Ribbed Package Geometry for Reducing Thermal Warpage and Wire Sweep During PBGA Encapsulation

Sen-Yeu Yang, Shin-Chang Jiang, and Wen-Shu Lu

***Abstract*—The effects of changing package shape into ribbed geometry on thermal warpage and wire sweep of PBGA are investigated in this paper. Three rib geometries (border, diagonal, and cross) with a variation of rib widths and thicknesses are compared with the original plane geometry. Finite element analyses of thermal warpage during the reflow process of PBGA molding with and without ribbed geometry are carried out. Numerical modeling shows that the border rib has the least thermal warpage at the reflow condition. Flow visualization was performed to study the effect of rib geometry on wire sweep, and demonstrates that wire sweep in the ribbed packages is significantly less than that in the original nonribbed package.**

***Index Terms*—Finite element analysis, flow visualization, plastic ball grid array, ribbed package geometry, thermal warpage, wire sweep.**

I. Introduction

BALL grid array (BGA) packages have emerged as the package of choice. An explosive growth in research and development efforts has been witnessed in recent years [1]. Plastic BGA (PBGA) employs resins as encapsulant for economical and productive reasons. Although PBGA has several advantages over fine-pitch quad flat pack (QFP) such as smaller package area and higher inputs/outputs (I/Os), potential reliability problems such as coplanarity have to be solved. PBGA is basically a composite structure consisting of different materials with different elastic moduli and coefficients of thermal expansions (CTEs). The thermal expansion mismatch between the materials generates thermomechanical stress at temperatures above and below the molding temperature and especially at the reflow temperature. The excessive thermomechanical stresses generated can result in warpage problems as shown in Fig. 1. This coplanarity-related concern has been increasing rapidly as a consequence of trends for achieving a high I/O density with a package that is as small and thin as possible. Liang [2], Oota *et al.* [3], Ho *et al.* [4], and Mertol [5], investigated the effect of geometry such as thickness and dimension, and material properties such as CTE, Tg, and elastic moduli on coplanarity and their sensitivity. It was found that substrate warpage is the main cause of poor coplanarity. Increasing substrate thickness, higher substrate Tg and Young's Moduli, and thinner encapsulant can reduce warpage. No research has attempted to investigate the effect of redistributing encapsulant into a ribbed geometry on warpage of PBGA. Ribbing is a common practice in enhancing structural rigidity [6]. This paper is devoted to investigating the possibility of changing package geometry by adding a rib structure to reduce thermal warpage during the reflow condition. Numerical stress and structure analysis based on Finite-Element-Method is employed to predict the thermal warpage of a package with the original plane structure and various ribbing structures.

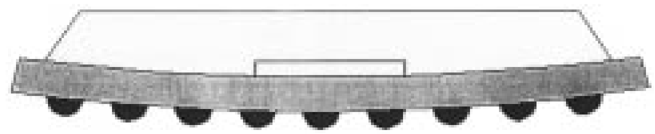

Fig. 1. Warpage of plastic ball grid array package may cause coplanarity problem in solder balls during reflow.

While developing an innovative ribbed package geometry for reducing thermal warpage, wire sweep is another challenging problem. Wire sweep is a common defect in plastic integrated high density packages. Most integrated circuits are encapsulated by transfer molding of epoxy molding compounds (EMCs). During the filling stage, the high viscosity epoxy exerts a drag force on the wires. If the wire sweep is too big, neighboring wires may touch, resulting in a short-circuit. With the trend of high wire density, thinner cavity depth, and higher filling rates, the wire sweep problem is becoming critical. To minimize wire sweep, a general practice involves adjusting lead frame design, mold design, device layout, molding compound and process parameters based on experience and trial-and-error. These practices are expensive and time-consuming. Many researchers have developed analytical and numerical models to predict the wire sweep [7]–[10]. Flow visualization experiment is another effective technology to comprehend the flow-related phenomena. Many researchers have successfully applied the visualization technique to unveil process mysteries [11]–[14]. In this study, the encapsulating mold is covered with a transparent top plate and a CCD camera is used to observe the cavity filling process during transfer molding. The wire sweep during filling cavities for original plane package and ribbed packages are to be measured and compared.

