Influence of Pad Shape on Self-Alignment in Electronic Packaging

DO H. AHN,[1] JIHYE LEE,[2,5] CHOONG D. YOO,[3] and YONG-SEOG KIM[4]

1.—Commercial Vehicle Product Planning Team, Hyundai Motor Co., Chonju, Korea. 2.—Department of Future Technology, KIMM, Daejeon, 305-343 Korea. 3.—Department of Mechanical Engineering, KAIST, Daejeon, Korea. 4.—Department of Material Science, Hongik University, Seoul, Korea. 5.—E-mail: jihyelee@kimm.re.kr

Anisotropic self-alignment of the noncircular pads is investigated to reduce the misalignment in electronic packaging, and the effects of the direction and length ratio of the noncircular pads are analyzed. The restoring forces of circular and noncircular pads are calculated numerically using the surface evolver and are compared with the experimental data. The restoring force in the minor-axis direction of the noncircular pad becomes largest followed by the circular pad and the major-axis direction of the noncircular pad. Directionality increases with the length ratio, which implies that more accurate alignment can be achieved in the specific direction.

Key words: Self-alignment, pad shape, surface evolver, directionality of noncircular pad

INTRODUCTION

The dimension of electronic devices has been reduced significantly to meet the demands of higher packaging density. One of the most widely used packaging methods is the ball grid array (BGA), including the flip chip where the solder balls provide electrical and mechanical interconnections between the chip and substrate. The BGA package is not only suitable for high packaging density but also generates the self-aligning effect. The chip is aligned to the pad on the substrate during reflow soldering because the molten solder tends to minimize the energy of the solder joint. Self-alignment is thus applied to precise positioning of the optical and electronic packages.

Most of the research on self-alignment has been focused on the circular pad, which has isotropic characteristics. The solder profiles and self-alignment were calculated through numerical analysis and the predicted results were compared with the experimental data.[1–6] Among the various numerical techniques, the energy method including the surface evolver has been widely used to accurately predict the solder joint geometry and self-alignment.[2,6] An attempt was made experimentally to improve self-alignment in the particular direction using a strip-shape pad.[7] However, self-alignment of the noncircular pad was not analyzed in a quantitative way.

The influence of the pad shape on self-alignment is calculated numerically in this work using the surface evolver. Performance of the noncircular pad is evaluated considering the solder volume and length ratio of the pad. The predicted results are compared with the experimental data using the shear loading system.[5]

NUMERICAL ANALYSIS AND EXPERIMENTS

Analysis Using Surface Evolver

Self-alignment occurs by minimizing the energy of the molten solder joint, which consists of the surface energy of the solder and the potential energy of the solder and chip. These energies are expressed in the surface integral form as[8]

$$E = \int_S \gamma dS + \int_S \rho g \frac{z^2}{2} \vec{k} \cdot d\vec{A} + m_c g H \qquad (1)$$

where γ is the surface tension coefficient, ρ the mass density, $\vec{k}$ the unit vector opposite to gravity, m_c the chip mass, and H the chip height. The second term of Eq. 1 is the surface integral of the gravitational

(Received June 21, 2005; accepted October 7, 2005)

potential energy of the solder ($v_o \int \rho gz dV$). It is known that the surface energy is the dominant factor compared with the potential energy of the solder and chip weight. This becomes more prominent with smaller solder joints.

While the solder profile is calculated using the surface evolver through minimization of the total energy, the self-aligning effect can be represented using the restoring force. The restoring force in the normal and lateral directions is obtained by differentiating the energy as

$$F_N = \frac{\partial E}{\partial z} \quad \text{and} \quad F_L = \frac{\partial E}{\partial x} \qquad (2)$$

where the subscripts N and L are the normal and lateral directions, respectively. In the case of the noncircular pad, the lateral restoring forces in the major- and minor-axis directions are calculated by differentiating the energy in the corresponding direction.

