Effects of molding temperature on delamination of small outline transistor (SOT)

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Abstract. Delamination of small outline transistor (SOT) package has been a challenge to ensure good package reliability. Molding process parameter optimization is a practical & cost-effective alternative to reduce delamination of the plastic package. First, selective molding parameters, namely, molding temperature, transfer speed, transfer pressure & pre-heat temperature was varied in a full factorial experiment to determine the significance of each factor. It is observed from the complete factorial analysis that molding temperature was the most significant factor concerning delamination. Next, one factor at a time (OFAT) experimental design was conducted to confirm moulding temperature's repeatability. Molding temperature was identified as a significant factor on determining the delamination response of SOT packages. Lowering mold temperature resulting to lower percentage of delamination however proven to have an adverse on package curing density.

1 Introduction

Encapsulation is one of the vital processes in semiconductor packaging. Various factors such as delamination, poor adhesion between the epoxy molding compound (EMC) and the leadframe, mismatch between the material layers, can pose a serious threat to the reliability of electronic packaging [1-3]. Epoxy mold compound which is hygroscopic will absorb moisture will lead to serious defect such as electrochemical migration and popcorn effect [4-6]. Delamination is a failure mode that occurs as micro separation between interfaces of package, between EMC and leadframe substrate, die surface and wire. It is further exaggerated by the mismatch of Coefficient of Thermal Expansion (CTE) between packaging component [7]. The lack of adhesion will increase the probability of moisture and in worst condition electrolyte to ingresses toward the internal wire-die circuitry. High level of moisture would prove fatal and is one of the significant factors that would lead to bond-pad and metallic corrosion [8, 9].

Significant efforts have been made since 1970 to improve the reliability of plastic packaging devices, often driven by zero-delamination programs. Experts have analyzed packaging material, chip passivation, and production processes to find the correct recipe with minimal delamination [10]. However, one of the most researched and effective efforts for a zero-delamination package, the packaging material is often impractical as a quick solution and can be cost challenges. Process parameter optimization provides a fast alternative to reduce delamination for SOT plastic packaging, especially during molding. However, the DOE design of molding process parameter impact toward delamination is not a broad discipline [11].

The objective of this study is to determine the significant factor of molding process parameter toward the delamination of the small-outline transistor (SOT) package. In this paper, selective mold parameter such as mold temperature, transfer pressure, transfer speed and the pre-heat temperature has been plugged into an entire factorial DOE to determine the significant factors toward output response of delamination %. The critical factor was determined and repeated as one factor at time experiment (OFAT) to ensure repeatability. The parameter was then further optimized toward a minimal degree of delamination. As delamination was set as the primary indicator for this experiment, several other responses were selected as secondary indicators to understand the confounding effect of varying the significant factor, namely visual mechanical defects and curing density.

2 Methodology

Molding process key controllable parameters was a practical opportunity to improve delamination of plastic packaging devices, specifically during the mold filling and curing process. EMC selected for this experiment is a combination of OCN-Phenolic, which was kept constant across the experimental leg (figure 1). As shown in Table 1, a 2-level design with four factors is converted to sixteen experimental legs with one centre-point leg. Full factorial DOE was selected as its offer valuable insights, firstly the insights on the effects of interaction between factors itself & secondly insight between

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factors and output responses. The test vehicle selected for this entire factorial DOE was a typical small outline transistor (SOT) package conducted on the common reel-to-reel (RtR) process platform. The copper leadframe with the silver-plated post was die-bonded and wire-bonded. The first step during the molding process is to verify the chase's temperature via an external probe to ensure input variable accuracy. Next is the injecting of the hot melted EMC into the mold cavity. Heat in the cavity will accumulate in the first few injecting cycles until it cyclically stabilizes the temperature [12]. Therefore, any set-point of mold chase verification is through the external probe applied for both variables of curing & pre-heating temperature. Measurement of delamination is by C-Scan mode of Scanning Acoustic Tomography (SAT) machine Sonoscan D9000 with a 50-75 GHz frequency range. Delamination % is the interface between EMC and leadframe area for singulated units for both copper metal and silver post. Quantification of delamination percentage is by Sonoscan D9000s software. The result is input to the statistical software for factorial design analysis in figure 2.

