INDIUM CORPORATION
TECHNICAL PAPER

Advancements in Formic Acid Soldering Materials Technology for Power Device Packaging

Authored by: Dean Payne, Joseph Hertline, Lily Bai, and Ryan Mayberry, Indium Corporation.

Abstract

For high-power devices, the performance of interconnect materials within the packaging is critical to achieve efficiency and longevity. Formic acid soldering is a proven and scalable technique to achieve ultra-low voiding, optimal RDS-on, and thermal performance for active devices and interconnects within power modules [1, 2]. For this effort, a novel flux-free solder paste technology is evaluated for application in power discrete components and power modules with die-attach, interconnect, and component soldering. Empirical data is captured to characterize solder voiding performance and demonstrate the scarcity of residue under industry-common reflow scenarios, as measured through TGA and surface analysis.

Introduction

Thanks to the enhanced capabilities seen in reflow soldering equipment in recent years, fluxless reflow soldering utilizing formic acid (HCOOH) together with vacuum has become a prevalent technique for power electronics packaging. This is especially true for power module assembly, where this technique may be employed for die-attach, die top interconnects, and substrate-to-base plate soldering. Up to this point, the solder used in this application is presented as solid preforms of the selected alloy. Typical solder paste, which is approximately 50% flux by volume, is not employed for this process due to the inevitability of post-reflow flux residues. Given that cleaning of these assemblies after reflow is challenging or not possible, and the associated risks of electromigration and encapsulant compatibility directly impact the potential for early device failures, fluxless is the technique of choice. A novel approach to fluxless soldering with formic acid and vacuum is the utilization of a fluxless solder paste. The flux vehicle associated with traditional solder paste is replaced by a binder system that fully decomposes during the reflow process at a temperature below the liquidus temperature of the alloy. Virtually zero residue remains after reflow and no cleaning is required. As is the case with the preform process, the ultra-low level of voiding achievable due to the vacuum and the elimination of volatile flux components minimizes the thermal and electrical resistance within the system, ensuring optimum efficiency [3]. No post-reflow residue means that no cleaning is required, plus there are no concerns regarding the compatibility of subsequent process steps such as wire-bonding, encapsulation, or over-molding. Both preform solder and fluxless paste may be utilized on a single device, providing increased flexibility to the assembly process.

DEAN PAYNE

Dean Payne is a product manager (semiconductor). Responsible for driving profitable growth of our power semiconductor materials, which include high-Pb die-attach paste, high-temperature Pb-free solutions, and sintering materials; collaborating with internal departments, including sales, technical service, R&D, production, and quality; providing support for all Semiconductor and Advanced Assembly Materials. Dean is based at Indium Corporation's Asia-Pacific Operations in Singapore.

Dean has more than 13 years of experience in the semiconductor/wafer fabrication. He holds multiple certifications from the University of Wales and Coleg Gwent in the United Kingdom, including the Level 3 National Vocational Qualification in electrical and electronic engineering, the Higher National Certificate in electrical and electronic engineering, and the Higher National Diploma in engineering.

email: dpayne@indium.com
Full biography: www.indium.com/corporate/team

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Formic Acid for Oxide Reduction

One of the primary functions of flux during reflow soldering is the removal of metal oxides from the surfaces of both the solder medium (preform or powder) and the parts being bonded. The oxides need to be removed in order to allow a metallurgical bond to form when the molten solder reacts with the bonding surface, by means of an intermetallic compound (IMC). In a fluxless process, the oxide reduction function is carried out by gases or gas vapours within the reflow oven or chamber. Such gases employed as reducing agents include hydrogen (H_2) and formic acid (HCOOH). One of the clear benefits of formic acid over hydrogen or forming gas, a mixture of hydrogen and nitrogen, is the temperature at which the gas “activates” and starts the oxide reduction process. Formic acid is most effective at scavenging surface oxides when at a temperature between 180–250°C. In comparison, hydrogen becomes effective at reducing metal oxides when above 250°C, which is above the liquidus temperature of many commonly used solder alloys. In the case of forming gas, that effective temperature is increased further.

Table 1.

