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Power Modules: Typical Failure Modes and How to Solve Them

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Introduction to the Power Electronics and Power Module Market

Figure 1: Industrial applications for power electronics

Power electronics are present in our everyday lives in many applications. High-efficiency lighting, elevators, motor converters, solar energy, welding, industrial frequency converters, pumps, and a variety of other industrial applications that depend on power electronics.

In fact, power electronics is so predominant in our lives that the market is expected to grow to over $44 billion by 2025/2026. A subset of power electronics set to grow at a record pace is the power module market, specifically the IGBT power module market is expected to be around $10 billion by the same period.

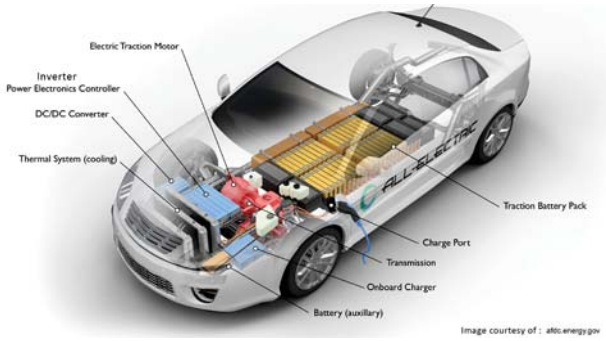


Figure 2: Automotive EV inverters are driving the power module market—image courtesy of afdc.energy.gov.

Power Modules have a nearly 30-year history since their first introduction to the market. Over the years, many enhancements to die technology, materials, and packaging have led to a broad acceptance of them in many end-use applications. Some of the original market drivers for power modules were energy savings, cost reduction, and improved end-user application performance. In addition to traditional market drivers, the electrification of cars (EV/HEV) is becoming a leading market driver for the power modules market and will continue for years to come. By 2030, there are expected to be over 50 million electrified vehicles on the road worldwide, with nearly half of the market made up of vehicles powered by 48 volts battery systems.

Provided growth drivers for the HEV/EV market remain in place, there are tremendous opportunities ahead for power modules. These include the infrastructure for EV battery charging, the on-board battery charging system in the EV/HEVs, the 48V battery system, and other auxiliary functions. All of these opportunities drive the power module market even more substantial. This growth should continue to be rapid, as evidenced by the investment into EV technologies in virtually every major car-producing nation and by the major automotive manufacturers.

Given the high safety requirements for vehicles in general, reliable power module construction is critical. One of the critical challenges faced in power modules is thermal management. Several semiconductor packaging variants were developed to address specific market/end-use application needs/requirements. Their design concepts were created by the thermo-electrical requirements, reliability, and power output requirements for each application.

Different Types of Power Modules

Frame-Based Package

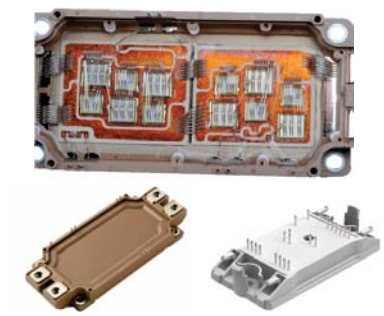


Figure 3: Typical frame-based power module packaging.

The most common power module type is the frame-based module (Figure 3), consisting of the base plate or water/air cooled base plate, the DBC or ABS substrate with the soldered or sintered dies (other components). Wire/ribbon bonding is the most common interconnect technology used to connect the dies to appropriate places on the substrate and the contact leads.

The module is enclosed in the plastic package. The cavity is filled with SilGel to protect the DBC substrate(s) and the dies from oxidation/contamination and Al/Copper wires/ribbons from oxidation and vibration. This packaging variant is also available without the base plate.

Intelligent Power Module Over-Molded Package

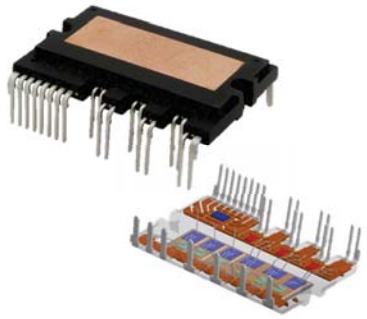


Figure 4: Typical intelligent power module (IPM) over-molded packaging.

