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In-plane load measuring technique for the strength test of MEMS micro-cantilever

HUAN Yong, ZHANG Taihua & YANG Yemin

State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China

Correspondence should be addressed to Huan Yong (email: huany@lnm.imech.ac.cn)

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Abstract An in-plane load measuring technique is developed to perform the strength test of the micro-cantilever. Based on electromagnetism theorem, Micro UTM (Universal Testing Machine) was in-house made with the load range ±1 N and the displacement range ±300 μm. It applies an in-plane load on the free-end of the micro-cantilever. The load acts as a bending moment for the root of the cantilever, but as a torque for the anchor. The results show that for samples with different sizes the ultimate loads range from 1.3 to 69.8 mN and the calculated torque is approximately proportional to the square of the bonding length. Two failure modes, fracture at the root of the cantilever and fracture at the anchor, are observed by micro examination to the debris, which indicates that there is a critical design to achieve the strength balance between the cantilever and the anchor. The work demonstrates that Micro UTM is a powerful instrument for the strength test of the micro-cantilever and similar micro-structures.

Keywords: test, in-plane, strength, micro-cantilever.

Micro-cantilever bonded on glass substrate is a typical structure extensively used in sensors, actuators, RF-switches, etc[1−4]. It is necessary for MEMS (microelectromechanical system) designers to know the strength of the micro-cantilever. Usually, there are two typical methods to evaluate the strength:

(i) The first method is to measure the deformation of the cantilever, and then to calculate the stress through finite-element-method (FEM) or analytical calculations. Kristian *et al.*[5] developed a MEMS device for the beam bending test, in which an electrostatic actuator was fabricated together with the beam. The in-plane deformation of the beam was controlled and measured by the integrated electrostatic actuator. According to the deformation acquired in the test, the stress was calculated using FEM. This method is convenient because the displacement is easier to measure than the load in MEMS design. Nevertheless it is notable that the results of FEM strictly depend on the knowledge of the materials' properties. As it cannot be accurately obtained especially at the joint of two materials, there may be somewhat distinction between the calculated and the true stress.

(ii) The second method is to directly measure the load on the micro-cantilever. This method gets rid of the disadvantage of FEM mentioned above and directly obtains the ultimate load. In ref. [6], the fracture test of silicon micro-cantilevers was performed by this means, in which the out-plane load, applied on the micro-cantilever using a micrometer, was measured by a force transducer. In recent years, as the size of MEMS devices decreased gradually, Nano Indenter is used in the bending test of the micro-cantilever[7−10]. It can conveniently apply and measure the out-plane load on the free end of the micro-cantilever with high resolution. Unfortunately, these tests were only concerned with the out-plane load tests. In fact, in a lot of MEMS devices, especially the electrostatic actuators[11,12], the cantilever endures a tiny load parallel to the substrate, meaning that an in-plane load test is needed. However, it is very difficult for many custom-made instruments to apply and measure the in-plane load, even for Nano Indenter. Therefore, an in-plane load measuring technique is developed in the present paper to perform the strength test of the micro-cantilever.

1 Equipment

Micro UTM (Universal Testing Machine) was in-house made especially for the tension, compression and bending tests with the load range 10^0—10^2 mN. In this paper, it is used to perform the strength tests of the micro-cantilevers. The whole test system consists of a load unit, a computer and a signal process unit, as shown in Fig. 1. The load unit is designed based on electromagnetism. It consists of a coil suspended in a uniform magnetic field (Fig. 2). When the current gets through the coil, the electromagnetic force is produced. If the magnetic density B is a constant, the magnetic force $F_e(t)$ is proportional to the excitation current $I(t)$, i.e., $F_e(t) \sim I(t)$. Therefore, the magnetic force can be easily measured by the current. The relationship be-

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tween the excitation current and magnetic force has been calibrated, as shown in Fig. 3. The nonlinearity is only 0.2%.

The displacement of the load axis is measured by a capacitive sensor. The load range of the present Micro UTM is ±1 N with a resolution of 10 μN. The displacement range is ±300 μm with a resolution of 15 nm.

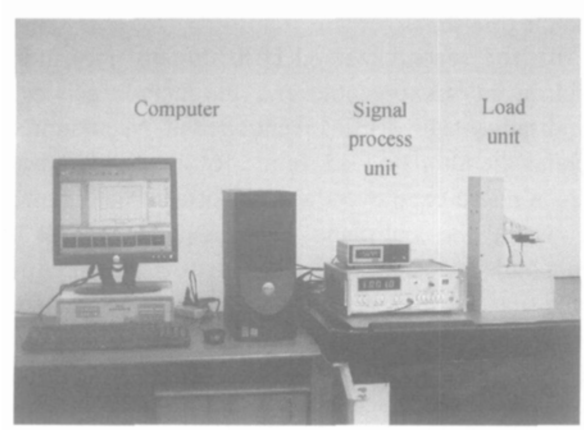

Fig. 1. Micro UTM system. It consists of the load unit, the single process unit and the computer.