Experiments

Experiments were conducted to measure the restoring force of the solder joint using the eutectic solder ball (63% Sn-37% Pb) of 760-μm diameter. Figure 1 shows the specimens having the circular and rectangular pads. The pad consisted of 35-μm thickness Cu layer, and Ni and Au layers of 1- and 0.1-μm thickness were electroplated subsequently above the Cu layer. The solder mask was coated on the specimen surface except for the pad area. The dimensions of the specimen was 15 × 15 mm and the distance between pads was 5 mm. The diameter of the circular pad was 400 μm, and the dimensions of the rectangular pad was 1420 μm × 350 μm.

The experimental setup in Fig. 2 was similar to the shear loading system by Josell.[5] It consisted of the heater to melt solder ball at 230°C, the moving plate to impose the shear force on the solder joint, and the position sensitive device (PSD) sensor to measure the displacement of the upper specimen with 1-μm resolution. When the moving plate was inclined using the screw, the shear force was exerted on the solder joints due to the weight of the inclined upper specimen. In the case of the rectangular pad, displacements of the upper specimen in the major- and minor-axis directions were measured using the PSD sensor.

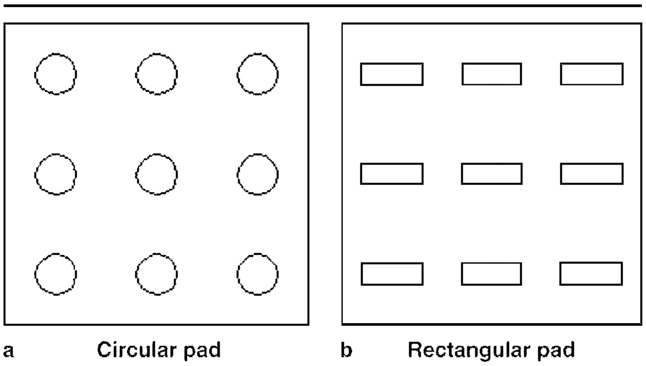

Fig. 1. Specimen configuration: (a) circular pad and (b) rectangular pad.

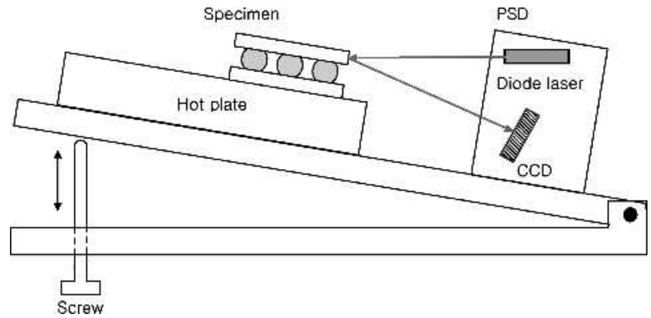

Fig. 2. Schematic of shear loading system.

The average forces exerted on the solder joints are calculated in the normal and lateral direction as

$$f_N = m_c g \cos\theta / N, \;\; f_L = m_c g \sin\theta / N \qquad (3)$$

where θ is the inclined angle and N the number of the solder joints. Since the inclined angle θ is less than 15°, the normal force is almost constant.

