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Dimensional measurement of high aspect ratio micro structures with a resonating micro cantilever probe

M. Yamamoto, H. Takeuchi, S. Aoki

Abstract In non-destructive dimensional measurement of high aspect ratio micro structures (HARMS), optical methods cannot offer full three dimensional information due to the lack of observation light. Again, conventional mechanical measurement, such as a surface profiler or a coordinate measurement machine, cannot be applied because their stylus is too large. Furthermore, the AFM, though popular among the semiconductor industry, is also limited in terms of dimensional measurement, because its system is usually designed for planar samples. Thus, we have developed a new sensor-integrated micro resonating cantilever probe and a new dimensional measurement machine, which allows the probe's vertical access to microstructures in a sample. The new probe is made of tungsten carbide super hard alloy and possesses design flexibility according to its intended application. Validity of the system is confirmed through the measurement experiment of EDM drilled and chemically etched micro holes.

1 Introduction

Recent development in the field of high aspect ratio micro structure technologies (HARMST) accelerates the need for nondestructive measurement of such structures.

Among various HARMS measurement, micro hole measurement is recognized as one of the most important industrial applications. For example, contemporary micro nozzle tests have been done by actually spraying liquid from the holes. The drawback; the test fails to give the exact location of the defect, thus stirring a desire for the measurement of hole profile and internal surface roughness. Again in the micromachine field, micro gears by EDM and LIGA are beginning to be used in practice. The evaluation of tooth surface roughness and wear of such gears call for a new measurement method.

HARMS measurement has inherent difficulties because high walls stand with extremely narrow spacing for probing means. Because the vertical surface doesn't reflect light back, optical methods are not suitable for three-dimensional evaluation. Thus, measurement with physical contact probes seems to be the promising solution for HARMS nondestructive evaluation.

The first approach for HARMS measurement is conventional mechanical probing measurement such as coordinate measurement machine (CMM). The smallest probe readily available as of present is ϕ0.2 mm. Because the probing force decides the minimum probe size, low contact force systems have been investigated (for example, [Pril et al. (1997)] and [Schepperie et al. (1998)]). Although these approaches have succeeded in realizing 1 μN probing force and ϕ100 micron fiber probes respectively, the difficulty of probe assembly limits further downsizing of the CMM probe.

Another promising approach for HARMS measurement is the AFM. Because most AFM systems are designed for planer samples like Si wafers, they employ a light leverage method to detect the probe's strain. As a result, when the probe is inserted into microstructures, the detective light can easily be obstructed and the system fails. One exception is critical dimension AFM (CD-AFM) [Vachet and Young (1995)]. Equipped with a flare-shape tip, this device can measure a trench of maximum 8 μm depth and minimum 0.5 μm width, which is used for devise isolation in LSI process. Thanks to the recent progress in AFM probe technology, some AFM probes have their own integrated strain sensor (for example, [Indermuhle et al. (1997) and Itoh and Suga (1993)]). These probes can be vertically inserted into micro holes and can measure the surface, once the measurement setup is prepared. Although the AFM approach seems to be a good candidate for HARMS measurement, its rigid probe dimension can be an obstacle. In other words, requirements for probe dimension can change according to the measurement sample because the probe and its tip dimension decide the maximum depth, maximum protrusion and minimum gap it can handle. Lithographically manufactured AFM probes cannot change shape once the mask pattern and the process conditions are fixed.

The third approach for HARMS measurement is to utilize a flexible manufacturing technology for custom-

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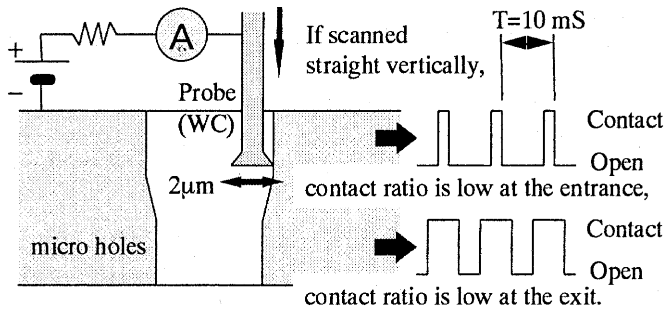

Fig. 1. Conventional micro hole measurement technique (VS)

