ORAL REFERENCE: ICF10 0193OR

FRACTURE TOUGHNESS TESTS FOR MICRO-SIZED SPECIMENS

K. Takashima[1], Y. Higo[1] and M. V. Swain[2]

[1] Precision and Intelligence Laboratory, Tokyo Institute of Technology,
4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan.
[2] Faculty of Dentistry and Department of Mechanical & Mechatronic Engineering,
The University of Sydney, Australian Technology Park, Everleigh NSW 1430, Australia.

ABSTRACT

A fracture toughness testing method appropriate to micro-sized specimens has been designed and fracture tests have been performed on micro-sized specimens for MEMS applications. Cantilever beam type specimens with dimensions of 10 x 10 x 50 μm^3 were prepared from a Ni-P amorphous thin film and notches with different directions, which are perpendicular and parallel to the deposition growth direction, were introduced by focused ion beam machining. Fatigue pre-cracks were introduced ahead of the notches. Fracture tests were carried out using a newly developed mechanical testing machine for micro-sized specimens. Fracture behavior is different between the two types of specimens. K_{IC} values were not obtained as the criteria of plane strain requirements were not satisfied for this size of the specimen, so that the provisional fracture toughness K_Q values were obtained. The K_Q value of the specimen with crack propagation direction being parallel to the deposition growth direction was 4.2 $MPam^{1/2}$, while that with crack propagation direction being perpendicular to the deposition growth direction was 7.3 $MPam^{1/2}$. These results suggest that the electroless deposited amorphous alloy thin film has anisotropic mechanical properties. It is necessary to consider the anisotropic fracture behavior when designing actual MEMS devices using electroless deposited amorphous films.

KEYWORDS

Fracture toughness, Thin film, Micro-sized specimen, MEMS, Anisotropy

INTRODUCTION

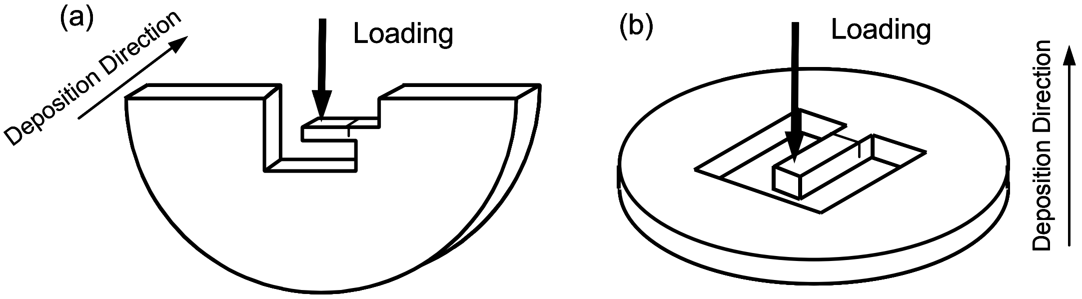
Microelectromechanical systems (MEMS) or microsized machines are under intensive development for utilization in many technological fields such as information and biomedical technologies. These MEMS devices are usually fabricated from a thin film deposited on a substrate by suitable surface micromachining techniques, and the micro-sized elements prepared from a thin film layer are used as mechanical components. The evaluation of fracture toughness of thin films is then extremely important to ensure the reliability of MEMS devices. In addition, micro-elements on MEMS devices are considered to be subjected to load in both the direction of "in-plane" and "out-of-plane" of the thin film. The fracture toughness values for both in-plane and out-of-plane directions are thus required for actual design of MEMS devices, as the fracture toughness of thin films prepared by sputtering or other deposition techniques has been considered to have anisotropy even for amorphous alloys [1].

In this investigation, micro-sized cantilever type specimens were prepared from an electroless deposited Ni-P amorphous alloy thin film and fracture tests for two types of specimens with different crack growth dierctions, which are "in-plane" and "out-of-plane" of the thin film, were performed. Fracture behavior of the specimens is then discussed.

EXPERIMENTAL PROCEDURE

The material used in this investigation was a Ni-11.5 mass%P amorphous alloy thin film electroless plated on an Al-4.5 mass%Mg alloy. The thickness of the amorphous layer was 12 μm and that of the Al-4.5 mass%Mg alloy substrate was 0.79 mm. A disk with a diameter of 3 mm was cut from the Ni-P/Al-Mg sheet by electro discharge machining. The amorphous layer was separated from the Al-Mg alloy substrate by dissolving the substrate with a NaOH aqueous solution.