![Molding Process Diagram](image)

**Fig. 1.** Full factorial experimental design, four selective input variables tested for molding key controllable parameters.

**Table 1.** Full factorial experimental design, four selective input variables tested for molding key controllable parameters slightly more complex table with a narrow caption

| Run Order | Molding Temperature (°C) | Transfer Speed (mm/s) | Transfer Pressure (Bar) | Pre-heat Temperature (°C) |
|-----------|--------------------------|-----------------------|-------------------------|--------------------------|
| 1         | +                        | 0                     | +                       | -                        |
| 2         | +                        | -                     | -                       | -                        |
| 3         | +                        | +                     | -                       | -                        |
| 4         | -                        | +                     | +                       | +                        |
| 5         | -                        | -                     | +                       | -                        |
| 6         | -                        | +                     | -                       | -                        |
| 7         | -                        | +                     | +                       | +                        |
| 8         | -                        | -                     | -                       | -                        |
| 9         | +                        | +                     | -                       | +                        |
| 10        | +                        | -                     | +                       | +                        |
| 11        | -                        | -                     | +                       | +                        |
| 12        | +                        | -                     | -                       | +                        |
| 13        | -                        | -                     | -                       | +                        |
| 14        | +                        | +                     | +                       | -                        |
| 15        | +                        | +                     | +                       | +                        |
| 16        | 0                        | 0                     | 0                       | 0                        |
| 17        | -                        | +                     | +                       | -                        |
Fig. 2. Quantifying delamination via SAT on EMC-leadframe interface.

3 Results and Discussion

Full factorial DOE identifies the critical input parameters for the molding process, which significantly impacts the singulated unit's delamination. Based on the average delamination percentage (%) analysed, table 2 shows a statistical model with a strong coefficient of determination $R^2 = 96\%$ representation of total variation. Furthermore, the P-value for molding temperature is $<0.05$, statistically concluding that molding temperature was exclusively the significant factor toward mean delamination percentage (table 3).

Table 2. Model Summary from full factorial DOE

| S     | R-sq     | R-sq (adj) | R-sq (pred) |
|-------|----------|------------|-------------|
| 0.0057517 | 96.96%   | 90.87%     | 68.83%      |

Table 3. Coded coefficients from full factorial DOE

| Term                        | Effect  | Coef  | SE Coef | T-value | P-value | VIF |
|-----------------------------|---------|-------|---------|---------|---------|-----|
| Constant                    | 0.01761 | 0.00144 | 12.25   | 0.000   |         |     |
| Curing Temp                 | 0.03360 | 0.01680 | 11.68   | 0.000   | 1.00    |     |
| Trans Pres                  | 0.00611 | -0.00305 | 0.00144 | -2.12   | 0.087   | 1.00|
| Tran Speed                  | 0.00504 | 0.00252 | 0.00144 | 1.75    | 0.140   | 1.00|
| Pre heat temp               | 0.00030 | -0.00015 | 0.00144 | -0.11   | 0.920   | 1.00|
| Curing Temp*Trans Pres      | 0.00683 | -0.00341 | 0.00144 | -2.37   | 0.064   | 1.00|
| Curing Speed                | 0.00431 | 0.00216 | 0.00144 | 1.50    | 0.194   | 1.00|
| Curing Temp*Pre heat temp   | 0.00193 | -0.00097 | 0.00144 | -0.67   | 0.532   | 1.00|
| Trans Pres*Tran Speed       | 0.00205 | 0.00102 | 0.00144 | 0.71    | 0.508   | 1.00|
| Trans Pres*Pre heat temp    | 0.00674 | 0.00337 | 0.00144 | 2.34    | 0.066   | 1.00|
| Tran Speed*Pre heat temp    | 0.00263 | 0.00131 | 0.00144 | 0.91    | 0.403   | 1.00|