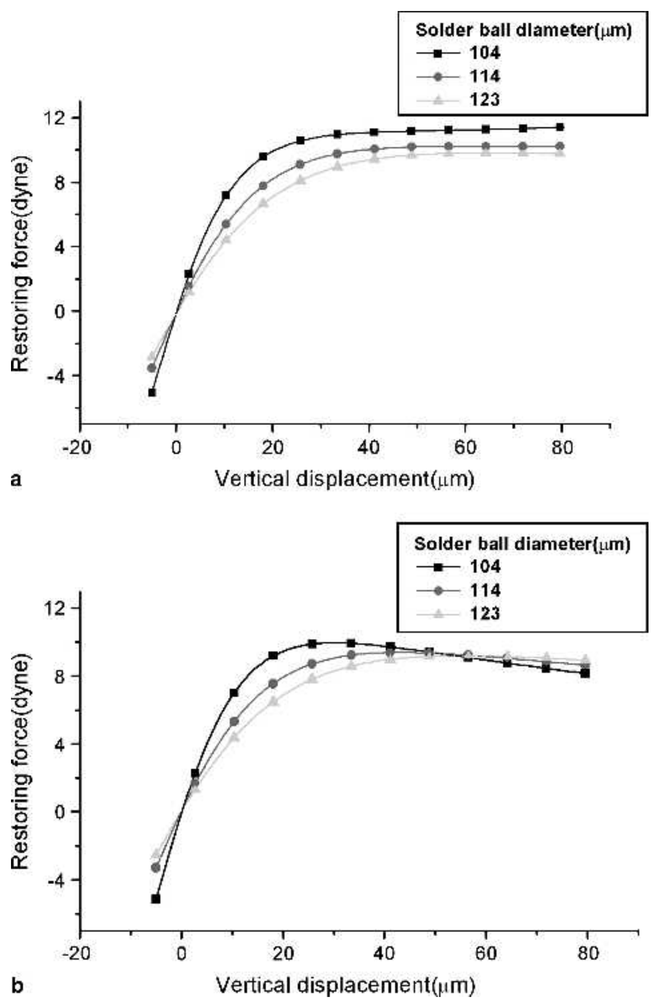

Fig. 3. Calculated normal restoring force for (a) rectangular pad and (b) elliptical pad.

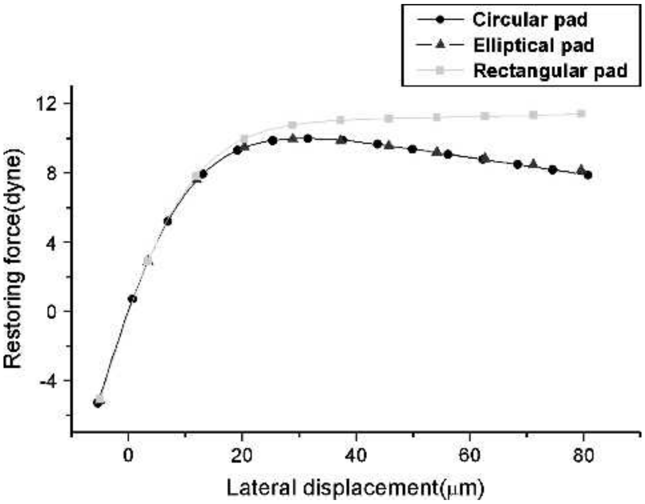

Fig. 4. Comparison of normal restoring force with respect to pad shape.

RESULTS AND DISCUSSION

The normal and lateral restoring forces of the solder joints on the circular, elliptical, and rectangular pads are calculated using the surface evolver. Material properties of the eutectic solder for the calculation are as follows: the mass density is 8.4 g/cm^3, the surface tension coefficient is 325 dyne/cm,[1] and the weight exerted on the solder ball is 4 mg. The perfect wetting condition of the molten solder on the pad is assumed.