Two types of micro-sized cantilever beam specimens with different notch orientations were prepared from the amorphous layer by focused ion beam machining, and are referred to as "in-plane type specimen" and "out-of-plane type specimen" as shown in Figs. 1 (a) and (b), respectively. Figures 2(a) and (b) show



In-plane type specimen

Out-of-plane type specimen

Figure 1: Two types of specimen orientations. The crack propagation direction is perpendicular to the deposition growth direction for in-plane type specimen (a), while the crack propagation direction is parallel to the deposition growth direction (b).

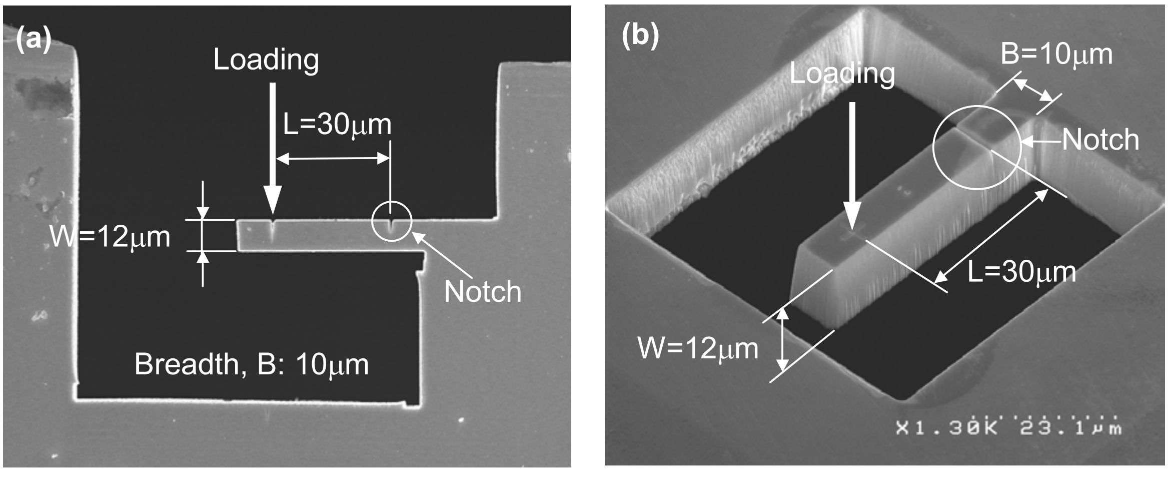


Figure 2: Scanning electron micrographs of micro-sized specimens prepared by focused ion beam (FIB) machining. (a) in-plane type specimen and (b) out-of-plane type specimen. Notches were also introduced by FIB.

scanning electron micrographs of the micro-sized specimens. The crack will propagate perpendicular to the deposition direction in the in-plane type specimen, while the crack will propagate parallel to the deposition direction in the out-of-plane type specimen. The breadth of the specimen, B, was 10μm, the distance from the loading point to the notch position, L, was 30μm, and the width of the specimen, W, was 10μm. Notches with a depth of 2.5 μm were introduced into the specimens as shown in Fig. 1 by focused ion beam machining. The width of the notch was 0.5 μm, and the notch radius was thus deduced to be 0.25 μm. The notch position was 10 μm from the fixed end of the specimen.

In our previous studies [2, 3], we have demonstrated that the introduction of a fatigue pre-crack is required to evaluate fracture toughness even for micro-sized specimens. A fatigue pre-crack was then introduced ahead of the notch in air at room temperature under constant load amplitude using a mechanical testing machine for micro-sized specimens, which was developed in our previous investigation [4, 5]. The length of the fatigue pre-crack was adjusted to be approximately 2.5 μm. The total crack length over specimen width (a/W) was then approximately 0.5 for all the specimens. Fracture tests were also carried out in air at room temperature using the same mechanical testing machine which was used for introducing fatigue pre-cracks.

RESULTS AND DISCUSSION

Fracture Behavior

Figure 3 shows load-displacement curves during fracture tests for the in-plane and the out-of-plane type specimens. The fracture behavior is different between these two types of specimens. The maximum load of the out-of-plane type specimen is higher than that of in-plane type specimen in spite of the size of specimen and the length of fatigue pre-crack being approximately the same. This suggests that the electroless plated Ni-P amorphous thin film exhibits anisotropic fracture behavior.

