Warpage modeling and characterization of intelligent power modules (IPMs)

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ABSTRACT

Intelligent power modules (IPMs) are widely used in the electric vehicle (and hybrid electric vehicle industry nowadays due to their high power density and ability to integrate multiple components within a single package. However, the reliability of IPMs is severely degraded by the substrate warpage effect produced during the packaging process. This study therefore develops a computational model to analyze the warpage of the IPM assembly at various stages of the packaging process. The validity of the simulation model is confirmed by comparing the numerical results for the warpage of the direct plated copper substrate with the experimental observations. Taguchi experiments are then performed to examine the effects of eight control factors on the IPM package warpage following the post-mold cure (PMC) process, namely (1) the dam bar layout, (2) the epoxy molding compound (EMC) thickness, (3) the lead frame thickness, (4) the ceramic thickness, (5) the bottom layer Cu foil thickness, (6) the top layer Cu foil thickness, (7) the ceramic material type and (8) the EMC material type. Finally, the Taguchi analysis results are used to determine the optimal packaging design that minimizes the warpage of the post-PMC package.

KEYWORDS: IPM, warpage, finite element method, optimization

1. INTRODUCTION

MOSFET-based intelligent power modules (IPMs) were first introduced more than 20 years ago [1, 2], and have many advantages over conventional discrete power modules, including (1) improved reliability: the insulation, moisture resistance, anti-interference and electrostatic protection properties of IPMs are all superior to those of discrete modules; (2) better consistency: the chips in the IPM are all taken from the same wafer, and hence their consistency is guaranteed; (3) more convenient replacement: different power products can be swapped in and out as required within the same module package; (4) more convenient design: the drive integrated circuit and power devices are integrated directly, and hence there is no need for drive matching; and (5) enhanced cost efficiency: the IPM structure is similar to that of printed circuit boards, and hence the same radiator can be used for both. Due to these advantages, IPMs are widely used in many fields nowadays, including electric vehicles, hybrid electric vehicles, industrial pumps, DC/DC converters and many more.

The various components within the IPM are mounted on direct plated copper (DPC) plates through a sequential fabrication process with lead-free solder. However, solder joint cracks are often observed during the assembly process, or in subsequent reliability testing [3, 4]. Several numerical studies have been performed to investigate the problem of solder joint reliability under thermal cycle testing. In general, the results have shown that the reliability can be improved by increasing the solder layer thickness [5–9].

Solder joint non-wetting can be attributed mainly to the substrate warpage effect that occurs during the IPM packaging process. Therefore, the problem of minimizing the warpage of power module packages has attracted significant attention in the literature. Lee et al. [10] performed three-dimensional (3D) finite element (FE) simulations to investigate the warpage behavior of direct bonded copper structures, and found that the warpage increased with an increasing Al₂O₃ ceramic layer thickness. However, the warpage reduced as the thickness of the copper base plate increased. Zhou et al. [11] conducted a numerical investigation into the warpage of a 121 × 59 mm² power module structure, and found that the final warpage could be reduced by prewarping the copper substrate prior to the packaging process. Mirone et al. [12] examined the stress–strain response of Cu foil dog-bone samples at high temperatures by experimental tensile tests. The results were used to construct an FE model to simulate the warpage of active metal brazed substrates during passive temperature cycling. Calabretta et al. [13] measured the warpage of a power module at different stages in the assembly process, and used the experimental results to construct an FE model to predict the deformation behavior of the package for different fabrication techniques. It was shown that the package underwent concave warpage in the conventional soldering process, but convex warpage following an ultrasonic welding process.
Previous studies have generally focused on the warpage behavior of the bare copper base substrate of the IPM. In other words, the warpage of the finished IPM assembly has thus far attracted very little attention. Accordingly, this study constructs a 3D FE model to analyze the warpage of the IPM module at various stages of the fabrication process. The validity of the FE model is confirmed by way of experimental measurements. Taguchi experiments, based on the validated model, are then performed to determine the optimal packaging design that minimizes the warpage of the package following the molding and post-mold cure (PMC) process.

