THE ECONOMICS OF DIE ATTACH VOIDING IN LED ASSEMBLIES

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"You can't manage what you don't measure:

Each 1% increase in void area decreases the lifespan of an LED by up to 2,000 hours"

Abstract – Continuous improvements in high brightness light emitting diode (LED) technologies have opened up the possibility for utilization of these devices for general illumination. However, before LEDs can replace traditional lighting sources, improvements to their thermal management schemes, particularly the bonding technologies that hold the device components together, must be developed to ensure consistent color quality and competitive operational lifetimes. In this paper we trace a direct connection between the amount of die attach voiding and the lifetime of the LED.

I. INTRODUCTION

One of the largest obstacles to the widespread utilization of high brightness light emitting diodes (LED) for general illumination is thermal management. Localized heat generation is characteristic of the semiconductors utilized in these devices. For maximum lumen output, color consistency and device lifetime, this heat must be removed efficiently to allow the LED junction temperature (T_J) to remain stable. Maintaining a stable junction temperature over long periods of operation is the main goal of LED thermal management.

The rate at which an LED module will age is highly dependent on the temperature at the p-n junction and will accelerate over time. As a result, service life values are only valid provided that certain p-n junction temperatures (T_j) are not exceeded. Service life values are statistical values determined during test runs undertaken by LED manufacturers and do not reflect the precise behavior of individual LEDs.

The same applies to LED brightness values. The heat generated at the p-n junction impairs the efficiency of the light generation process and results in a measurable drop in brightness.

II. CASE STUDY

To better illustrate the economics of LED die attach voiding, we analyze a real life scenario. One of our customers is a large contract manufacturer new to the LED luminaires market. They offer two warranty options to their customers: a standard 38,000-hour warranty for free or an extended 50,000-hour warranty for extra cost. It is understood that a single LED failure results in a luminaire fail.

For this analysis we will assume the following pricing model:

- Price of a single luminaire: $100
- Price of 50,000-hour extended warranty: $20
- Production and distribution costs: $35
- Warranty cost: $5

The pricing model is based on the expectation that within the standard warranty period the company will receive up to 5% in returns, and up to 20% in returns within the extended warranty period.

This LED manufacturer wanted to better understand if the amount allocated to warranty costs was enough. As an entrant in the LED market they understand the sensitivity of price competitiveness. They can currently fabricate LED luminaires at a reasonable profit margin, but fear that these margins will be destroyed by return of product within warranty.

A. *Void Area and Operating Temperature*

To determine the operating temperature of an LED mounted onto a substrate, first we need to calculate the thermal resistance between the LED and the substrate. This thermal resistance, R, is given by:

$$R = \frac{x}{A_{CONTACT} * k}$$

where x is the thickness of the die attach, k is the thermal conductivity of the material, and $A_{CONTACT}$ is the total area of contact between the LED and the substrate. This area A is given by:

$$A = A_{CONTACT} + A_{VOID}$$

where A is the total area between the LED and the substrate, and A_{VOID} is the total voiding area with no thermal contact between the LED and the substrate. The temperature difference (ΔT) between the LED and the substrate can be calculated as:

$$\Delta T = \Phi * R$$

where Φ is the head flow measured in Watts. This relationship between the LED junction temperature (T_j) and the substrate temperature (T_s) can be better illustrated in Figure 1. Thus, the LED junction temperature is:

$$T_j = \Delta T + T_s$$

which shows that the temperature of operation of the LED is going to be higher than the substrate temperature by ΔT. This is a very important equation, because it allows us to determine the junction temperature as:

$$T_j = \Phi * \frac{x}{(A - A_{VOID}) * k} + T_s$$

This equation also shows us the critical impact that voids have in the operating temperature of LEDs. All parameters in this equation are constants, except the void area. The heat flow (Φ) is a function of the power being dissipated by the LED, which in turn is determined by the current and voltage applied onto the LED. The thickness (x) is fixed, as it is the total area between the LED and the substrate (A). The thermal conductivity of the material (k) is a constant. For this analysis we also consider the temperature of the substrate (T_s) to be a constant. This allows us to further simplify this equation as:

$$T_j \propto e^{A_{VOID}}$$

This relationship shows us the operating temperature (T_j) of the LED grows exponentially with the void area (A_{VOID}). For this reason it is critical to keep the voiding area to a minimum.

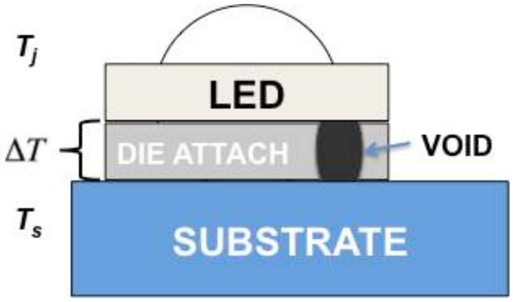

Figure 1 – Temperature distribution in the LED assembly, from substrate to junction

B. *100% X-Ray Inspection*

The first step in this research was to understand the quality parameters of the customer's production line. The need to set a benchmark is critical in this analysis so that we can understand what is working and what needs to be improved.