The IPM module (Figure 4) consists of a copper leadframe that has contact leads soldered to the DBC substrate. The power dies are soldered to DBC and the Al wires are used to interconnect the dies to the appropriate contacts on the substrate. The package is over-molded, leaving the DBC substrate's backside exposed for contact with the heat sink.

Dual-Sided Cooling Over-Molded Package

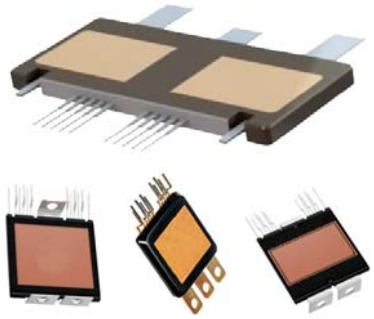


Figure 5: Typical dual sided cooling (DSC) over-molded packaging.

The Dual-Sided Cooling (DSC) package (Figure 5) has both sides exposed to the cooling surfaces, as the name indicates. The package consists of two DBC or AMB substrates where the power dies and the spacers are either soldered or sintered. The gate wires are wire bonded to the appropriate place on the substrates. The substrates are soldered together; creating a "sandwich" that connects the power dies to the spacers. The structure is over-molded such that the backsides of the DBCs are exposed to allow for contact with the heatsinks or heat exchangers.

Thermal Management within Power Modules – a Cause for Failure

The long-term reliability of the power modules has always been a concern since the beginning of the market development. Over the years, many enhancements have been made to the materials, die technology, and the overall packaging assembly technology to address power module long-term reliability. One of the key challenges, if not the main, is the thermal management of the power module. The power dies generate heat as they switch high currents. The construction of the power module is designed to remove heat from power dies as efficiently as possible. The key to the long-term reliability of the power modules is keeping the power dies at the lowest temperature during their operation.

The soldered interface between the power die and the substrate and the substrate to the base plate are the critical points for thermal conductivity to efficiently conduct heat from under the power dies. These interfaces are areas where material selection is extremely important. This is due to the heat transfer (heat resistance) and the respective Coefficient of Thermal Expansion (CTE). As the surfaces heat up, they expand. If the rate of expansion is different between the joined surfaces, the mechanical stresses will accumulate and after a number of thermal cycles, will eventually lead to the development of the fracture (crack) in the joining material (solder) and potential failure of the device/module. The described failure mechanism will accelerate if the soldering quality between the surfaces (die to DBC substrate or DBC substrate to base plate) is poor, i.e., excessive voiding. Figure 6 shows the CTE values of the typical materials used inside the power module.

Coefficient of Thermal Expansion	
Si	2.6 u/m/°C 20°C - 300°C
SiC	4 u/m/°C 20°C - 300°C
Al_2O_3	6.8 u/m/°C @ 20°C - 300°C
AlN	4.7 u/m/°C @ 20°C - 300°C
Copper	16.7 u/m/°C @ 20°C - 300°C

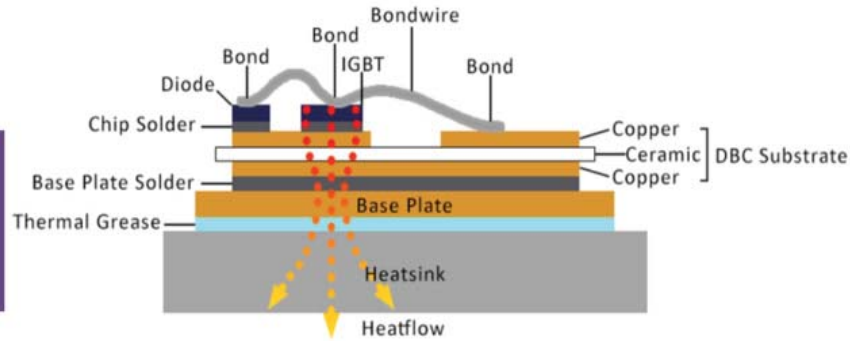


Figure 6: Coefficient of thermal expansion is critical to thermal management in power modules.

The presence of voids causes poor heat transfer and will be a conduit for crack propagation. As mentioned before, the careful selection of the materials for the assembly of the power modules has been the key to ensuring long-term reliability. Soldering alloy is one of these materials that plays a crucial role in mitigating the CTE mismatches between the Si or SiC dies and DBC/AlN substrates and the substrates and the base plates.

