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Nanometer-Scale Manipulation and Ultrasonic Cutting Using an Atomic Force Microscope Controlled by a Haptic Device as a Human Interface

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We describe a nanometer-scale manipulation and cutting method using ultrasonic oscillation scratching. The system is based on a modified atomic force microscope (AFM) coupled with a haptic device as a human interface. By handling the haptic device, the operator can directly move the AFM probe to manipulate nanometer scale objects and cut a surface while feeling the reaction from the surface in his or her fingers. As for manipulation using the system, nanometer-scale spheres were controllably moved by feeling the sensation of the AFM probe touching the spheres. As for cutting performance, the samples were prepared on an AT-cut quartz crystal resonator (QCR) set on an AFM sample holder. The QCR oscillates at its resonance frequency (9 MHz) with an amplitude of a few nanometers. Thus it is possible to cut the sample surface smoothly by the interaction between the AFM probe and the oscillating surface, even when the samples are viscoelastics such as polymers and biological samples. The ultrasonic nano-manipulation and cutting system would be a very useful and effective tool in the fields of nanometer-scale engineering and biological sciences. [DOI: 10.1143/JJAP.47.6181]

KEYWORDS: atomic force microscope, nanofabrication, haptic device, scratching

1. Introduction

Scanning probe microscopes (SPMs) are well known as surface imaging tools at nanometer-scale resolution. SPMs can be used not only for surface observation but also for local surface modification. The typical modification technique using an SPM is to directly scratch on surfaces with the probe. The contact between the probe and the surface can be maintained at a constant force, thus allowing reliable modification by scratching on the surface.[1–8] However, some polymeric materials and biological samples exhibit complicated scratched behavior, such as bundle formation, due to a sliding interaction between a probe of an atomic force microscope (AFM) and a viscoelastic surface,[7,8] making it difficult to cut polymer surfaces smoothly for nanometer-scale fabrication. Furthermore, it is challenging to control surface cutting in the case of inhomogeneous materials such as polymer blends and biological samples, because of their inhomogeneous stiffness. As a result, other force feedback techniques are needed to realize flexible control of scratching forces.

In the realm of force feedback control, haptic technology refers to technology that supplies an interface between the operator and a machine via the operator's sense of touch while applying forces. This emerging technology has been widely used in various fields such as games, computer-aided design, medical simulations, and remote control robotics. Recently, haptic technologies have been introduced in nanometer-scale manipulations using AFMs.[9,10] Using a haptic device, an operator can directly move an AFM probe on a surface and feel the response from the surface being AFM manipulated. The haptic technique should be very useful for nanometer-scale manipulations and fabrications, particularly in the fields of biology and anatomy.

For modification of polymer surfaces, we have described how ultrasonic scratching, that is, scratching with an ultrasonic oscillating probe, is effective to machine on polymer surfaces without distortion.[11,12] By combining ultrasonic scratching with haptic technology, we hope to develop a nanometer-scale ultrasonic cutter that will be a very effective tool in the fields of nanometer-scale engineering, biology, and anatomy.

In this paper, we describe a nanometer-scale manipulation and scratching techniques based on an AFM coupled with a haptic device consisting of a pen-like handle. By handling the pen of the device, an operator can directly move the AFM probe to manipulate nanometer-scale objects and scratch a surface for nano-fabrication with fine human sensomobility. As a demonstration of a manipulation using this system, nanometer-scale spheres were controllably moved on a mica surface. As a demonstration of surface modification, the ultrasonically cutting of polymers and biological samples is discussed in comparison with conventional scratching in the contact mode.