Reducing Agent	Effective T Range	Oxide Suitability
Formic Acid HCOOH	180–250°C	CuO, Sn_2O_3, NiO, Sb_2O_3
Forming Gas 5% H_2 in N_2	>300°C	CuO, Sn_2O_3, NiO
Hydrogen 100% H_2	>250°C	CuO, Sn_2O_3, NiO, Sb_2O_3

Looking at the formic acid oxide reduction mechanism in fluxless reflow soldering;

- Formic acid molecules come in direct contact with surface oxides
- Thermal energy from the reflow profile helps to activate and decompose the formic acid to reactive species (CO and/or H_2)
- Electrons donated from the reactive species to the metal oxides reduce the metal ion
- Byproducts CO_2 and H_2O are removed, resulting in oxide-free metal

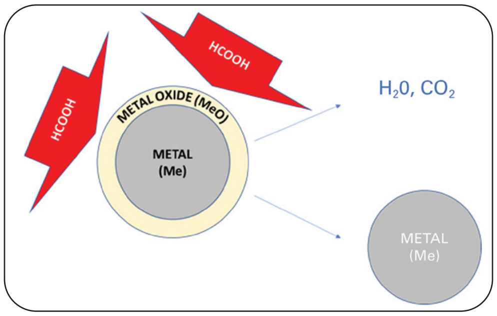

Figure 1. Formic acid metal oxide reduction.

Fluxless Soldering with Preform Solder

In power module assembly, fluxless soldering with formic acid has become mainstream. Preform solder can be used in multiple locations within the assembly stack-up, such as substrate-to-baseplate attach, die-to-substrate attach, and also clip-to-die top attach, and shown in the schematic below for a basic power module device.

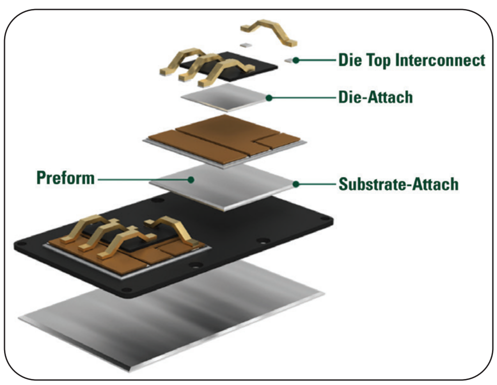

Figure 2. Traditional power module construction.

They may even be used to attach other components within the modules, such as NTCs/thermistors. Preform solder is solid and dry and offers no holding force to the parts in the assembly. For this reason, when adopting a fluxless soldering process, fixtures are commonly utilized to hold assemblies together. These fixtures can cause additional complications and process time. They also add additional thermal

JOSEPH HERTLINE

Joseph Hertline is the Product Manager for Engineered Solder Materials, focusing on power electronics applications. He is responsible for driving the growth of the power electronics product line through development and implementation of marketing strategies supported by customer experience, emerging technologies, and industry feedback. Hertline also collaborates with Indium Corporation’s sales, technical support, R&D, production, and quality teams to serve existing customers and grow new business in his designated market.

Hertline earned a bachelor’s degree in mechanical engineering and an MBA from Clarkson University in Potsdam, N.Y. He is a Certified SMT Process Engineer (CSMTPE).

email: **jhertline@indium.com**
Full biography: **www.indium.com/corporate/team**

mass, so more energy is necessary in the reflow process. By utilizing a tacking agent during reflow, it is possible to remove the fixtures from the assembly, making the process faster and less complicated. A solution of solvents that provides the necessary tack force to keep assembly parts together in the reflow process, and then evaporate during reflow, leaving no observable residue, is a proven alternative to fixtures. The cleanliness of this process has been confirmed via elemental analysis of surfaces reflowed with and without the tacking agent applied, and no difference is observed.

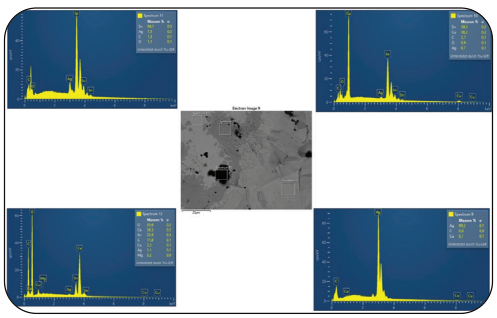

Figure 3. EDX results comparing with and without tack agent.

