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Characterizing vibration-assisted atomic force microscopy (AFM)-based nanomachining via perception of acoustic emission phenomena using a sensor-based real-time monitoring approach

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ABSTRACT

The emerging atomic force microscope (AFM)-based nanolithography offers promising opportunities for nanopatterning applications. However, critical issues reside in the nanomachining process because the heterogeneous material properties and machine tool (AFM tip) quality variations can create significant uncertainties at this nanoscale. Therefore, in-process monitoring is essential for timely anomaly detection and real-time process characterizations. This paper reports a sensor-based monitoring approach that allows classifications of different conditions of vibration-assisted nanopatterning in real-time by automatically selecting acoustic emission spectral responses that distinguish different amounts of material removal. It opens up an avenue toward process characterizations and mechanisms discovery in vibration-assisted nanoscale manufacturing.

1. Introduction

The emerging atomic force microscopy (AFM)-based nanopatterning shows great potential for fueling the demand for cost-effective custom maskless lithography in numerous applications. Various AFM-based nanopatterning processes have been investigated for different nano-fabrication purposes, such as mechanical direct scratching [1–3], dynamic plowing [4,5], electrical-field-assisted nanolithography [6–9], thermal–mechanical removing [10–12], and depositions [13,14]. The vibration-assisted AFM-based nanomachining process has been innovated recently [15–17] to reduce the tip wear and improve the nanopatterning efficiency in processes involving mechanical contact of tips. By integrating in-plane vibration, this AFM-based nanomachining process can fabricate 3D nanopatterns on different materials with high fidelity [18,19].

However, the imaging and inspection of nanopatterns by vibration-assisted AFM-based nanomachining can only be carried out via post-imaging processes [20]. Such offline techniques cannot provide real-time information reflecting the success or failure of the process and require extensive time and effort for fabricated nanopattern characterizations. Additionally, deficiency in real-time informatics impedes the process parameters tuning for desired feature dimensions during nanomachining. Moreover, the post-imaging using AFM scanning may wear the AFM tips (causing increased tip radius and degraded tip sharpness), resulting in the low fidelity for both nanomachining and post-imaging processes. Therefore, devising a real-time monitoring and characterization approach for nano-fabrication would allow in-process evaluations and timely interventions for quality assurance to increase efficiency and significantly reduce the rework time and costs.

The readily available information provided by the AFM setup includes deflection and torsional signals. These indirect signals have limited accuracies because the AFM probes manifest significant variations in the cantilever's stiffness and spring constant, even from the same batch [21]. Therefore, utilizing such signals to predict the nanomachining process's success via sensor-based modeling approaches becomes challenging. The acoustic emission (AE) sensor captures elastic waves sourced from the material deformation, fracture, and friction during the material removal processes. Therefore, this highly sensitive sensor shows potential for in-process monitoring and real-time inspection for precision machining [22,23]. Reports related to the investigations into machining mechanisms during AFM scratching have been reported elsewhere [24,25]. Compared to previous studies, our current setup incorporates vibrations to facilitate material removals, which poses a problem in analyzing the AE characteristics because the AE bursts/waveforms are highly coupled with process vibrations, and the conventional measures (e.g., energy levels and count rates) may not be accurate.

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In this report, we present a pilot testing showing the validity of applying AE-sensor for in-process monitoring and characterizations of vibration-assisted AFM-based nanomachining process, which opens up a new avenue towards process characterizations and mechanisms discovery for vibration-assisted AFM nanomachining.

2. Hardware setup and experiment description

The vibration-assisted AFM-based nanomachining experiments were performed inside a commercial AFM system (XE7, Park Systems Corporation, Suwon, South Korea) with an in-house fabricated vibration stage. As shown in Fig. 1 a), two piezoelectric actuators are mounted perpendicularly at the bottom of the aluminum pillar, where the sample is placed on top of the pillar. In-plane circular xy-vibration at 2 kHz is generated on the sample by driving two piezoelectric actuators with two sinusoid waveforms, between which a 90-degree phase shift is set. The sample is prepared by spin-coating a 200 nm PMMA layer on a silicon substrate and then post-baked at 180 °C for 90 s. A signal generator (USB-6259, National Instruments, Austin, TX, USA) and two signal amplifiers (PX200, PiezoDrive, Shortland, NSW, Australia) with an amplification rate of 20 are used to generate input signals for the piezoelectric actuators. The sample mounting plate is attached with an AE sensor (s9225 from Physical Acoustics, Princeton Jct, NJ, USA). A data acquisition (DAQ) system (using the NI-USB-6259) is implemented to gather the AE sensor signals at a sampling rate of 500 kHz. The DLC190 AFM probe is applied for nanomachining on the PMMA sample.