2. Experimental Procedure

2.1 *AFM coupled with haptic device human interface*

Figure 1 shows a schematic diagram of the nano manipulation and surface modification system based on an AFM controlled by a haptic device. We employed a commercial haptic device that has a pen-like handle with a serial rink mechanism (PHANTOM Omni, SensAble Technologies). A homemade system consisting of an AFM, controller,[13] and software was modified to include the haptic device for the manipulation and control of ultrasonic cutting. With respect to lateral movements in the x- and y-directions, a signal from the haptic device is sent to the personal computer, and then the signal is sent to the piezo drive circuit passing through a digital-to-analog converter. In our experiments, 1 mm of lateral displacement of the pen handle corresponds to 15 nm in movement of the AFM probe. The topographical signal detected in the AFM controller is fed to the personal computer, and then the signal is converted to the displacement in the z-direction of the pen handle of the haptic device. Using this process, nanometer-scale topographical information detected by the AFM can be scaled up to millimeter movements of the pen handle of the haptic device, and the nanometer-scale

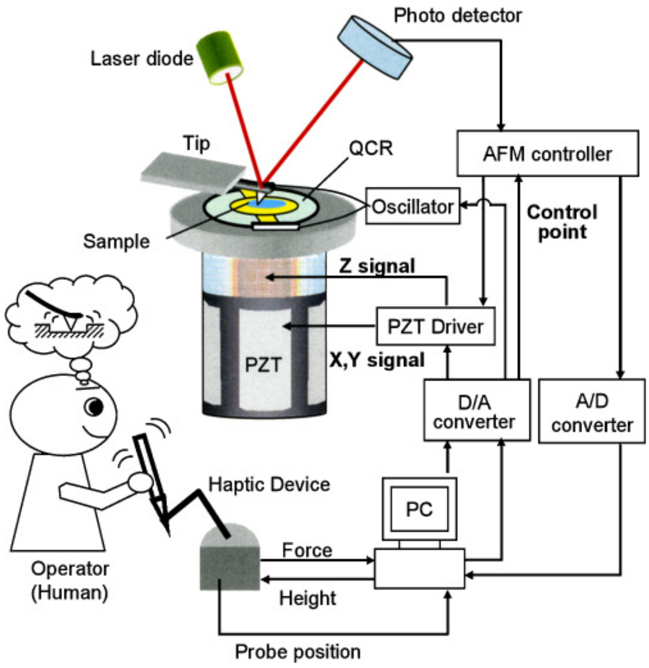

Fig. 1. (Color online) Schematic diagram of the experimental setup of an AFM with a nano manipulator and an ultrasonic nano-cutter. The AFM is coupled with a haptic device, so the operator feels the response from the sample during scratching.

topography on the surface can be felt in the operator's fingers holding the pen handle. In our system, surface roughness of 1 nm corresponds to 3 mm in movement of the pen handle haptic device. During the manipulation, if the operator pushes the pen handle haptic device against the response, a signal is sent to the personal computer to calculate and convert the force feedback signal, and then the converted signal is sent to the feedback controller to change the setting point of the feedback control. The system changes the force between the probe and the surface in response to pushing by the operator. By this sequential process, the operator can change the applied force between the probe and the surface by feeling the force from the surface via the haptic device.

2.2 *Ultrasonic scratching*

Figure 2 is a drawing of the AT-cut quartz crystal resonator (QCR) used as a sample substrate for ultrasonic cutting. The direction of the crystal oscillation depends on the crystallographic orientation. The AT-cut QCR provided mechanical shear oscillation. The shear deformations of the QCR are parallel to the surface of the crystal plate. The sample was prepared on the surface of the QCR. A polished QCR was employed (Nihon Dempa Kogyo) as the AFM sample substrate. The wafer plate was 8.5 mm in diameter and 0.33 mm thick. The resonance frequency of the QCR was 9 MHz.

In these experiments, we used polymeric and biological samples to test the ultrasonic cutting performance. Polycarbonate films were prepared as a polymer sample. The polymer solution, 50 µl of polycarbonate (2 mg/mL in 1,2-dichloromethane), was cast by spin-coating the solution onto QCR wafers at 2000 rpm for 5 s. For biological samples,