This development became the catalyst for fluxless paste development.

Fluxless Solder Paste Development

With conventional solder pastes used in conventional reflow processes, the flux vehicle plays a crucial role in removing surface oxides and enhancing the wetting capability of the solder. There are various key ingredient types that perform specific functions, and the following are some of the common component types:

Rosins or resins – can account for up to 50% of the flux vehicle (by weight) in RO/RE classified solder pastes. They perform multiple functions, from optimizing the paste consistency, protecting the solder powder from oxidation, and encapsulating volatile remnants post-reflow.

Solvents – various different solvents are included in flux vehicle formulations. Intentionally having different boiling points and evaporation temperatures, the solvent system is removed from the paste gradually during the thermal profile. Solvents also ensure the paste's working life.

Activators – added for the purpose of oxide reduction, typical examples are organic acids or halogens/halides. Activation occurs at elevated temperatures, starting the reaction and removal of metal surface oxides.

Thixotropic agents – these serve the function of controlling paste rheology, viscosity, and thixotropic behaviour, directly impacting paste workability when stencil printing or dispensing.

Others – certain flux formulations may include other additives like surfactants, wetting agents, and corrosion inhibitors.

In comparison, a fluxless paste developed for formic acid soldering would see the rosins, activators, and other additives with a more complex solvent system. Some thixotropic agents remain to give the paste the rheology required for dispensing and printing applications. By utilizing a binder system made up almost entirely of a complex solvent system, the capability to remove surface oxides is also removed, hence the need for reflow to be performed under reductive atmospheres like formic acid. Also removed are the constituent parts associated with post-reflow flux residues, so virtually no residue is present post-reflow.

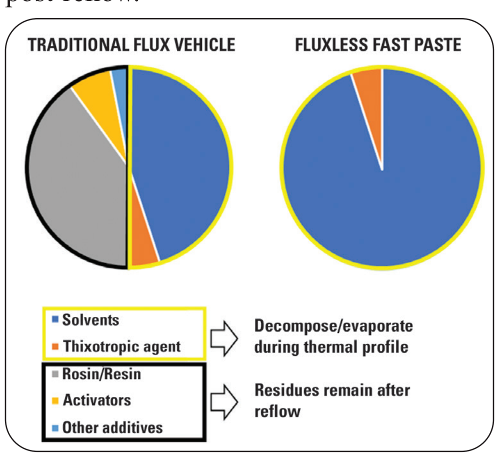

Figure 4. Comparison of flux and fluxless binder.

LILY BAI

Lily Bai is responsible for leading the lab team in Suzhou, China, and performing applied activities in and out of a lab environment. Her focus generally, but not exclusively, is on flux solutions for the PCB assembly and semiconductor assembly markets. She has extensive experience in material design, selection, and processing. She also collaborates with sales, PM, production, and quality teams to promote new materials to customers.

Lily holds a master's degree in organic chemistry from Soochow University.

email: lbai@indium.com
Full biography: www.indium.com/corporate/team

The evaporation of the flux/binder components during a thermal profile can be measured by thermogravimetric analysis (TGA). TGA is a technique to measure the change in mass of a material as a function of temperature and/or time under a controlled atmosphere. The fluxless binder system was compared against a traditional rosin-based flux vehicle and an organic acid-based ultra-low-residue flux vehicle via TGA, and the results were recorded.

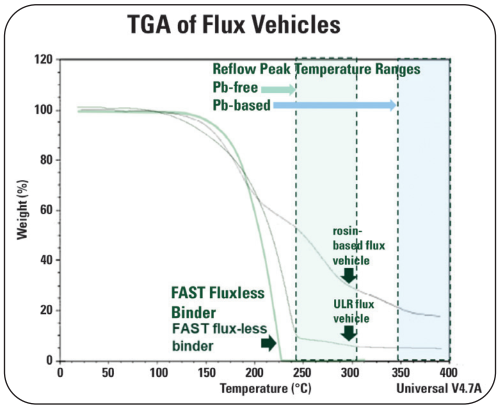

Figure 5. TGA comparison.

The fluxless binder system for formic acid reflow had 100% loss of mass when exposed to temperatures above 250°C, typical peak temperatures for Pb-free solder reflow process.

