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Acoustic Emission Monitoring of AFM Nano Scratching for ductile and brittle materials

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Abstract

An atomic force microscope (AFM) with suitable tips has been used for nano fabrication/nanometric machining purposes. In this paper, acoustic emission (AE) was introduced to monitor AFM machining of both a brittle material (silicon) and a ductile material (copper). With a specially designed experimental setup, AE responses were sampled, under various cutting conditions including ramped load to investigate machining characteristics for cutting depth changes. By analyzing the experimental results, it can be concluded that measured AE energy is sensitive enough to detect the changes in the mechanism of material removal including the ductile-brittle transition during nanometric machining.

Key Words: Nanometric machining, Acoustic Emission monitoring, Ductile-brittle transition, AFM

1. Introduction

Ultra precision machining of brittle materials is attracting interest due to its usefulness in high-tech applications such as semiconductor products and high-end optical components. For brittle materials, ductile mode cutting with limited depth of cut (under the critical depth of cut, fig. 1) is commonly practiced to avoid brittle fracture damage and to have stable/controllable material removal. In fact, as recent technical advances require higher manufacturing precision such as high form accuracy and brittle surface finish on the order of nanometers, ductile regime cutting of brittle material has become more attractive. For nano order processes, AFM with suitable tips has emerged as a competitive machining tool. Several experimental studies regarding nanometric processes can be found in the literature [2-5]. Fang [2] analyzed characteristics of nanometric machining with varying process conditions such as scratching speed and contact pressure. In general, however, since the cutting dimension of AFM machining is on the order of nanometers, the process mechanism is very hard to analyze. For that reason, little research has been pursued regarding basic mechanisms of the nanometric process including the ductile/brittle regime cutting mechanism and the transition between the two modes.

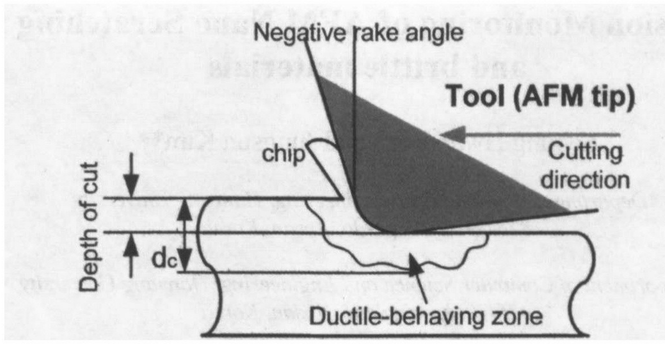


Fig. 1. Schematics of ductile regime machining and critical depth of cut [1]

The purpose of this study is to perform basic experiments and analysis on nanometric machining using AFM, and to characterize the nanometric machining mechanism including the ductile/brittle transition. As in-process monitoring is essential for ultra-precision machining, acoustic emission (AE) sensing has been applied to nanometric processes and corresponding signal analysis results are discussed.

2. AFM machining mode

During AFM nano scratching, material is removed by wear/abrasion between the material surface and the tool. During the process, there are four distinct regimes that occur as a result of the increase of tool engaging depth before fracture [6]: no wear, adhering, ploughing, and cutting. Only elastic deformations occur in the no wear and adhering regimes, whereas plastic deformation occurs mainly after ploughing, which is defined as plastic deformation of the workpiece without material removal. As the scratching depth increases beyond the ploughing regime, machining chips start to form. Therefore, chip formation can be used to classify the plastic deformation regime: ploughing mode (without chip formation), and cutting (or stable (ductile) material removal) mode. After the cutting mode, if the scratching depth exceeds the critical depth of cut (dc [7], see Fig. 1), then brittle fracture (cracks) can be initiated. The detection of dc are important during nano-scale material processes of brittle materials.

3. Acoustic emission signal analysis and in process monitoring of nano scratching

In the case of nano scale machining, such as AFM machining, real-time process monitoring is critical for results from accurate machining traces to measurement and analysis. Moreover, as the size of the surface features during the process is minute, a more sensitive sensor is needed [8, 9]. In this research, an acoustic emission sensor is introduced to monitor and analyze nanometric machining using AFM. Fig. 2 shows examples of applicable sensors according to the level of precision. Rich machining information inside AE signals can be investigated in the domains of time and frequency using various signal processing techniques according to process features. Processed signals can be used for determining the machining states and real time process monitoring.