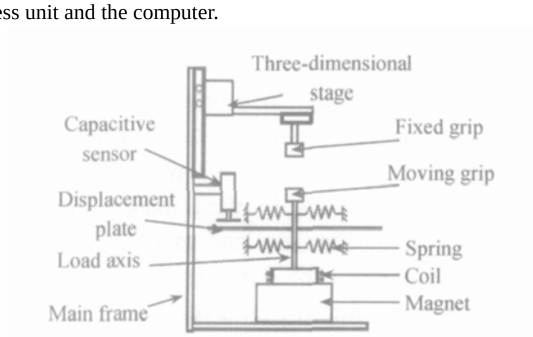

Fig. 2. Schematic illustration of Micro UTM load unit. It consists of a coil suspended in uniform magnetic field.

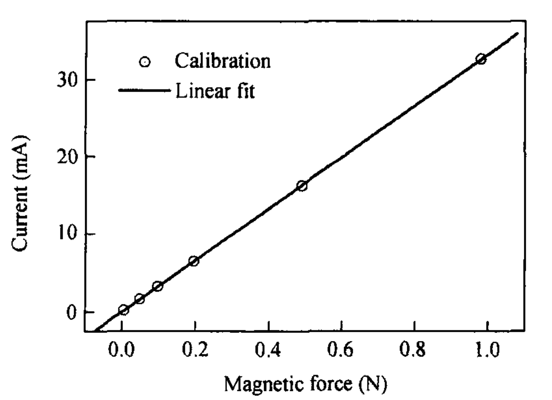

Fig. 3. Relationship between the excitation current and magnetic force. The nonlinearity is only 0.2%.

2 Experiments

Micro-cantilevers bonded on the glass substrate were selected for this test, which were representative in MEMS. Firstly, the silicon wafer was etched in KOH to form a lot of rectangle protruding blocks with the height of 4 μm, named silicon block. Secondly, silicon block and glass substrate was anodically bonded together at the temperature of 380℃ and the voltage of 1200 V. Thirdly, the silicon wafer was etched again in KOH to form the desired micro-cantilevers. Finally, the silicon wafer was thinned down to 76 μm and aluminum was splashed on the silicon surface. The structure of the micro-cantilever is illustrated in Fig. 4. It can be summarized that the thickness of all the cantilevers is 76 μm, and the clearance between the cantilever and the substrate is 4 μm.

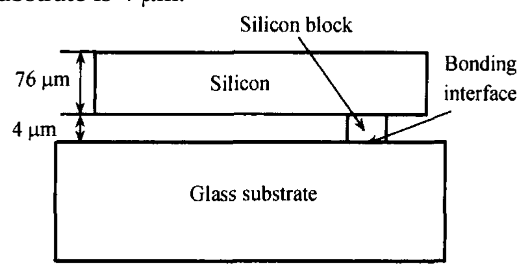

Fig. 4. Schematic illustration of the micro-cantilever. The thickness of all cantilevers is 76 μm and the clearance between the cantilever and glass substrate is 4 μm.

Total 41 samples were tested in this work. The minimum size of the tested samples is 300 μm×36 μm×76 μm, with a bonding area of 17 μm×17 μm. The maximum size of the tested samples is 1704 μm×200 μm×76 μm, with a bonding area of 120 μm×120 μm.

The samples were fastened on the fixed grip of Micro UTM. A slim probe was settled on the load axis, which integrated with the coil. When a custom current got through the coil, the probe moved up or down together with the load axis. A linear increasing load parallel to the substrate was applied on the free end of micro-cantilever through the movement of the probe. The whole test process was controlled by a computer. The load position can be adjusted through the three-dimensional stage on the load unit. In order to avoid the friction, a proper distance of about 40 μm must be maintained between the probe and the glass substrate of the sample. The deformation process of the sample was in-situ captured by the microscope settled in front of Micro UTM. The experiment setup is shown in Fig. 5. Finally, the destroyed samples were examined in a mi-

