Determination of Elastic-Plastic Properties of Metallic Thin Wires by Small-Span Bending Test

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Abstract

A mechanical testing methodology for thin wires based on small-scale bending under lateral load is reported. Geometrical configurations of the wire prepared on a substrate are firstly rearranged for the testing by manipulating it utilizing Joule heating. A small-span bending load is applied at the local area of the wire with two opposite probes, and the small force acting on the loading tip is measured with a capacitance sensor. From the load-displacement relationships obtained by the experiments, Young's modulus and yield strength of the thin wire are successfully determined.

1. Introduction

Various kinds of metallic thin wires have been expected to be used in nanoelectromechanical systems (NEMS) or microelectromechanical systems (MEMS) as structural, electrical, optical or thermal components. In the application of metallic thin wires, the mechanical properties of wires must be the important issue to ensure the reliability of NEMS or MEMS. The brittle wire may not be suitable as components because the fracture of the wires occurs suddenly and their fracture strength varies. On the other hand, if the wires show ductile behavior, the fracture of the wires becomes predictable. Therefore, understanding the elastic-plastic properties of the wires must be the first step of controlling the fracture behavior of metallic thin wires.

In evaluating the properties of thin metallic wires, testing by atomic force microscope (AFM) and nanoindentation are well reported [1-5]. Especially, the AFM is now most promising way to obtain the mechanical properties of materials because it can detect very small force. Usually in AFM based (tensile or bending) tests, the samples are fixed on AFM tip or substrate. However, it is very hard to develop a suitable setup for testing due to the difficulty in handling the small-scaled objects. A large number of gold nanowires were scattered on a substrate having grooves, and the wires which crossed the grooves were selected for testing after the ends of the wires were welded at the grooves edges by laser [1]. This technique for sample preparation can be used for mass-produced objects, but may be restricted for the conventional samples prepared. Moreover, in the AFM based technique, the deformation shape is difficult to be monitored during experiment.

In this paper, the testing methodology for determining the elastic-plastic behavior of thin metallic wires is reported. The cutting and welding techniques for thin wires using Joule heating [6] are used in handling the thin wire samples, and the experimental setup suitable for small-span bending is realized. The higher stress field in the wire is locally developed with the closely-coupled force probes and the load displacement relationships of the Pt thin wire for various probe distances are recoded. From the relationships, Young's modulus and yield strength of the Pt thin wire are successfully determined.

2. Testing Scheme

The testing material is considered as linear hardening elastic-plastic behavioral. The stress (σ)-strain (ε) relationships for the material can be expressed as

$$\varepsilon = \frac{\sigma}{E}, \qquad \text{for } \sigma \leq \sigma_Y, \tag{1}$$

and

$$\varepsilon = \frac{\sigma_Y}{E} + \frac{\sigma - \sigma_Y}{E'}, \qquad \text{for } \sigma > \sigma_Y. \tag{2}$$

Here σ_Y, E and E' are yield strength, Young's modulus and hardening modulus, respectively, and these three parameters should be decided for describing the elastic-plastic properties of the materials.

The tensile test may be the simplest one and the mechanical properties of materials can be directly determined from the stress-strain relationship. However, in case of thin wire specimens, they are likely to be broken at the grips due to unacceptable scratch and the stress concentration at these regions. Therefore, the bending tests are best choice to determine the mechanical properties of small-scaled objects [7].

The configuration of the proposed testing is illustrated in Fig 1(a). A one end fixed sample is considered for bending at its free end by two opposite probes. As the loading is considered close to a fixed support C and far from the fixed end A, higher stress field due to large bending occurs locally across the loading probe B and this eliminates the problem of failure at the root of the sample. The typical load-displacement curve obtained by the bending test contains the elastic and elastic-plastic regions [Fig. 1(b)]. If the load and displacement in the elastic zone are P_e and δ_e respectively, then the value of E can be obtained as

$$E = \frac{P_e b^4 (2L + a)^2}{12 L^3 I \delta_e} - \frac{P_e b^3}{3 I \delta_e}, \tag{3}$$

where I is the area moment of inertia of the sample and the other parameters are shown in Fig. 1 (a).

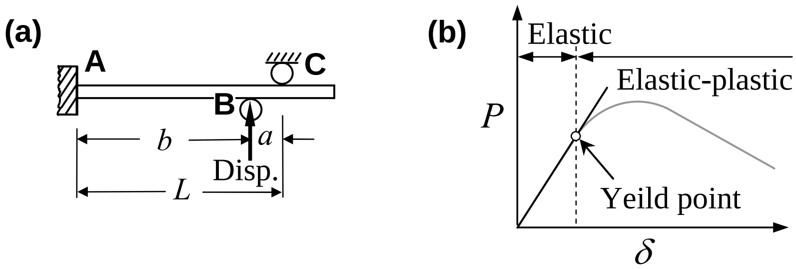

Fig. 1. (a) Schematic of loading configuration. (b) Elastic and elastic-plastic regions on a typical force-displacement curve.