To validate the presented monitoring schemes, a set of nanofabrication (scratching) experiments is devised with varying cutting forces (50, 150, 250, 350, and 450 nNs) on a PMMA sample surface with a scratching length of about 1 μm. The scanned machined trenches were captured in Fig. 1 b). Fig. 1 c) was a line profile across five trenches. It may be noticed that the varying forces create significantly distinct patterns on the machined surfaces. The machined trench widths (based on the varying cutting force from 50 nN to 450 nN) are 16 nm, 43 nm, 53 nm, 69 nm, and 82 nm, and the trench depths are 1.0 nm, 4.8 nm, 8.2 nm, 12.1 nm, and 16.4 nm, respectively. The collected AE signals, along with the spectrograms, are shown in Fig. 2. This set of experiments with the real-time collected sensor signals is used to investigate the validity of the AE sensor setup in characterizing different nano-fabrication conditions.

3. Characterizations of nano-fabrications via a temporal-spectral based classification tool on ae signals

The AE signal captures the transients, i.e., time-varying frequency patterns associated with the material deformation and

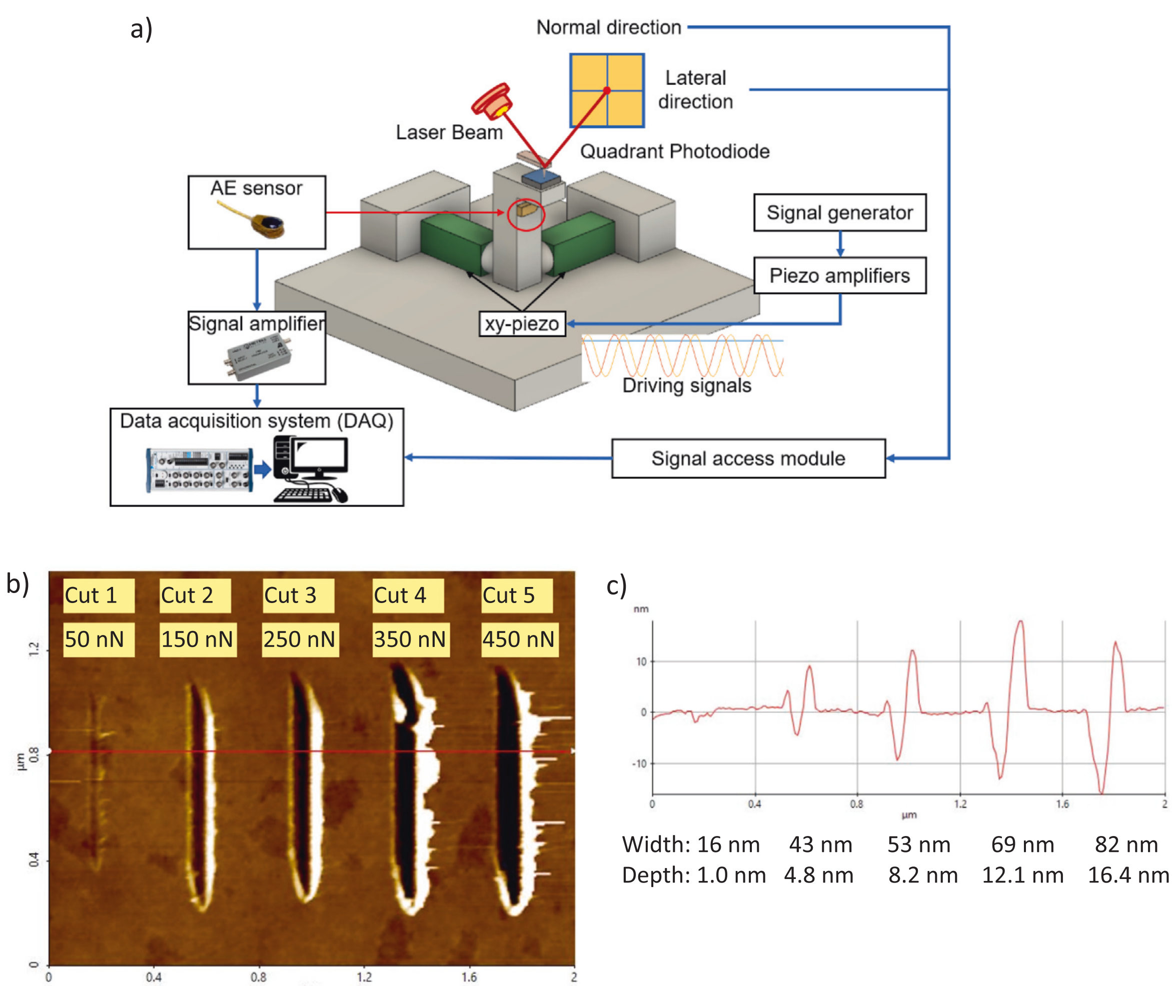

Fig. 1. (a) The AFM-based nano-lithography setup with mounted AE sensor and the associated data acquisition system (DAQ) for synchronously gathering in-process monitored AE signal, (b) the surface morphology after five nano-fabricated trenches (from left to right) using varying cutting forces as 50, 150, 250, 350, and 450 nNs, respectively, and (c) the surface profile (heights and widths) of the machined trenches.