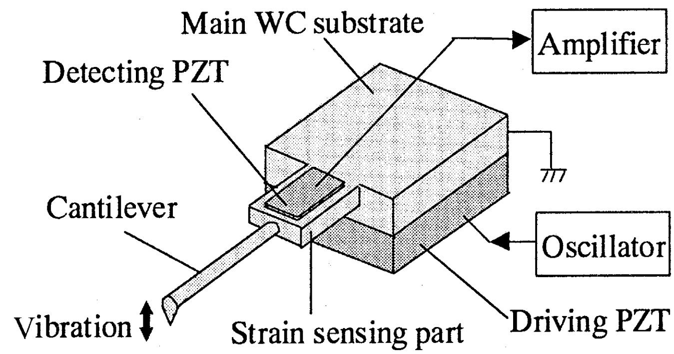

Fig. 2. Structure of RVS probe

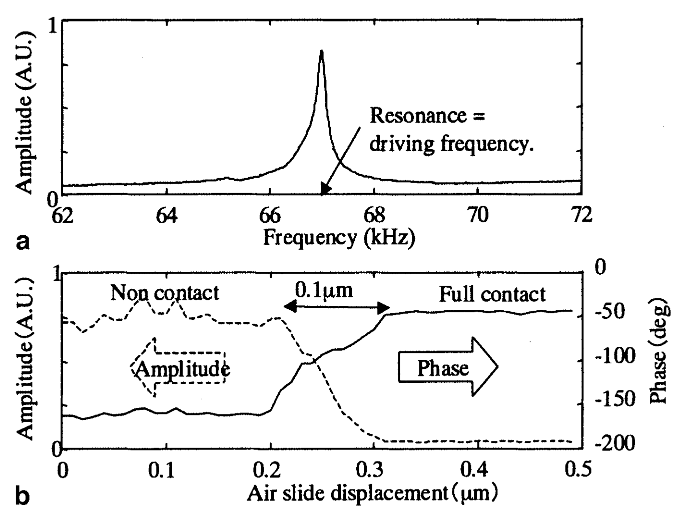

Fig. 3a, b. RVS probe properties. **a** Frequency response; **b** contact detection characteristics

made probes. Such an example is the vibroscanning (VS) method [Masuzawa et al. (1993)] that uses a probe machined by WEDG technology [Masaki et al. (1990)]. WEDG is a variation of EDM and works as a NC lathe for micro parts. The VS measurement principle is shown in Fig. 1. The probe is vibrated at a low frequency, 100 Hz, with amplitude of 2 μm. When the probe hits against a surface, an electric current is detected. By measuring the contact time per vibration period, the probe's position can be controlled at a constant distance from the surface. As is clear from its principle, the VS method cannot be applied to nonconductive samples. Measurement error can occur even in cases where the sample is covered by a thick oxide layer. Nevertheless, the VS method is a robust measurement tool for on-the-machine evaluation of micro EDMed sample [Yamamoto et al. (1996)]. To overcome the shortcoming of the VS method, the twin probe vibroscanning method was proposed [Masuzawa et al. (1997)]. By utilizing the twin cantilever and detecting the conductivity between them, contact to the surface can be detected irrespective of the sample's electric conductivity. Drawbacks which still remain include the fact that the electric contacts are open to the air and vulnerable to dust and oxidation. Moreover, the total thickness of the probe cannot be minimized, as it requires two cantilevers.

Based on the above-mentioned survey, we have concluded that a combination of AFM technology and VS technology gives the best methodology for HARMS measurement. In other words, the new probe should accompany an AFM-like integrated strain sensor while maintaining VS's flexible probe shape control.

2
A new probe and measurement principle

In a new probe, the key is how to form a strain sensor on a cylindrical cantilever machined by WEDG. Our solution is to divide the cantilever and strain sensing part as shown in Fig. 2. The main WC substrate is made of tungsten carbide super hard alloy, which is a popular material as a mechanical probe for its high hardness and Young's modulus. From the substrate, the cantilever part is shaped by WEDG. The strain sensing part is a WEDG machined thin flat part on which a detecting PZT plate is glued. When the cantilever is resonated by the driving PZT, its strain is measured by the detecting PZT. The contact of the probe can be detected by observing the amplitude of the strain signal. We call the technology "resonance mode vibroscanning method" (RVS) with respect to the fact that it employs the same cantilever technology as in VS. Figure 3a shows the frequency response of a probe possessing a cantilever 900 μm in length and 40 μm in thickness. The Q of resonance is 400. Figure 3b illustrates the change of vibration signal when the contact occurs. The tip amplitude is set to 0.1 μm. These results indicate the probe's detecting ability of over 0.1 μm. Calculating from probe stiffness of 500 N/m, the contact force is predicted to be less than 50 μN.