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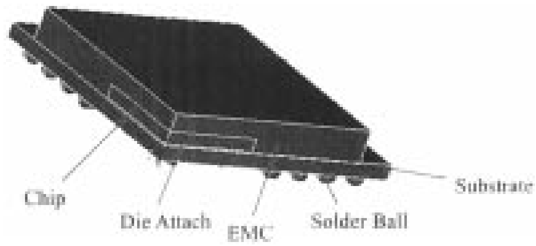

Fig. 2. Detailed construction of PBGA packages included in the FEM model.

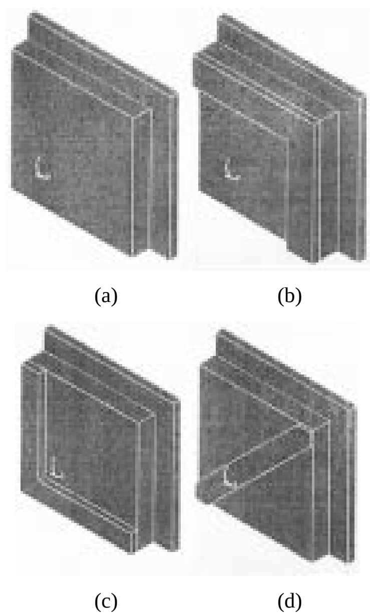

Fig. 3. Sketches showing geometries of packages (a) original plane package, (b) package with border ribs, (c) package with cross ribs, and (d) package with single diagonal rib.

II. Finite Element Model

The thermal warpages during reflow process in plane and ribbed PBGA packages are studied using a commercial finite element software ANSYS. The original plane package under investigation is a 196-pin perimeter cavity-up PBGA. There are four arrays of peripheral solder balls with 1.27 mm pitch. The solder material is eutectic Pb–Sn solder (63 Sn/37 Pb). A 8 mm $\times$ 8 mm $\times$ 0.5 mm IC chip is bonded on to a 21 mm $\times$ 21 mm $\times$0.6 mm bis-maleimide-triazine (BT) substrate with 0.07 mm thick thermally conductive adhesive. The package is square with body size of 18 mm$\times$18 mm$\times$1.3 mm. Due to the symmetry of the package only one quarter of the package (as shown in Fig. 2) is modeled using 3-D 10-node tetrahedral element, solid87 in ANSYS. Mechanical properties of all materials are assumed to be isotropic linear elastic, except BT substrate. The model consists of the chip, die attach, epoxy molding compound (EMC), solder ball, and substrate.

There are three types of ribbed packages investigated in this research: 1) "border": 18 mm $\times$ 18 mm$\times$ 1.3 mm package surrounded with a rib as shown in Fig. 3(b); 2) "cross": 18 mm $\times$ 18 mm $\times$ 1.3 mm with two cross ribs as shown in Fig. 3(c); 3) "diagonal": 18 mm $\times$ 18 mm $\times$ 1.3 mm with a diagonal rib as shown in Fig. 3(d). The combination of widths and thicknesses of the ribs are shown in Table I. The summarized dimensions and material properties used in this simulation are shown in Tables II and III.

The thermomechanical analyses are used to predict the nodal deflection distribution. Since one quarter of the package is modeled, the symmetry boundary conditions are used along the cut planes where the adiabatic condition is prescribed. To model the reflow process, the packages are heated to 160 °C. The thermal loading is assumed to be 135 °C above the stress free reference temperature (T_{ref} =25 °C). The deflections of the solder balls at 160 °C are then compared to the nonstressed condition. Warpage is defined to be the maximum deflection difference among all bottom nodes of solder balls. The warpage in

TABLE I
COMBINATION OF WIDTH AND THICKNESS FOR BORDER, DIAGONAL AND CROSS RIBS (ON 18 mm $\times$ 18 mm $\times$ 1.3 mm PACKAGE)

	Width(mm)	Thickness(mm)
A1	1	0.5
A2	1.5	0.5
A3	2	0.5
A4	3	0.5
B1	2	0.25
B2	2	0.5
B3	2	0.75
B4	2	1

TABLE II
MATERIAL PROPERTIES AND IMPORTANT DIMENSIONS USED IN THE THERMAL WARPAGE SIMULATION

	Chip (Die)	Molding Compound (EMC)	BT Substrate	Solder Ball	Die Attach
Young's Modulus(GPa)	131	16	26 (xy) 11 (z)	17	0.7
Poisson's Ratio	0.3	0.25	0.39 (xz,yz) 0.11 (xy)	0.4	0.3
CTE (ppm/℃)	2.8	15	15 (xy) 52 (z)	21	40
Thermal Conductivity (W/m℃)	150	65	0.3	50	1
Density (kg/m^3)	2330	1660	1660	8460	
Specific Heat(J/kg • ℃)	712	1672	1672	957	
Dimension(mm)	8(width) 0.5(height)	18(width) 1.3(height)	21(width) 0.6 (height)	0.71(diameter) 0.36(height)	8.75(width) 0.07(height)