Alloy Selection

Based on the application, different alloys may be selected for fluxless soldering. In large power module assembly, Pb-free alloys are most commonly selected. For discrete power devices and small SMD power modules, high-Pb solder is still the most common choice. For Sn-based Pb-free alloys, the melting temperatures for the commonly used alloys range from ~220°C to more than 240°C, meaning reflow peak temperatures can be as high as 280°C. For high-Pb solders, melting temperatures are around 300°C based on the alloy composition. Reflow peak temperature for high-Pb solder is commonly in excess of 350°C. Due to the huge difference in process windows, fluxless paste formulations were made with both Pb-free alloys and Pb-based alloys and screened for suitability using representative process conditions for the applicable application. Tests for suitability include:

i. Open wetting test with judgment on wetting performance, observed satellites or solder-balls, and observed residue
ii. Component or die-attach
iii. Voiding

Results for Pb-Free, 132 Series FAST Paste

Twelve different binder formulations were included for the initial screening. An open wetting test was conducted using the PiNK Vadu100 vacuum reflow system with formic acid. To ensure the reflow is performed under low-O_2 atmosphere, all air is first evacuated from the chamber by vacuum and the chamber purged with N_2. There are two formic acid steps, one during soaking and one during the ramp-to-peak temperature, and both are followed by vacuum evacuation of the chamber. Finally, the chamber is flooded with N_2 for the cool-down step.

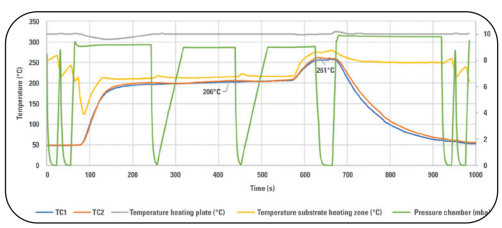

Figure 6. Formic acid reflow profile.

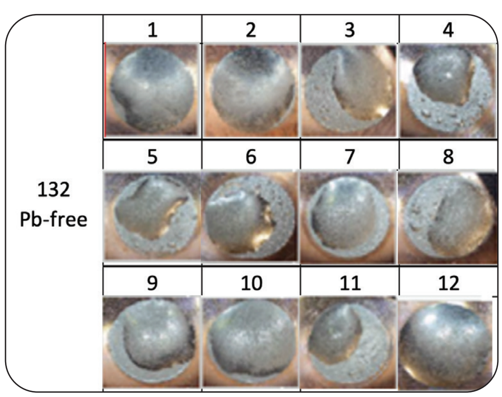

Figure 7. Pb-free paste open wetting.

RYAN MAYBERRY

Ryan Mayberry is responsible for generating test strategies, data sets, and application guidelines for the Engineered Solder Materials (ESM) product line. He collaborates with the Sales, R&D, Operations, and Quality departments as a subject matter expert to enable key pursuits in the growing power electronics and thermal market segments by developing process recommendations and supporting new product qualifications for a successful customer experience.

Ryan earned his bachelor's degree in Materials Science and Engineering from Rutgers University in New Brunswick, NJ. He is a Certified SMT Process Engineer (CSMTPE) and a Six Sigma Green Belt.

email: rmayberry@indium.com
Full biography: www.indium.com/corporate/team

Formulations 2 and 12 were down-selected for further evaluations. Following the open wetting evaluation, a representative sub-assembly was created to simulate a component soldering scenario commonly used in power module systems, such as with thermistor temperature sensors. In this phase of the evaluation, the pass criteria included the degree of edge fillet on the ends of the component, as well as prevention of tombstoning. Both formulations presented good solderability results, desirable fillet formation, and no observations of tombstone defects. With two formulations down-selected based on the initial reflow trials, the suitability for both stencil printing and needle dispensing was confirmed by evaluation. Metal loads were optimized for the different paste delivery methods, and the optimal process parameter settings were determined. Both pastes exhibited very similar behaviour; paste volume was very consistent, with no significant changes in transfer volumes seen when tested after 10 hours of continuous printing vs. freshly applied paste. Also, no significant change was seen in transfer volume when freshly applied paste was compared against paste that had been staged on the stencil for 1 hour, showing good response-to-pause characteristics. Both formulations were able to dispense entire syringes without clogging or skipping dispenses, both for single-needle and multi-needle dispense heads. With workability confirmed for formulations 2 and 12, trials could begin with customers and industry partners. A 10 x 10mm Si IGBT can be successfully soldered onto a ceramic AMB substrate for power module assembly. No cleaning was necessary post-reflow, and the voiding measured by X-ray was on average around 1%.