If the linearity in P-δ relation is remained up to the yield point then σ_Y can be determined as

$$\sigma_Y = \frac{P_Y a b^2 d}{4IL^3}\left(2L + a\right), \tag{4}$$

where P_Y is the yield load and d is the diameter of the testing wire.

3. Experimental

The sample used in this study was Pt thin wire with d = 770 nm. For the testing configuration described in Fig. 1(a), the cutting and welding techniques [6] utilizing Joule heating were used to prepare the sample. Figure 2(a) shows the setup for welding of the thin wire. The tips of the Pt thin wire and the In wire substrate was contacted with nano-manipulator, and the constant direct current was applied to the contacting portion of wire. As a result, higher temperature at the contacting region of wire and substrate was developed due to Joule heating and dissimilar metal weld joint between Pt and In was formed. To avoid the change in property in Pt sample due to Joule heating, Indium having lower melting point of about 430 K, which is much lower than that of Pt, was used as a welding metal. After the welding of Pt wire and the In substrate, the Pt wire was cut to have the desired length. The details of cutting the Pt wire at the prescribed point can be seen in the reference [6]. Figure 2(b) shows the FE-SEM micrograph of the joint between the Pt thin wire and the In wire, and the welded region was found to be rigidly fixed. In the bending experiment the welded end of the Pt wire is considered as the fixed end of the testing sample.

In the test setup, a force sensor, a piezo stage and two nano-manipulators (one carrying the sample and the other carrying the piezo stage), were set on a single platform, see Fig. 3(a). The sample was taken on a sample carrier and by using manual nanomanipulation, the sample was placed just touching the fixed probe with desired flexural length. The loading probe of the force sensor was placed against the sample as shown in Fig. 1(a). The force sensor was composed of a cantilever and a capacitive sensor. The deformation in sample and the corresponding load for the testing were recorded in a computer directly. The deformation pattern was also monitored/recorded by a digital microscope. The probe was prepared by using a small piece of 20 μm diameter W wire taking it on a needle like substrate by light curing resin, see Fig. 3(b). To have the smooth contact of the loading and supporting probes with the sample, the probe tips were cut as 5 μm diameter cylindrical surfaces using focused-ion-beam machining.

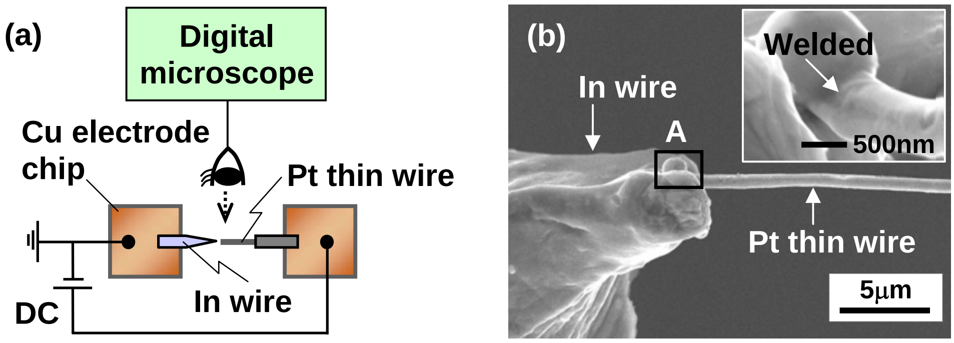

Fig. 2. (a) Setup for welding the Pt thin wire onto the In wire by Joule heating. (b) The welded Pt/In structure. The magnification view of the part A is inserted in the same figure.

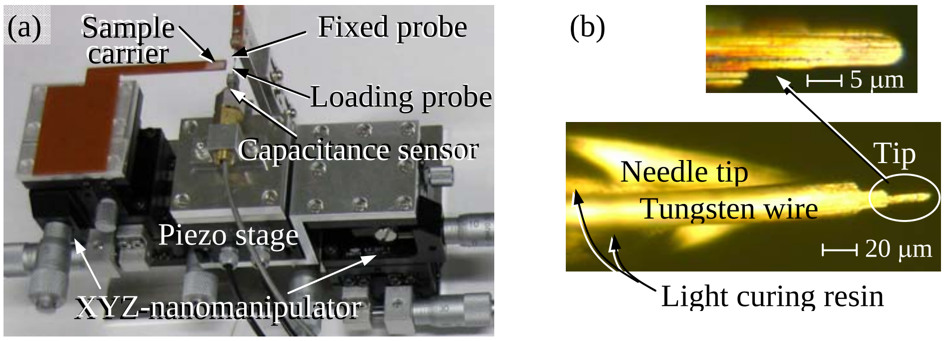

Fig. 3. Photographs of the (a) experimental setup and (b) probe tip.

4. Results and Discussions

The experimental force-displacement (P-δ) relationship obtained for a sample of diameter, d = 770 nm with the flexural lengths, L = 65μm and a = 12μm is shown in Fig. 4. The value of E was determined by Eq. (3) from the linear part of the experimental P-δ relation. With this value of E large deformation elastic finite element analysis (FEA) of the bending test was performed and the obtained force-displacement relationship is plotted with the experimental curve. This FEA was done to confirm the location of the yield point in the P-δ curve. From Fig. 4, it is clear that the yield point is situated at just end of the linear part of P-δ curve, and therefore, using the force and deformation at this point the value of σ_Y was determined directly from Eq. (4).