Thermal conductivity plays a vital role in keeping the power module cool. The effective heat transfer will directly depend on the thermal conductivity of each component inside the power module. By removing the heat from the inside of the power module, the relative expansion or contraction can be kept to the lowest level, which leads to lower mechanical stresses between the soldered surfaces. Figure 7 shows the specific thermal conductivity of the materials used in the power module.

Thermal Conductivity	
Si	148 W/mK @ 20°C
SiC	120 W/mK @ 20°C
Al_2O_3	24 W/mK @ 20°C
AlN	170 W/mK @ 20°C
Copper	231 W/mK @ 20°C

Figure 7: Specific thermal conductivity of the materials used in the power module.

During the power module operation, the stack of materials, such as Si, Copper, Ceramic, will experience thermal stresses due to differences in Coefficient of Thermal Expansion (CTE) between them. After a finite number of temperature cycles, such stresses will lead to solder fatigue and cracking between soldered materials. This, in turn, leads to the increased temperature in the power module, which results in diminished performance and possible power module failure.

The photos in Figure 8 show the typical solder cracking along the soldered interface between the DBC substrate and the base plate. The image on the right shows how the cracking is developing as the power module is exposed to a number of thermal cycles. The cracking typically starts developing from the outside and propagates inward.
As the solder cracking develops, the thermal conductivity becomes worse. As a result, the temperature inside the power module becomes higher. This leads to excessive bond surface relative movement due to CTE mismatch between the wire bonded surfaces.

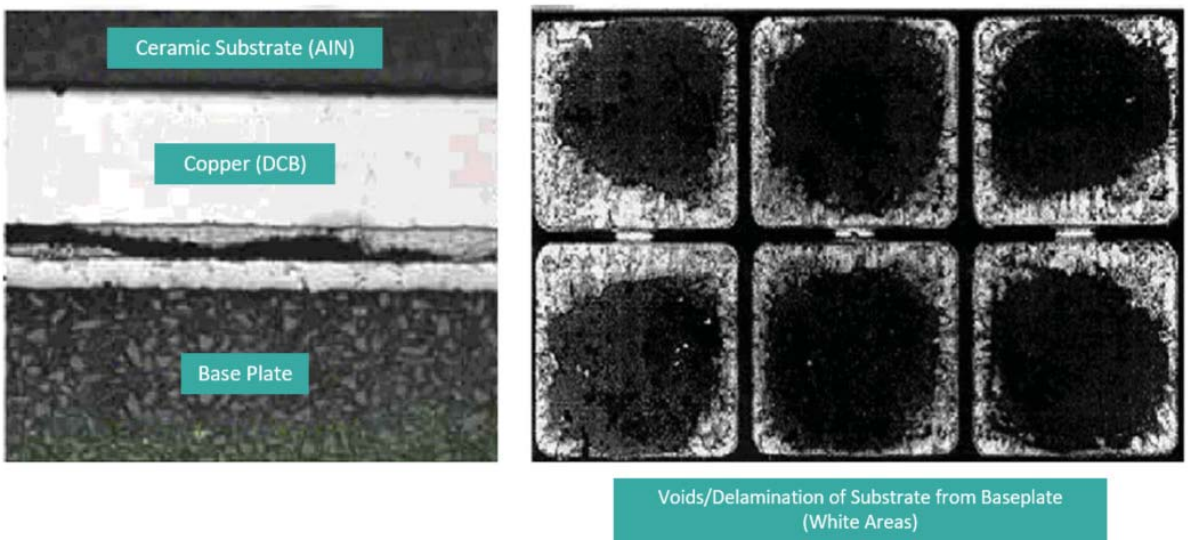


Figure 8: Solder cracking along the soldered interface between the DBC and baseplate.

Case Study: Reducing Power Module Failures with Low Void Solutions on Large Substrates

The following case study was performed to demonstrate the low void soldering process between for typical soldering surfaces inside the power module, where a large size DBC substrate was soldered with preform to Ni plated base plate. By achieving low void soldering results, it is possible to achieve a larger number of thermal cycles, thus extend the life span of the power module.