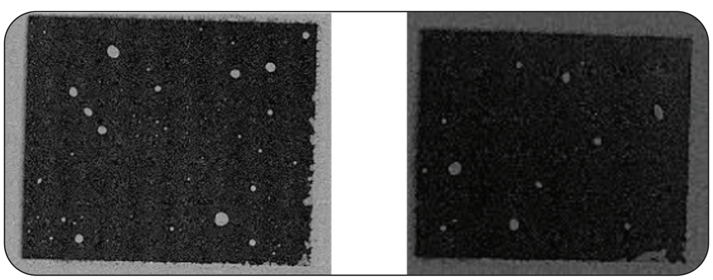

Figure 8. Pb-free fluxless paste voiding.

Results for Pb-Based, 124 Series FAST Paste

As with the Pb-free paste development, multiple formulations of binder with high-Pb solder were screened for suitability in the initial development stage. For high-Pb paste, the target application is die-attach for discrete power semiconductor devices and clip-attach in power devices. Internal screening tests were carried out using an HVT vacuum reflow oven with formic acid.

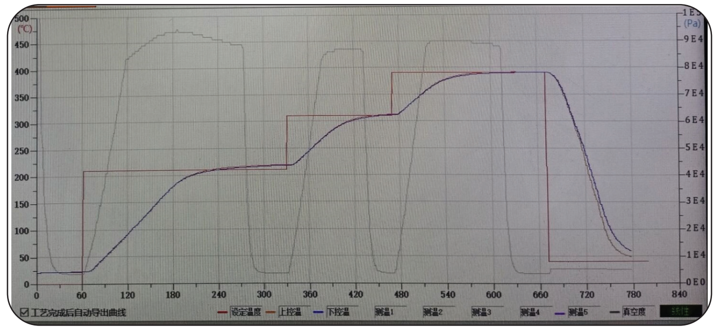

Figure 9. Formic acid reflow profile.

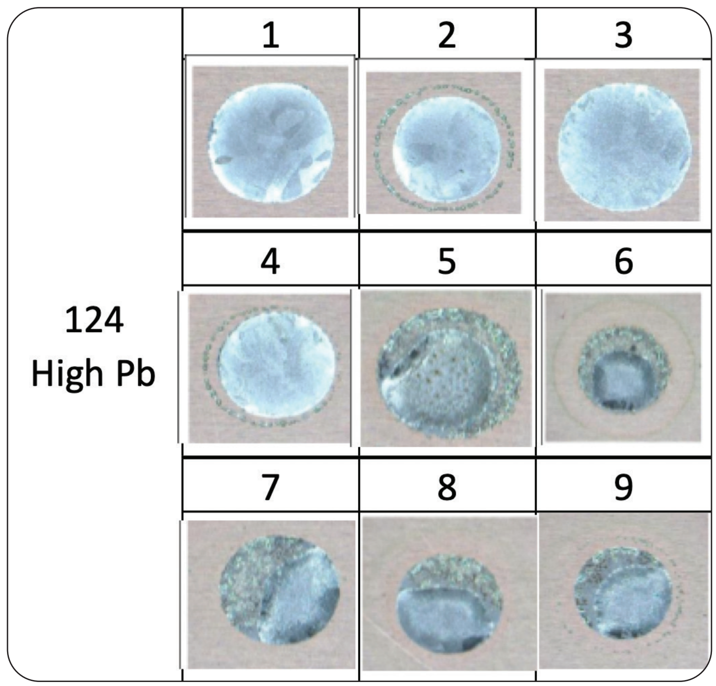

Figure 10. High-Pb paste open wetting.

Formulation 3 was selected for subsequent testing. Open wetting was carried out on paste deposits that had been dispensed and paste that had been stencil printed with both 5 x 5mm and 10 x 10mm apertures. Good wetting and edge definition were observed. Voiding results after die-attach were measured to be below 2% voids on average.

