WARPAGE AND WIRE SWEEP ANALYSIS OF QFN MOLDED ARRAY STRIP USING MODELING AND EXPERIMENTAL METHODS


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ABSTRACT

In this paper, both experimental and modeling works were resorted to analyze the warpage and wire sweep of QFN molded strip. The effect of QFN package size was investigated to provide the relation between warpage and metal to mold compound ratio. Design guideline for optimum metal to mold compound ratio has been obtained. Nonlinear large deformation of finite element analysis has been performed to investigate the effect of die size and mold compound material properties on the warpage and stress induced. Thermal loading was applied to simulate the cooling process after molding stage. For wire sweep analysis, full factorial design is performed by using three factors, i.e. transfer time, transfer force, and two types of mold compound. The detailed result was shown that the new mold compound induced lower die stress but slightly higher wire sweep than current material.

INTRODUCTION

The Quad Flat No-lead (QFN) technology produces a near chip size leadframe based molded package in a land grid array format. It is known as a small package, good production yield and high in thermal and electrical performance. However, due to large matrix of molded strip of these packages as illustrated in Fig. 1, the excessive warpage and over stress by thermal mismatch of different materials of package occur during manufacturing process. The package warpage is primarily from internal stress of the package that cooled from the molding temperature to the room temperature.

A large coefficient of thermal expansion (CTE) mismatch is associated will result in strength with the of interfacial shear and peeling stresses occur at near the free edges and corners, will act as stress concentration points. When the local stress level in the packages of these sites exceeds the bond strength of the interface, an interfacial crack will propagate [1]. Therefore, it is importance practically to be modeled stated of stress model through analytical equipment, so susceptibility to mechanical failure which predicted without trial and error of expensive test.

There are several factors that affect warpage, but underlying package geometries and molding compound properties are top among the causes. While a set of molding compound properties may produce very little warpage in one array package, they
may generate completely unacceptable warpage in another due to the variations in package geometries. In order to ensure the minimum warpage in these types of array packages, regardless of varying geometries, molding compound properties have to be adjusted and customized for each package. Because of the package geometry is generally predefined in the design process and rather cumbersome and costly to alter; modification of the materials properties of the package components is the only logical and cost-effective means of adjusting package warpage.

Figure 1: Crossbow warpage on QFN molded array strip.

EXPERIMENTAL METHOD

In this paper, both experimental and modeling were used for analyzing warpage and wire sweep on QFN molded strip. For experimental work, QFN package size 3 mm x 3 mm, 4 mm x 4 mm, 5 mm x 4 mm, 5 mm x 5 mm, and 7 mm x 7 mm in units sizes were used. This provides the relation between warpage and metal to mold compound ratio. The performance of the new epoxy molding compound (EMC) with low stress properties is compared against current production EMC in the wire sweep study. The materials properties of these two EMC are shown compared in Table 1. The new EMC has lower coefficient of thermal expansion (CTE).

Table 1: Comparison of properties of two EMC.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Old EMC</th>
<th>New EMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral flow</td>
<td>cm</td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td>Gel Time @ 175°C</td>
<td>sec</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>CTE 1</td>
<td>e-6/C</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>CTE 2</td>
<td>e-6/C</td>
<td>39</td>
<td>34</td>
</tr>
<tr>
<td>Tg</td>
<td>deg.C</td>
<td>140</td>
<td>135</td>
</tr>
<tr>
<td>Flex.modulus @ RT</td>
<td>N/mm²</td>
<td>28000</td>
<td>29000</td>
</tr>
<tr>
<td>Water absorption</td>
<td>%</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
<td>2.03</td>
<td>2.04</td>
</tr>
</tbody>
</table>

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Die with dimension of 2 mm x 2 mm and 5 mm x 5 mm in unit size were mounted onto the QFN molded array strip with two different EMC, as to study the effect of die size and EMC material properties. Non-linear large deformation finite element analysis (FEA) has been performed for more detailed observation. From the FEA, performed earlier [2], it was observed that EMC with low CTE induced shown lower die stress. For the wire sweep analysis, design of experiment (DOE) was performed using three factors, i.e. transfer time, transfer force, and two types of EMC.

Finite Element Model
Finite element method is a method of finding approximate mathematical solutions to physical problems. A good analysis and interpretation of results is required to know an acceptable approximation [3]. As the leadframe and EMC become thinner, the structure is more flexible and easy to deform. In this case, large deformation theory (nonlinearity geometrical) should be applied in FEA to get correct solution, in which the stiffness of matrix and load vectors may vary with the deformation process. For the large deformation of a thin plate with large area, buckling may happen during thermal loading, which can be characterized by geometrical nonlinear modeling.