A study of the soldering process was conducted as part of the SST 8300 Series Automated Vacuum Pressure Soldering System capability demonstration. To demonstrate the low void soldering results, a base plate (Copper with Ni sulfamate plating), with both SAC 305 and Sn95Sb5 solder alloys preforms and a DBC substrate, were used. See the Figure 9.

The study consisted of the following materials:

- Base plate: Copper with Ni sulfamate plating, Concave shape, dimensions 105 x 45 mm.
- Preforms: SAC305 and Sn95Sb5, both 33 x 63 mm, 200 microns thick.
- DBC substrate: (Cu/Al2O3/Cu), 34 x 64 mm.

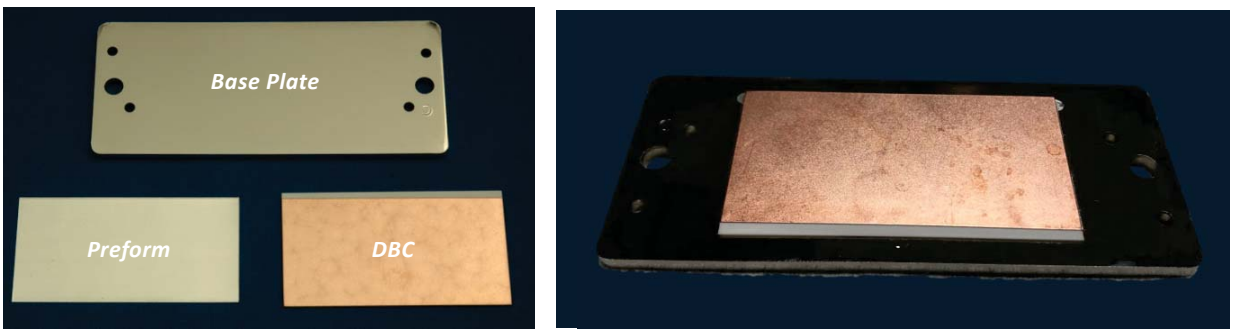


Figure 9: Base plate DBC preform (on the left) and completed sample (on the right)

For this evaluation, graphite tooling (Figure 10) was developed to locate the DBC substrate over the Ni plated base plate. Weights were used to apply force on the substrate to ensure good contact with the preform. Five tooling sets were placed inside the 8301 chamber, one in each corner and one in the chamber's center. The intent was to demonstrate the chamber's temperature uniformity and the soldering results repeatability in various parts of the chamber.

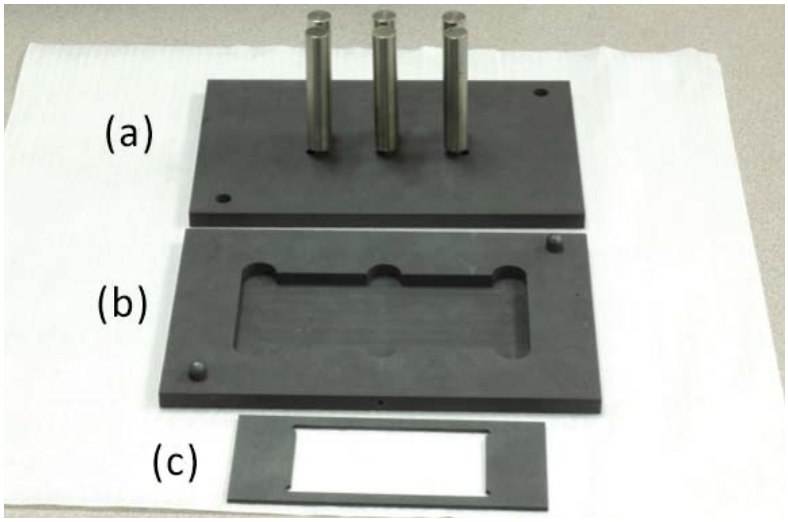
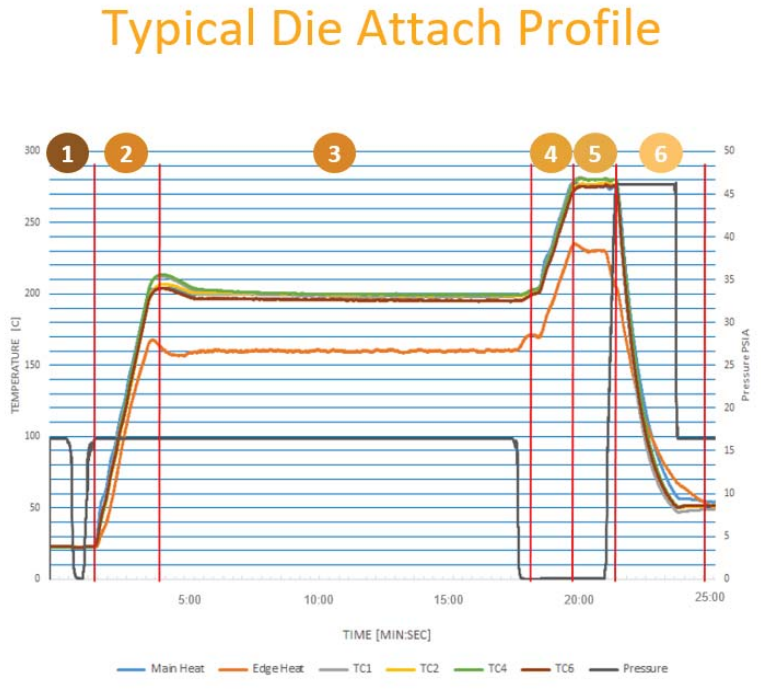