As crack opening displacement was not able to be measured for these specimen, the crack initiation load was not able to be determined. The maximum load was then assumed to be the crack initiation load and this load was used to calculate fracture toughness value. Stress intensity factor, K, is calculated from the equation for a single edge notched cantilever beam specimen [6]. The total pre-crack length was measured from scanning electron micrographs of the fracture surfaces. The calculated provisional fracture toughness values (K_Q) for the out-of-plane and in-plane specimens are 7.3 and 4.2 MPam$^{1/2}$,

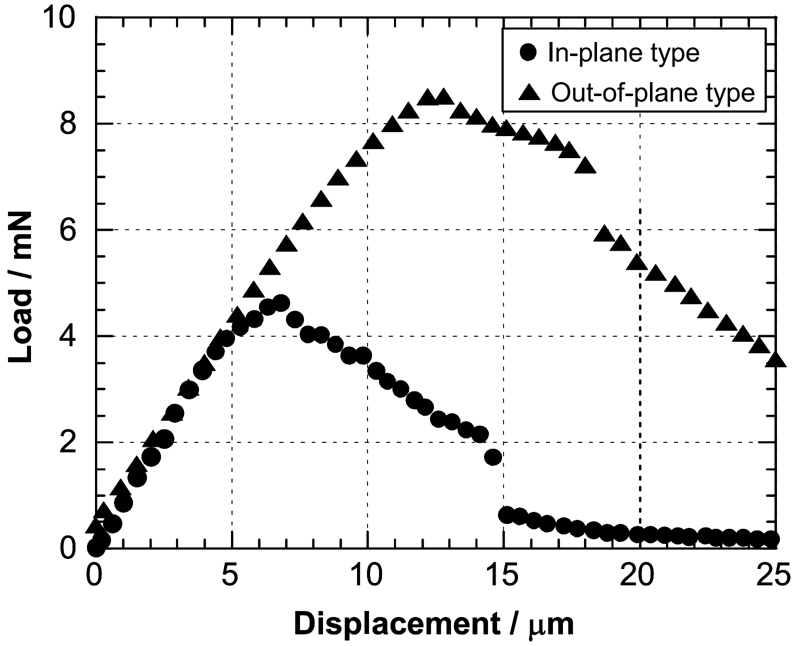


Figure 3: Load-displacement curves for in-plane and out-of-plane type micro-sized specimens.

respectively. However, these values are not valid plane strain fracture toughness values (K_{IC}), as the criteria of plane strain requirements were not satisfied for this specimen size. Actually, a plastic zone was observed clearly at the crack tip. As the plane strain requirements are determined by K and σ_y (yield stress), it is rather difficult for micro-sized specimens to satisfy these requirements. Consequently, another criterion such as J integral might be required to evaluate fracture toughness of such micro-sized specimens.

Fracture Surfaces

Figures 4 (a) and (b) show scanning electron micrographs of fracture surfaces for the specimens with different crack orientations. Fine equispaced markings aligned perpendicular to the crack propagation direction are observed ahead of the notch. This kind of markings were also observed on fatigue fracture surface of micro-sized Ni-P amorphous alloy specimens in our previous investigation [7], and are considered to be striations. Vein patterns which have been observed on static fractured surfaces on Ni-P amorphous alloy are visible ahead of the fatigue pre-cracked region. The fracture surface of the in-plane type specimen is relatively flat. In contrast, the fracture surface of the out-of-plane type specimen is rough, and the crack seems to propagate tortuously. The difference in K_Q values is considered to result from the difference in fracture surface morphologies.