The key metric we measured was the void area between the LED die and the substrate. We selected void area as a key metric because it can

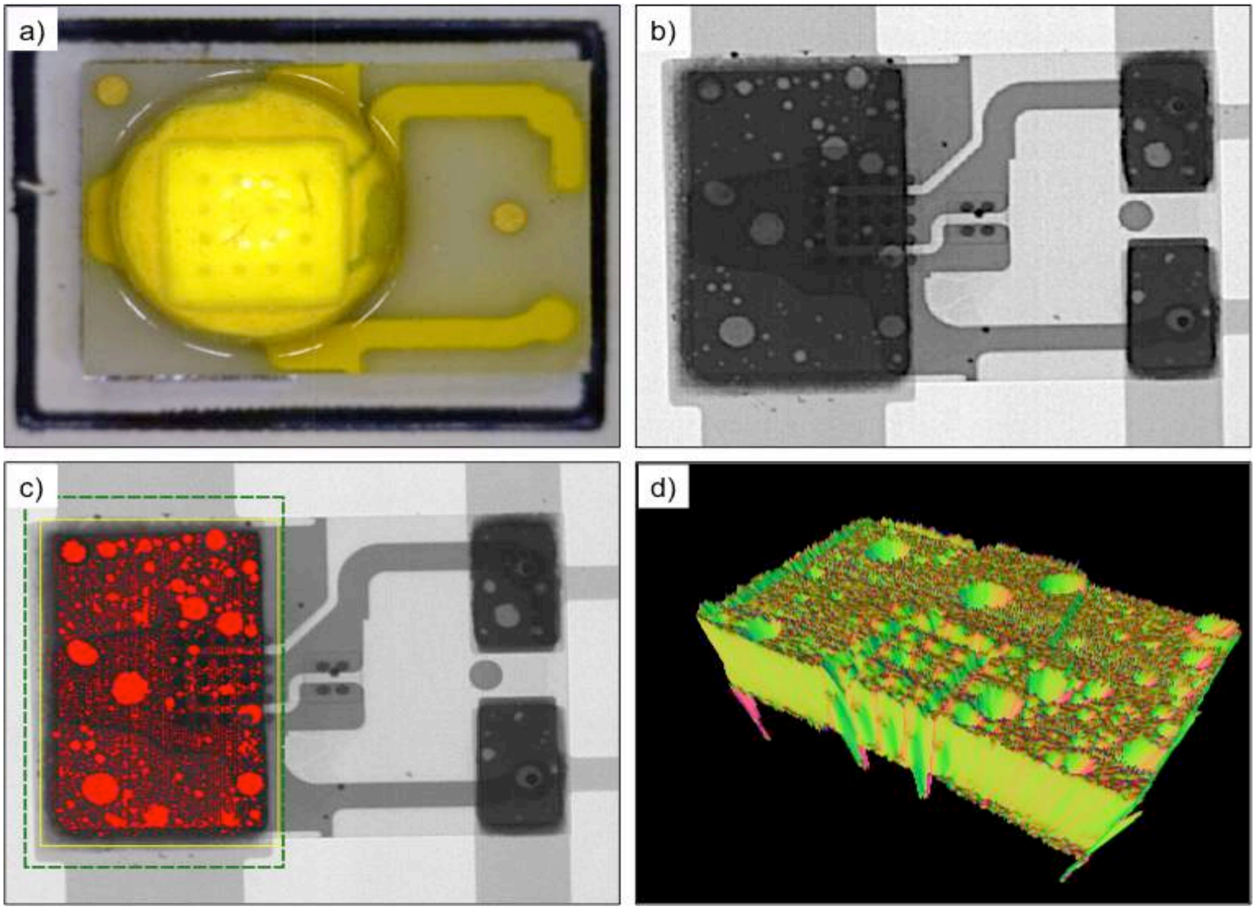

Figure 2 – a) Photo of LED assembled onto substrate, b) x-ray inspection image of LED, c) x-ray inspection image with identified and measured voids using TruView 5 software, d) 3D rendering of die attach voids

be measured in a non-destructive way by using an x-ray inspection system. Furthermore, the size and shape of void, combined with its location in the luminaire, provided us with important insight on the type of manufacturing issue we may be dealing with. For more details please see Process Control section in this paper.

