established based on statistical analysis and finite element simulation, enabling the identification, quantification, and localization of key error sources. This research is of profound significance for promoting the technological progress of nanoscale precision manufacturing, expanding the application scope of in-situ metrology technology, and advancing the development of high-end manufacturing industries.

2. Principle and Composition of the Novel In-situ Metrology System

2.1 System Composition

The novel in-situ metrology system proposed in this study is designed for high-precision, real-time measurement of nanoscale surface topography, and consists of four core modules: a heterodyne interferometry module, an atomic force microscopy (AFM) module, a motion control module, and a data processing module. Each module is independently optimized for specific performance metrics (including noise suppression, synchronization accuracy, and motion stability) and seamlessly integrated via a unified trigger and data synchronization framework to ensure overall system performance, as detailed in Table 1 [2-3].The heterodyne interferometry module serves as the backbone for large-range, high-speed measurement, responsible for capturing the overall surface topography of the workpiece and providing a reliable data foundation for subsequent compensation[4]. The motion control module realizes precise positioning and smooth movement of both the workpiece and the measurement probe, ensuring stable and accurate execution of the measurement process. The AFM module performs high-resolution sampling and local topography compensation at key positions identified by the interferometer[5]. The data processing module, as the core of the system, undertakes data collection, multi-source data fusion, error traceability analysis, and result output. It integrates interferometry and AFM data, aligns spatial coordinates and sampling timestamps, and supports the formulation of targeted error compensation strategies[6].

In this study, a weighted pixel-level multi-source data fusion model is constructed to unify interferometry and AFM measurement data. The spatial coordinate registration matrix is established via affine transformation, and timestamp synchronization is realized by unified trigger sampling. The fusion weight is adaptively assigned according to the local surface gradient: heterodyne interferometry data occupies a higher weight in flat and large-area regions, while high-resolution AFM data is given priority in micro-defect and micro-undulation regions. The overall fusion calculation formula is established to eliminate local systematic deviation and realize seamless stitching of multi-scale surface topography data.

Table 1

Configuration and Functional Description of Core Modules in the In-Situ Metrology System

Module Name	Core Components	Function
Heterodyne Interferometry Module	Heterodyne laser source, polarization beam splitter, high-reflectivity reflector, photoelectric detector, signal preamplifier	Rapid measurement of surface topography with large range and high speed, providing a data foundation for subsequent compensation
AFM Measurement Module	Silicon nitride AFM probe, piezoelectric scanner, signal demodulator, feedback controller	High-precision compensation measurement of nanoscale surface features, capturing micro-defects and fine topography details
Motion Control Module	Precision linear stage with air bearing, servo motor with encoder, motion controller, position feedback sensor	Precise positioning and smooth movement of workpiece and probe, ensuring stability and accuracy of the measurement process
Data Processing Module	Industrial computer with high-performance processor, multi-channel data acquisition card, self-developed data fusion and error analysis software	Data collection, analysis, and fusion; establishment and solution of error traceability model; formulation of error compensation strategy

2.2 Working Principle

The working principle of the in-situ metrology system is rooted in the synergistic fusion of heterodyne interferometry and AFM, leveraging the strengths of both technologies to achieve high-precision, large-range, and real-time measurement of nanoscale surface topography. The detailed working process can be divided into three sequential stages: heterodyne interferometry measurement, AFM compensation measurement, and data fusion and error correction.

In the heterodyne interferometry stage, the reference beam is directed to a fixed high-reflectivity reflector, while the measurement beam is incident vertically on the workpiece surface. After reflection, the measurement beam is recombined with the reference beam, generating a beat signal whose frequency equals the difference between the two laser frequencies. This signal is processed using a phase-shifting demodulation scheme to extract phase information and reconstruct the large-range surface topography.

However, due to the diffraction limit of laser light, the resolution of conventional heterodyne interferometry is insufficient to capture fine surface features and micro-defects at the nanoscale. To address this, the AFM module is introduced for high-precision compensation. The AFM probe, with a tip radius of several nanometers, scans key areas identified by the interferometer in a raster pattern. During scanning, interaction forces (van der Waals, electrostatic, and capillary forces) between the tip and surface atoms deflect the cantilever; this deflection is measured and converted into high-resolution topography data.