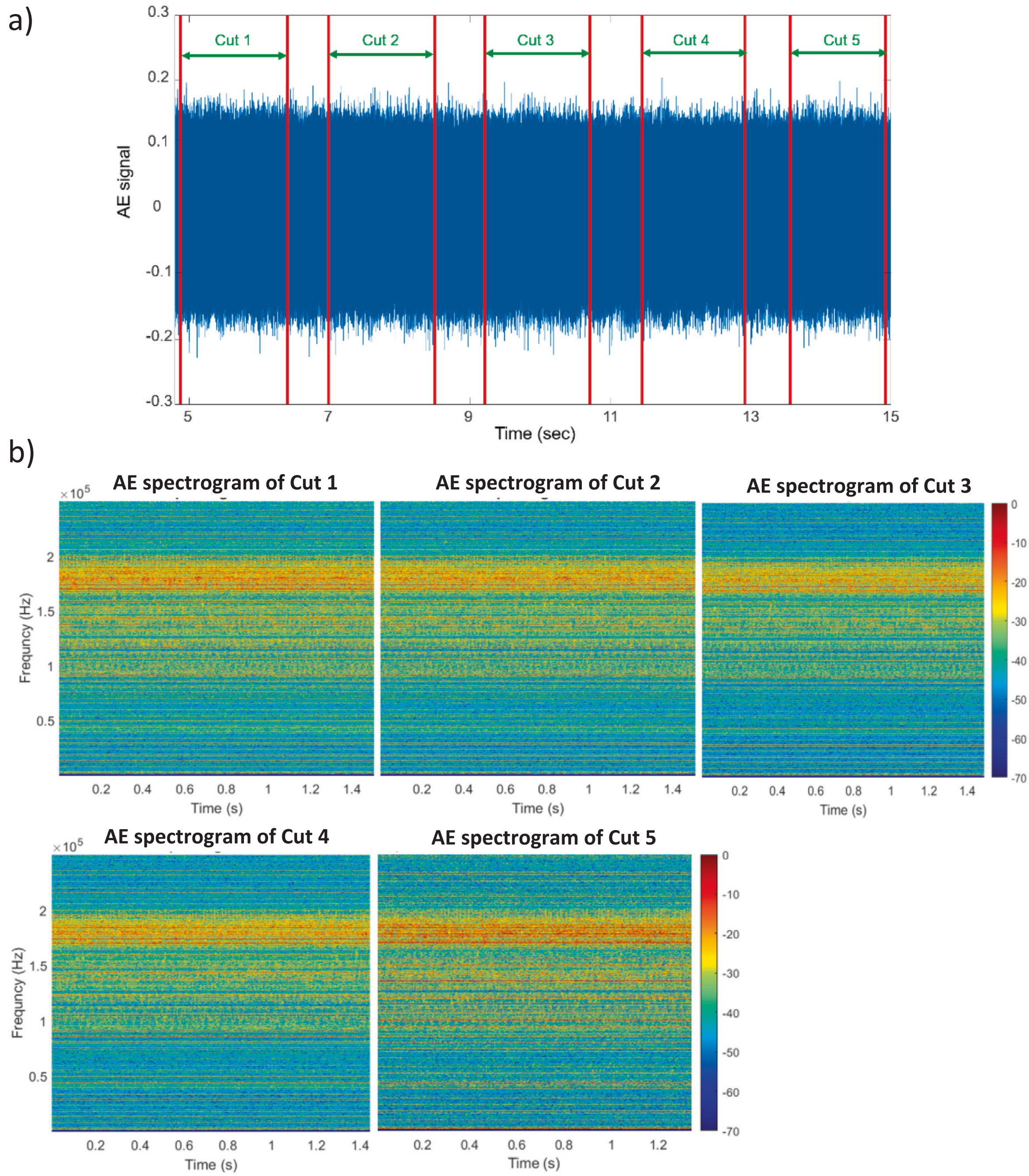

Fig. 2. (a) The segmented AE signals under five different cutting forces, and (b) the corresponding spectrograms showing the transient patterns (time-varying spectral features).

fractures at irregular intervals during machining [26]. First, the temporal-spectral features of the transient AE signals are extracted via a sliding window with the fast Fourier transformation shown as the spectrogram in Fig. 3 a), where the x-axis is the time index and the y-axis is the frequency range, and the energy of various frequency bands (in dB) is represented using a color map. Next, the extracted spectral features are used as inputs for a random forest model [22] for classifications of different cutting conditions [see Fig. 3 b)]. The random forest implicitly selects the features (subsets of frequency bands) that contribute most to the classification problem. The selected features are associated with the Gini importance values, which intuitively suggest their significances in the classification problem, i.e., characterizing different machining conditions.

The results based on the presented random forest are shown in Fig. 4. Fig. 4 a) is the confusion matrix that suggests that the approach can accurately (∼100 %) predict different cutting conditions based on the temporal-spectral features. It, therefore, shows the significance of the AE sensor signals toward process characterizations at the nanoscale level of machining.

To further understand why the AE signal can distinguish different nanopatterning conditions, we also test the AE signal capability in characterizing machining conditions vs surface scratching (no material removed) on the current AFM setup nano-fabrications.

