Transactions of the Materials Research Society of Japan 28 [2] 413-416 (2003)

Experimental Evidence for No Beam Force Effect on a Foil Deformation by Irradiation of Heavy Ions at MeV Energies

Hidetsugu Tsuchida†*, Ichiro Katayama‡§, Sunchan Jeong‡, Hidemi Ogawa†
Naoki Sakamoto† and Akio Itoh¶
†Department of Physics, Nara Women's University, Nara 630-8506, Japan
*Fax: 81-742-20-3378, e-mail: t-hide@phys.nara-wu.ac.jp
‡Institute of Particle and Nuclear Studies, KEK, Tsukuba 308-0801, Japan
§Fax: 81-298-79-6072, e-mail: ichiro.katayama@kek.jp
¶Quantum Science and Engineering Center, Kyoto University, Kyoto 606-8501, Japan
§Fax: 81-75-753-5828, e-mail: itoh@nucleng.kyoto-u.ac.jp

We have investigated, with a high precision laser displacement meter, irradiation-induced foil deformation of a metallic aluminum by a heavy ion of MeV-energies. In previous observation, unexpected and interesting phenomena, in which the foil was deformed just like a metal spring under beam-on and beam-off conditions, were observed. In short, the deformation was reversible. A large deformation, which is 800-μm deflection at the center of a 3 mm diameter, was observed for a high-purity (99.99%) Al foil of 2-μm thickness irradiated with 8-MeV Si beams. In order to interpret the giant deformation, we carried out further studies on an effect of a beam force exerted on a foil. It was found that the effect of the beam force is negligible and is not the main factor causing the deformation.

Key words: Ion-beam irradiation, Reversible deformation, Metallic foil

1. INTRODUCTION

Irradiation effect is one of the most important subjects in material science. We have studied the interaction between an ion beam and a target foil by using a laser displacement meter to find phenomena *in situ* under beam irradiation. We have performed experiments of (i) direct measurement of a beam force exerted on a target foil [1] and (ii) a deformation of a foil caused by ion irradiation [2]. In the latter experiment, interesting results were obtained. For a metallic Al foil of 2-μm thickness irradiated with heavy ions at MeV energies, a reversible deformation was observed without any plastic deformation. Namely, the foil is deformed just like metal spring under beam-on and beam-off conditions. Furthermore, the deformation is significantly large that it is even visible to naked eyes. To our knowledge, few studies have been carried out on the reversible deformation of metallic foils by ion beam irradiation. Hence, a mechanism of the reversible deformation is not well understood.

In this work, we studied effect of a beam force exerted on a target foil on the deformation of a foil. The beam force was measured by torsion balance method, which we have developed [1]. Result is compared with that calculated on the basis of the model for mechanical deformation. Also, we investigated three-dimensional profile for deformation of a foil. From the obtained results, a main factor causing the deformation is discussed.

2. EXPERIMENT

2.1 Foil deformation measurements

An experimental method is described in our previous paper [2]. Briefly, the experiment was performed with a 1.7 MV Tandem Pelletron accelerator of Nara Women's University. Irradiation was done at the room temperature in vacuum of below 10^{-5} Pa. A well-collimated beam of 3 mm in diameter with a uniform intensity distribution was directed perpendicular to a surface of a foil. The beam spot size was measured by using a plate on which a fluorescent substance of ZnS was painted. An 8-MeV Si^{4+} ion was used as a projectile beam. A target foil was an Al of 2-μm thickness. The foil was clamped between two stainless steel plates (sample holder). A diameter of self-supported area of the target foil was 7 mm. The range of the projectile in Al is 4.22 μm, calculated from SRIM [3], so that the projectile penetrates completely through the target foil.

Deformation of a foil was measured with a high precision laser displacement meter (LDM) of Keyence Inc., Japan, which has an accuracy of 0.1 μm. The LDM was set at the atmosphere. A probe laser beam from the LDM is incident on backside of a foil through a vacuum tight glass window. The LDM was mounted on a XY-scanning stage. A three-dimensional deformation profile was obtained by scanning the probe laser beam over the surface of a foil. The amount of the foil deformation was measured from the difference between two position signals from the LDM obtained for beam-on and beam-off conditions.