In this paper, nonlinear large deformation FEA has been performed to investigate the impact of die size and mold compound material properties on the warpage and stress induced. Oota and Shigeno [4] had performed both experiment and FEA for Ball Grid Array (BGA) warpage analysis. The results showed that it was possible to reduce the warpage and die shear stress either by lower CTE or higher glass transition temperature, $T_g$, of EMC, with CTE has a more remarkable effect. The reduction of flexural modulus reduces shear stress applied to the chip, but has little effect in reducing warpage.

Design of Experiment (DOE) on Wire Sweep of QFN Package
Design of experiment (DOE) is an analytical tool of the traditional one-factor-at-a-time method because it is efficient, takes into account interactions among variables, and can eliminate all causes of variation except the one of interest. Based on statistic theories, DOE is a structured, which organized method for determining the relationship between factors and the output of a process.

The objective of this DOE is to evaluate the wire sweep in QFN package during molding process. This is focused on two-level factorial design, in which each input variable was varied at high and low levels [5]. This two-level design has three factors, i.e. two types of EMC, transfer force, and transfer time. The test vehicle and materials are same as those used in FEA. Fig. 2 shows the x-ray images of a QFN unit in the molded strip. Two wires were bonded diagonally so that maximum wire length can be obtained to study the wire sweep effect.
Warpage Measurement

Warpage measurements are attractive because the packages can be chosen at random from a batch and their warpage can be measured by using a laser profiler or by some other methods. The measurements are cost effective, nondestructive, and can be undertaken quickly. In this study, the warpage values were taken by using measuring microscope. This microscope offers versatility and high performance three-axis measurement of parts and electrical components, with very high precision.

Each strip has four blocks. The locations of warpage measurement were chosen at the four diagonal corners of each block as illustrated in Figure 3. The maximum value of vertical displacement difference between the central point and the four corner points is defined as the block warpage. The maximum warpage value of the four blocks is taken as the warpage of the molded strip.

RESULT AND DISCUSSION

Different package sizes have different unit density inside one leadframe strip. This will generate different metal to mold compound ratios after molding process. By having different volumes of mold compound filler in the molded strip, the strip warpage will not be the same due to the thermal mismatch among different components.

The effect of QFN package size is investigated having different mass values. The

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mass of bare leadframe strip ranged from 20.8 to 23.6 gram. The relation between strip warpage and leadframe mass is demonstrated in Figure 4. It can be seen from the line graph that as the mass increased, the molded strip warpage reduced. The strip warpage also depends on the CTE of the EMC, which will be explained further using FEA in this paper. Hence, design guideline for optimum metal to mold compound ratio can be obtained.

Figure 4: Warpage displacement variation with leadframe mass.

The unit package size is 7 mm x 7 mm with 48 leads. Due to the small CTE value of the EMC compared to the copper leadframe material, both die sizes showed “frowning face” (negative) strip warpage. Figure 5 compares the warpage for different die sizes and EMC. The graph shows that smaller die size and new EMC type induced higher magnitude of warpage. The new EMC has smaller CTE than current EMC used in production floor.

Figure 5: Warpage variation with die size and EMC.

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Four FEA models were constructed to study the effect of die size, i.e. molded strip with no die, single die (SD) size 2 mm x 2 mm (SD 2x2), single die (SD) size 5 mm x 5 mm (SD 5x5), and stacked die (DD) with 3 mm x 3 mm and 5 mm x 5 mm (DD3&5) die sizes. In this model, thermal loading is applied to simulate the cooling process after molding, i.e., from 175°C to 25°C. At molding temperature, the package is assumed to be stress free. The FEA warpage result of the molded strip at the room temperature for different CTE of EMC is shown in Figure 6. It was shown that the FEA warpage result has the same trend as in the experimental study. Larger die size has less “frowning face” warpage. When the CTE of EMC approached the CTE of leadframe, the molded strip warpage reduced.

![Figure 6: Warpage for different die size and EMC CTE.](image)

![Figure 7: Warpage contour of molded strip model SD 5x5.](image)

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The warpage direction was changed when the CTE of EMC exceeded the CTE of leadframe. There is no significant warpage change of stacked die package compared to single die model. The warpage contour plot of single die model SD 5x5 with EMC CTE 12 is depicted in Figure 7.

The die first principal stress for all the three models is shown in Figure 8. Principal stress theory provides satisfactory results for brittle material, which fails without yielding. From the FEA result, it can be seen that small die size (2 mm x 2 mm) in a relatively large package size (7 mm x 7 mm) caused highest die stress, followed by the model 5x5. Stacked die model with daughter die size 3 mm x 3 mm (DD x3x3) has lower die stress than the mother die (MD 5x5). This indicated that stacked die package could perform as robust as single die package.