TABLE III
COMBINATION OF WIDTH AND THICKNESS FOR BORDER RIBS (ON 18 mm $\times$ 18 mm $\times$ 1.2 mm PACKAGE)

	Width(mm)	Thickness(mm)
C1	0.5	0.25
C2	0.5	0.5
C3	0.5	0.75
C4	0.5	1
C5	1	0.25
C6	1	0.5
C7	1	0.75
C8	1	1
C9	1.5	0.25
C10	1.5	0.5
C11	1.5	0.75
C12	1.5	1

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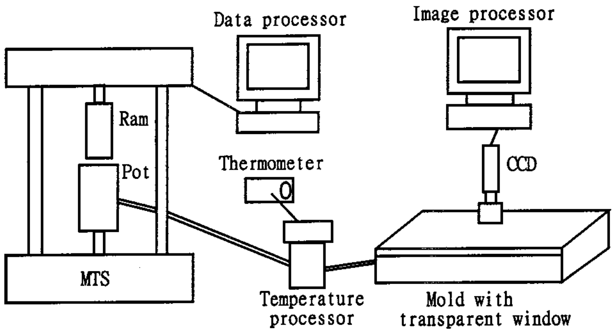

Fig. 4. Schematic of facilities for flow visualization experiment.

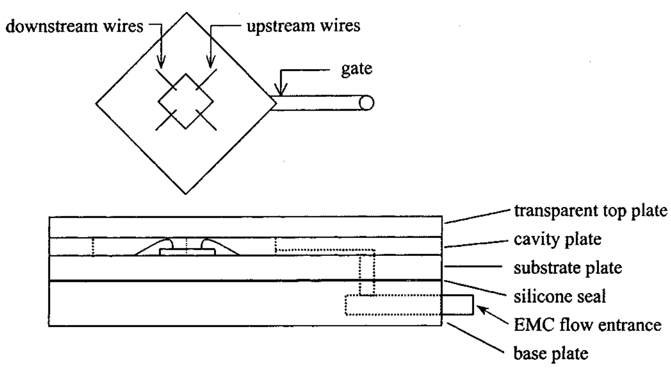

Fig. 5. Sketch showing the detailed construction of mold: 1) transparent top plate, 2) cavity plate, 3) substrate plate, 4) silicone seal, and 5) base plate with gate. The flow entrance, gate, upstream, and downstream wires are also marked.

the ribbed packages are compared with warpage in the original plane package.

III. Experimental Setup for Flow Visualization

To help understand the effects of the ribbed package geometry on the filling process and wire sweep during the transfer molding of the epoxy molding compound (EMC), wire displacements are observed during the transfer molding process for the original (no rib) and border-rib cavities. The flow-visualization set-up is shown in Fig. 4. A scaled-up mold with transparent window was constructed for this study as shown in Fig. 5. The mold was composed of four plates. The top plate is made of transparent poly(methyl-methacrylate) (PMMA) for flow visualization. The top plate, cavity plate and substrate plate form the package cavity (dimensions shown in Fig. 6). A square PMMA chip (30 mm $\times$ 30 mm $\times$ 1 mm) with four brass wires is attached on the substrate plate. The brass wire used is EDM wire HTF (HITACHI, Japan) The base plate provides the resin entrance and runner. The epoxy resin used is D.E.R.331 (Dow Chemical). Since its viscosity is sensitive to temperature, a temperature monitoring system is implemented between the pot and cavity. The transfer molding experiments were conducted with a material testing machine (MTS-810, MTS). The epoxy is pushed at constant flow rate from pot to cavity. The flow rate can be regulated with specified stroke control through the machine controller. A digital CCD camera (SONY XC-77) with image processing card (Meteor 330 S/N AE 68577) is used to capture the cavity filling process.