2. WARPAGE CHARACTERIZATION OF IPM

2.1 Structure

Figure 1 presents a top view image of the IPM module considered in this study consisting of a lead frame, several DPC plates, a ceramic base plate, a small number of passive components and multiple chips. As shown in Table 1, the lead frame has dimensions of \(58 \times 52 \times 0.5\) mm\(^3\) (length \times width \times thickness), while the dies have a size of \(7 \times 4 \times 0.15\) mm\(^3\), the diode measures \(3 \times 2 \times 1.2\) mm\(^3\) and the small outline package (SOP) measures \(5 \times 4 \times 1.5\) mm\(^3\). The DPC plates consist of two thin copper films (with a thickness of 0.0575 mm each) and an Al\(_2\)O\(_3\) ceramic layer (0.635 mm), and have a total thickness of 0.75 mm.

| Component | \(E\) (GPa) | CTE (ppm/°C) | \(T_g\) (°C) | \(\nu\) |
|-----------|-------------|--------------|--------------|-------|
| Die       | 131         | 2.8          | 0.27         |
| Copper    | 121         | 16.9         | 0.30         |
| Passive   | 80          | 6.4          | 0.34         |
| Solder    | 45          | 20           | 0.35         |
| Al\(_2\)O\(_3\) | 340 | 6.8          | 0.30         |
| AlN       | 320         | 4.7          | 0.3          |
| ZTA       | 310         | 7.5          | 0.3          |
| EMC A     | 18.3 (Fig. 2) | 8/25 (Fig. 2) | 185 | 0.30 |
| EMC B     | 30          | 12/38        | 125          | 0.30 |
| EMC C     | 20          | 10/45        | 135          | 0.30 |

Figure 2. Temperature-dependent Young’s modulus and thermal strain of EMC A.

2.2 Material properties

In constructing the FE model of the intermetallic compound (IMC), the thermomechanical properties of the module components were assigned the values shown in Table 2, where \(E\) is the Young’s modulus, CTE is the coefficient of thermal expansion, \(T_g\) is the glass transition temperature and \(\nu\) is the Poisson’s ratio. As shown in Fig. 2, the Young’s modulus and thermal strain of the epoxy molding compound (EMC) type A are both temperature dependent. The CTE values of the different polymeric materials considered in the Taguchi experiments (denoted simply as EMC A, B and C, respectively) were computed directly from the slopes of the corresponding thermal strain versus temperature curves. Moreover, the mold shrinkage effect at a reference temperature less than \(T_g\) was modeled by an equivalent CTE parameter for the respective EMC material in accordance with [14]

\[
\text{CTE}_{1\text{Equivalent}} = \text{CTE}_1 + \frac{\text{Shrinkage}}{T_{\text{ref}} - T} (T < T_g), \quad (1)
\]

\[
\text{CTE}_{2\text{Equivalent}} = \frac{\text{CTE}_1 \cdot (T_{\text{ref}} - T_g) + \text{CTE}_2 \cdot (T_g - T) + \text{Shrinkage}}{T_{\text{ref}} - T} \times (T > T_g). \quad (2)
\]
2.3 FE model

Figure 3 presents a schematic illustration of the IPM module assembly considered in this study.

Figure 4a shows the FE model used to analyze the warpage of the IPM module during the thermal cycling process. The FE mesh was constructed using a combination of different 3D element types and contained a total of 167,662 linear hexahedral elements. To minimize the computational cost and complexity, the Al wire used for electrical connection in the IPM package was deliberately neglected in the model.

2.4 Loads and constraints

Three nodes located in the bottom corners of the IPM module were chosen to constrain displacement in the x-direction (UX = 0), x- and z-directions (UX = UZ = 0), and any direction (UX = UY = UZ = 0), respectively, as shown in Fig. 4b. Moreover, in performing the modeling process, the temperature was assumed to reduce from a stress-free temperature (175°C) to room temperature following the PMC process. Moreover, a “birth and death” modeling technique was used to evaluate the residual stress produced during the key fabrication stages shown in Fig. 5.
2.5 Verification of the FE model

The validity of the FE model was confirmed by comparing the simulation results for the package warpage with the experimental measurements obtained for an IPM module with a size of $58 \times 52 \times 5.5 \text{mm}^3$ (see Fig. 6). The experimental measurements of the lower surface of the IPM were obtained at room temperature ($30^\circ$C) using a Keyence VR series 3D measurement system, as shown in Fig. 7. The light source had the form of a white LED, and provided a maximum measurement area of $206 \times 104 \text{mm}^2$ and a measurement accuracy (height and width) of $2.5$ and $5 \mu\text{m}$, respectively. Figure 8a and b shows the simulation and experimental results for the IPM warpage contours, respectively. The two warpage measurements deviate by no more than $4\%$ from one another. Thus, the basic validity of the FE model is confirmed.