Figure 2a shows a photograph of a single LED assembled onto a SinkPAD II^{TM} substrate. Figure 2b shows the x-ray image of the same LED, while Figure 2c shows the void detection measurement on the LED using the TruView 5 software. The image in Figure 2d is a 3D rendering of the die attach to better display the voiding area. The die attach voids can be clearly identified and measure in the x-ray images.

Further analysis was done to better visualize the negative impact voids have in the thermal conductivity of the die attach. Figure 3 shows the scanning electron microscopy image of a LED cross section. The dark areas in this image show the voids between the LED and the substrate.

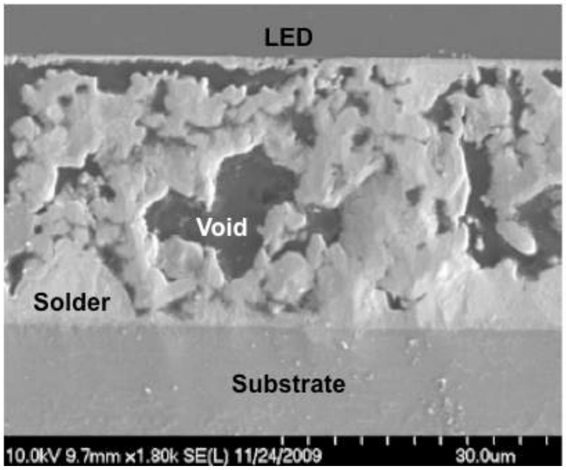

Figure 3 – Scanning electron microscopy of LED assembly showing thermal gap created by voids

As seen in Figure 3, the void acts as a thermal barrier. As a result, heat generated by the LED cannot easily reach the thermal sink (substrate).

The consequence of having a diminished thermal path is an increase in operating temperature.

C. *The Experiment*

For this analysis we inspected a total of 1,000 LEDs and measured the die attach voiding of each of these devices. To accomplish this task we utilized a TruView 200 X-Ray inspection system, as seen in Figure 4. This is an x-ray inspection system capable of collecting the data and processing the void measurements automatically. The automated process was paramount to the processing of the daunting task of inspecting 1,000 LEDs.

Figure 4 – TruView 200 x-ray inspection system used to measure the die attach voids in LEDs

With the results from this x-ray inspection we created the histogram in Figure 5 with the distribution of void area. The large number of devices inspected lead to a normal distribution with a mean void area of 49.7% and a standard deviation of 9.8.

We could have completed the analysis here, but we were interested in determining the real cost of voids. Is the distribution we found appropriate or not to our customer's pricing model? Are they charging enough for the extended warranty?

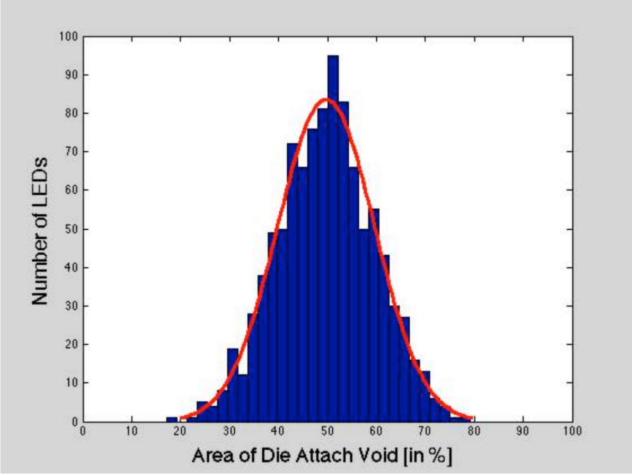

Figure 5 – Distribution of void area in a population of 1,000 LEDs assembled onto a thermal sink substrate

III. THE COST OF A VOID

Based on the results from the previous section, we can determine the real cost of the die attach void. The next step in this analysis is to use the LED manufacturer's data on the lifespan of the LED as a function of operating temperature. Although these are not deterministic numbers, they allow us to estimate how many of the sold luminaires will return from the field.

The relationship between the expected lifespan of the LED and the junction temperature is shown Figure 6.

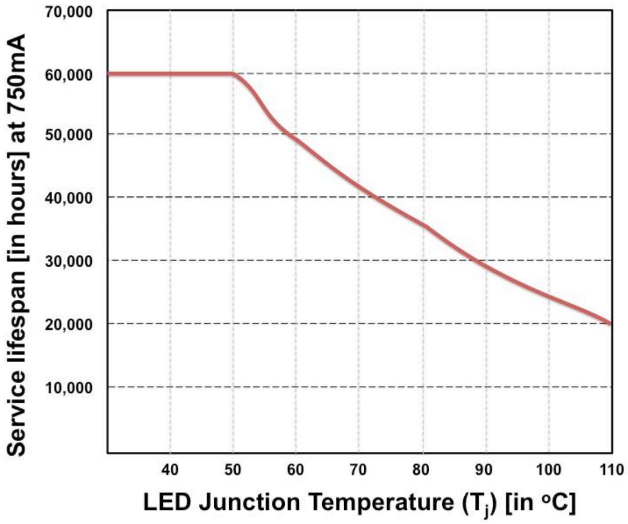

Figure 6 – Plot showing the relationship between junction temperature (T_j) and LED service lifespan

We measured a set of LEDs in operation and determined several points to relate void area and operating temperature. Based on this information we were able to relate the amount of voiding we measured to the expected junction temperature of the LED, as seen in Figure 7.