The fabrication process of the RVS probe is shown in Fig. 4. First, the PZT thin plate is glued to the WC substrate. The PZT plate is patterned by sand-blast machining, forming PZT islands. The WC substrate is separated into pieces by wire cut EDM. Then the piece is placed onto an alumina substrate with the driving PZT and electric wiring, forming a probe cartridge. At the last step, the probe cartridge is mounted on the WEDG machine, and the cantilever and strain sensing part are machined. Forming the cantilever after cartridge assembly enables it to be accurately aligned to the cartridge, thus guaranteeing high mounting accuracy on the measurement machine. Finally, each manufactured probe cartridge can have a custom-made probe shape for each application thanks to WEDG's NC machining.

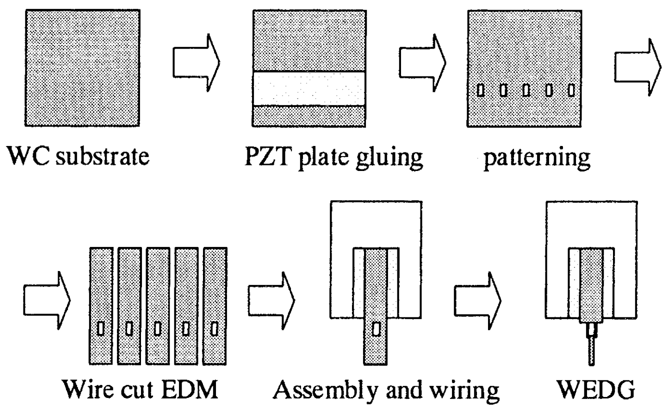

Fig. 4. Fabrication process of RVS probe

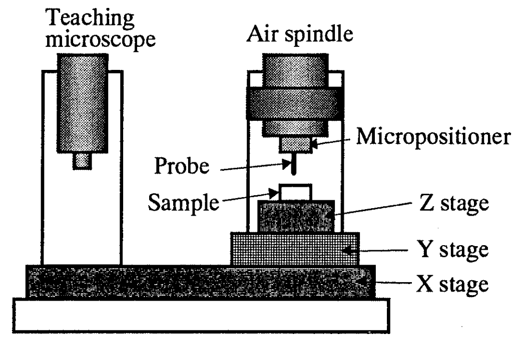

Fig. 5. Configuration of measurement machine

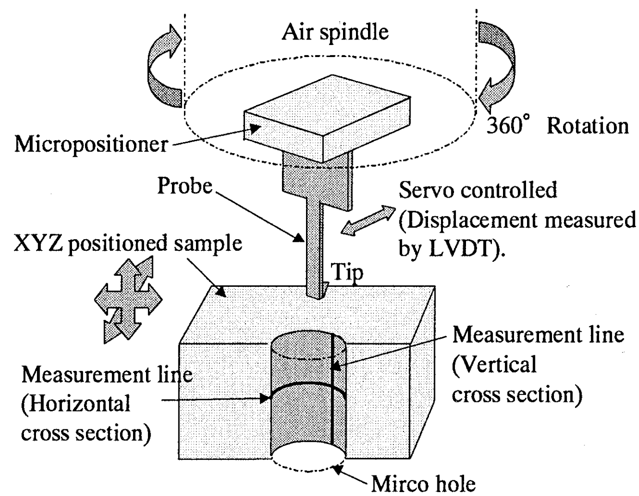

Fig. 6. Micro hole cross section measurement

3
Measurement machine

In conventional CMM, the measurement probe can easily be observed by the naked eye. In HARMS measurement, on the other hand, even inserting the probe into the region of interest is a painful process. To handle HARMS's specific difficulties, we have also developed a dedicated measurement machine.