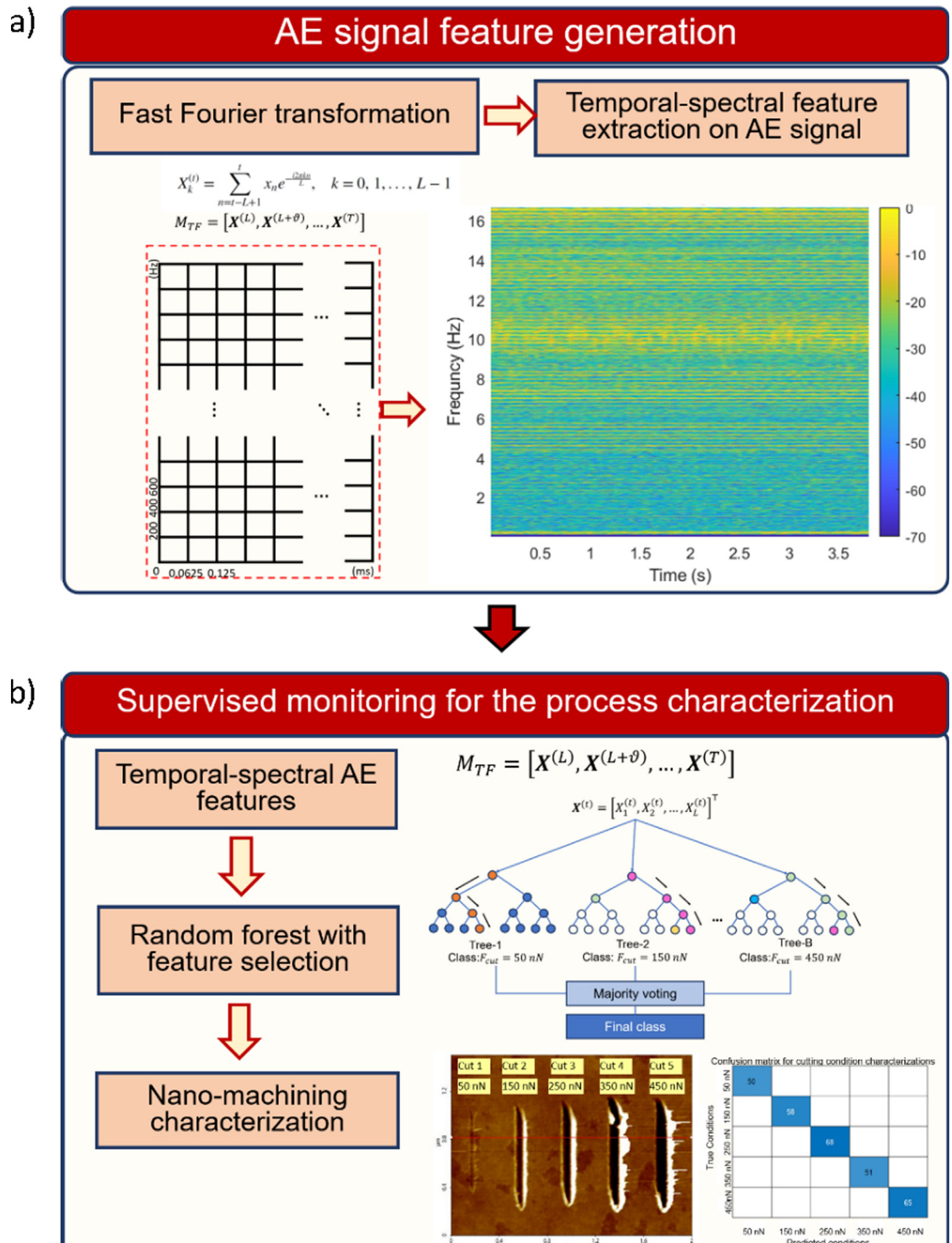

Fig. 3. The framework of the sensor-based machine learning approach for characterizations of different nano-fabrication conditions: (a) the applied temporal-spectral analysis for feature extractions from AE signals, and (b) a random forest algorithm that uses AE spectral features for process characterizations.

Results also show 100 % accuracy in detecting cutting vs non-cutting scratching [see Fig. 4 b) to d)]. The AE signals [in Fig. 4 c)] are highly nonstationary and time-varying, which exhibits the nature of intermittent dynamics. As shown in Fig. 4 e), our presented approach allows finding the most significant spectral features by their importance values. It may be noticed that the frequency bands around 150 kHz and the low-frequency range from 30 kHz to 50 kHz contribute to the classification problem. These spectral bands are highly correlated to the acoustic emission frequency response for PMMA/acrylic material failure [27]. Therefore, the proposed monitoring scheme allows accurate estimations of the nanomachining conditions based on frequency features capturing the AE responses related to material failures during vibration-assisted nanomachining.