Based on the statistical model, the Pareto chart of standardized effect for molding process parameters was plot as of figure 3. The factor bar in the Pareto chart that crosses the reference line is statistically significant. For example, only the 'A' bar representing the molding temperature by far crosses the reference line of 12.71, whereby the other factors did not. Figure 3 also sequence the factors in order of significance. It is observed that the mold curing temperature has strongest effect for mean delamination percentage. Thus, the combination of molding temperature and transfer pressure (A.B. in the chart) followed the molding temperature even the effects were not as high. The main effect plot shows every factor's relationship toward the response of delamination percentage as in figure 4. First, molding temperature, the most significant factor toward delamination percentage, reflected a steep linear line and directly correlated to the response. Next, transfer pressure
shows a slightly inclined linear line and, but the correlation is inverse toward the output response. Finally, the pre-heat temperature has minimal impact on the mean delamination percentage, and its correlation was insignificant.

**Fig. 3.** Pareto chart of standardized effect of molding process parameters.

**Fig. 4.** Main effect Plot for interaction between factors vs mean of delamination percentage.

The full factorial DOE (table 3) has high statistical confidence, indicating that mold temperature has the highest impact on delamination. Next, a confirmation DOE was conducted in the One Factor at Time (OFAT) experimental design as of figure 5. This DOE has two critical objectives. The first is confirming the response of mold curing temperature toward delamination, and the second is identifying the optimum process window of molding temperature for this SOT package. As the interaction between all four input variables has been identified through full factorial DOE in the prior stage, OFAT design provided a cost and time practical step in fulfilling the said objectives. As shown in table 4, OFAT DOE consisted of five experimental legs. It is designed to mirror the full factorial DOE experimental space but with 2-extra centre points. The run order 3 was the nominal value, Tm°C. The minimum molding temperature value, Tm-10°C and the maximum value, Tm+ 10°C, was like the last full factorial DOE of table 1.

**Fig. 5.** OFAT experiment design, molding temperature were varied while other was put as constant.
Procedurally, the experiment is like the full factorial experiment. In addition, output response observation extends beyond delamination, the visual inspection and curing density. Curing density measures the level of cross-linking completion of cured mold compound, usually via the Differential Scanning Calorimetry (DSC) technique. The typical visual mechanical defects are due to the different heating rates during the mold curing process of the SOT plastic package, which is bleeding, void and porosity [13]. The analysis of the impact of molding curing temperature on the delamination percentage is the variance (ANOVA) and Levene's equal variance test. For analysis of mean (figure 6), there was a statistical difference between group means as the P-value was <0.05. The Boxplot graph of mold curing temperature (figure 5) shows that molding temperature correlates with delamination. The highest setting of mold curing temperature at Tm+10°C suggested the delamination percentage can reach 19.6%. In contrast with the lowest Tm-10°C, the maximum delamination percentage is 3.3%. Therefore, the statistical conclusion is the reducing the mold curing temperature for a small outline transistor (SOT) package can significantly reduce delamination percentage.

Next, Levene's test of equal variance revealed that there are also differences between groups spread across the mold temperature, as P-value < 0.05 (figure 7). The interval plot shows that the lowest mold temperature, Tm -10°C have a significantly lower spread than the highest Tm +10°C, representing higher stability. Therefore, based on analysis of variance (ANOVA) and Levene's test of equal variance, it is suggested that setting a mold curing temperature to a lower side could yield a lower mean & improve the stability of SOT package delamination. The mold temperature regression to the delamination percentage is due to the resin's wettability [13]. Longer gel time would enable the resin to travel steadily with minimal expansion mismatch between resin, die and leadframe interface, thus reducing the probability of delamination.