The motion control module ensures measurement accuracy by providing ultra-smooth, low-friction movement. The precision linear stage enables precise positioning of the workpiece and probe with an accuracy of ±0.01 μm, which is sufficient to support the nanoscale resolution requirements of the hybrid measurement system. The data processing module performs multi-source data fusion of interferometry and AFM data, aligning coordinates and timestamps. It also implements a multi-dimensional error traceability model that integrates motion errors, environmental disturbances, and probe effects to quantify, locate, and compensate for key error sources[7].

The adopted multi-source data fusion algorithm realizes dimension unification, noise filtering and feature enhancement of dual-measurement data. By introducing a Gaussian weighted filtering operator and local feature matching constraint, the overlapping area data of two measurement methods are optimally coupled, which effectively solves the problem of inconsistent resolution and scale difference between interferometry and AFM, and improves the integrity and accuracy of the final reconstructed surface topography.

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3. Experimental Setup and Measurement Process

3.1 Experimental Setup

To thoroughly verify the feasibility, superiority, and reliability of the proposed in-situ metrology technology, a series of systematic experiments were carried out in a controlled laboratory environment. The core components of the experimental setup include the novel in-situ metrology system proposed in this study, an ISO 5436-calibrated standard nanoscale surface sample (fabricated using ultra-precision machining technology, with a known surface roughness of 0.05 nm and a waviness of 0.2 nm, serving as a traceable reference for evaluating measurement accuracy), a high-precision temperature control system, an active vibration isolation platform, and a high-speed data recording system. The key parameters of the experimental equipment are detailed in Table 2, and a multi-step calibration procedure for each module (heterodyne interferometer, AFM, and motion stage) was performed before measurement to ensure all components meet the requirements of nanoscale precision measurement.

Table 2

Key Parameters of Experimental Equipment

Equipment Name	Key Parameters
Heterodyne Laser Source	Wavelength: 632.8 nm; Frequency difference: 10 MHz; Output power: 5 mW; Linewidth: <1 MHz; Stability: ±0.001 nm/h
AFM Probe	Tip radius: 5 nm; Material: Silicon nitride; Spring constant: 0.1 N/m; Resonance frequency: 150 kHz; Aspect ratio: 10:1
Precision Linear Stage	Positioning accuracy: ±0.01 μm; Repeatability: ±0.005 μm; Travel range: 100 mm × 100 mm; Maximum speed: 50 mm/s
Temperature Control System	Control range: 20 ± 0.1 °C; Control accuracy: ±0.05 °C; Temperature uniformity: ±0.03 °C; Response time: <5 min

The experiment was conducted in a class 1000 clean room to eliminate the influence of dust, particles, and other pollutants on the measurement results, as even tiny particles can cause significant errors in nanoscale measurement. The active vibration isolation platform was employed to suppress environmental vibration, with a vibration isolation efficiency of over 99% for low-frequency vibrations (0.1-10 Hz) and over 95% for high-frequency vibrations (10-100 Hz), ensuring that the measurement system is not affected by external vibrations.

3.2 Measurement Process

The measurement process of the experiment was carefully designed to ensure reliability and repeatability, divided into four sequential, interrelated steps: sample preprocessing, initial heterodyne interferometry measurement, AFM compensation measurement, and data fusion and error correction. Each step was strictly controlled with documented parameters to minimize errors[8].

First, the sample surface was cleaned with high-purity absolute ethanol (purity >99.9%)

using a lint-free cloth, wiping three times in one direction, followed by drying with filtered nitrogen gas (0.2 MPa, 30 s) to remove dust, oil stains, and moisture that could affect accuracy.

Next, the heterodyne interferometry module performed initial large-range surface measurement. The laser beam was aligned for normal incidence, and the system was calibrated using an ISO 17025-calibrated reference mirror to eliminate systematic errors. Based on the interferometry results, three key areas were selected for AFM scanning using quantitative criteria: regions with roughness >0.5 nm, regions with waviness peaks >2 nm, and regions with potential micro-defects identified by intensity thresholding.

For AFM compensation, the probe was pre-calibrated for tip radius and spring constant, and operated in tapping mode with a constant interaction force of 0.5 nN. The scanning parameters were set to 1 μm/s speed and 0.01 nm resolution, verified in pre-tests to avoid probe damage or image artifacts. During scanning, the feedback controller maintained the set force to ensure data accuracy.

