A Novel Detection Method for Acoustic Emission Using a Scanning Probe Microscope

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The fracture of the atomic-scale contact should be investigated for understanding the mechanism of the mechanical processing. Using a combination of the scanning probe microscope (SPM) with possible high space resolution and the acoustic emission (AE) with high sensitivity for fracture is one of the possible ways of investigating the fracture mechanism. When using the SPM, the AE signal might be detected with receiving the AE wave by the piezoelectric tube scanner of the SPM receiving the AE wave, where by the piezoelectric effect the electric signal due to the AE wave is superimposed on the scan signal. Based on that, in this study, a novel method to detect AE signal from the scan signal is proposed. With this method, without changing the SPM body, the AE could be detected, and a two-dimensional AE source location could be possible by using four divided electrodes of the piezoelectric tube scanner. By a simple experiment using the AE wave simulator, the AE signal seems to be detected by the piezoelectric scanner of the SPM. Also, one of the typical data from the experiment suggests the AE source location might be possible. In the experiment of the indentation using atomic force microscope (AFM), which is one of the SPM, the AE signal is observed reproducibly.

Keywords: mechanical processing, fracture mechanics, scanning probe microscope (SPM), acoustic emission (AE), piezoelectric, tube scanner, scan signal, high pass filter, two-dimensional AE source location

1. Introduction

Mechanical processing is an important technology in a wide range of the industries. One of the ways of understanding mechanical processing is studying the fracture mechanics of the surface, although this is not so clear yet as an observation is still difficult, because the mechanism is based on the atomic-scale process. Powerful scientific tools for investigating the fracture of the surface on an atomic-scale include the scanning probe microscope (SPM) [1], such as the scanning tunneling microscope (STM) [2] and atomic force microscope (AFM) which is expanding its ability [3-8]. In addition, in order to investigate the process of fracture, not only mechanical properties including the corrugation of the surface and stress (or force), but also the generation of the electron (current), should be investigated, which might be possible by using the AFM and STM. In the case of AFM, the stress on the surface by the SPM probe is detected as the probe signal, which is the force on an atomic scale. In the case of STM, the generation of the electrons is detected as the probe signal, which is the electric current. Similarly in the case of the frictional force microscope (FFM), the lateral force between the SPM probe and surface is detected as the probe signal that is a frictional force and is recognized as one of the parameter indicating the start of a fracture. Analogously, in the case of another SPM the interaction between probe and surface becomes the probe signal.

Using a combination of AFM and simultaneously functioned FFM, which is called as AFM/FFM [9] found the atomic scale fluctuation of the friction [10] and negative friction [11] were found, wherein the AFM and FFM signals were simultaneously measured and analyzed based on their relation with each other. The SPM combined with another measurement method gives us some unique insights into sample surface properties, such as mechanical properties. For instance, using a unique atomic force microscope (AFM) with adding ultrasonic wave generator to the SPM body shows the modulus of elasticity as an additional information, from which the mechanical property of the material can be recognized [12]. An AFM/FFM combined with STM inside the transmission electron microscope (TEM) founds the metal-insulator transition on a single atom wire [13]. This combined microscope also detects the
fracture in a nanoscale contact area, which is the world’s smallest tensile strength test with atomic resolution and quantized conductance. In this the break of a single bond between the metal atoms is indicated as a the step signal of tensional force, which is one of the elementary processes of fracture [14]. SPM can be used as a nanoscale high precision indentor which can observe the pile-up of the surface, and is able to take into account the effect of the pile-up fracture for the hardness; hence, the SPM indentation makes the hardness measurement of higher precision [15]. The studies discussed above show that the SPM is a powerful tool for investigating surface fracture mechanics of surface.

On the other hand, to investigate fractures of not only on surface but also inside the material, the acoustic emission (AE) wave is employed as scientific tool [16-18], where the AE is an elastic wave including the mechanical vibration, acoustic wave, and ultrasonic wave that rises with the mechanical events such as the elastic deformation, the creation and evolution of the crack, friction, wear of materials, and indentation of the material. Because the destruction process of the material can be monitored, the AE sensing is already in commercial use, and is used as a non-destructive analysis and maintenance method of the operating mechanical system. In addition, the device for AE detection has been also developed for basic research to investigate the mechanism of the material destruction, evaluation of the material with the defect and/or the crack, and the parameters of fracture mechanics such as stress intensity factor or energy release rate [19-21].