2.2 Measurements of a beam force exerted on a target foil

Measurements were carried out with a torsion balance method. The method is schematically depicted

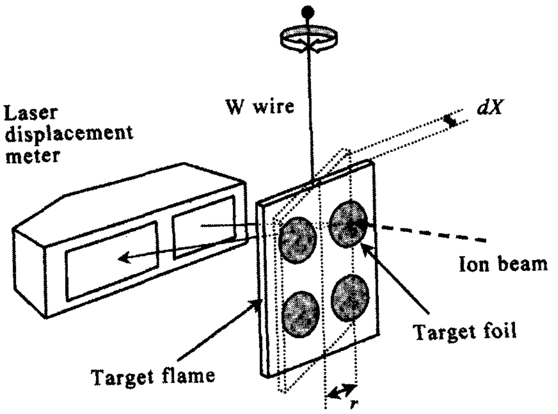

Fig.1 Schematic drawing of experimental method for measurement of a beam force exerted on a foil. The foil mounted on the flame was irradiated with ion beam. The influence of the torsional vibration due to the irradiation of the probe laser is negligible.

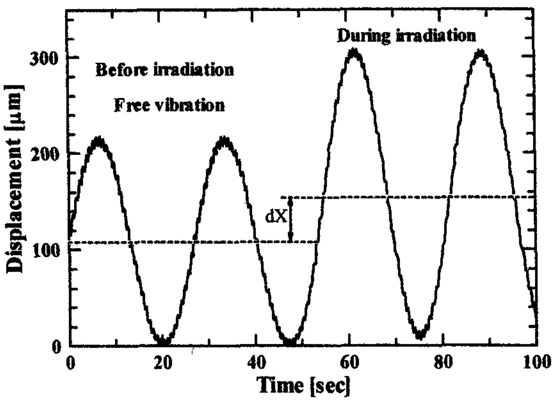

Fig. 2 Time spectra of torsional vibration for the target flame. An Al foil of 2-μm thickness mounted on a target flame was irradiated with an 8 MeV Si^{4+} beam of 100 nA. The dX denotes the amount of shift of equilibrium position due to irradiation.

in Fig. 1. A flame of 3 mm thick Al (42.5 mm in length, 40 mm in width) was hung with Au-coated W wire of 30-μm in diameter in a vacuum chamber. The same Al foil used for the deformation experiments was mounted on the flame. A torsional vibration of the flame was measured using the laser displacement meter.

A beam force exerted on the foil was measured as follows. First, a free torsional vibration of the flame is measured, which provides an equilibrium position of the vibration. Next, the Al foil mounted on the flame is irradiated with a continuous ion beam. The equilibrium position, then, changes due to the momentum transfer from the ion to the target foil. An example of experimental results for change in the equilibrium position is shown in Fig. 2. The shift dX of the equilibrium position can be seen. The amount of shift was about 50-μm for irradiation of 8 MeV Si^{4+} of 100 nA. The beam force, f^{exp}, is given by KdX/r^2, where K is the torsional rigidity, r is the length of arm between the center of beam spot and the rotation axis of torsion pendulum. The value of K is obtained from the measured period of torsional vibration for the flame and the calculated moment of inertia for the flame, or from the

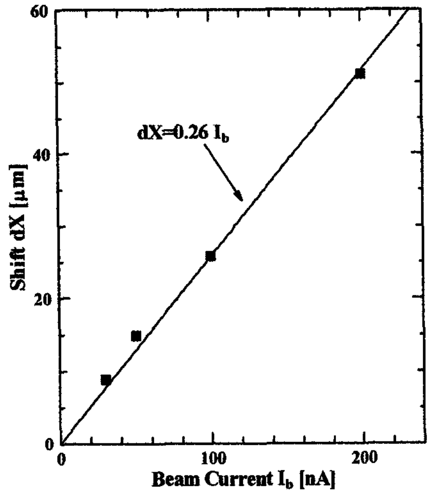

Fig. 3 The amount of shift dX for equilibrium position of torsional vibration as a function of beam current. The solid line is least-squares fitting applied to the data points.

modulus of rigidity for the W wire used. The K is calculated to be about 0.89 g cm^2/s^2. The measured r was about 1.1 mm. In order to get the value of f^{exp} as a function of beam current, we measured a shift dX of an equilibrium position of the vibration as a function of beam current I_b (nA). The result is shown in Fig. 3. The value of dX increases linearly with increasing the beam current.