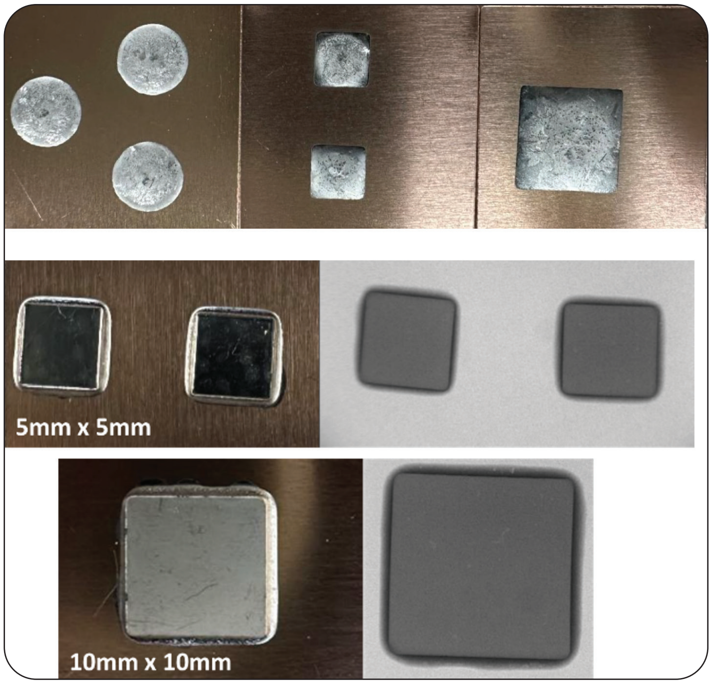

Figure 11. Formulation #3 reflow results.

Die shear, a commonly used technique to determine the quality of the die-attach process, was carried out to compare the bond strength of the FAST fluxless solder paste with formic acid reflow vs. typical values expected from standard high-Pb solder with conventional reflow process. Die shear was carried out both at time zero (post-reflow) and also after both 500 cycles and 1,000 cycles of thermal cycling between -65°C and 150°C. Typical die shear values for high-Pb solder are between 20–40MPa, depending on other factors such as surface finish, process conditions, etc., and this was the case for the fluxless paste reflowed with formic acid. The average die shear strength at time zero was 31.7MPa, after 500 cycles the average was 28MPa, and after 1,000 cycles the average was 28.3MPa. This showed that the die shear strength for fluxless paste reflowed with formic acid was comparable to traditional solder paste with conventional reflow for the same alloy system.

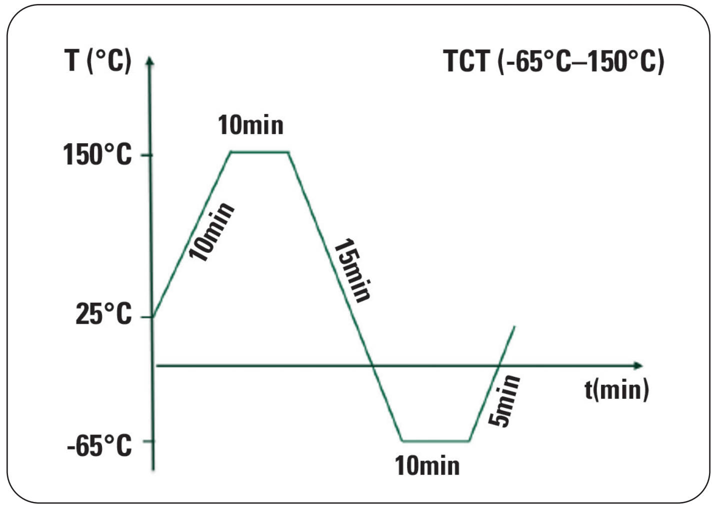

Figure 12. Thermal cycling profile.