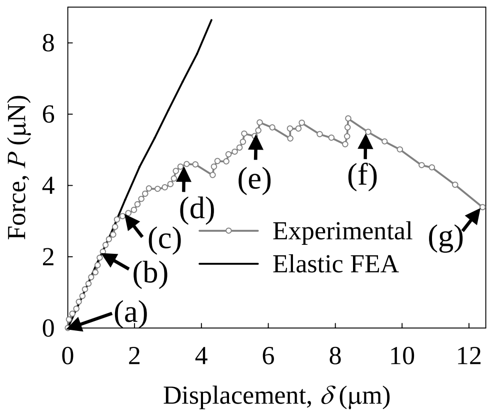

Fig. 4. P-δ relationships obtained by experiment and large displacement elastic FEA.

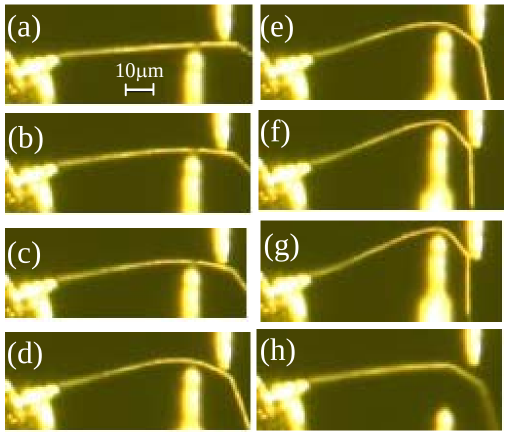

Fig. 5. Photographs of the sample at the different stages of loading (a) just before loading, (b)-(g) gradually increasing loading and (h) after unloading.

In the experiment, the visualization of the deformation pattern is a good advantage over the conventional techniques. For better understanding, few photographs for different stages of bending are presented in Fig. 5. The shape of different bending patterns shown in Fig. 5 can be realized by observing their corresponding location in P-δ curve as shown by the arrow heads in Fig. 4. From the bending patterns, it was clear that less bending occurred at the root of the wire and maximum bending took place across the tip of loading probe. After unloading the root region of the wire returned to its original shape. Therefore, it was confirmed that large plastic deformation of the wire was achieved across the loading point without affecting the root of the wire. From this direct observation, it is clear that the obtained P-δ relationships contain the information of the plastic behavior of the Pt thin wire. Therefore, the elastic-plastic FEA must be a powerful tool for determining the value of E' [7].

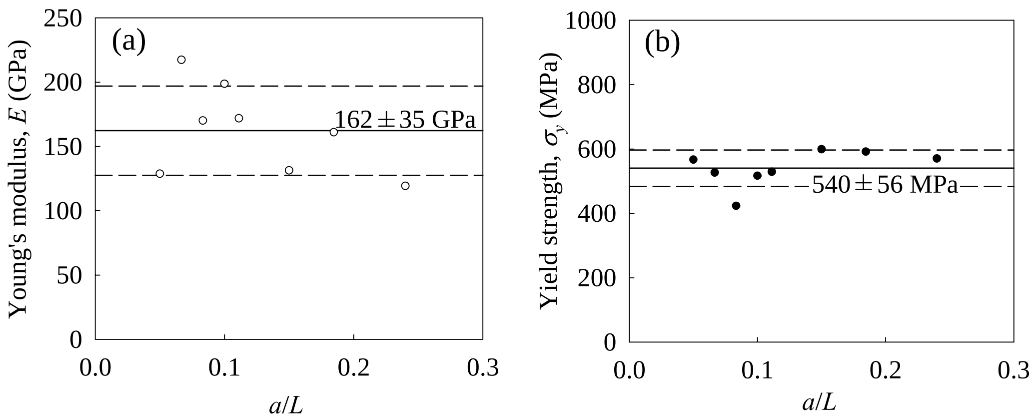

Fig. 6. (a) Young's modulus and (b) yield strength obtained for testing with different flexural lengths.

Different experiments were performed with the variation of flexural lengths in thin wire bending and the E and σ_Y were determined. These results are presented in Fig. 6 with the variation of a/L ratio used in the experiments. The average values of E and σ_Y for the Pt thin wire were found as 162 ± 35 GPa and 540 ± 56 MPa, respectively. The value of E was observed a bit scattered whereas that of σ_Y were found very close to the average value.

5. Summary

The testing methodology based on three-point bending for determining the elastic-plastic behavior of metallic thin wire was reported. The local plastic deformation in the wire was successfully induced with the closely-coupled force probes. Here for the sample arrangement, the thin wires were cut and welded by Joule heating. The value of Young's modulus and the yield strength of the wire were successfully determined from the experimental load-displacement relationship.

Acknowledgement

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