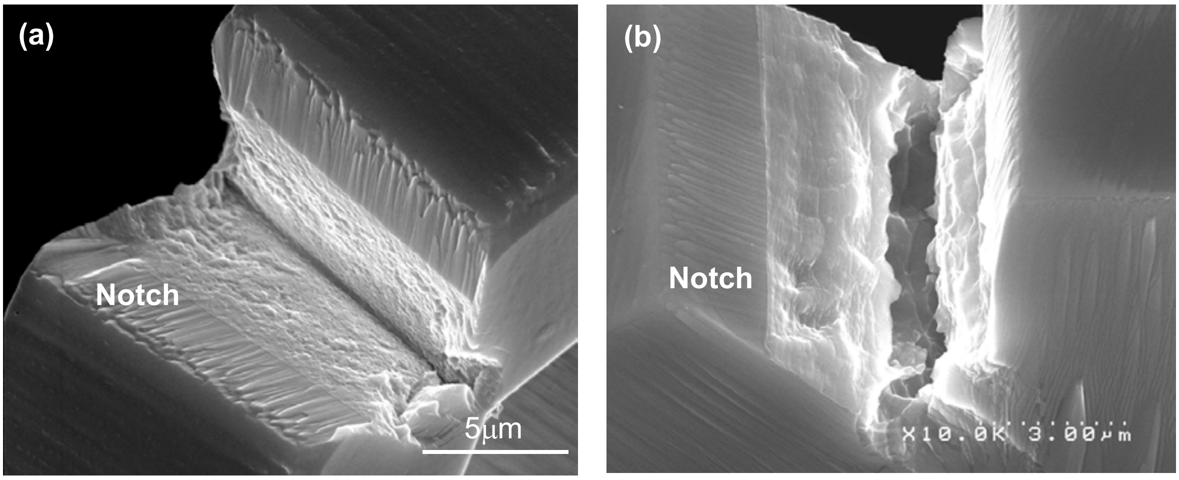


Figure 4: Scanning electron micrographs of fracture surfaces of (a) in-plane type specimen and (b) out-of-plane type specimen, respectively.

Another notable feature of the fracture surface is the existence of slant fractured regions near the side surfaces of the crack. The width of the slant fractured region is approximately 1 μm for in-plane type specimens and 3 μm for out-of-plane type specimens. If these are shear lips, these regions should be plane stress dominated regions. The expected width of the shear lip is then calculated based on fracture mechanics [8]. The calculated value of shear lip width at K_Q is 1.2 μm for in-plane type specimen and is 3.4 μm for out-of-plane type specimen (the value of σ_y = 2.0 GPa in this amorphous alloy thin film was quoted in this calculation [9]). These sizes are very close to those of the slant fractured regions in Figs. 3 (a) and (b). Therefore, these slant fractured zones are considered to be plane stress dominated regions and the flat region is considered to correspond to plane strain dominated one.

Origin of Anisotropic Fracture

The provisional fracture toughness, K_Q, of the out-of plane specimen was much higher than that of the in-plane specimen. Electron diffraction pattern of the Ni-P amorphous alloy thin film (the beam direction is parallel to the deposition growth direction) showed only a halo pattern which is characteristic of an amorphous phase. Therefore, there is no medium or long range ordering in the direction perpendicular to the deposition growth direction in this amorphous thin film. However, it has not been confirmed whether there is medium or long range ordering in the direction parallel to the deposition

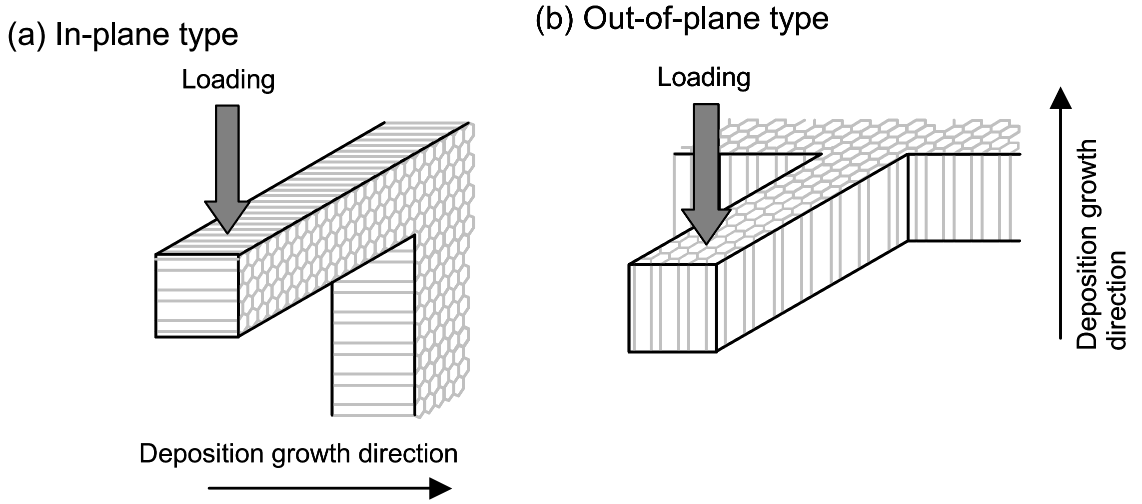


Figure 5: Schematic images of columnar structure aligned towards the growth direction in the elecroless deposited Ni-P amorphous alloy thin film.