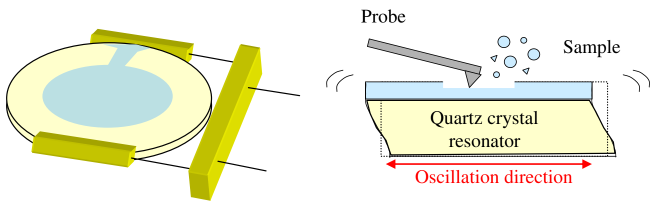

Fig. 2. (Color online) AT-cut quartz crystal resonator. The shear deformations of the AT-cut QCR are parallel to the surface of the crystal plate. The QCR oscillates at its resonance frequency of 9 MHz with an amplitude of a few nanometers. The samples are prepared on the wafer of the QCR. The oscillating sample surfaces are scratched with the AFM probe for ultrasonic cutting.

collagen fibrils taken from rat tail tendons were placed on the wafer plate of the QCR using tweezers and then dried with a stream of dry air.

Prepared QCR wafers were put on the AFM sample holder located on a piezoelectric tube scanner, as shown in Fig. 1. The cantilever employed in the experiments was commercial and designed for contact mode operation (Olympus OMCL-TR800PSA). The spring constant of the cantilever was 0.57 N/m.

The piezoelectric tube scanner was used for loading the force and moving the sample against the tip. With respect to the tip scratching the surface, the sample surface was moved in x–y directions by the tube scanner with QCR oscillation under applied loading force. In this paper, we refer to scratching on the surface with QCR oscillation as ultrasonic scratching.

2.3 *Manipulation and fabrication*

The AFM manipulation proceeds as follows. First, the surface topography is ascertained just before the manipulation by the AFM, and then the topographical image is displayed on a screen in front of the operator. After observing the image on the screen, the operator moves the AFM probe using the haptic device to modify the surface. During the process, the operator can recognize the probe position as a cursor on the AFM image. During the manipulation, the trajectory lines of the probe movement are drawn on the AFM image. In the haptic device, the pen handle has a button to turn on the oscillator of the QCR for ultrasonic scratching. Thus the operator can start and stop ultrasonic scratching at any position on the surface while feeling the response from the surface. After the manipulation or the cutting, the processed surface is obtained by the normal AFM operation.

3. Results and Discussion

3.1 *Manipulation of nanometer-scale objects*

The haptic feedback system is useful for nanometer-scale manipulation of micrometer- or nanometer-scale objects. As a demonstration of the AFM manipulator, nanometer-scale spheres were moved on a flat substrate. Figures 3 and 4 show manipulation of the nanometer-scale sphere using a mouse and the haptic device. Polystyrene nano-spheres 100 nm in diameter were scattered on an atomically flat mica substrate. The direction of the long axis of the cantilever is parallel to the vertical axis of the AFM images. After observing the

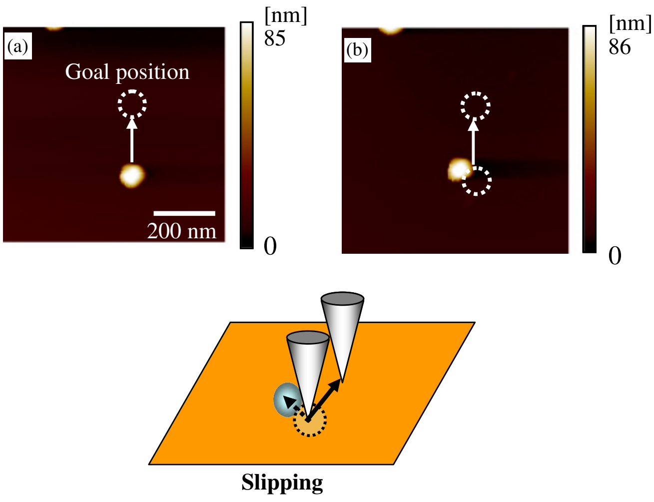

Fig. 3. (Color online) Nanometer-scale manipulation of polystyrene spheres using the AFM without the haptic device. (a) Topographical image before the manipulation. The operator tried to move the target sphere to the goal in the image. (b) Topographical image after the manipulation. The sphere was slightly dislocated from the original point.