Figure 10: (a) Graphite top plate with free-floating weights, (b) graphite boat to locate the base plate and (c) graphite insert to locate the preform and DBC substrate.

The solder alloy's mechanical properties and thickness play a significant role in absorbing the relative motion between the two joined surfaces during the thermal cycles. The ability to achieve low void soldering results using the wide range of solder alloys without flux is one of the critical requirements for modern vacuum reflow ovens.

The SST 8300 utilizes a unique combination of vacuum and gas pressure above atmospheric, to reduce voids close to 1%. This method is ideally suited for large surface areas, such as DBC to base plate soldering.

The chamber within the 8300 utilizes edge-heating elements to enable the chamber to achieve temperature uniformity over the entire thermal process area with a guaranteed temperature uniformity +/-2%.



Note:
Four monitoring thermocouples were inserted into the tooling fixtures located in the corners of the chamber. The profile shows how well the actual temperature tracks the programmed temperature and the temperature uniformity.

Figure 11: Typical die attach profile from the SST 8300 automated vacuum soldering system.

A typical die attach profile (Figure 11) for the 8300 consists of 6 different phases taking the package from a vacuum purge, introduction of Formic Acid, through reflow and eventually cooling, which collapses any voids in the solder.

1 – Vacuum Purge: During the first stage of the soldering, surfaces are cleaned from the surface contaminants and surface oxides. At the same time, oxygen is removed from the chamber by vacuum purge(s). Vacuum purges are accomplished by vacuum being pulled and then by quick chamber pressurization to atmospheric pressure. At the end of the stage, the dislodged contaminants are evacuated with vacuum via the exhaust.

2 – Ramp up to Pre-Bake/Formic Acid Surface Cleaning: The temperature is ramped up to about 200ºC.

3 – Pre-Bake/Formic Acid Surface Cleaning: As the temperature reaches 200ºC, the process of "pre-bake" or removal of moisture from the soldering surfaces, tooling/fixtures, and the chamber begins. At the same time, Formic Acid fumes are introduced with Nitrogen as a carrier gas. This is a necessary step when the flux-less soldering process is used. The concentration (ratio of the Formic Acid fumes vs. N2) can be adjusted based on the soldering surface. In the case study, a 6% concentration was used.

As an oxide cleaning solution, the use of Formic Acid is most effective with solder alloys whose melting temperatures are below 300ºC. For the solder alloy with melting temperatures above 300ºC, Forming Gas is commonly used. It is a premixed gas with 5%H2 and 95%N2. During this stage, the exhaust is open. All the moisture and the components resulting from the chemical reaction between the Formic Acid and the surface oxides are safely removed from the chamber. At the end of this stage, the exhaust is closed. The chamber's pressure quickly changes from the atmospheric pressure to a vacuum level of about 5 torr. It is a critical point of the soldering profile. This is called pressure level P1.

4 – Ramp to Reflow: The temperature is rapidly increased to reflow temperature level.