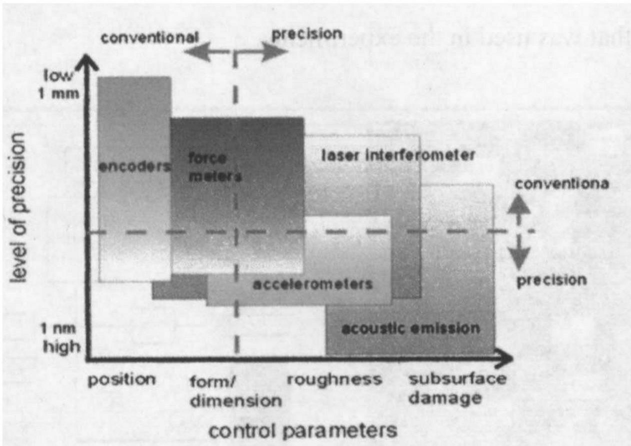


Fig. 2. Sensor application vs. level of precision [9]

As in bulk machining, in-process monitoring can be an essential tool to analyze nano scale material removal processes including the ductile/brittle transition during nano scratching of brittle materials. The generation of AE signals is subject to the characteristic of object materials used in the nanometric machining process. For ductile materials, continuous AE signals are mainly generated due to plastic deformation. For brittle materials, burst AE signals are generated by crack propagation and fractures [10]. A typical signal characteristic is shown in fig. 3.

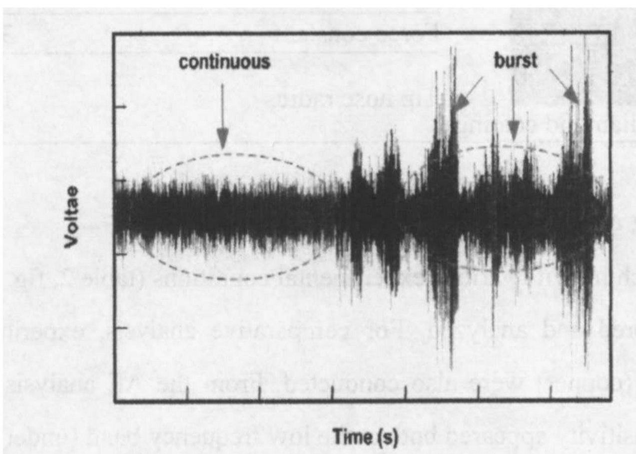


Fig. 3. Typical AE signal characteristics [10]

4. Experimental setup

The AFM used in this study is Auto Probe M5 of TM Microscopes and the workpiece materials are Si(100) and copper. The cantilever specifications are listed in table 1. A PICO broadband AE sensor by physical acoustics corporation was used. AE signals were amplified by 40dB using a PAC-1220 pre-amplifier and then were conditioned using a PAC-AEDSP-32 Board. The signals were analyzed through various signal processing methods including FFT, count rate and AE frequency ratio. Fig. 4 shows the schematic of the AFM and AE monitoring system that was used in the experiments.

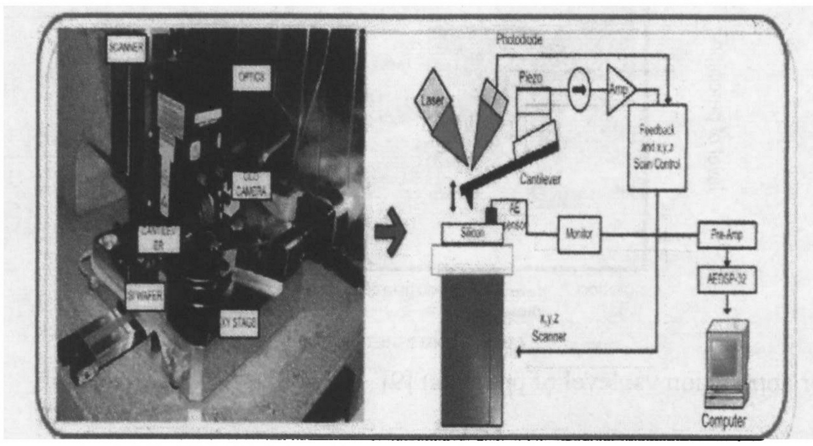
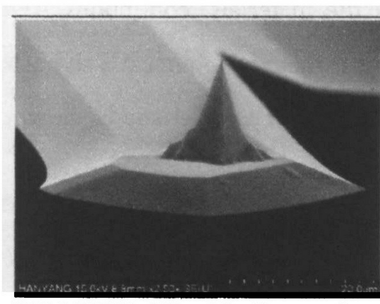