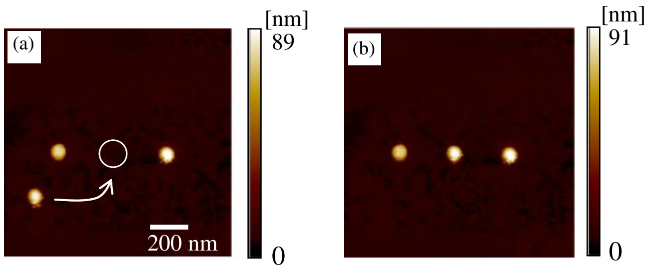

Fig. 4. (Color online) Nanometer-scale manipulation of polystyrene spheres using the AFM with the haptic device. (a) Topographical image before the manipulation. The operator tried to move the target sphere to the goal in the image. (b) Topographical image after the manipulation. The target sphere was successfully moved to the goal.

topographical image, the operator moves the probe toward the target sphere. With respect to such an approach, in general for AFM manipulations using the normal mouse, the operator tries to move the mouse to position the probe on the target sphere. However, even if the probe position can be recognized as a cursor on the PC screen, the operator cannot feel the reaction from the mouse as the probe touches the sphere. Thus, it is very difficult to move the sphere to an exact point. In our experiments, the sphere could not be moved to the goal, and in many cases, the sphere was just dislocated because of slipping in response to probe manipulation, as shown in Fig. 3. When using an AFM coupled with a haptic device, however, the operator can feel the reaction according to the deflection of the cantilever, and the operator can recognize whether the probe touches the sphere and then move it to a certain point. In Fig. 4, the lower sphere could be successfully moved toward the middle point between two spheres. In our experiments, polystyrene spheres were prepared by dropping the colloidal solution on the substrate and then naturally drying it. Thus, relatively strong forces of up to 60 nN are required to loosen the sphere from its initial position because of the adhesion between the sphere and the

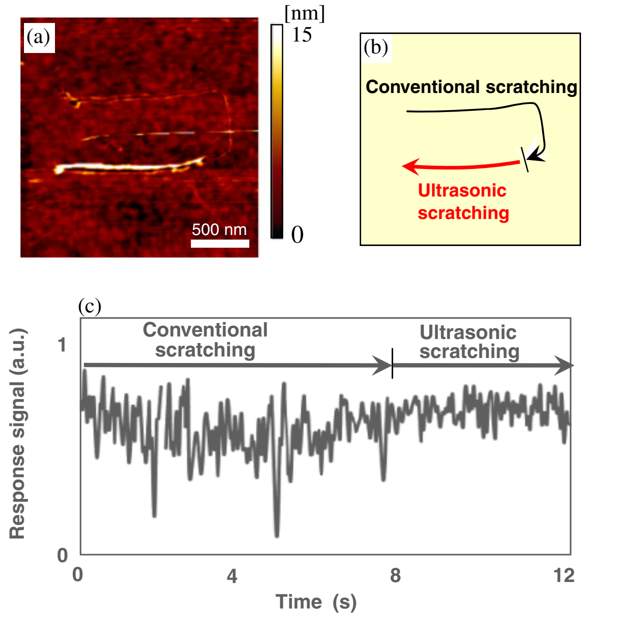

Fig. 5. (Color online) Scratched line on a polycarbonate film using the haptic device. (a) Topographical image of scratched line. The upper part of the line was scratched by conventional scratching, i.e., scratching without QCR oscillation. The lower part of the line was scratched by ultrasonic scratching, i.e., scratching with QCR oscillation. (b) Sequence of drawing the scratch. (c) The response of the feedback in the haptic device while making the scratch.

surface. Once the sphere was dislocated from its initial location, it could be moved with a loading force of less than 20 nN. However, the movement of the sphere was complicated. Thus, the operator had to keep recognizing the existence of the sphere by searching for it and touching it with the probe. It took a few minutes to move it a distance of about 500 nanometers. In our experiments, the manipulation succeeded 7 times out of 10 similar trials. Therefore, even in such a difficult process, this system would be very useful for manipulating nanometer-scale objects.