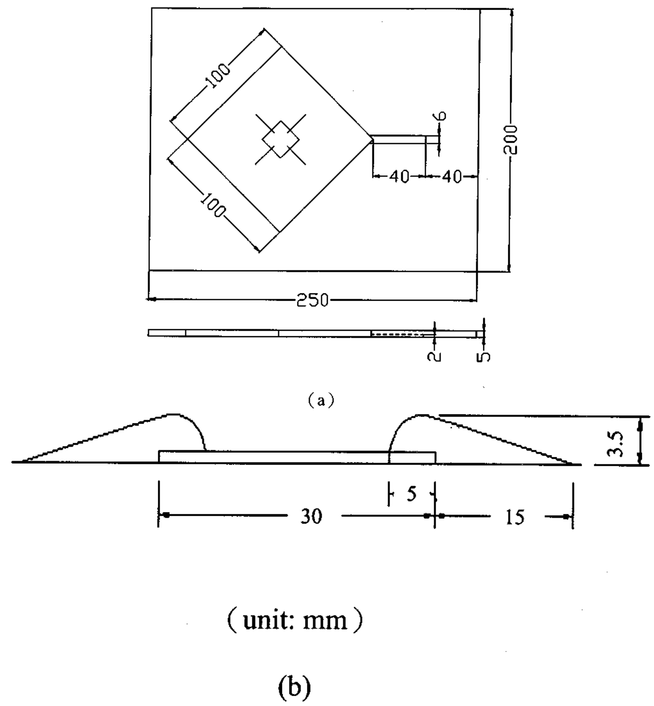

Fig. 6. Sketch showing (a) geometry of the cavity and (b) typical wirebond geometry.

IV. Results and Discussion

A. Distribution of Thermal Deflections of Original Package and Ribbed Packages

Fig. 7 shows the distribution of thermal deflections in the original package. Several iso-deflection lines are marked with values. There is a calculated deflection value associated with each node. The largest substrate deflection occurs at the outer corner. Similar distributions are found in a package with border rib, a package with diagonal rib and a package with cross rib.

The coplanarity will be determined by the variation in deflections of solder balls. The warpage is defined as the maximum difference among deflections of the central bottom nodes in the 48 solder balls.

Fig. 8 presents the warpage for the ribbed packages versus warpage for the original package. The term "warpage relative to original" is defined as the warpage (maximum deflection difference among bottom nodes) in ribbed package divided by the warpage in original plane package. The border, diagonal, and cross ribs are presented in multiple columns to show results of different rib dimensions (e.g. w1-t 0.5 is the case with rib width 1 mm and rib height 0.5 mm) for each rib geometry. A value of 100% indicates the same warpage as that in original plane package under reflow condition. A value of warpage relative to original of less than 100% implies reduce in warpage as compared to the original plane package. There is an improvement in coplanarity. A positive value indicates the overall concave-convex configuration is similar to that predicted in the original plane package, while a negative value implies a contrary pattern.

According to the results of numerical analysis, warpage relative to original of all ribbed packages are all less than 100%. This implies that warpages in ribbed packages with specified dimensions are all smaller than that in original plane package.

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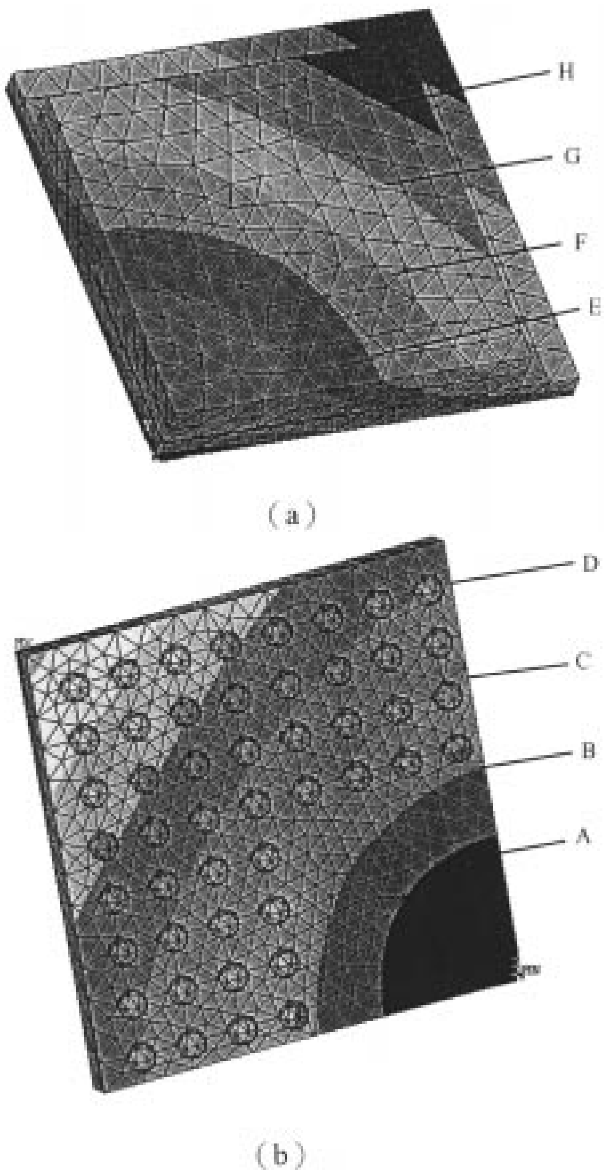