![Figure 8: First principal stress at die component for three models.](image)

![Figure 9: Die stress contour for single die 2 mm x 2 mm.](image)
FEA result showed that lower CTE of EMC induced lower die stress. Therefore, EMC with low CTE should be used in order to obtain a more robust QFN package. Figure 9 show the contour of the single die at first principal stress on model SD 2x2 with EMC CTE. Since the highest stress is located at die internal portion rather than die edge, it has lower risk for die crack. The maximum stress value is also below the silicon die strength.

The die stress plot for mother die (MD 5x5) with EMC CTE 16 in the stacked die package is shown in Figure 10. The highest point is also located at the internal portion.

![Figure 10: Die stress plot for mother die 5 mm x 5 mm.](image)

### Table 2: Ten runs result of wire sweep analysis.

<table>
<thead>
<tr>
<th>Run #</th>
<th>EMC</th>
<th>$F$ (kgf)</th>
<th>$T$ (s)</th>
<th>WSweep(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Old</td>
<td>730</td>
<td>8</td>
<td>6.46</td>
</tr>
<tr>
<td>2</td>
<td>Old</td>
<td>730</td>
<td>12</td>
<td>6.64</td>
</tr>
<tr>
<td>3</td>
<td>Old</td>
<td>806</td>
<td>8</td>
<td>6.60</td>
</tr>
<tr>
<td>4</td>
<td>Old</td>
<td>806</td>
<td>12</td>
<td>6.77</td>
</tr>
<tr>
<td>5</td>
<td>New</td>
<td>730</td>
<td>8</td>
<td>7.49</td>
</tr>
<tr>
<td>6</td>
<td>New</td>
<td>730</td>
<td>12</td>
<td>7.53</td>
</tr>
<tr>
<td>7</td>
<td>New</td>
<td>806</td>
<td>8</td>
<td>7.18</td>
</tr>
<tr>
<td>8</td>
<td>New</td>
<td>806</td>
<td>12</td>
<td>7.16</td>
</tr>
<tr>
<td>9</td>
<td>Old</td>
<td>768</td>
<td>10</td>
<td>6.11</td>
</tr>
<tr>
<td>10</td>
<td>New</td>
<td>768</td>
<td>10</td>
<td>7.29</td>
</tr>
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</table>
Wire Sweep Analysis

Two-level design with three factors generates eight possible factor combinations. This full factorial design provides results that show effects free from confounding, that is, all effects are distinguishable from other effects. By having center point for the two numeric factors, result of the ten runs are recorded in Table 2, where the wire sweep percentage is chosen as the response characteristic.

Figure 11: Main effects plot for wiresweep response.

Figure 12: Interaction plot for response (wire sweep).

The main effects plot in Figure 11 shows that the wire sweep in the molded strip is influenced mostly by EMC type, but very little by the transfer force (xF) and
transfer time \((xT)\). When new EMC was used, the wire sweep increased. The interaction plot in Figure 12 shows the wire sweep was increased an interactive relation between EMC and transfer force. Shorter transfer time induced less wire sweep for old EMC. There is no interaction between transfer force and transfer time.

The x-axis in the Pareto chart (Figure 13) is the analysis result of effect. The larger the value, the greater is the influence on the response characteristics. The EMC type and the transfer force \((xF)\), and their interaction demonstrate the major influence on the analysis response.

![Figure 13: Pareto chart of the standardized effect.](image)

![Figure 14: Cube plot for wire sweep response.](image)
The conditions of optimum level from the cube plot (Figure 14) are old EMC, center point of transfer force and time. The minimum response wire sweep is 6.11%.

CONCLUSION

The warpage shape and severity is determined by package size, die size, and mold compound properties. From the QFN package size study, it can be observed that as the leadframe mass increased, the molded strip warpage reduced. By using nonlinear large deformation FEA and experimental work, it shows that larger die size has less “frowning face” warpage. When the CTE of EMC approached the CTE of copper leadframe, the molded strip warpage reduced. The warpage direction changed when the CTE of EMC exceeded the CTE of leadframe. Small die size in a relatively large package size caused highest die stress. There is no significant warpage change of stacked die package compared to single die model. Stacked die model has lower die stress compared to a single die model.

The DOE results show that wire sweep in the molded strip is influenced mostly by EMC type, but very little by the transfer force and transfer time. Shorter transfer time induced less wire sweep for old EMC. There is no interaction between transfer force and transfer time. The conditions of optimum level are old EMC, center point of transfer force and time. The minimum response wire sweep is 6.11%. Although new EMC has slightly higher wire sweep, FEA results show that EMC with lower CTE induced smaller die stress. Therefore, EMC with low CTE should be used in order to obtain a more robust QFN package.

REFERENCES


[3]. C.C. Ng, (2001); Approximations and Limitations of Finite Element Analysis in Electronic Packaging, International Conference on Advances in Packaging, Singapore, 202-209.


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