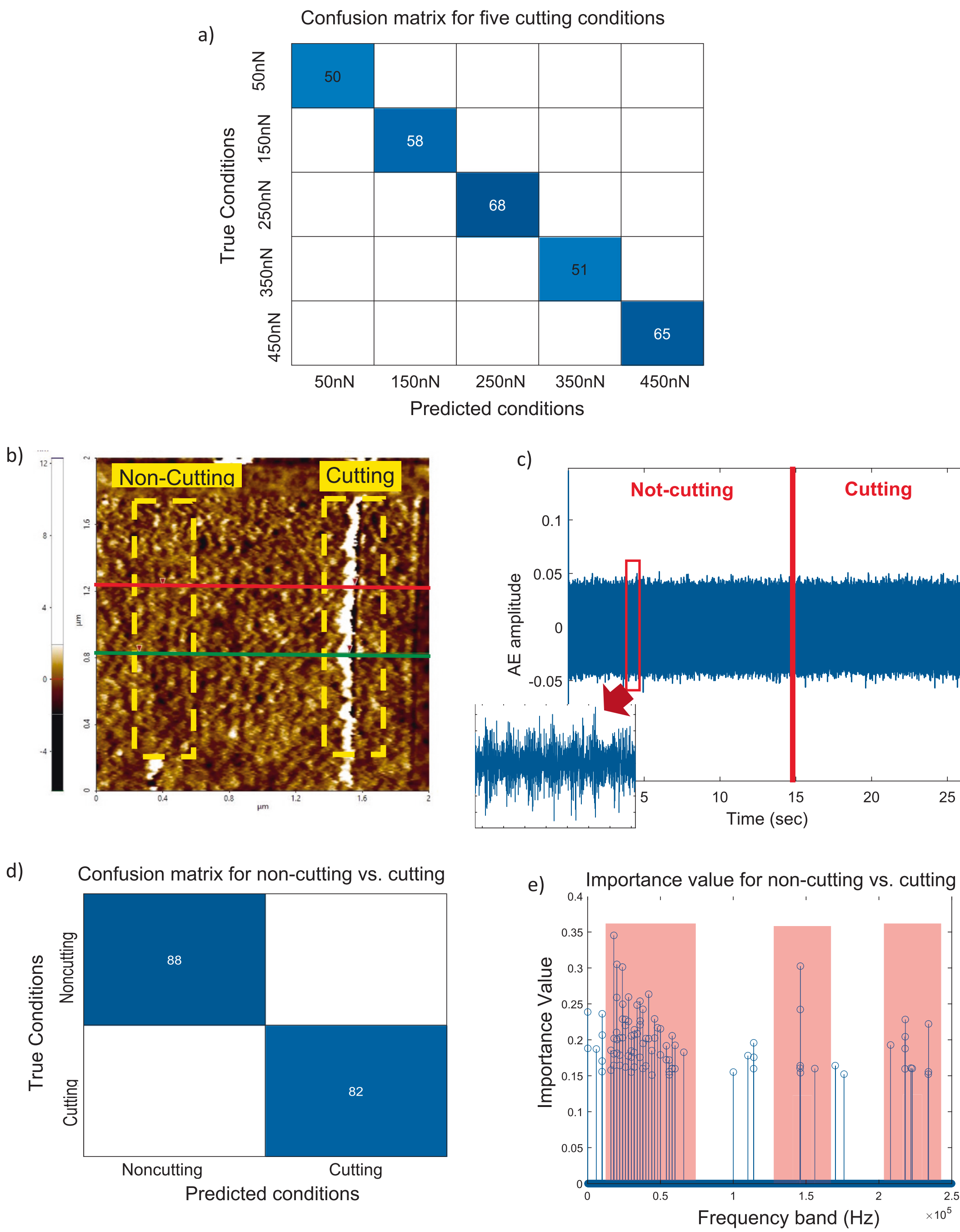

Fig. 4. (a) The confusion matrix showing the high accuracy of classification of different nano-fabrication conditions, (b) the surface profile of non-cutting surface scratching (of about ∼ 0.1 nN downforce) and cutting (second box with a trench left), (c) the segmented AE signals under non-cutting vs cutting conditions, (d) the confusion matrix showing high accuracy of classifying non-cutting and cutting conditions, and (e) the most significant frequency responses contributing to the classification of cutting vs non-cutting processes (importance values on the y-axis).

4. Conclusions and future work

This paper reports an AE sensor-based monitoring scheme toward process characterizations of material removal processes under nano-fabrications. The major contributions can be summarized as follows:

1. This letter reports a pilot testing that enables the sensor-based monitoring for the vibration-assisted AFM-based nano-manufacturing process via characterizing the temporal-spectral features emanated from the intermittent AE signal. The temporal-spectral feature-based random forest approach allows accurate characterizations for nano-fabrication under different levels of cutting forces;
2. The most significant spectral AE features in distinguishing differences between cutting conditions are highly correlated to the failure modes of PMMA materials. Therefore, this presented framework automatically selects the characteristics of intermittent AE signals under the vibration-assisted AFM-based nano-machining, which will help to unravel the fundamental understanding of vibration assisted nano-machining.

In the future, investigations into micromachining and the mechanism explanations for nano-fabrication will be conducted using the presented monitoring scheme.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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