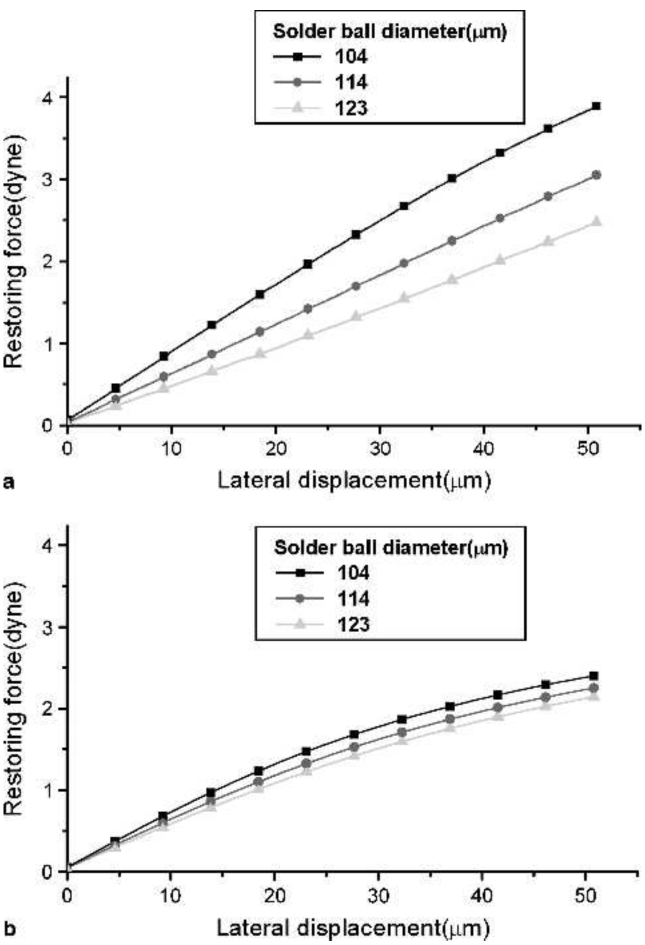

Fig. 5. Calculated lateral restoring force of rectangular pad: (a) force in minor-axis direction and (b) force in major-axis direction.

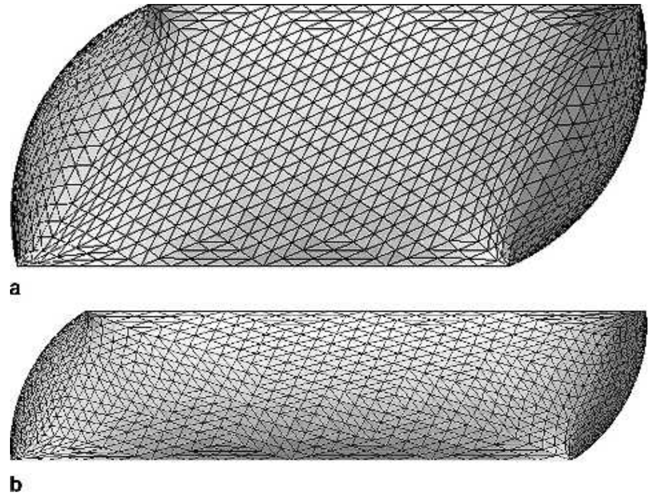

Fig. 6. Deformed surface profile due to displacement in (a) minor axis and (b) major axis.

In order to compare the calculated results with the previous studies,[1,6] solder ball diameters of 104 μm, 114 μm, and 123 μm are used in simulation. In this case, the diameter of the circular pad is 100 μm, the diameters in the major and minor axes of the elliptical pad are 144 μm and 72 μm, respectively, and the dimension of the rectangular pad is 127 μm × 64 μm such that the ratio of the major length to minor length is 2. The area differences between the pad shapes are less than 3.5%. Simulation is also conducted using the solder ball diameter and pad dimensions of the experiments.

Figure 3 shows the calculated restoring forces in the normal direction for the rectangular and elliptical pads with solder ball diameters of 104 μm, 114 μm, and 123 μm. The normal restoring forces of the

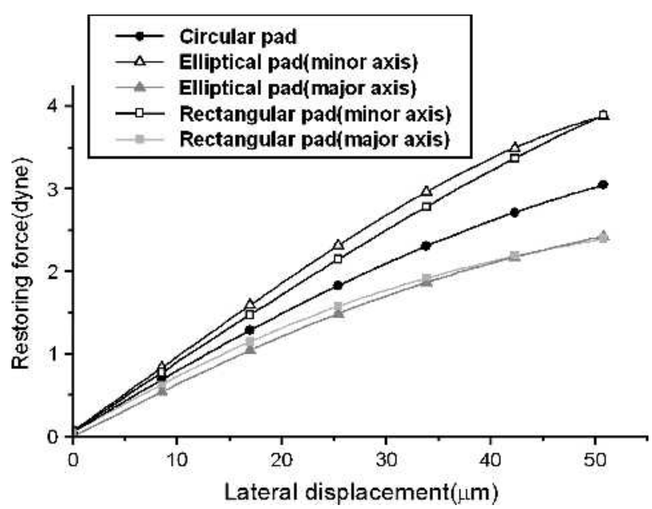

Fig. 7. Comparison of lateral restoring force with respect to pad shape.