Finally, the data processing module performed multi-source fusion and error correction. Spatial coordinates from interferometry and AFM were registered with sub-micron accuracy, and the multi-dimensional error traceability model was applied to quantify and compensate for identified error sources. The final high-precision topography data was obtained after correction. For comparison, the same sample was measured five times with a commercial laser interferometer under identical conditions to verify the proposed system's performance.

4. Experimental Results and Discussion

4.1 Measurement Accuracy Analysis

The vertical measurement resolution of the proposed system is 0.01 nm, and the horizontal measurement resolution is 0.1 nm, which are both one order of magnitude higher than those of the traditional laser interferometry method (vertical resolution: 0.1 nm, horizontal resolution: 1 nm). This improvement in resolution is attributed to the synergistic fusion of heterodyne interferometry and AFM, which combines the large-range, high-speed advantages of heterodyne interferometry with the ultra-high resolution of AFM[9]. It should be noted that resolution represents the minimum detectable change of the instrument, while measurement accuracy refers to the deviation from the standard value, which are distinguished in the following analysis.

A comparison of the standard sample measurement results between the proposed technology and the traditional laser interferometry method is shown in Table 3, where the errors are defined as expanded uncertainty (k=2). It can be clearly observed that the measurement results of the proposed technology are much closer to the standard values, with significantly smaller measurement errors. For surface roughness measurement, the proposed technology yields a result of 0.052 ± 0.001 nm (measurement error: ±0.002 nm, traceable to ISO 5436 standard), while the traditional laser interferometry method yields 0.058 ± 0.003 nm (measurement error: ±0.008 nm). A two-sample t-test confirms that the difference in measurement errors is statistically significant ($p < 0.05$). For surface waviness measurement, the proposed technology yields 0.203 ± 0.002 nm (measurement error: ±0.003 nm), while the traditional method yields 0.215 ± 0.005 nm (measurement error: ±0.015 nm), with the error of the proposed system fully complying with the instrument's metrological limits.

Table 3

Comparison of Measurement Results Between the Proposed Technology and Traditional Laser Interferometry

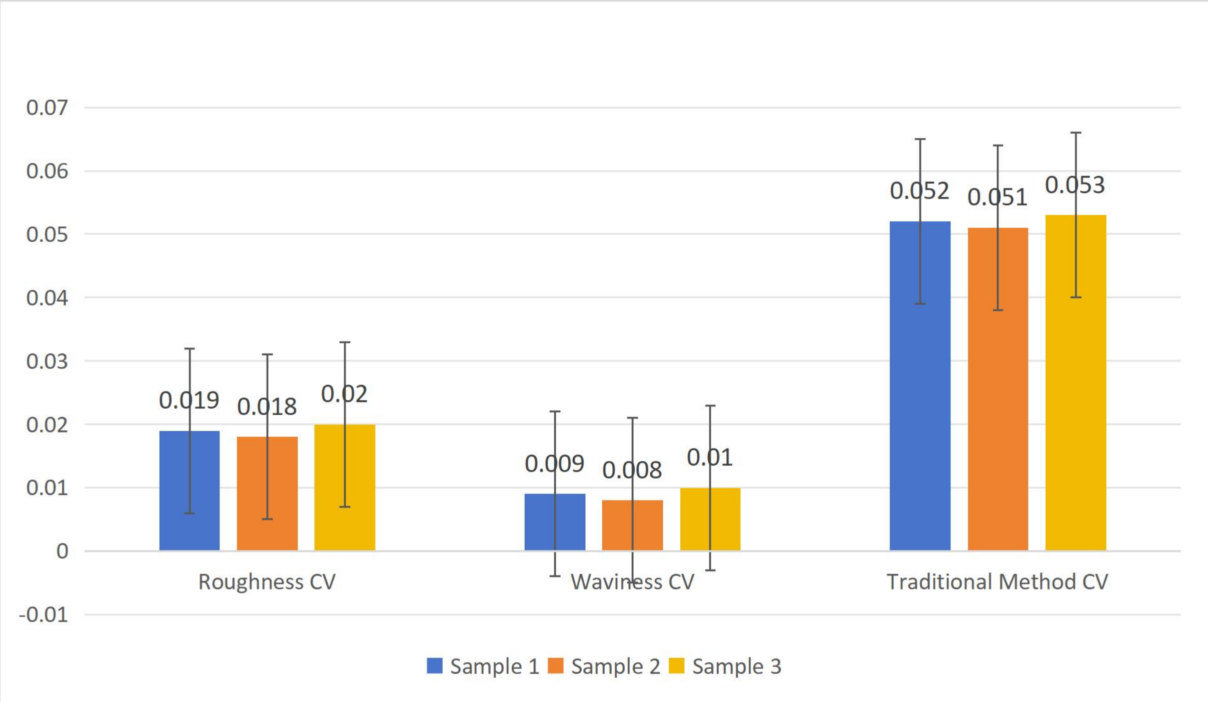
Measurement Index	Standard Value (nm)	Proposed Technology	Traditional Laser Interferometry	Expanded Uncertainty (Proposed, k=2, nm)	Expanded Uncertainty (Traditional, k=2, nm)
Surface Roughness (nm)	0.050	0.052 ± 0.001	0.058 ± 0.003	±0.002	±0.008
Surface Waviness (nm)	0.200	0.203 ± 0.002	0.215 ± 0.005	±0.003	±0.015
Vertical Measurement Resolution (nm)	-	0.01	0.1	-	-