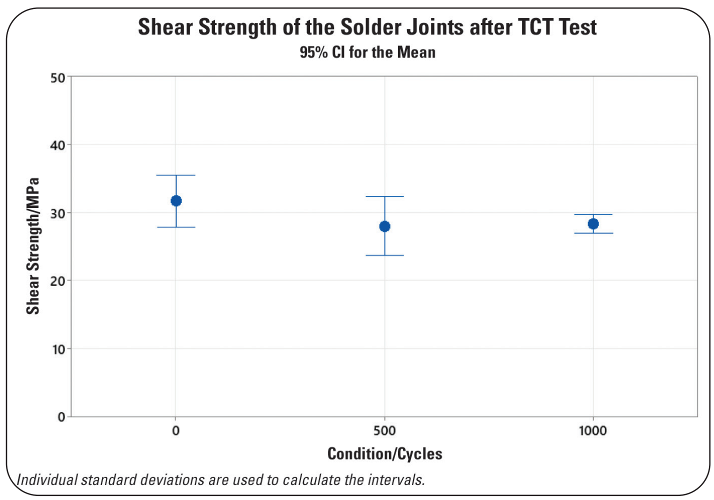

Figure 13. Die shear results.

Conclusions and Further Work

Soldering with formic acid vs. soldering with a flux for power electronics assembly is a process already adopted and with numerous benefits. Elimination of the post-reflow flux residues means that no cleaning step is required post-reflow. This shortens overall process times, reduces cost for the user, and is also more beneficial to the environment due to the removal of cleaning chemical waste disposal. Whilst preform solder either with fixtures or with a tacking agent is the mainstream today, new developments in fluxless solder paste technology offer more choice and flexibility when it comes to material and process choices going forward. Fluxless solder can be used in conjunction with preform solder in complex assemblies, such as the power modules shown in the following figure.

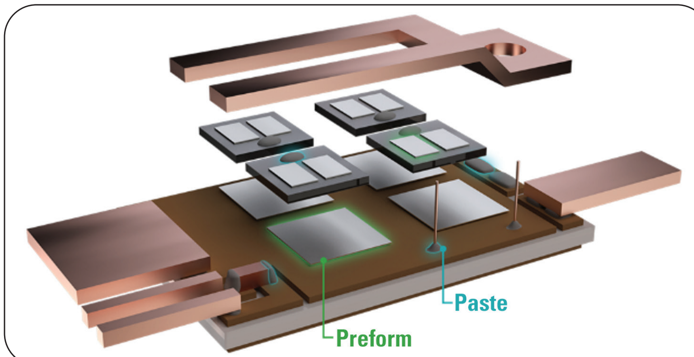

Figure 14. Example assembly utilizing both preforms and paste.

Alternatively, it can be used independently for applications like die- and clip-attach for power discrete packages as illustrated in the schematic below.

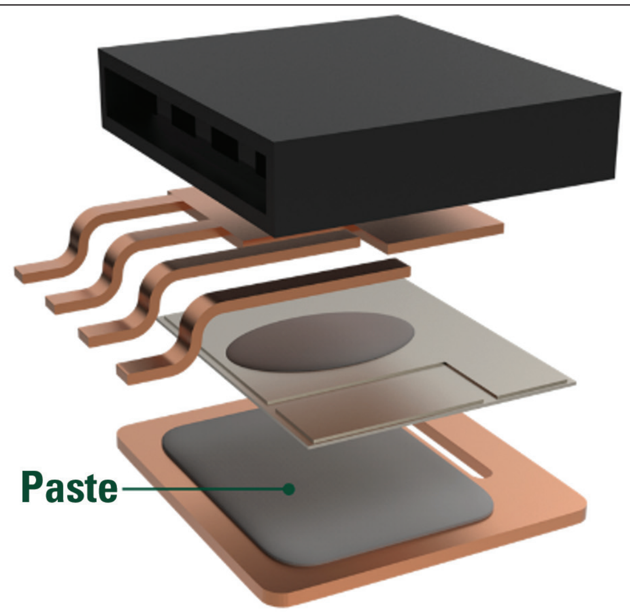

Figure 15. Discrete package example.

With the feasibility proven, the workability assured, and with qualifications ongoing, fluxless solder paste is set to become a key addition to the portfolio of materials developed for Fluxless Assembly Soldering Technologies (FAST). Post-reflow ionic assessment of the fluxless solder paste is still a work in progress and will be reported in subsequent updates to this work. For the device functionality and reliability data, work is ongoing with the end users of the solder paste as the qualifications progress.

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