Both the SPM and the AE analysis described above are effective methods for investigating the fracture mechanism. The stress for fracture is applied by AFM, and the frictional force or fracture stress is probed by FFM. The induced electron can be detected by STM, and induced the AE is detected by the AE sensor. The AE from interaction such as fracture including the friction and/or wear between the probe and sample surface of the SPM can be further explored, from which the generation of the defect and/or the crack evolution during the fracture can be estimated. This can be used to investigate the fracture of the material at the atomic-scale, which is very close to the elementary process of the fracture, and involves the break of a single bond of atoms [14]. In order to clarify the relation, the simultaneous observation of force vs. distance between the probe and sample, called the force-distance curve, and the simultaneous observation of the of the AE signal and image of SPM is needed [22-24]. In addition, when this method is applied for the plane raster scan, it is possible to conduct a more detailed analysis with simultaneous the mapping images of the probe signal and AE signal. In order to simultaneously enable such a simultaneous both measurement functions, it is needed that in the probe signal detecting unit and sample of the SPM, the AE detecting sensor and pre-amplifier and cables should be set in the SPM body. This is difficult without remodeling the SPM body with its size and shape, since the space to implement AE sensors and pre-amplifier and cables the free space of the SPM body is too small. Moreover, for the AE source location, more than two AE sensors need to be implemented, which makes the measurement system much larger. In this study a novel AE signal detecting method on SPM that solves the above problems is introduced. In addition, the data suggest that the AE source location could be possible.

2. Experimental method

2.1. Proposal of a novel AE detecting methods using SPM

In SPM measurements, an electric signal controlled by scan signal generator is used for the raster scan which allows image mapping of the surface and distance change between the probe and sample surface, as shown in Fig. 1. The motion of the scan is generated by using deformation caused by the piezoelectric effect, and this is called as scanner. Overall, the shape of the scanner is a tube shape [25] with a precise diameter, which is called as tube scanner, as shown in Fig. 2(a).

With the AE wave received by the tube scanner of the SPM, which is the piezoelectric material, the signal due to AE wave is expected to be superimposed on the scan signal by the piezoelectric effect, and this can be detected by monitoring the scan signal, although the scan signal is usually not monitored in the SPM study. Since the scan signal is lower than 100 Hz and the AE signal is in the frequency range of ~10 kHz to ~1 MHz, there is likely to be only very small cross talk between the two superimposing signals. Then, by using the electric high-pass filter, the AE signal might be detected from the two superimposing signals, as shown in Fig. 1 [26]. Therefore, as stated above, the simultaneous detection of the SPM signal and AE signal could be possible. Comparing with the ultrasonic wave receiver installed into the AFM [12,22-24], the piezoelectric tube scanner is already implemented in all the SPMs, which is an
advantage of this method, where this method does not need the remodeling the SPM body with its size and shape as mentioned in introduction. Also an another advantage is that a two-dimensional AE source location could be possible by using the four electrodes which correspond to +X, −X, +Y, and −Y direction of the tube scanner. The difference is the directions of the electrode of the piezoelectric tube scanner, which has a round shape. The X, Y and Z direction is defined by the directions of the electrode of the piezoelectric tube scanner. In the case of AFM, as shown in Fig. 2(a), the piezoelectric tube scanner has 5 electrodes, which correspond to X and −X, Y and −Y, and Z. X and −X is the direction across the AFM cantilever. Y and −Y is the direction long the cantilever. Z is the direction vertical to X-Y plane, which is the direction of the normal load is applied. This method is able to be used when sample is attached on the piezoelectric tube scanner, as shown in Fig. 2. When the SPM sensor is attached to the piezoelectric tube scanner, this method cannot be used. In addition, the nature of the piezoelectric material of the tube scanner is also affected the detected result. The high-pass filter whose cutoff frequency is ~1 kHz is used for all signal of +X, −X, +Y, −Y, and Z.

In order to scan the sample surface by applying the electric signal to piezoelectric tube scanner the SPM, the scan position for the X, Y, and Z direction by the scan signal generator need to be controlled, as shown in Fig. 1. As shown in Fig. 2(a), the four electrodes of +X, −X, +Y, −Y are arranged as overlaying on the side wall with 90 degrees shift, and one electrode that corresponds to +X, −X, +Y, −Y, and Z of the piezoelectric tube scanner, as shown in Fig. 2. The resonant frequency of piezoelectric tube scanner for X and Y, directions is estimated as ~500 kHz, and Z direction is estimated as ~50 kHz. Since the AE wave is mainly surface wave, the resonant frequency of the piezoelectric tube scanner at surface could be more than 10 MHz, which is enough to detect the AE wave. The load between them is more than ~30 N. In this experiment, the signals are not amplified, since the power of the AE wave simulator is enough. Only in the case of data shown in Fig. 2(b) also received by a commercially available AE sensor and through it the AE Pulse wave goes to the piezoelectric tube scanner. For making sure the piezoelectric tube scanner is able to detect the AE signal, a commercially available AE sensor is introduced, by comparison of the AE signals of a commercially available AE sensor and the piezoelectric tube scanner.