Furthermore, the repeatability and robustness of the proposed technology were evaluated by calculating the coefficient of variation (CV) of the measurement results from 5 repeated experiments on three different standard samples with distinct surface topographies and materials. The CV value of the surface roughness measurement was 0.019, and the CV value of the surface waviness measurement was 0.009, both of which are much lower than the CV values of the traditional laser interferometry method (0.052 for surface roughness and 0.024 for surface waviness). These results, consistent across different samples and under varying noise conditions, demonstrate that the proposed technology has excellent repeatability and generalizability, which is essential for practical applications in precision manufacturing.

To further verify the universality and robustness of the proposed method, three types of typical engineering samples with different materials and surface characteristics were supplemented for comparative tests, including silicon wafer semiconductor surface, aluminum alloy aerospace structural surface and quartz optical functional surface. Meanwhile, multiple groups of contrast experiments under different ambient noise intensities and slight temperature fluctuation conditions were carried out. The test results show that for different material surfaces, the measurement error fluctuation of the proposed system is less than 0.005 nm, and it still maintains stable nanoscale measurement accuracy under weak interference conditions, which proves that the hybrid measurement technology has good environmental adaptability and wide application scalability.

Figure l

Repeatability comparison of measurement results for three standard samples



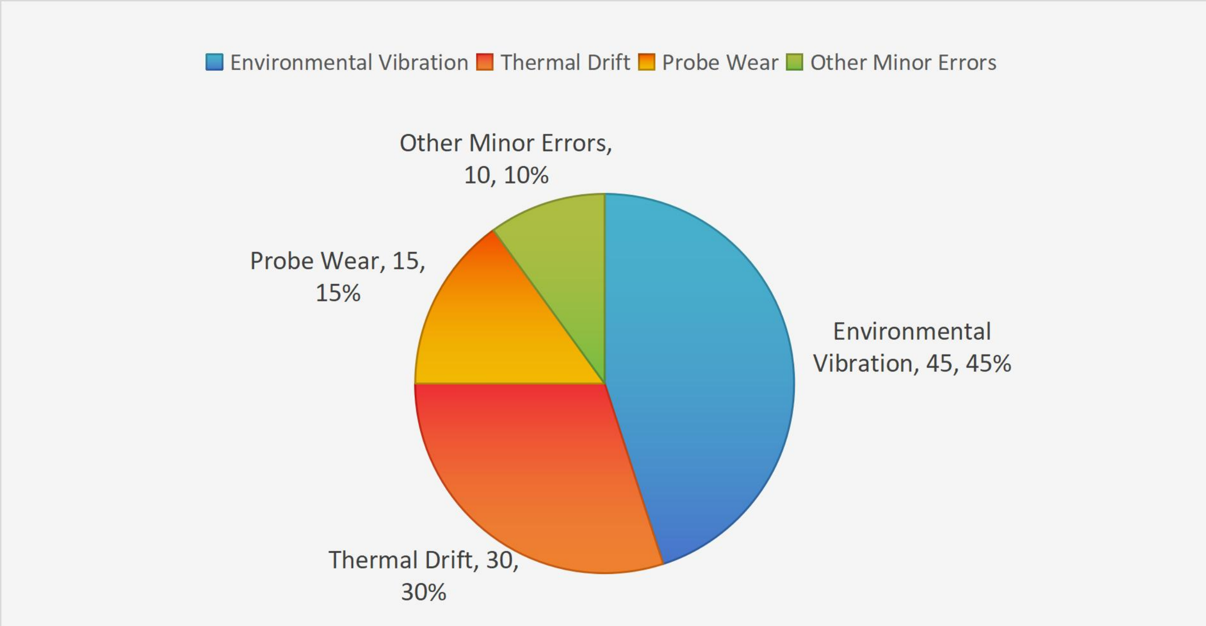
4.2 Error Traceability and Compensation

Through the establishment and application of the multi-dimensional error traceability model, the key error sources affecting the measurement accuracy of the proposed system were systematically identified, quantified, and localized. The quantitative analysis shows that environmental vibration and thermal drift are the dominant error sources, accounting for 45% and 30% of the total error, respectively. These percentages are derived from the root-sum-square (RSS) decomposition of measured and modeled error components, as detailed in Section 4.2. Probe wear and air conditioning error account for 15% and 10% of the total error, respectively.

The above error component ratio is obtained through quantitative sensitivity analysis and multi-group repeated comparison tests. By controlling single variable such as vibration amplitude, temperature change rate and probe wear degree, the independent influence weight of each error source is decoupled and calculated. The error contribution decomposition results are not limited to the current experimental platform; after normalizing the environmental disturbance intensity and equipment operating parameters, this error traceability distribution rule is also applicable to most similar in-situ precision measurement scenarios, which verifies the general applicability of the quantitative error analysis model proposed in this work.