5 – Reflow: At the Reflow stage, the temperature remains at the reflow level, typically for a few minutes, to ensure the solder's flow on the soldering surfaces. At the end of the reflow stage, the gas (N2) pressure quickly increases, as high as 3-3.5 ATM. This is called pressure level P2. The pressure differential between P1 and P2 is the key to the void reduction technique used in all SST reflow ovens. The larger the pressure differential, the smaller the volume of voids is expected in the soldered interface.

6 – Void Collapsing and Cool Down: As the Nitrogen is introduced into the chamber with high pressure, it applies a uniform pressure to the soldered joints, causing the remaining voids to be squeezed out or collapsed. Simultaneously, the solder interface begins to cool down and solidifies in a low void state.

The Cooling stage continues to cool down the contents of the chamber. Either Nitrogen cooling and/or QuikCool™ cooling can be utilized to achieve the desired cool down rate.

Results of Case Study:

Once the reflow process was complete, the void ratio for the solder was checked with the X-Ray inspection. To make the examination easier, the backside of the base plate was milled-out. The typical X-Ray inspection photos for assemblies soldered with both SAC305 solder preform (Figure 12) and Sn95Sb5 (Figure 13) showed void levels near 1%.

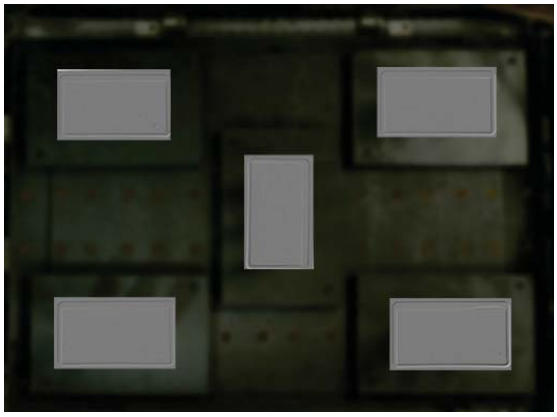


Figure 12: X-Ray inspection of SAC305 solder-preform showed less than 1% void.

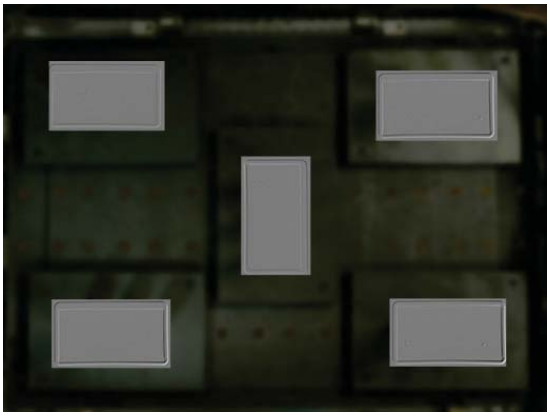


Figure 13: X-Ray inspection of Sn95Sb5 solder alloy show less than 1% void.

SAC 305 Profile Details

- Profile length – 25 minutes
- Formic Acid applied with 6% concentration
- Formic Acid cleaning process- 5min
- Melting temp. set at 260°C

Sn95Sb5 Profile Details

- Profile length – 25 minutes
- Formic Acid applied with 6% concentration
- Formic Acid cleaning process- 5min
- Melting temp. set at 275°C

Avg	1.00	0.84
Std. Dev	0.57	0.61

Sample #	SAC305	Sn95Sb5
1	1.5	1
2	2.39	0.52
3	1.24	2.63
4	0.5	0.87
5	0.13	0.63
6	1.25	0.27
7	1.58	0.32
8	0.67	0.47
9	0.65	0.6
1	0.49	0.8
11	0.47	1.1
12	1.26	0.2
13	0.79	1
14	1.17	1.5
15	0.93	0.7
Avg	1.00	0.84
Std. Dev	0.57	0.61

Figure 14: Profile details and results for 15 samples clearly shows less than 1% void for soldering large DBC substrate to NI plated base plates.

Conclusion:

Typical failures in IGBT power modules are often the result of CTE mismatches, which cause thermo-mechanical stresses that lead to solder fatigue and constitutes itself in the form of cracking or delamination. The overheating occurs in the areas of poor heat transfer (cracks/delaminations), which leads to faster crack propagation. The surface overheating also leads to wire/ribbon bond lifts or heel cracks.