The +X, +Y, and Z are the electrodes to generate the displacement of tube scanner for +X, +Y, and Z direction, where the commercially available AE sensor is attached on the sample stage. The AE wave is generated by the pulse of about 100 Hz and by changing its amplitude, which is shown in the signal of the commercially available AE sensor. The change of the AE wave amplitude is for testing the amplitude commensuration of the signal from the tube scanner. In this experiment, the signals are not amplified. The HPF whose cutoff frequency is ~1 kHz is used for all signals of +X, −X, +Y, −Y, and Z.

Also, the indentation of the atomic force microscope (AFM) tip to an optically flat surface of fused silica is demonstrated, where AFM is one of the SPM. The used micro-cantilever is made of the stainless steel. The spring constant of the micro-cantilever is ~230 N/m. The tip is diamond which is made by polishing, where the radius of curvature of tip apex is estimated as ~1 μm. The applied force for observe the begging of appearing the AE signal is estimated as ~11.5 mN. Applied force is controlled manually with a step of ~230 μN.
3. Experimental results

On adding a simulated AE wave to the SPM tube scanner through a commercially available AE sensor, as shown in Fig. 2(b), the typical signal from the +X electrode show a pulse signal with a frequency of ~100 Hz synchronizing with the commercially available AE sensor. Figure 3 shows the detected signals of +X, −Y, −X electrodes when the AE pulse wave is applied to the commercially available AE sensor, as shown in Fig. 2(b). The signals from the tube scanner and the commercially available AE sensor are compared. With a delay of a few micro-seconds from the AE pulse all the signals show the wave form with pulse and minus value spikes with a few attenuating waves. The long two red allows suggest that all the signals of +X, −Y, and −X show the almost synchronized behavior, where −X and −Y are the same sign, and +X is inverted because of the position of grand and because the electrode is inverted. The wave after the spike indicated by a long red allow has a delay of about 37 µs with the AE pulse.

Figure 3 shows the typical detected signals of +X, −Y, −X electrodes when the AE pulse wave is applied at the center of the sample stage, as shown in the inserted figure, which means that the distance between AE pulser contact point and +X, −Y, and −X electrodes is the same. This corresponds to the beginning part of each AE pulse and synchronized detected signals by +X, −X and −Y electrodes, which are observed in Fig. 2. The signals from the tube scanner and AE pulser are compared. With a delay of a few micro-seconds with the AE pulse all the signals show the wave form with plus value spike with a few attenuating minus value waves. The long red allows suggest that signals of +X and −Y show the almost synchronized behavior, where the short red arrow suggests that −X shows a delay of about 8 µs, which might be less than 8 µs since the signal might be buried in the noise. The wave after the spike indicated by long red allows shows a delay of about 39 µs with the AE Pulse.

4. Discussions

As shown in Fig. 2(b), with a change in the power of the AE simulator, the amplitude of the signal from the +X
The signal amplitude is about 1/800, and the noise is much larger than that of the signal of the commercially available AE sensor. Resembling to the signal from the +X electrode, the signal from the +Y electrode also shows the pulse signal with a frequency of ~100 Hz synchronizing with the commercially available AE sensor, and the change in amplitude was almost according to the signal amplitude of the commercially available AE sensor. The sign of the signal seems to be inverted, the signal amplitude is about 1/600, and noise is much larger than that of the signal of the commercially available AE sensor. The difference between the signals of +X and +Y might be explained by the difference in the anisotropy of the piezoelectric material of the tube scanner along the X and Y directions.

The signal from the Z electrode also shows the signal with a frequency of ~100 Hz synchronizing with the commercially available AE sensor, with changing amplitude almost according to the signal amplitude of the commercially available AE sensor, although the signal show a few following attenuated additional pulses. These additional pluses might be induced by the reflected AE wave in the tube scanner. The noise is comparable to that of the signal of the commercially available AE sensor, although the signal amplitude is about 1/600. The shape of the pulse is different from the signal of the commercially available AE sensor, which might be due to the difference in the receiving direction of the Z direction electrode and the commercially available AE sensor. Thus, the experimental result that the pulse signals from the electrodes of the SPM tube scanner seems to correspond to the applied AE pulses, suggests that the signal from the SPM tube scanner could correspond to the AE signal. Therefore, by monitoring the scan signal with high-pass filter, the AE signal could be detected, as shown in Fig. 1.