3.2 *Scratching on polycarbonate surface*

Figure 5 shows the scratched surface of a polycarbonate film using the haptic device. The direction of the long axis of the cantilever is parallel to the lateral direction of the AFM image. The scratched line was drawn with a single stroke at an average loading force of 120 nN. The moving speed was 300 nm/s. The first half of the line was scratched without QCR oscillation and last half after turning was scratched with QCR oscillation. The direction of the QCR oscillation was parallel to the long axis of the cantilever. As shown in this image, the line scratched without QCR oscillation is not seen clearly. On the other hand, the line part scratched with QCR oscillation is clearly seen. Figure 5(c) shows the feedback response of the force while operating the haptic device, which is reflected in the cantilever defection during scratching. For the part of the line scratched without QCR oscillation, the response indicates roughness and large amplitude. On the other hand, at the part scratched with QCR oscillation, the amplitude of the response is smaller than that of the scratching without QCR oscillation, even though the depth of the ultrasonically scratched part is

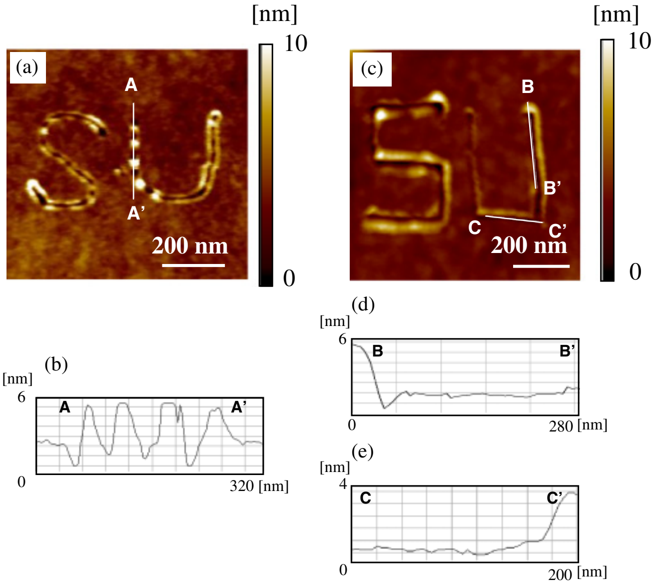

Fig. 6. (Color online) Surface of a polycarbonate film scratched using the haptic device. (a) The surface scratched without QCR oscillation. (b) Cross-sectional profile of the scratched line in (a). (c) The surface scratched with QCR oscillation. (d) Cross-sectional profile of the scratched B–B′ line in (c). (e) Cross-sectional profile of the scratched C–C′ line in (c). The letters "SU" stand for Shizuoka University.

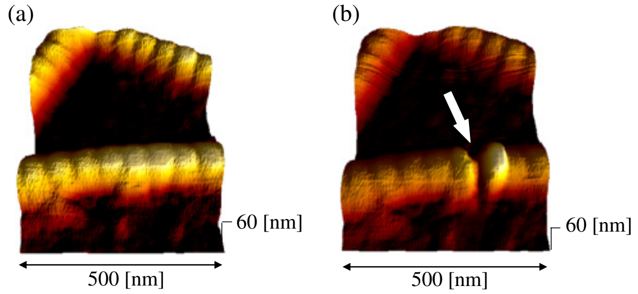

Fig. 7. (Color online) Collagen fibrils taken from a rat tail tendon. (a) Topographic image of the collagen fibrils before scratching. (b) Topographic image of the collagen fibrils after scratching.

greater than that of the conventionally scratched part. It is well known that it is difficult to cut polymer surfaces by conventional scratching due to their viscoelasticity.[7,8] Thus, the unstable deflection of the cantilever would be caused by an irregular stick-slip motion during scratching. As a result, the operator feels an irregularity in the haptic handle. On the other hand, in the case of ultrasonic scratching, the surface oscillates laterally with an ultrasonic frequency of 9 MHz, which generates high-speed repetitive scratching with an amplitude of a few nanometers. The speedy but small scratch can cut the polymer surface due to a reduction in the viscous damping properties of polymers.[11] As a result, the deflection of the cantilever is stable and the operator feels a smooth response.