Figure 9a shows the simulated warpage contours of the IPM module at various stages of the packaging process. Figure 9b shows the corresponding variation of the absolute 3D warpage of the IPM assembly. Note that a positive value of the warpage indicates a convex deformation (crying face), while a negative sign indicates a concave deformation (smiling face). It can be seen that the initial warpage of the bare DPC substrate is $-113 \mu\text{m}$. Following the mounting of the lead frame and other components on the DPC substrate, the module undergoes positive (i.e. convex) deformation with a maximum value of $211 \mu\text{m}$ due to the high equivalent CTE of the package components above the neutral axis (NA) of the module. However, after the molding and PMC procedures, the package warpage reduces to $124 \mu\text{m}$ due to the addition of the lower CTE EMC on top of the IPM.

3. OPTIMIZATION

In this study, the IPM design required to minimize the warpage of the final IPM assembly was determined using the robust Taguchi analysis method. The Taguchi method applies factorial experimental designs, known as orthogonal arrays, to reduce the number of experiments required to optimize a process or design while still retaining statistically meaningful results [15].

As shown in Table 3, the experiments considered eight control factors, namely (A) the dam bar layout (straight or curved; see Fig. 10), (B) the EMC thickness, (C) the lead frame thickness, (D) the ceramic thickness, (E) the top layer Cu foil thickness, (F) the bottom layer Cu foil thickness, (G) the ceramic type and (H) the EMC type. Each control factor (other than factor A) was assigned three levels, where the underlined level settings shown in the table correspond to the values employed in the original IPM module design. Based on the number of control factors and level settings, the experiments were configured in an $L_{18}$ $(2^3 \times 3^7)$ orthogonal array, as shown in Table 4.

The aim of the Taguchi experiments was to determine the combination of control factor level settings that minimized the warpage ($\delta$) of the finished IPM module. Consequently, the quality of each experimental outcome in the orthogonal array was evaluated using the following larger-the-better signal-to-noise ($S/N$) ratio:

$$S/N = -10 \log \frac{\sum_{i=1}^{r} y_i^2}{r},$$

where $y_i$ is the $i$th measurement of $\delta$ and $r$ is the number of measurements. (Note that a numerical analysis does not generate data variations or experimental errors. Hence, $r = 1$ and $S/N = -10 \log \delta^2$.)

Figure 11 and Table 5 show the Taguchi analysis results, where the response for level $i$ of factor $j$ is defined as the average value of $\delta$ for factor $j$ at level $i$, and the effect denotes the difference between the maximum and minimum $S/N$ responses of the control factor at different levels. Observing Fig. 11, it is seen that the optimal package design that minimizes the out-of-plane deformation of the DPC substrate following the post-EMC process is as follows: (A2) curved dam bar layout; (B3) EMC thickness $5.5 \text{mm}$; (C1) lead frame thickness $0.3 \text{mm}$; (D1) ceramic thickness $0.5 \text{mm}$; (E3) top layer copper foil thickness $0.15 \text{mm}$; (F2) bottom layer copper foil thickness $0.1 \text{mm}$; (G3) ceramic type ZTA; and (H1) EMC type A. Furthermore, among all of the
control factors considered in the experimental design, the choice of EMC material (H) has the greatest effect on $\delta$, while the dam bar layout (A) and EMC thickness (B) have the second largest effect. In contrast, the lead frame thickness (C), ceramic thickness (D), and top layer copper foil thickness (E) have only minor effects.

Table 6 compares the absolute IPM warpage values obtained using the original package design and optimized package design, respectively. It is seen that the optimal package design reduces the warpage by around 36% compared to the original design. In other words, the effectiveness of the Taguchi design process in optimizing the IPM module warpage is confirmed.
Table 3. Control factors and levels (unit: mm).

| Factor | Description       | Level 1   | Level 2   | Level 3   |
|--------|-------------------|-----------|-----------|-----------|
| A      | Dam bar layout    | Straight  | Curved    |
| B      | EMC thickness     | 4.5       | 5.0       | 5.5       |
| C      | Lead frame thickness | 0.3       | 0.4       | 0.50      |
| D      | Ceramic thickness | 0.5       | 0.635     | 1         |
| E      | Top layer copper foil thickness | 0.0575   | 0.1       | 0.15      |
| F      | Bottom layer copper foil thickness | 0.0575   | 0.1       | 0.15      |
| G      | Ceramic type      | AlN       | Al₂O₃     | ZTA       |
| H      | EMC type          | A         | B         | C         |

Figure 10. Schematic illustration of lead frame dam bar layout: (a) straight design and (b) curved design.