As in Fig. 5, the measurement system has a teaching microscope, measurement probe, and XYZ stage. As the positional relationship between the microscope focal point and probe tip is fixed, once a operator instructs points in the microscope image, the probe can be automatically inserted into the sample and perform the measurement automatically. The sample is positioned by an XYZ air slide system. The XY air slides are actuated by two linear motors with feedback of a 10 nm resolution linear scale. The Z stage is guided by air slide and driven by ball screw. The Z stage position is monitored by a 20 nm linear scale but employs no feedback control. The smooth motion of the air slide guarantees submicron measurement accuracy. The micropositioner, under which the probe is vertically held as shown in Fig. 6, consists of a PZT actuator, displacement amplifying mechanism and a LVDT sensor. By the micropositioner, the tip contact condition is kept constant and its position is monitored by LVDT. Since the micropositioner's servo control is limited to one direction, a rotary air spindle with an accuracy of over 0.1 μm is equipped. Using the operator's registered instructions, the spindle rotates the micropositioner so that the probe tip faces the measurement surface at the right angle.

4
Experiment

Here we demonstrate our system through some measured results. Figure 7 shows measured results of a ϕ200 μm EDM hole in the tool steel plate of 1000 μm thickness. The inset photo is an optical microscope observation. Vertical and horizontal cross sections of the hole are illustrated in the chart respectively to the left and right. The arrows from right to left show the corresponding layer at each depth. Although the optical image doesn't show any

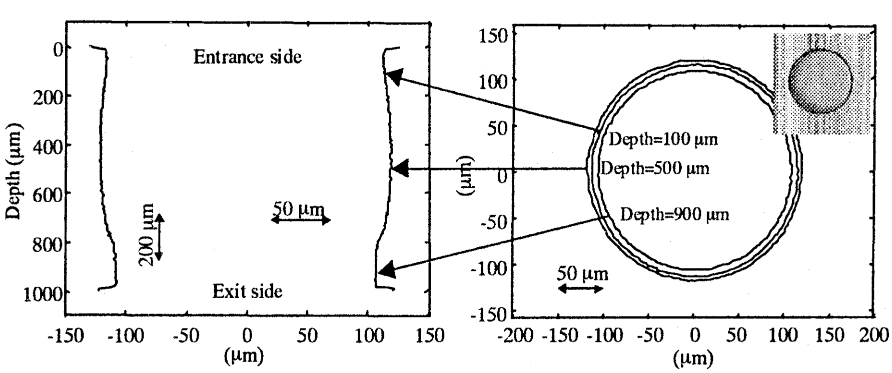

Fig. 7. Vertical and horizontal cross sections of EDM micro hole

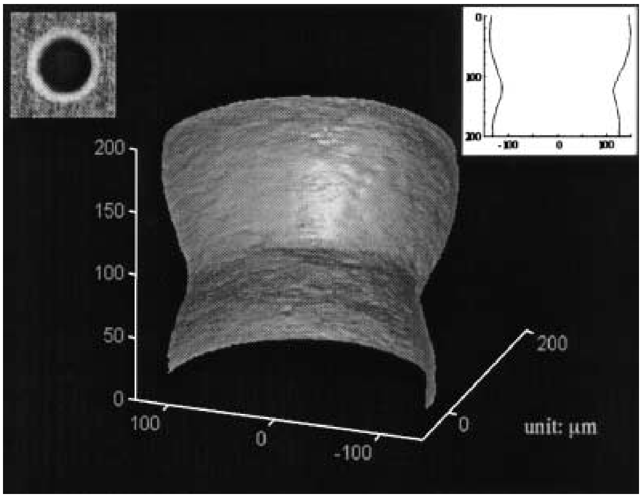

Fig. 8. Three dimensional rendering of etched micro hole

information of the inner surface, the vertical cross section measurement clearly shows a barrel shape cross section. This shape can be explained as electro discharge gap variation along the axis; the gap is influenced by the machined debris ejection condition. These results suggest that such measurements can be used to optimize the machining parameters.

Figure 8 is the three dimensional display of a double-side etched hole. An optical microscope image and a vertical cross section are shown in the upper left and right hand corners respectively. The measurement was done by consecutive cross sectioning at 1.8-degree interval and all cross sections are smoothly reconstructed in three-dimensional space later. The figure helps us to intuitively perceive the hole shape and surface roughness. As this measurement can be done totally nondestructively, it can be a powerful tool for etching process control.