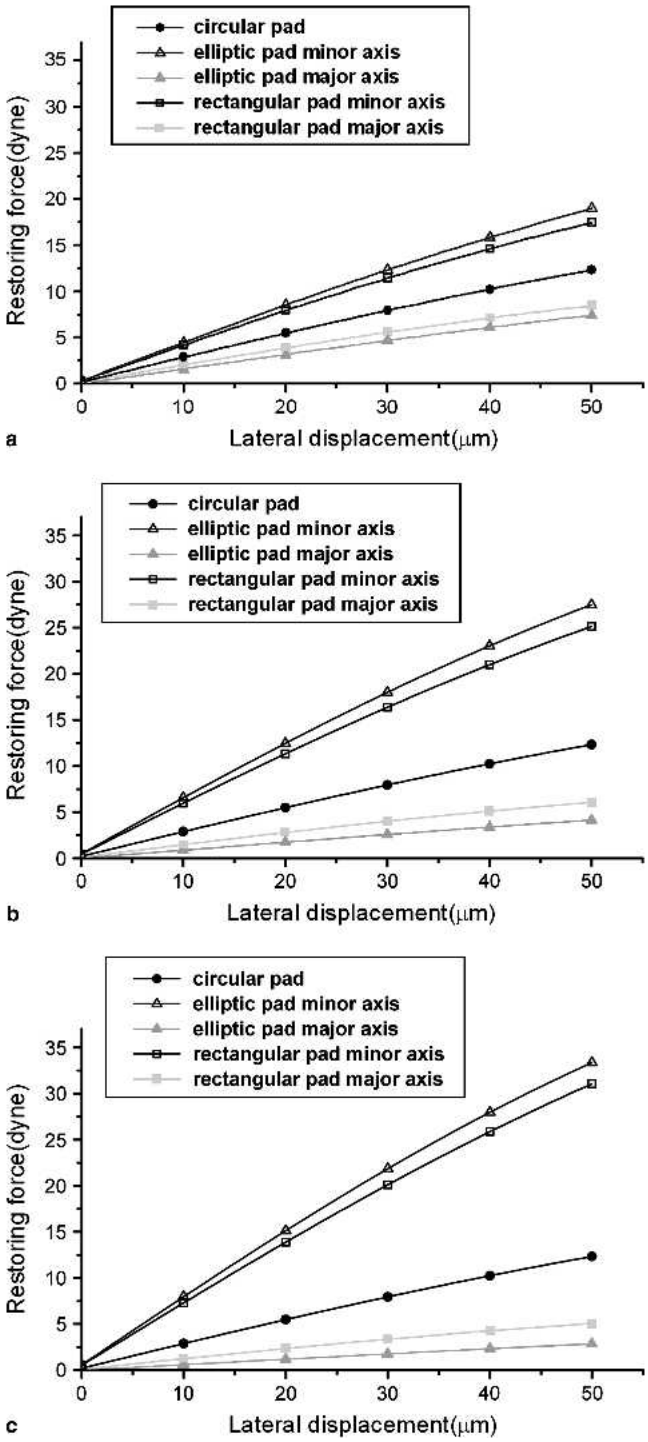

Fig. 8. Effect of length ratio of noncircular pad on lateral restoring force: (a) 2:1, (b) 4:1, and (c) 6:1.