Fig. 4. Schematic of AFM nano scratching and AE monitoring setup

Table 1. The shape of AFM tip and cantilever specifications

	Standard mode of operation	Non-contact
	Cantilever length	85 μm
	Cantilever width	28 μm
	Cantilever thickness	2 μm
	Force constant	35 N/m
DT-NCHR (Si with diamond coating)	Tip nose radius	100 nm

5. Nano scratching and AE analysis

During nano scratching with various experimental conditions (table 2, fig. 5), generated AE signals were monitored and analyzed. For comparative analysis, experiments for ductile material workpieces (copper) were also conducted. From the AE analysis results for nano scratching, signal sensitivity appeared both at the low frequency band (under 100kHz) and the high frequency band (250kHz~450kHz). Fig. 6 (a) shows the increase in AE count rate caused by growing contact force. Fig. 6 (b) shows the AE ratio, which is the ratio of high frequency amplitude to low frequency amplitude. In the case of ductile material workpieces (copper), one can see that the signal of the high frequency band (caused by plastic deformation), is relatively stronger than that of the low frequency band (caused by crack generation).

Table 2 Experimental conditions for nano scratching

Exp. No.	1	2	3	4	5	6	7	8	9
Force (μ N)	30	30	30	60	60	60	90	90	90
Scan speed (μm/s)	1	5	10	1	5	10	1	5	10

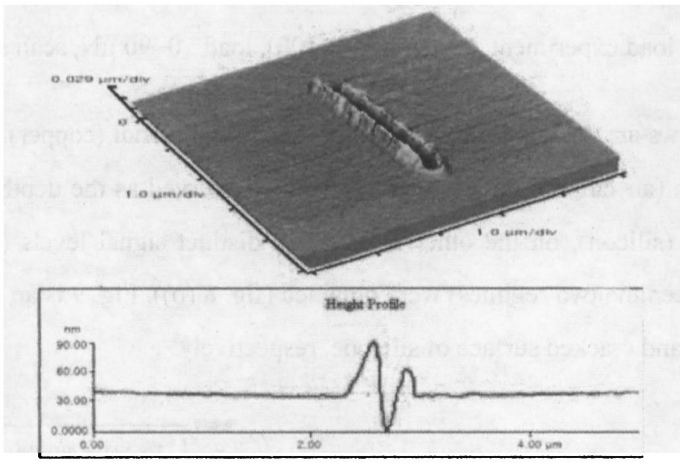
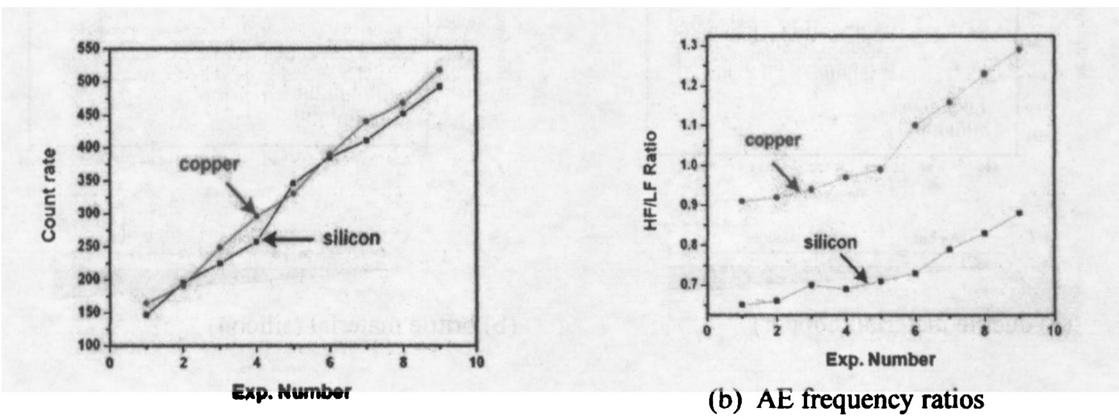


Fig. 5. Typical AFM image from nano scratching



(b) AE frequency ratios

(a) AE count rates

Fig. 6. AE monitoring results

6. Ramped load experiment and monitoring of ductile/brittle transition

To observe the transition from ductile to brittle cutting during continuous movement, the AFM tip load was linearly increased from 0 to 90 μN. Fig. 7 describes the nano scratch experiment and shows cross sections with increasing cutting depth at designated measuring points A, B and C, respectively.