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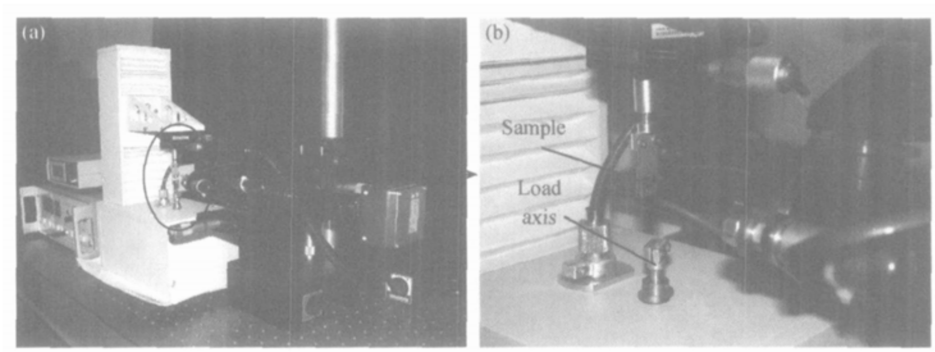

Fig. 5. Setup of experiment. (a) A microscope is settled in front of Micro UTM load unit; (b) close-up of the sample and load axis.

croscope to investigate the failure modes.

3 Results and discussion

It is notable that the anchor is usually in good condition in the out-plane load tests[8,10]. However in the in-plane load tests, the load acts as a bending moment for the root of the cantilever, but as a torque for the anchor, which may result in the fracture of the cantilever and the anchor. It is distinctly confirmed by the test results.

A typical load-displacement curve is shown in Fig. 6, where the ultimate load is 32.8 mN. To different size samples, the ultimate loads range from 1.3 to 69.8 mN. Considering the difference of the force arm, the ultimate load can be transformed into the bending moment for the root of the cantilever or the torque for the anchor. In this work, the bending moment and torque are approximate in value; so it only illustrates the relationship between torque and the bonding length in Fig. 7. It can be found that the ultimate torque is approximately proportional to the square of the bonding length.

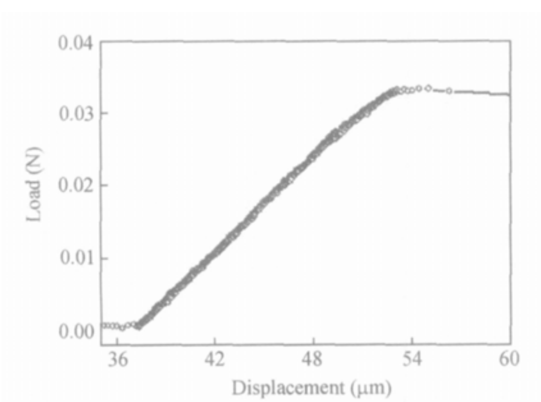

Fig. 6. Load-displacement curve of a sample. The ultimate load is 32.8 mN.

These data are significant not only for MEMS design but also for further mechanics analysis. In this paper we only aim to present the testing technique. Detailed mechanics analysis of the tested micro-cantilever will be involved in other work. Through more experiments, an experiential formula can be built to direct the design of the cantilever and the anchor.

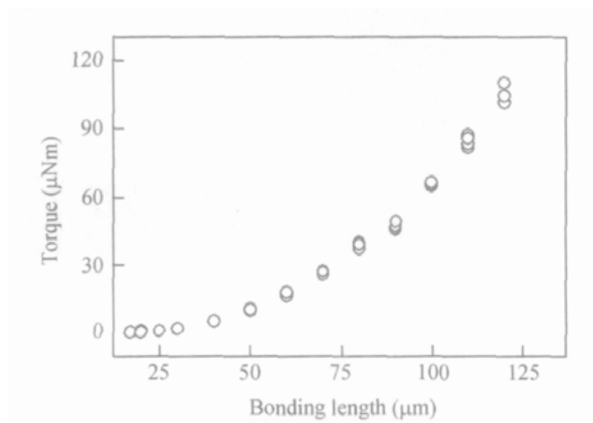

Fig. 7. Relationship between ultimate torque and bonding length. The ultimate torque is approximately proportional to the square of the bonding length.

By the microscope settled in front of Micro UTM, the micro-cantilever is observed abruptly blown out at the end of the test. It is a pity that we cannot capture the detail because of the absence of the high-speed video at that time. According to the image capture frequency, the total fracture process is estimated to last no more than 62.5 ms. The maximum deformation of the micro-cantilever is too small to observe compared with its size, just as shown in Fig. 8.