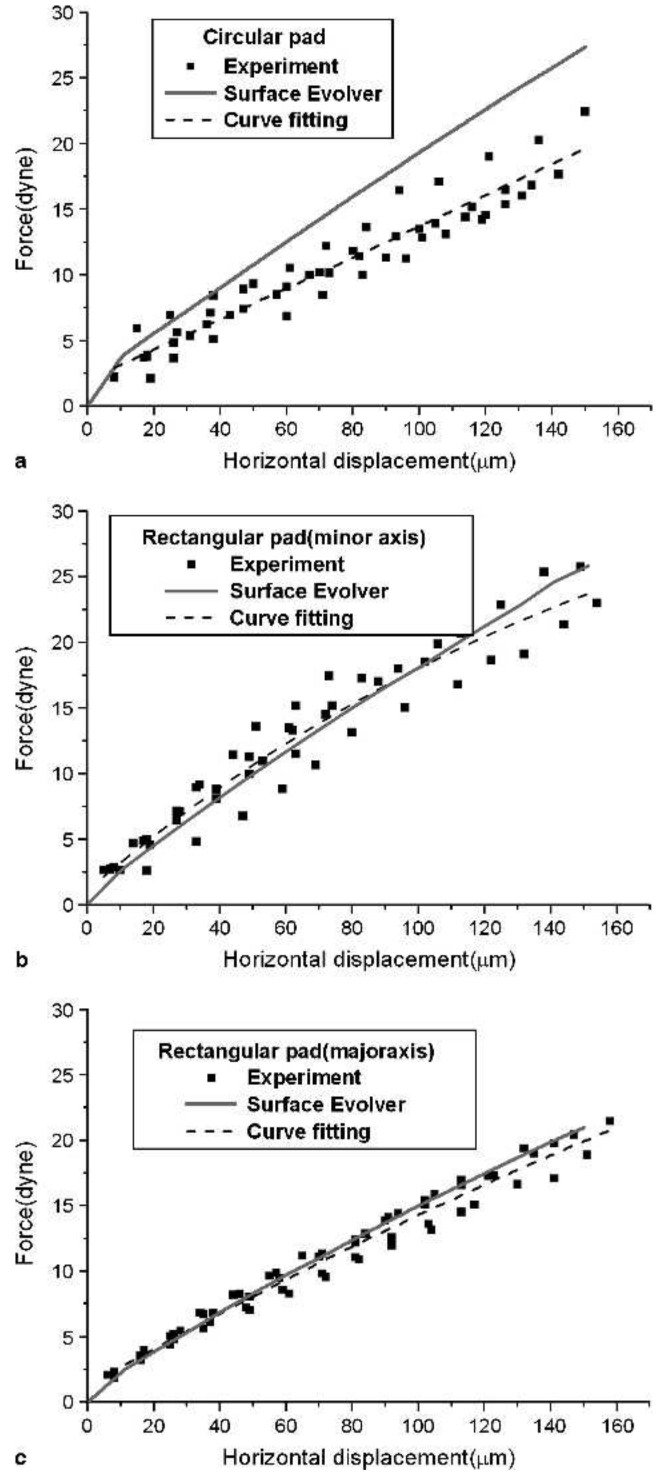

Fig. 9. Comparison of calculated restoring force with measured data for the 760-μm-diameter solder ball: (a) circular pad, (b) rectangular pad with minor axis displacement, and (c) rectangular pad with major axis displacement.

rectangular and elliptical pads increase with smaller solder because the surface area changes more with smaller solder. While the restoring force increases with the displacement from the equilibrium position, it becomes almost constant when the displacement exceeds 20 μm, because the change rate of the solder surface area remains constant with larger displacement. This phenomenon agrees with the results of the circular pad.[6]

The normal restoring force depending on the pad shape is compared in Fig. 4 for the 104-μm diameter solder ball. While the self-alignment is not affected by the pad shape around the equilibrium position, the restoring force of the rectangular pad is larger than those of the circular and elliptical pads, especially for the displacement greater than 20 μm. It appears that the sharp corner of the rectangular pad induces larger surface area change than the circular and elliptical pads. In general, the pad shape does not have significant effects on self-alignment in the normal direction near the equilibrium position.