With this case study, it has been demonstrated that using the above method of vacuum reflow utilized in an SST 8300 Series Automated Vacuum Soldering System, it is possible to achieve a very low void soldering result (around 1% on average) while soldering a large DBC substrate to Ni plated base plate with SAC 305 or Sn95Sb5 preforms. The low void rate mitigates the likelihood of solder fatigue and overheating, reducing failure rates and increasing IGBT power module reliability.

REFERENCES

[i] Compiled estimate from various sources.

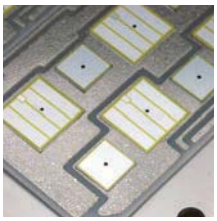
[ii] Compiled estimate from various sources.

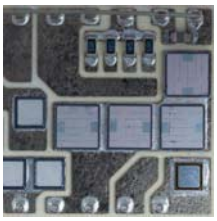
[iii] *Van-Nhat Lea, Lahouari Benaboua, , Quang-Bang Taoa, Victor Etgens – Modeling of intergranular thermal fatigue cracking of a lead-free solder joint in a power electronic module. International Journal of Solids and Structures, 106-107 (2017)*

SST 8303

AUTOMATED 3-CHAMBER VACUUM PRESSURE SOLDERING SYSTEM

The SST 8303 Automated Vacuum Pressure Soldering System is setting new industry standards for flux-less soldering by providing highly reliable and reproducible solder interfaces with industry leading void rates.





QUIKCOOL™
QuikCool™ is an auxiliary cooling unit designed to rapidly reduce the temperature of the target plate to enable a faster production process. The entire process takes place in one chamber to reduce handling and increase speed of production.

AUTOMATION ROBOT
A Cartesian gantry automation robot efficiently moves part carriers from conveyors to/from the chamber.

CHAMBER WITH EDGE HEAT
Unique edge heating elements enable the chamber to achieve temperature uniformity over the entire thermal process area.

USER-FRIENDLY SOFTWARE
User-friendly windows-based software makes it easier for operators to use the machine and makes it easier for programmers to efficiently develop profiles and perform real-time process analysis.

- **High Accuracy and Precision**
  A Cartesian gantry system automatically shuttles part carriers in/out of each chamber, performing each movement with high accuracy and precision.

- **Graphite Heating Element**
  Precise temperature control; no warping; absorbs thermal shock

- **Temp. Up to 500°C**
  Wide range of solder alloys & other interconnect materials

- **Formic Acid System**
  Reduces metal oxide layer for fluxless, low-void soldering

- **Positive Gas Pressure in Chamber**
  Effective means to collapse solder voids over larger surface area

- **Maximum Flexibility**
  Can operate as a stand-alone unit or integrated into an automated production line. SMEMA compliant.

- **Single Chamber Process**
  Minimizes maintenance and lowers cost of ownership

- **Remote Maintenance**
  Remote support for the equipment through LAN connection

- **Traceability**
  Equipment stores all profile runs and logs system events

SELECTED 8303 OPTIONS

- Formic Acid
- Flux Trap
- Moisture Analyzer
- Oxygen Analyzer
- Up to 6 Monitoring Thermocouples per chamber
- Water Chiller/recirculator
- Dry Vacuum Pump
- Mid-Vac < 10^{-5} Torr (1.33 x 10-5 mBar)

TYPICAL APPLICATIONS

- IGBT Modules
- GaAs/GaN/SiC Die Attach
- High Intensity LED Attach
- CPV Solar Cell Assembly
- Copper Clip Soldering
- Hermetic Sealing of Hi-Rel Packages
- Power Module Assembly
- Die Attach for Pressure Sensors
- Multilayer Ceramic Capacitors
- High Power Laser Module Assembly
- Hermetic Sealing of IR Image Sensors

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Making the connected world possible by delivering a Total Process Solution™ for advanced photonic and microelectronic device assembly processes utilized in today's smart, connected devices. With a focus on flexibility, speed, and accuracy, Palomar's Total Process Solution includes die bonders, wire and wedge bonders, vacuum reflow systems, along with Innovation Centers for outsourced manufacturing and assembly, and Customer Support services, that together deliver improved production quality and yield, reduced assembly times, and rapid ROI.

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