5 Discussion

Figure 9 shows several variations of the probe tip. Probe (a) is a commonly used shape. The axis is ϕ40 μm and tip length is 40 μm. Probe (b) is a ball shaped probe, which is an analogy from a CMM probe. Probe (c) is an ultra high aspect ratio probe, ϕ12 μm in diameter and 1000 μm in length. The minimum possible diameter as of present is 10 μm, attempts for smaller diameter resulted in the bend of the probe caused by residual stress.

RVS application for HARMS measurement is basically limited by the available probe shape. Figure 10 is a rough sketch of the RVS application area, taking micro holes as examples.

In the chart, CD-AFM and CMM application areas are also drawn for comparison. The area of RVS ranges from 20 to 500 μm in diameter and 10–2000 μm in depth. The smallest diameter is defined by the thinnest possible probe, and the maximum comes from the competition with CMM. The maximum depth is decided by the WC substrate size we prepare. As we limit the probe's aspect ratio to less than 100, the maximum aspect ratio of the hole should be less than 30. As is clear from the chart, the RVS method fills the vacancy between CD-AFM and CMM.

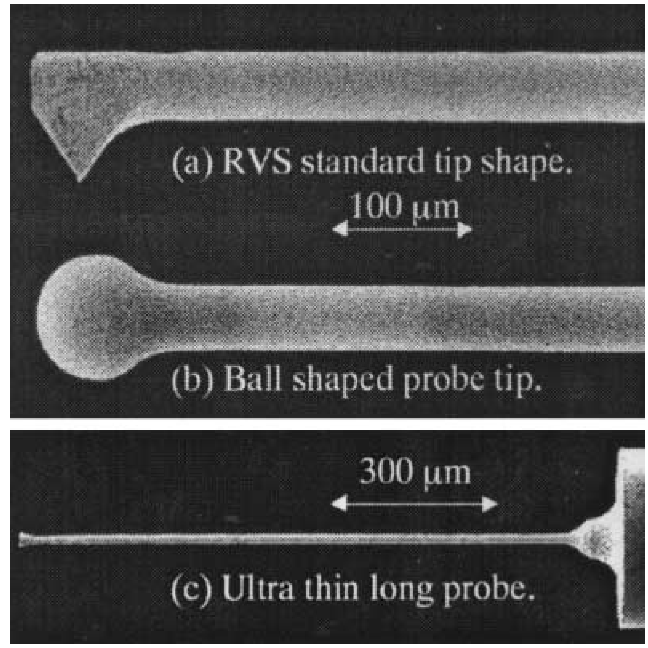

Fig. 9. RVS probe shape variations

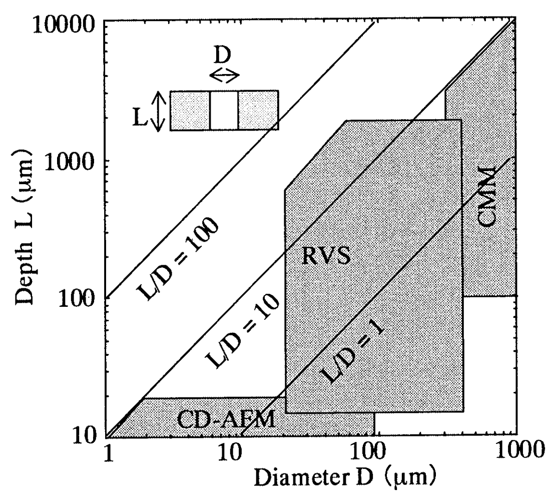

Fig. 10. RVS Application area in HARMS measurement

One drawback of the RVS probe is its relatively uncertain tip radius. Because EDM uses electro discharge heat to remove material, EDM craters on the workpiece are inevitable. The tip curvature radius is directly affected by the craters, and varies from 0.5 to 2 μm in our SEM observations. In order to make the tip shape constant, we are now preparing a debarring process for the tips.

6 Conclusion

Based on a survey of the current technology for HARMS measurement, we have proposed a new approach: the resonance mode vibroscanning method (RVS). The RVS probe inherits favorable characteristics of both VS and AFM methods. It is made of tungsten carbide super hard alloy and has flexibility in its shape and size (VS properties). It also has an integrated strain sensor to detect contact at a low contact force (AFM properties). The probe is attached to a newly proposed HARMS dimensional measurement machine. The internal profile of EDMed and chemically etched holes were examined. These results illustrate the validity of RVS for its intended application as a method for HARMS measurement.

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