growth direction. The difference in K_Q values and fracture surfaces between these two specimens suggests that there is some ordering towards the growth direction. Actually, anisotropic magnetic properties have been often observed for sputtered and deposited amorphous thin films [10]. Consequently, there may exist some columnar type domain structures oriented towards the deposition growth direction as schematically shown in Fig. 5. Actually, such a columnar structure was observed for electro-deposited amorphous Fe-P alloys [11]. If there is such a columnar structure aligned towards the growth direction, the cantilever specimens have an anisotropy. This may be one reason that the K_Q of the out-of-plane specimen is higher compared to that of the in-plane specimen.

CONCLUSIONS

Fracture tests have been performed on micro-sized cantilever beam specimens prepared from an electroless plated Ni-P amorphous alloy thin film. Two types of specimens with different crack growth directions, which are perpendicular and parallel to the deposition growth directions, were prepared to investigate anisotropic fracture behavior of the thin film.

Fracture behavior is different between the two types of specimens. As K_{IC} values were not obtained because the criteria of plane strain were not satisfied for this micro-sized specimen, the provisional fracture toughness K_Q values were measured. The K_Q value of the specimen with crack propagation direction being parallel to the deposition growth direction was 7.3 MPam$^{1/2}$, while that with crack propagation direction perpendicular to the deposition growth direction was 4.2 MPam$^{1/2}$. This result suggests that the electroless plated Ni-P amorphous alloy thin film has anisotropic fracture properties. It is important to consider the anisotropic fracture behavior when designing actual MEMS devices using electroless deposited amorphous films.

Acknowledgment – This work was partly supported by the Grant-in-Aid for Scientific Research (B) (2) No. 12555186 from the Ministry of Education, Science, Sports and Culture, Japan.

REFRENCES

1. Lewis D. B. and Marshall, G. W. (1996) *Surface and Coating Tech.*, **78**, 150.
2. Ichikawa, Y., Maekawa, S., Takashima, K., Shimojo, M., Higo, Y. and Swain, M. V. (2000). In: *Materials Science of Microelectromechanical Systems (MEMS) Devices II,* pp. 273-278, deBoer, M. P., Heuer, A. H., Jacobs, S. J. and Peeters, E., (Eds). The Materials Research Society, Pennsylvania.

3. Takashima, K., Shimojo, M., Higo, Y. and Swain, M. V. (2000). In: *Proc. Microscale Systems: and Measurements Symposium*, pp.32-35, Soc. for Experimental Mechanics, Inc.
4. Takashima, K., Kimura, T., Shimojo, M., Higo, Y., Sugiura, S. and Swain, M. V. (1999). In: *Fatigue '99 (Proc. 7th Int. Fatigue Cong.)*, pp. 1871-1876, Wu, X-R. and Wang, Z-G., (Eds). Higher Education Press, Beijing.
5. Higo, Y., Takashima, K., Shimojo, M., Sugiura, S., Pfister, B. and Swain, M. V. (2000). In: *Materials Science of Microelectromechanical Systems (MEMS) Devices II*, pp. 241-246, deBoer, M. P., Heuer, A. H., Jacobs, S. J. and Peeters, E., (Eds). The Materials Research Society, Pennsylvania.
6. Okamura, H. (1976). *Introduction to Linear Fracture Mechanics*, Baifukan, Tokyo, (in Japanese).
7. Maekawa, S., Takashima, K., Shimojo, M., Higo, Y. and Swain, M. V. (2000). In: *Materials Science of Microelectromechanical Systems (MEMS) Devices II*, pp. 247-252, deBoer, M. P., Heuer, A. H., Jacobs, S. J. and Peeters, E., (Eds). The Materials Research Society, Pennsylvania.
8. Knott, J. F. (1976). *Fundamentals of Fracture Mechanics*, Butterworths, London.
9. Morita, A., Takashima, K. and Higo, Y., to be published.
10. Lanchava, B., Hoffmann, H., Bechert, A., Gegenfurtner, S., Amann, C. and Rohrmann, I. (1997) *J. Magnetism and Magnetic Materials*, **176**, 139.
11. Armyanov, S., Vitkowa, S. and Blajiev, O. (1997) *J. Appl. Electrochemistry*, **27**, 185.