3. RESULTS AND DISCUSSION

We discuss here an effect of a beam force exerted on a foil in the reversible deformation. From the data shown in Fig. 3, the f^{exp} as a function of beam current I_b (nA) becomes to be

$$f^{exp} = 1.93 \times 10^{-5} I_b \quad (\text{g cm/s}^2). \qquad (1)$$

This result is in good agreement with value calculated from the momentum transfer of a projectile ion in the foil penetration. The calculated beam force, f^{cal}, is given by

$$f^{cal} = \frac{I_b}{qe}\sqrt{2ME}\left(1-\sqrt{\frac{E'}{E}}\right), \qquad (2)$$

where q is the charge state of the projectile ion, e the elementary electric charge, M the mass of the projectile ion. E and E' are the incident and the outgoing energies of the projectile ion, respectively. The E' is calculated to be about 2.92 MeV, which is obtained from TRIM code [3].

We estimate the amount of deformation due to the beam force exerted on the foil by the formula for calculating the mechanical deformation in the following case. The force is exerted to the foil of 3.5 mm radius (a) (which corresponds to the radius of self-supported area for the target foil), where the edge of the foil is fixed and the radius (b) of the area applied the force is 1.5 mm

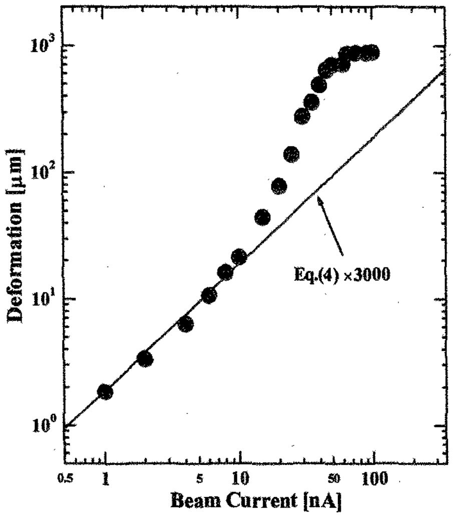

Fig. 4 Comparison of the amount of deformations expected from the effect of beam force (solid line) with the experimental data (closed circle) taken in Ref. [2]. The data is the result for deformation of an Al foil (99.99% purity) of 2-μm thickness.

(which corresponds to the radius of the beam spot). The amount of deformation, H, is given by

$$H=\frac{pb^4}{16D}\left\{\frac{a^2}{b^2}-ln\left(\frac{a}{b}\right)-\frac{3}{4}\right\},\qquad(3)$$

where $P=f/\pi b^2$, $D=Yl^3/\{12(1-v^2)\}$, f is the applied force, Y is the Young's modulus for Al in the room temperature (7.03×10^{10} N/m^2), and l is the thickness of a foil, v the Poisson ratio (0.345). Combining Eq. (1) and Eq. (3), we obtain the amount of deformation h^{cal} as a function of the ion-beam current, where the amount of deformation corresponds the peak height of the bell-shaped deformation as shown in Fig. 5. The h^{cal} is given by

$$h^{cal}=6.3\times10^{-4}I_b\ \ (\mu\text{m}).\qquad(4)$$

Figure 4 shows a comparison of the amount of deformations expected from the effect of beam force with the experimental data taken in Ref. [2]. The data shows a linear dependence in the beam current ranging from 1 to 8 nA. In this range, the calculated deformation amount is three-orders magnitude smaller than experimental values, indicating that effect of the beam force is negligible. Therefore, the beam force plays a minor role in the deformation.

There is other experimental result that effect of the beam force is not main factor causing the deformation. Figure 5 shows results of three-dimensional deformation profile for 2-μm thick Al foil during irradiation of 8 MeV Si^{4+} beam. Here, attention is paid in the direction of the deformation. In Fig. 5 (a), the foil is deformed in the direction of the incident beam (forward deformation). On the other hand, in Fig. 5 (b), the deformation appears in the opposite direction of the incident beam (backward

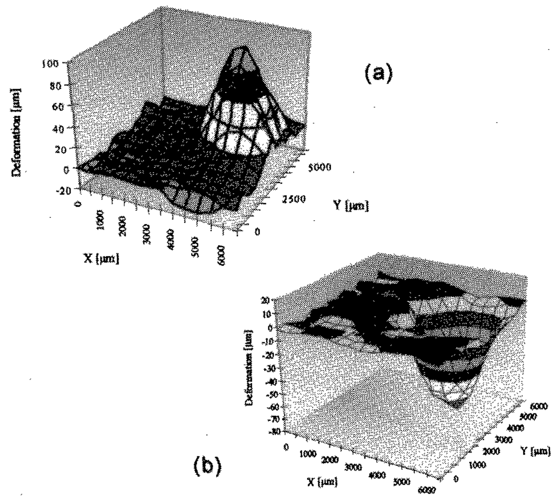

Fig. 5 Forward and backward deformations for Al foil (99.7% purity) of 2-μm thickness during irradiation of 8 MeV Si^{4+} of 160 nA (a) and 140 nA (b). In (a), the deformation appears in the same direction to incident beam, whereas in (b), in the opposite direction.