Fig. 7. Distribution of deflections under reflow condition in plain (nonribbed) package at (a) EMC and substrate and (b) solder balls and substrate. Warpage is defined as the maximum difference among deflections of the central bottom nodes of the solder balls. Gradient lines: $A = -4.77\ \mu$m; $B = -1.97\ \mu$m; $C = 0.841\ \mu$m; $D = 3.65\ \mu$m; $E = 6.46\ \mu$m; $F = 9.26\ \mu$m; $G = 12.1\ \mu$m; $H = 14.9\ \mu$m.

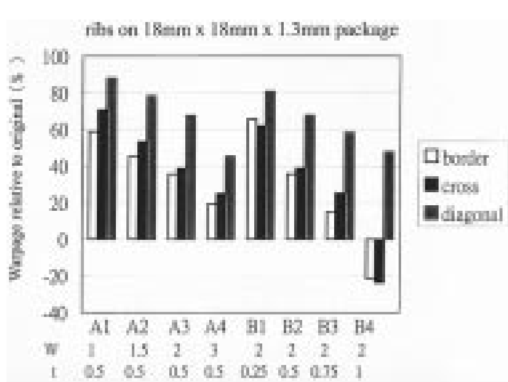

Fig. 8. Warpages in packages with various rib configurations and dimensions normalized by the warpage in the original plane package. Values less than 100% imply that warpage in packages with ribs is less than that in the original plain package.

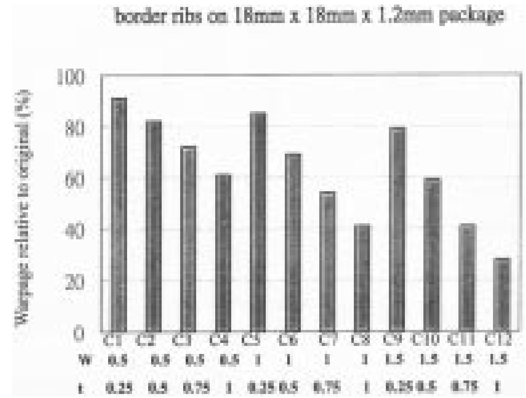

Fig. 9. Warpage relative to plain package in packages with border ribs of various dimensions. The reduction in thermal warpage is significant even with thickness of EMC reduced.

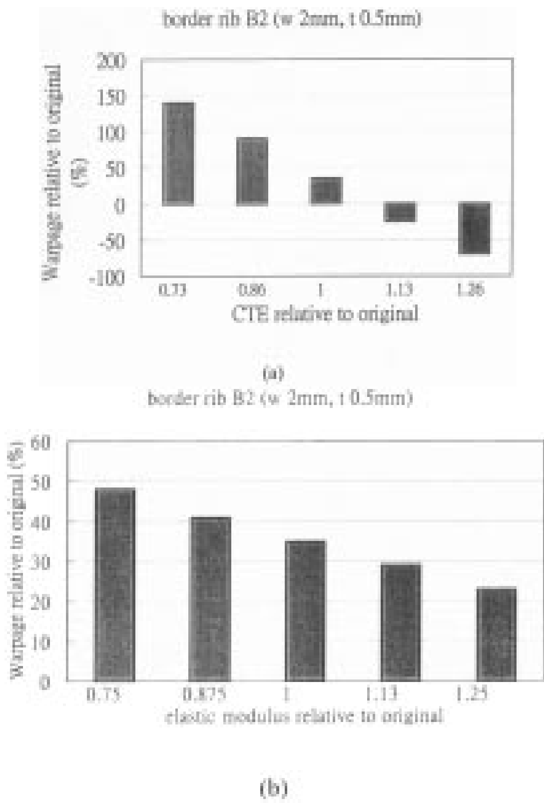

Fig. 10. Effects of (a) coefficient of thermal expansion and (b) elastic modulus of ribs in thermal warpage of packages with border ribs relative to original plane package. Increasing rigidity of rib reduces warpage, but CTE of the rib should be close to that of EMC.