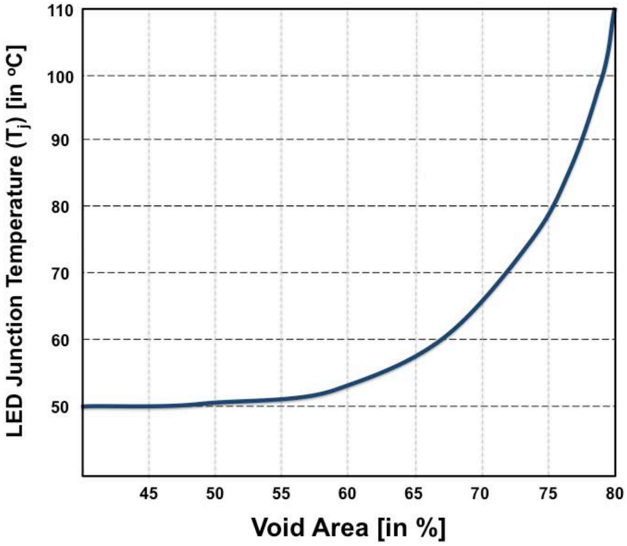

Figure 7 – Relationship between void area and LED junction temperature

By merging the previous measured relationship with the estimated lifespan data provided by the LED manufacturer, we were able to create the distribution shown in Figure 8.

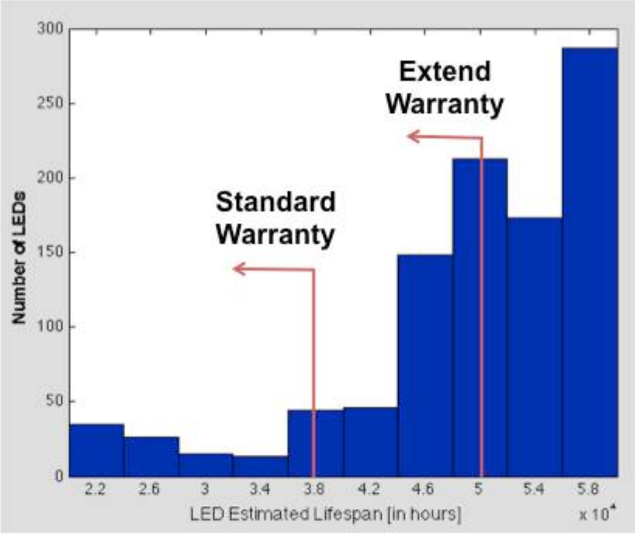

Figure 8– Distribution of LED population showing estimated lifespan

This data shows that out of the 1,000 LEDs inspected, 133 are expected to fail within the standard warranty period, while 540 are expected to fail within the extended warranty of the device. Since this product has been in the market for over a year, the customer was able to validate this data.

IV. PROCESS CONTROL

Tight control of the manufacturing process is paramount to the profitable success of an LED luminaire producer. In this analysis we worked with our customer with several aspects of manufacturing to improve yield and reduce voiding. Although not extensive, this is a partial list of activities covered in this engagement:

- Substrate surface cleanness
- Substrate and LED metallization
- Reflow oven temperature profile
- Paste selection, dispensing, and storage
- LED and substrate handling and storage

V. CONCLUSION

The results of this analysis showed that this customer far underestimated the expected cost of return products. Not only the pricing model utilized by the company had a deficit within the standard warranty; it had an even larger deficit within the extended warranty period. In consequence, the company had to temporarily change its pricing structure to compensate for product shipped with the deficient manufacturing process. Furthermore, a complete overhaul of the manufacturing process was done to bring it to tighter standards. The void area is now utilized as the key metric to measure process control quality. The TruView 200 X-Ray is used daily to measure the void of sample luminaires. Current data shows that the mean void area dropped to 35% with a standard deviation of 4.5. Thus, they were able to reduce the pricing for their luminaries. This reduction greatly increased their competitiveness in the market.

VI. REFERENCES

1. “Sintered Conductive Adhesives for HB-LED Thermal Management,” Creative Electron’s SBIR Program funded by the US Department of Energy.