Self-alignment in the lateral direction is more important than that in the normal direction for electronic and optical packaging. Figure 5 illustrates the lateral restoring force of the rectangular pad in the major- and minor-axis directions for various solder volumes. The lateral restoring force is smaller than the normal force, which agrees with the previous results of the circular pad.[6] The restoring force increases almost linearly with the displacement and also increases with smaller solder volume. The solder volume has more significant effects on self-alignment in the minor-axis direction than in the major-axis direction, because a larger surface of the solder joint along the major axis is deformed by the displacement in the minor-axis direction, as shown in Fig. 6.

Figure 7 illustrates the lateral restoring force depending on the pad shape for the 104-μm-diameter solder ball. The largest restoring force is obtained with the noncircular pads in the minor-axis direction followed by the circular pad and the noncircular pads in the major-axis direction. Therefore, the restoring force of the noncircular pad depends on the pad direction, and larger self-alignment can be obtained in the minor-axis direction.

The effects of the length ratio of the pad on the lateral restoring force are shown in Fig. 8, where the solder ball diameter is 760 μm and the pad area is fixed to 0.5 mm^2 for the calculation. The lateral restoring force in the minor-axis direction increases with the length ratio because the surface area along the major axis becomes larger. In order to obtain the restoring force of the noncircular pad larger by 2 times than the circular pad, it is necessary to increase the length ratio greater than 4, which may restrict the pad design on the limited area of the chip surface. It is also noted that misalignment in the major-axis direction can be increased with disturbances because self-alignment in this direction is lower than the circular pad. When the noncircular pad is applied to the optoelectronic package with laser diode, for example, the major axis of the pad should be parallel to the direction of the laser irradiation to reduce the lateral offset.

The calculated and measured restoring forces are compared in Fig. 9 for the solder ball of 760-μm diameter on the rectangular and circular pads. The calculated restoring forces show reasonably good agreement with the experimental results. While the surface evolver predicts the experimental results accurately for the solder ball of 760-μm diameter, it is applicable to smaller solder volume and pads having various configurations.

CONCLUSIONS

Self-alignment of the noncircular pad is analyzed numerically using the surface evolver and the predicted results show reasonably good agreement with the experimental results. The normal restoring force is larger than the lateral force. In the case of the lateral restoring force, the noncircular pad has directionality such that the restoring force in the minor-axis direction is largest followed by the circular pad and the major-axis direction. Directionality of the noncircular pad increases with the length ratio, which can be applied to reduce the misalignment in the specific direction. However, a large length ratio of the noncircular pad is needed to generate meaningful self-alignment compared with the circular pad, which may restrict the pad design on the limited chip area.

ACKNOWLEDGMENTS

The authors appreciate the financial support from KOSEF (Korea Science and Engineering Foundation) and the BK-21 Project.

REFERENCES

1. S.K. Patra and Y.C. Lee, *J. Electron. Packaging* 113, 337 (1991).
2. K.-N. Chiang and C.-A. Yaun, *IEEE Trans. Adv. Packaging* 24, 158 (2001).
3. S.M. Heinrich, M. Schaefer, and S.A. Schroeder, *J. Electron. Packaging.* 118, 114 (1996).
4. N. van Veen, *J. Electron. Packaging* 121, 116 (1999).
5. D. Josell, W.E. Wallace, J.A. Warren, D. Wheeler, and A.C. Powell IV, *J. Electron. Packaging* 124, 227 (2002).
6. Y.J. Jung, D. Ahn, C.D. Yoo, and Y.-S. Kim, *J. KWS* 20, 789 (2002).
7. J. Sasaki, H. Honmou, M. Itoh, A. Uda, and T. Torikai (Paper presented at Lasers and Electro-Optics Society Annual Meeting, 8th Annual Meeting Conf. Proc. IEEE 1, San Francisco, CA, Oct. 30–31, 1995).
8. K. Brakke, *Exp. Math.* 1, 141 (1992).