Furthermore, it is found that adding border ribs is more effective in reducing thermal warpage than adding cross and diagonal ribs.

B. Effects of EMC Thickness, Dimensions, CTE, and Rib Elastic Modulus on Warpage

Packages with border ribs are the best among the three ribbed packages, not only because of reduced warpage overall, but also due to the convenience for subsequent marking and printing. The following studies of changing package thickness and material properties will be limited to the package with border ribs.

Fig. 9 shows the attempt to reduce the original EMC thickness in packages with border ribs. The warpage relative to orig-

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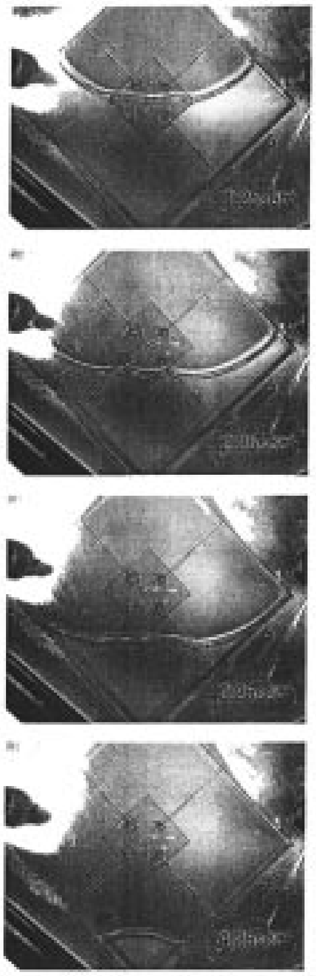

Fig. 11. Photographs show the filling process and wire sweep in cavity for original plane package. Wire sweep is observed after the epoxy resin flows across the bondwires.

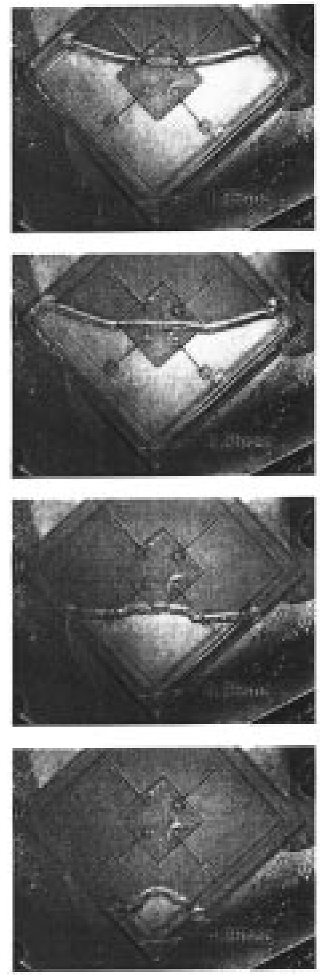

Fig. 12. Photographs show the filling process and wire sweep in cavity for package with border ribs. Reduced wire sweep is observed because the excessive flow along the thick channel for molding border rib reduces the flow across the bondwires.

inal is defined as the warpage in 1.2 mm thick package with border rib of specified dimension divided by the warpage in 1.3 mm thick plane package without rib. As can be seen, with the EMC thickness reduced from 1.3 mm to 1.2 mm, it is still possible to achieve much less warpage in the border rib packages for all rib dimensions. This implies that a improved coplanarity can be achieved even with less EMC material by redistributing the EMC from plain geometry to more bending-resistant ribbed geometries.

It is possible that a different material could be used for the ribs. For example, one could select copper as a rib material for enhancing heat transfer. However, the difference in CTE and elastic modulus may affect the relative warpage. Fig. 10 demonstrates the sensitivity of warpage to rib CTE [Fig. 10(a)] and modulus of elasticity [Fig. 10(b)]. For CTE, deviation from the CTE of original EMC worsens the warpage. However, increasing the elastic modulus of the rib reduces the warpage.