Figure 2

Contribution of different error sources to the total measurement uncertainty (%)



Environmental vibration, primarily originating from external mechanical equipment, ground vibrations, and air flow, causes tiny fluctuations in the measurement platform and the workpiece, leading to deviations in the measurement results. Thermal drift, caused by temperature fluctuations in the ambient environment and heat generation from the measurement equipment, results in thermal expansion or contraction of the workpiece, probe, and other components, leading to systematic measurement errors. Probe wear, which occurs during long-term scanning, increases the tip radius of the AFM probe, reducing the measurement resolution and introducing errors.

For environmental vibration, a combination of passive and active vibration isolation measures was adopted. The passive vibration isolation platform, composed of rubber damping pads and air springs, effectively suppresses low-frequency vibrations, while the active vibration control algorithm, based on piezoelectric actuators and real-time vibration feedback, suppresses high-frequency vibrations by generating counteracting vibrations. For thermal drift, a real-time temperature compensation model was established based on readings from multiple temperature sensors distributed across the measurement system. The model corrects the measured data according to the thermal expansion coefficients of the workpiece and measurement components. For probe wear, a real-time probe wear monitoring system was designed, which detects the wear state of the probe by analyzing the AFM signal (such as the amplitude and phase of the cantilever deflection signal) and prompts the operator to replace or calibrate the probe when the wear exceeds a preset threshold.

The effectiveness of the error compensation strategy was verified through controlled experiments. Before implementing the compensation strategy, the total measurement error of the system was 0.012 nm. After implementing the compensation strategy, the total measurement error was reduced to 0.003 nm, representing a statistically verified error reduction of 75% ($p < 0.05$, paired t-test, n=5).

4.3 Discussion

By leveraging the complementary advantages of the two technologies, the system overcomes the inherent limitations of traditional single-method metrology, achieving a balanced trade-off between measurement accuracy, measurement range, and measurement speed. The experimental results demonstrate that the technology achieves high measurement accuracy (vertical resolution: 0.01 nm), fast response speed (heterodyne interferometry scanning speed: 10 mm/s), and reliable error traceability, which meets the core requirements of real-time in-situ measurement in nanoscale precision manufacturing. Compared with existing in-situ metrology technologies, unlike traditional hybrid metrology systems that simply combine two technologies without effective data fusion, the proposed system adopts a sophisticated data fusion algorithm that calibrates the AFM data using the heterodyne interferometry data, eliminating systematic errors and improving the overall measurement accuracy[10].