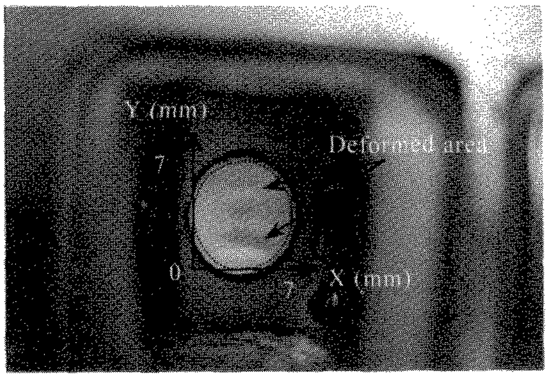

Fig. 6 Photograph of a deformation for 2-μm thick Al foil (99.7% purity) with a slit (two holes of 1.6 mm diameter with a 2 mm separation distance) in front of the target foil. (See text)

deformation). The forward and backward deformations were observed during the same run of beam-on and beam-off irradiations. The result suggests that the deformation is not due to the beam force exerted on the foil.

In Fig. 5, it should be noted that the deformed area is almost the same as the beam spot size, implying that the foil deformation causes by directly induced-irradiation processes. In order to study the deformed area in more detail, the deformation profile of the foil caused by two spatially separated beams was measured using a slit with two holes in front of the target foil. We prepared three kinds of slits with two holes of 1.6 mm in diameter with a distance L of 2, 1.5 and 1 mm between two boundaries, respectively. Figure 6 shows an example of a snap shot photograph of the deformation profile measured with the slit of L=2 mm.

Two peaks attributable to these holes are clearly observed without overlapping. The same result was observed for other slits of L=1.5 and 1 mm. A series of results indicate that the spread of the deformed area on the beam boundary is less than 0.5 mm. Thus, we conclude that the deformation appears almost within the beam hitting area. It is well known that beam irradiation causes effect on heating. If the thermal heating process is a main factor causing the deformation, the irradiation effect may extend over the whole foil and the deformed area shown in Fig. 6 may overlap because Al metal has a good thermal conductivity. The result is very important in understanding the cause of the deformation, implying that thermal heating effect is not significant in the deformation of a metallic Al foil. It is necessary that further study on effect on irradiation heating in the reversible deformation of a metallic Al foil.

4. SUMMARY

We investigated experimentally contribution of the beam force exerted on the foil on the deformation by a torsion balance method. The result provides strong evidence that the measured beam force exerted on the foil is insufficient to cause the observed deformation. Also, the observation of the backward deformation indicates that the deformation is not due to the beam force. From systematic investigations on the deformed area caused by irradiation, the deformation was found to occur almost within the beam hitting area. This result implies that the heating effect due to irradiation is not main factor causing the deformation of metallic Al foil. The phenomenon of the present study, to our knowledge, has not been reported before. We are planning a further study on a deformation of other metallic foils.

ACKNOWLEDGMENTS

We thank Drs. N. Yamada (NRLM) and N. Kishimoto (NIMS) for useful comments and discussions. We also thank Mr. J. Karimata for his experimental assistance. Authors I.K. and S.C.J acknowledge the encouragement of T. Nomura and E-group staff of KEK. This work was supported by a Grant-in-Aid from the Japanese Ministry of Education, Science, Sports and Culture.

REFERENCES

[1] I. Katayama, S.C. Jeong, H. Tsuchida, H. Ogawa, N. Sakamoto and A. Itoh, *J. Chin. Chem. Soc.*, **48**, 455-59 (2001).

[2] H. Tsuchida, I. Katayama, S.C. Jeong, H. Ogawa, N. Sakamoto and A. Itoh, *AIP Conf. Proc.*, **576**, 931-34 (2001).

[3] J. Zieglar, J. F. Biersack, U. Littmark, "The Stopping and range of ions in matter (Computer Code SRIM Version 2000)", Pergamon press, New York (1985)

(Received December 21, 2002; Accepted March 26, 2003)