C. Comparison of Wire Sweeps in Border Ribbed and Original Package Cavities

Fig. 11 displays the photographs reproduced from the CCD frames showing the cavity filling process during transfer molding of EMC in the original cavity. The profile of the resin fronts is parabolic, and it's profile changes with time. After the resin passes the chip, the resin front is retarded, showing the chip exerting significant resistance on flow. Wire sweep can be observed as soon as resin flows across the bondwires.

Fig. 12 shows the flow patterns during filling the cavity for the border rib package. Due to the racetrack effect (i.e., resin flows faster in the thicker sections), the profile of the resin front is straighter than that in a original cavity. In addition, less wire sweep is observed in cavity for package with border rib.

Fig. 13 shows the maximum wire sweeps measured in cavities for the original package and ribbed packages at different flow rates. The wire sweep s is evaluated by the ratio d/l, where d is the maximum lateral wire deflection projected onto the plane of the lead frame and l is the span of the bondwire. Wire sweep increases with flow rate. The flow rate is expressed in term of Reynolds number Re. Re is defined as $\rho\, vh/\mu$, where v is the average flow velocity during filling, h is the cavity height, and μ is the viscosity of epoxy resin during filling. For the same Reynolds number, the wire sweeps in the cavity for ribbed packages are smaller than wire sweeps seen in the cavity for original plane package. A relatively large volume of resin flows through

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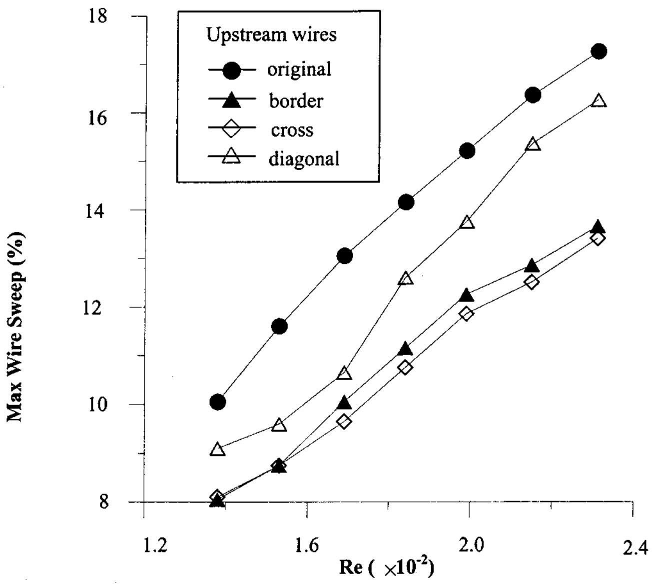

Fig. 13. Wire sweep in cavity for packages with ribs is significantly smaller than that in cavity for original plane package.

the cavity via the rib passages, lowering the velocity over the chip, and thus exerting less drag force on wire. As a result, the wire sweeps in the ribbed cavities are significantly less than for the original cavity.

V. Conclusions

The effect of changing package shape by redistributing plain epoxy molding compound (EMC) into ribbed geometries on thermal warpage of PBGA has been investigated in this study. Finite element analysis of thermal warpage during encapsulation of PBGA packages with ribbed geometries is performed. Three types of ribbing (border, diagonal and cross) with a numbers of combinations of rib widths and thicknesses are compared. In addition, the effect of such ribbed geometries on wire sweep is also measured by flow visualization experiments. The following conclusions can be drawn from this study.

1) The thermal warpage during reflow condition in ribbed packages (especially the package with the border rib) can be significantly reduced if the thickness and width of the rib are appropriately selected. Optimal rib dimensions depend on rib arrangement and EMC thickness. The reduction in thermal warpage can still be significant even with the thickness of the EMC being reduced.
2) Changing the thermal expansion coefficient of the border rib would not help reduce thermal warpage. However, increasing the Young's Modulus of the border rib would reduce thermal warpage.
3) The wire sweeps in cavities with ribs are significantly smaller than that in nonribbed cavities. For ribbed packages, the additional flow area in the mold cavity due to a rib (especially the border rib) serves as a flow guide, reducing the flow rate over the chip, and thus drag exerted on the wires.

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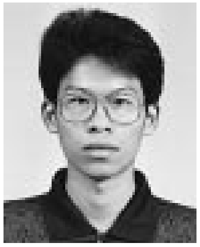

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