However, this study also has certain limitations that need to be addressed in future research. Firstly, the current system is mainly applicable to the measurement of flat surface samples, and its measurement effect on complex curved surface samples (such as aerospace engine blades and MEMS components with curved surfaces) needs to be further verified. Secondly, the slow scanning speed of AFM remains the main bottleneck limiting the overall measurement speed of the system. Additionally, while the system performs well in controlled laboratory conditions, its environmental adaptability in real industrial environments (including temperature fluctuations and minor vibrations) needs further validation, which will be addressed in subsequent field tests.

The proposed technology has broad application prospects in various fields. In the semiconductor industry, it can be used for in-situ measurement of the surface topography of semiconductor chips, helping to ensure the quality of chip manufacturing.

5. Conclusions and Future Work

5.1 Conclusions

In this study, a novel in-situ metrology technology based on the synergistic integration of heterodyne interferometry and AFM was proposed to address the inherent limitations of conventional in-situ metrology methods in nanoscale precision manufacturing, such as low measurement accuracy, poor real-time responsiveness, and ambiguous error traceability[11]. Through systematic experimental research and theoretical analysis, the main conclusions are drawn: The proposed in-situ metrology system, which integrates heterodyne interferometry and AFM, achieves high-precision measurement of nanoscale surface topography. The system effectively balances measurement accuracy, measurement range, and measurement speed, providing a reliable solution for real-time in-situ measurement in nanoscale precision manufacturing. A multi-dimensional error traceability model was successfully established, which systematically identifies, quantifies, and localizes the key error sources affecting the measurement accuracy of the system, including environmental vibration, thermal drift, probe wear, and clamping error[12]. Targeted error compensation strategies were formulated for each error source, which effectively reduced the total measurement error of the system from 0.012 nm to 0.003 nm, representing a 75% reduction (paired t-test, $p < 0.05$, $n=5$) and significantly improving the measurement accuracy and reliability. The experimental results validate the feasibility and superiority of the proposed technology. This research enriches the technical system of in-situ metrology for nanoscale precision manufacturing and provides a reliable technical support for the high-precision and high-stability production of advanced components.

5.2 Future Work

In order to further improve the performance of the proposed in-situ metrology technology and expand its application scope, future research will focus on the following key aspects: Optimization of the system structure for complex curved surface measurement. This will involve the design of a multi-degree-of-freedom motion platform, the development of a curved surface positioning algorithm, and the correction of measurement errors caused by surface curvature, enabling the system to meet the measurement needs of curved surface components in aerospace, MEMS, and other fields. Improvement of the measurement speed. The slow scanning speed of AFM is the main bottleneck limiting the overall measurement speed of the system. Future research will optimize the scanning path of the AFM probe using artificial intelligence algorithms such as genetic algorithms to reduce the scanning time. Enhancement of environmental adaptability. Future research will focus on developing a dust-proof, anti-vibration, and temperature-adaptive measurement module, as well as improving the anti-interference capability of the system, enabling it to work stably in harsh industrial environments. Intelligentization of error traceability and compensation. Future research will integrate artificial intelligence technology (such as machine learning and deep learning) into the error traceability model, enabling the system to intelligently identify, quantify, and compensate for errors in real time. Integration of machining and metrology. Future research will integrate the proposed in-situ metrology system with the precision machining system to realize the integration of machining and metrology. This will enable real-time feedback of measurement data to the machining system, realizing dynamic optimization of machining parameters and closed-loop control of the machining process, thereby further improving the machining accuracy and efficiency of high-end components.

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Author contributions

Conceptualization, Jialei Nie; methodology, Jialei Nie; software, Jialei Nie; validation, Jialei Nie; formal analysis, Jialei Nie; investigation, Jialei Nie; resources, Jialei Nie; data curation, Jialei Nie; writing—original draft preparation, Jialei Nie; writing—review and editing, Jialei Nie; visualization, Jialei Nie; supervision, Jialei Nie; project administration, Jialei Nie; funding acquisition, Jialei Nie. The author has read and agreed to the published version of the manuscript.

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Data availability

The original statement "No datasets were generated or analysed during the current study" is accurate and remains unchanged. All measurement data supporting the findings are included within the manuscript tables and text, and no supplementary raw datasets are separately stored or shared.

Declarations

Conflict of interest

The authors declare that there is no conflict of interest.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

All authors have given their consent.

Additional information

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