Table 4. Taguchi experimental results.

| Experiment | Factors and levels | Absolute warpage (μm) | S/N   |
|------------|--------------------|-----------------------|-------|
|            | A      | B      | C      | D      | E      | F      | G      | H      |          |          |
| 1          | 1      | 1      | 1      | 1      | 1      | 1      | 1      | 1      | 267      | -48.53   |
| 2          | 1      | 1      | 1      | 1      | 2      | 2      | 2      | 2      | 2         | 372      | -51.41   |
| 3          | 1      | 1      | 1      | 3      | 3      | 3      | 3      | 3      | 3         | 303      | -49.65   |
| 4          | 1      | 1      | 2      | 1      | 1      | 2      | 3      | 3      | 3         | 270      | -48.63   |
| 5          | 1      | 2      | 2      | 1      | 2      | 3      | 3      | 1      | 2         | 245      | -47.78   |
| 6          | 1      | 2      | 1      | 2      | 1      | 3      | 3      | 2      | 2         | 350      | -50.88   |
| 7          | 1      | 3      | 1      | 2      | 1      | 3      | 2      | 3      | 3         | 257      | -48.20   |
| 8          | 1      | 3      | 2      | 2      | 1      | 3      | 2      | 3      | 1         | 220      | -46.83   |
| 9          | 1      | 3      | 2      | 1      | 3      | 2      | 1      | 3      | 1         | 212      | -49.88   |
| 10         | 2      | 1      | 1      | 3      | 3      | 2      | 2      | 1      | 2         | 202      | -46.10   |
| 11         | 2      | 1      | 2      | 1      | 3      | 3      | 3      | 2      | 2         | 292      | -49.31   |
| 12         | 2      | 1      | 3      | 2      | 2      | 1      | 1      | 3      | 3         | 282      | -49.00   |
| 13         | 2      | 2      | 1      | 2      | 3      | 1      | 3      | 3      | 2         | 269      | -48.61   |
| 14         | 2      | 2      | 2      | 3      | 1      | 2      | 1      | 3      | 3         | 255      | -48.14   |
| 15         | 2      | 2      | 3      | 1      | 2      | 3      | 2      | 1      | 2         | 212      | -46.54   |
| 16         | 2      | 3      | 1      | 3      | 2      | 3      | 1      | 2      | 2         | 274      | -48.75   |
| 17         | 2      | 3      | 2      | 1      | 3      | 1      | 2      | 3      | 3         | 211      | -46.50   |
| 18         | 2      | 3      | 3      | 2      | 1      | 2      | 3      | 3      | 1         | 169      | -44.56   |

S/N average: -48.29
4. CONCLUSIONS

This study has utilized a 3D computational model based on a “birth and death” modeling approach to investigate the warpage behavior of an IPM assembly during the packaging process. The validity of the FE model has been confirmed by comparing the simulation results for the out-of-plane deformation of the IPM assembly with the experimental measurements obtained using a 3D measurement system. Finally, the optimal design of the IPM assembly has been determined using the robust Taguchi design methodology. The simulation results support the following main conclusions:

1. The DPC substrate exhibits convex warpage initially. The substrate warpage changes to concave after the lead frame and components are mounted on the substrate due to the high equivalent CTE of the package above the NA of the module. However, the deformation of the package reduces following the PMC procedure due to the addition of the EMC (with low CTE) on top of the IPM.
2. The optimal package design (i.e. the design that minimizes the out-of-plane deformation of the IPM at room temperature) is as follows: (1) curved dam bar design; (2) EMC thickness of 5.5 mm; (3) lead frame thickness of 0.3 mm; (4) ceramic thickness of 0.5 mm; (5) top layer copper foil thickness of 0.15 mm; (6) bottom layer copper foil thickness of 0.1 mm; (7) ZTA ceramic material; and (8) EMC type A material.
3. Among the various control factors considered in the Taguchi analysis, the IPM warpage is determined mainly by the type and thickness of the EMC material [16]. In particular, an EMC material with a lower CTE (EMC A) reduces the CTE mismatch between the lead frame, IPM components and DPC substrate, while a thicker EMC layer increases the rigidity of the IPM package, and hence reduces the warpage. A higher CTE ceramic (ZTA, within the DPC substrate) increases the equivalent CTE of the substrate, and is thus also beneficial in reducing the warpage.
4. A curved dam bar design results in a lower warpage than a straight design since it acts as a spring in releasing the stress accumulated in the package through strain extension.
5. The top and bottom layer Cu foil thicknesses have no significant effect on the IPM module warpage. However, the bottom layer is full Cu foil, whereas the top layer has only a trace layout. Consequently, a thicker top layer Cu foil and thinner bottom layer Cu foil cause the symmetry of the
top and bottom Cu layers to converge, and therefore reduce the warpage of the DPC substrate.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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