Figure 6 shows the surface of a polycarbonate film scratched using the haptic device. The letters "SU" stand for Shizuoka University. The direction of the long axis of the cantilever is parallel to the vertical axis of the AFM images. Figure 6(a) shows the surface scratched without QCR oscillation. The average loading force was 200 nN and the scratching speed was 300 nm/s. Figure 6(b) is the cross-sectional profile of the scratched line in Fig. 6(a). The topographical profile of the scratched line is not smooth. Periodic bumps appearing on scratched surfaces are generated by interactions between the probe and the viscoelastic polymer surfaces under strong loading force. The macromolecules are laterally stretched by the AFM tip, which may cause the surface distortion.[7] During the process, we could feel the irregularity in the scratching response in our fingers via the haptic device. Thus, rough morphology in the scratched line could be predicted during the manipulation.

To cut the polymer surface smoothly, we carried out ultrasonic scratching with QCR oscillation. Figure 6(c) shows the polycarbonate surface scratched by ultrasonic scratching. The direction of the QCR oscillation is parallel to the long axis of the cantilever. The average loading force was 70 nN and the speed scratching was 300 nm/s. Figure 6(d) is the cross-sectional profile of the scratched groove in Fig. 6(c). As shown in the image, the morphology of the scratched line is flat due to the progression of the cutting force under ultrasonic scratching as described. Figure 6(e) is the cross-sectional profile of the scratched groove in Fig. 6(c). Even though the direction of the scratched line is perpendicular to the oscillating direction of the QCR, the bottom of the groove is flat. The speed of the reciprocal small scratching at 9 MHz is very high in comparison with the speed of drawing the scratch. Thus it would effectively cut of the polymer surface smoothly, even if the scratching direction were different than that of the QCR oscillation. During the process, we cut the surface while sensing a smooth response in the haptic device.

3.3 *Cutting of biological sample*

Finally, we applied the system to a biological sample. Figure 7 shows the collagen fibrils taken from a rat tail tendon. In the AFM image, the collagen fibrils had a semi-cylindrical profile. They have periodic transverse grooves and ridges on their surfaces, which is known as D-periodicity.[14] We cut the gap position of the collagen fibrils by AFM scratching using the haptic device. The direction of the long axis of the cantilever was parallel to the vertical axis of the AFM images. In the case of normal AFM scratching without QCR oscillation, it was very hard to cut the collagen because the structure consists of fibrils and subfibrils. However, using ultrasonic scratching with the haptic device, it was relatively easy to cut the fibers. Figure 7(b) shows the collagen fibrils successfully cut by the system. The direction of the QCR oscillation was parallel to the vertical axis of the AFM image. During the cutting, we recognized the topographical change in the collagen by feeling the response of the haptic device. It was very useful to predict the result. By feeling the result with the haptic device, we could adjust the appropriate parameters such as loading force and moving speed to achieve certain results. As a consequence, the collagen fibrils could be successfully cut by ultrasonic scratching by applying a force above 200 nN at a speed of 100 nm/s. Therefore, using this system, we can realize a nanometer-scale ultrasonic cutter that may be an effective tool in the fields of nanometer-scale machining of synthetic and biological materials.

4. Conclusions

Nanometer-scale manipulations and novel scratching of local surfaces were carried out using an atomic force microscope coupled with a haptic device. The operator can feel the response to force during the processes. To test the system, nanometer-scale manipulation and fabrication were carried out. For manipulation, it was possible to move nanometer-scale spheres on a mica surface with relatively high reproducibility. For the fabrication, a polycarbonate surface was scratched. In conventional scratching, the surface was not carved smoothly, and the cutting force during the fabrication was felt as an irregular response in the haptic device. On the other hand, the surface was smoothly carved in the case of ultrasonic scratching. In that process, the cutting force was felt as a smooth cutting process in the haptic device. In terms of biological samples, collagen fibrils were successfully cut by ultrasonic scratching. The system may be very useful for many applications, especially in the fields of nanometer-scale engineering and manipulation of biological samples.

Acknowledgments

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