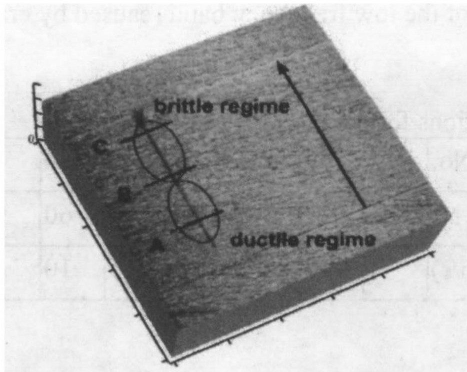
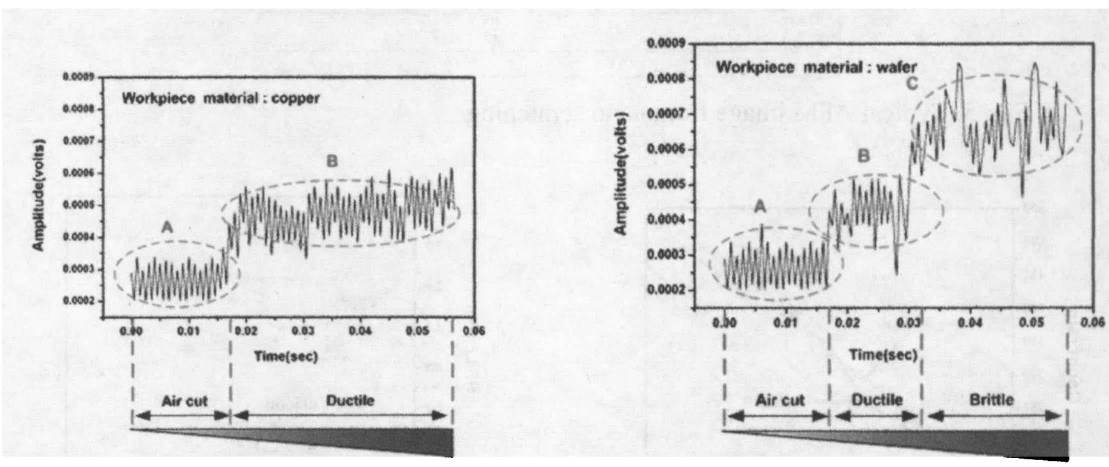


Fig. 7. Ramped load experiment. (material : Si(100), load : 0~90 μN, scan speed : 5 μm/s)

Fig. 8(a) shows an AE monitoring result for a ductile material (copper), in which only two distinct regimes (air cut and ductile regime) can be observed as the depth increases. For the brittle material (silicon), on the other hand, three distinct signal levels (ductile, brittle and transition between the two regimes) were obtained (fig. 8 (b)). Fig. 9 is an SEM images of the chip formation and cracked surface of silicone, respectively.



(a) ductile material (copper)

(b) brittle material (silicon)

Fig. 8 AE monitoring result

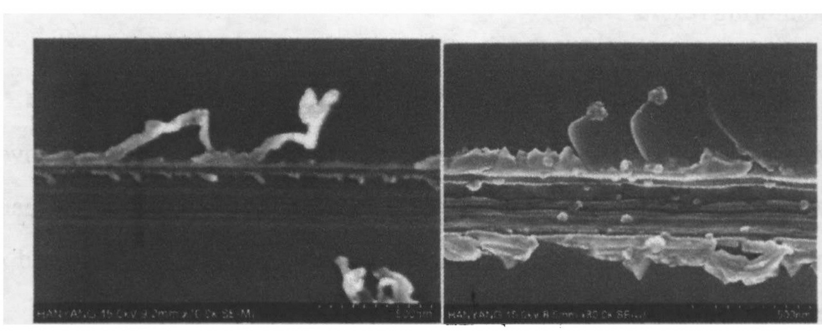


Fig. 9 SEM images of chip and crack formation (Si)

7. Conclusion

With the proposed real-time AE monitoring set up for nano scratching, the distinction between signals from different material properties was shown. Moreover, from the monitoring results, it was verified that AE has sufficient sensitivity to detect cutting depth changes at the nano scale and to differentiate typical machining characteristics such as the brittle-ductile transition during AFM machining of brittle materials.

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