**Table 4. Coded coefficients from full factorial DOE**

| Run Order | Molding temperature (°C) | Transfer speed (mm/s) | Transfer Pressure (Bar) | Pre-heat temperature (°C) |
|-----------|--------------------------|-----------------------|-------------------------|--------------------------|
| 1         | Tm + 10                  | Nominal               | Nominal                 | Nominal                  |
| 2         | Tm + 5                   | Nominal               | Nominal                 | Nominal                  |
| 3         | Tm                       | Nominal               | Nominal                 | Nominal                  |
| 4         | Tm - 5                   | Nominal               | Nominal                 | Nominal                  |
| 5         | Tm - 10                  | Nominal               | Nominal                 | Nominal                  |

**Fig. 6.** ANOVA delamination % distribution across mold curing temperature. 0+10°C as the highest level, 0-10°C as the lowest level and 0 as nominal point.
Visual inspection has been carried out to each leg to verify any visible mechanical defects such as void, incomplete fill & any plastic surface morphology change on the package finishing. Based on table 3 below, the observation is that reducing mold curing temperature will lead to higher visual failure, wherein the surface finishing of the plastic package became rougher, thus impairing unit marking. The highest mold temperature setting, $T_m+10^\circ C$ has 0 ppm failure, and when reduced to the nominal setting of $T_m$, the visual failure rate increased to 90 ppm. The lowest molding temperature $T_m -10^\circ C$ setting has the highest visible failure rate of 16010 ppm. Lowering the mold curing temperature will reduce the ability to release agents from migrating into the plastic surface during the curing process. From table 3, that curing density is directly proportional to molding temperature. The highest setting of molding temperature would give a curing density at 92%, while the lowest setting gives a curing density read-out at 84%. Thus, lower molding temperature would reduce the rate of cross-linking within EMC. Based on this experiment, the molding temperature of run-order 3 (figure A, set point 'Tm') was selected as an optimal parameter with a specific visual reject rate expected. The low curing density associated with this setting can be further improved by introducing the Post Mold Curing (PMC) process to intensify the cross-linking further.

| Run Order | Normalize mold temperature ($^\circ C$) | Visual mechanical defect | Curing density |
|-----------|----------------------------------------|--------------------------|----------------|
| 1         | $T_m + 10$                             | 0 ppm                    | 92%            |
| 2         | $T_m + 5$                              | 70 ppm                   | 90%            |
| 3         | $T_m$                                  | 90 ppm                   | 89%            |
| 4         | $T_m - 5$                              | 310 ppm                  | 86%            |
| 5         | $T_m - 10$                             | 16010 ppm                | 84%            |

4 Conclusion

The full factorial experiment has been conducted to screen four factors: molding temperature, transfer pressure, transfer speed, and pre-heating temperature toward response delamination percentage. The experiment revealed that molding temperature has the highest effect on SOT package delamination percentage and is directly correlated. In addition, one factor at a time (OFAT) experiment was conducted and confirmed the interaction of molding temperature concerning delamination percentage. Reducing molding temperature will reduce the mean & spread of delamination percentage of the SOT package. Therefore, an effective & practical effort to improve package delamination. However, reducing the molding temperature did not have a positive impact on visual mechanical & curing density. The lowest setting of mold...
temperature would result in 16010ppm of marking defect and lower curing density compared to the nominal and highest setting. Therefore, normalize mold temperature setting Tm was selected to obtain minimal & stable delamination but with a specific visual failure rate to be screened. As of lower curing density associated with normalized mold temperature setting, it is recommended to introduce the product into post-molding curing (PMC) heat treatment process to improve EMC cross-linking.

The authors would like to acknowledge the technical support provided by Nexperia Malaysia Sdn Bhd (grant number RR-2019-001) for research collaboration with Universiti Kebangsaan Malaysia.

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