Two failure modes are observed by micro-examination to the debris:

10 out of 41 samples fractured at the root of the micro-cantilever, shown in Fig. 9(a). The anchor seems in good condition. It is obvious that the bending moment causes the fracture, which indicates that the anchor is

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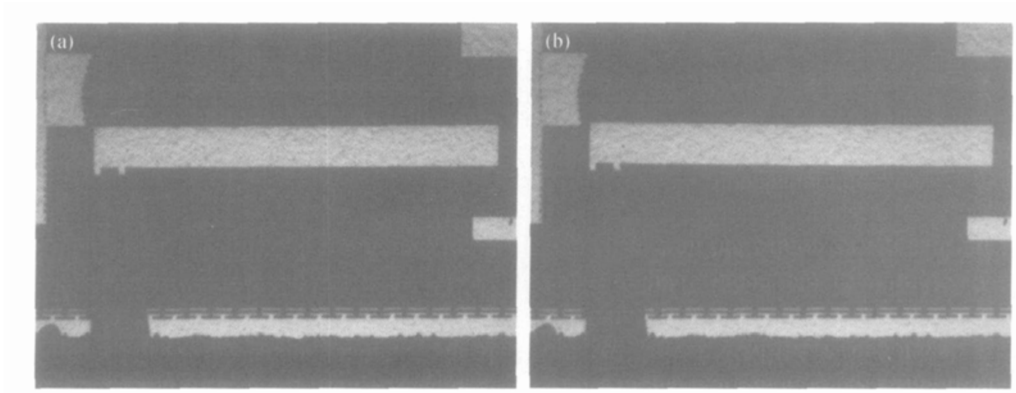

Fig. 8. Typical deformation process of the micro-cantilever with the size of 1657 μm×167 μm×76 μm. (a) No deformation; (b) the maximum deformation.

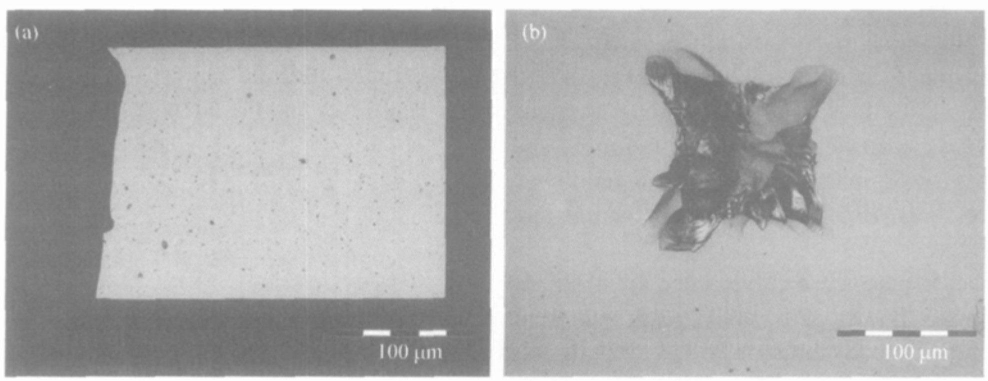

Fig. 9. Two failure modes of the samples. Fracture occurred at the root of the micro-cantilever (a) or the anchor (b).

designed stronger than the cantilever for these 10 samples. The anchor withstands the torque before the momently bending moment destroys the cantilever.

The other 31 samples fractured at the anchor, shown in Fig. 9(b), which is mainly caused by the torque. This indicates that the anchor is more delicate than the cantilever for these 31 samples. The anchor cannot survive the cantilever.

It is found that there is a transition state among them. 2 out of 4 samples, with the cantilever size of 1678 μm×180 μm×76 μm and the bonding area of 100 μm×100 μm, fractured at the root of the cantilever. The other 2 samples fractured at the anchor. This indicates there is a critical design to achieve the strength balance between the cantilever and the anchor.

4 Conclusions

An in-plane load measuring technique for the strength test of the micro-cantilever is developed in the present paper. For different size samples the ultimate loads range from 1.3 to 69.8 mN and the ultimate torque is approximately proportional to the square of the bonding length. These data are necessary not only for MEMS design but also for further mechanics analysis.

Tested micro-cantilevers are in-situ observed abruptly blown out within 62.5 ms. Two failure mode, fracture at the root of the cantilever or fracture at the anchor, are observed. It indicates that there is a critical design to achieve the strength balance between the cantilever and the anchor.

Compared with Nano Indenter, micro UTM can directly apply and measure the in-plane load on the free end of the cantilever. The whole test process can be easily *in situ* observed. This work demonstrates that Micro UTM is a powerful instrument for the strength test of the micro-cantilever and other similar micro-structure.

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