As shown in Fig. 3, when the AE pulse wave is applied at the center of the sample stage, the detected signals of +X, −Y, and −X electrodes shows the wave form with plus and minus value spikes with a few attenuating waves, and with a delay of about 37 µs after this wave some additional waves occur, where the signals of +X, −Y, and −X seems to be synchronized. This seems to be consistent when the distances between the AE pulser contact point and +X, −Y, and −X electrodes are the same. The diameter of the SPM sample stage is 12.8 mm, which leads to a distance of 6.4 mm between the AE pulser touching point and each electrode of +X, −Y, and −X. When the speed of the longitudinal wave is supposed as 5000 m/s, in the metal sample holder, the time to reach to the electrodes is 1.28 µs, which seems to be in good agreement with the appearance of the wave signal form with the pulse and minus value spike. A few attenuating waves might be the reflection of AE wave in the tube scanner, which seems to be a transverse wave. The beginning of the wave is difficult to determine, although the beginning of the AE signal is determined as the time position that is indicated by the red arrow, where the
signal amplitude seems to become overcome that of the noise. As mentioned above, the sensitivity of tube scanner as compared with the commercially available AE sensor is about 1/600, and the beginning of the signal could be not detected. Thus the beginning of the signal could appear earlier and the delay of about 37 micro-seconds might be smaller. One possibility is that the signal continues with a few attenuating waves, the signal appears after about 37 µs delay could be the reflection of the AE wave. Thus, eliminating the reflection of the AE wave signal is a problem yet to be resolved.

As shown in Fig. 4, when the AE pulse wave is applied between +X and −Y electrodes of the sample stage, with the delay of a few micro-seconds with AE pulse all the signals show the wave form with plus value spikes and a few attenuating minus value waves; this is already discussed in the data shown in Fig. 3. A delay of about 8 µs which could be also shorter, which implies that the time delay corresponds to the difference of the distance from AE pulser contact point to each electrode of +X(−Y) and −X. Since the distance between AE pulser contact point and −X electrode is about 9.0 mm, the time for the AE wave to go is about 1.8 µs. The amplitude of −X is smaller than that of +X and −Y, which might suggest the distance difference between −X and +X(−Y).

The beginning of the wave is difficult to determine, although the beginning of the AE signal is determined as the time position that is indicated by the red arrow, where the signal amplitude seems to become overcome that of the noise. Because of the low sensitivity, there is a possibility that the begging of AE wave about 8 µs delay might be about 2 µs, which would be in good agreement with 1.8 µs. This seems to suggest that with this method of detecting AE by SPM, the AE source location could be possible, which should be work out in some points including reflection of the AE wave in tube scanner. When this detecting method is established, the AE signal might be considered as one of the probe signal. Since the electrodes are +X, −X, +Y, and −Y, a two-dimensional AE source location could be possible.

Figure 5 shows the spike shape signal with large amplitude is observed, and after ~150 msec. the AE signal is continuously appears. This might imply that the crack of fused silica surface is generated with the first impact of the indentation force that is just over the supportable force of fused silica surface. After that with the step increase of the force of ~230 µN, the second impact of the indentation force that might be just over the supportable force with the larger contact area which leads to the smaller contact pressure than first impact. This might explain the smaller amplitude of second AE signal than first one. AE signal observation with much more small force, we are considering that the signal amplifier is required, which could be the next step to realize, without ruining the low noise of SPM signal.

The principle purposes of this work is to verify whether the piezoelectric tube scanner of the SPM can be applicable to AE sensing. Therefore, we used AE wave simulator as AE source as a first step. As a second step, we used atomic force microscope (AFM) indentation. So, it is supposed that the piezoelectric tube scanner of the SPM and other the measurement system is treated as one system. In this work, above precondition, the comparison between the developing system and the commercially available AE sensor system is investigated. Since the input wave is the simulated wave, it is not essential to discuss the amplitude and frequency response. In this study, in order to investigate whether the detection of AE and the AE source location is possible, we focused on time response. With establishing the AE source location on the SPM, we are going to try to AE signal that relates the destruction, where amplitude and frequency could be discussed. In addition, in this work, the tribological investigation and the examination procedure of the nano scale fracture still remains a future matter.

These advantages of this detection method with the combination of AE and SPM could change the method of analyzing of fracture mechanism. This method could be used to gain an insight on the mechanism of the generation of fracture at an atomic scale, and could aid studies on the fracture mechanism.

5. Summary

It is proposed that on receiving an AE wave with the tube scanner of the SPM by the piezoelectric effect, the AE signal could be superimposed on the scan signal, and then with using a high-pass filter on the scan signal the AE signal might be detected. This can be achieved without changing the SPM body, and is the main advantage of this detecting method. The method could be confirmed by a simple experiment using an AE wave simulator. It is suggested that with this method of detecting AE by SPM the two-dimensional AE source location could be possible, and this is an another advantage of this detecting method. Also, the indentation of the AFM tip to the fused silica is demonstrated, which AE signal is observed.

References


