Let’s gear up for our electric journey into the sky

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Abstract

Companies need to adapt when a market is evolving [1]. Henkel has understood the demand of the Urban Air Mobility market and is focusing on this future segment. The product portfolio consists of structural adhesives for the fuselage and a wide variety of extensively tested materials for all electronic applications. The following abstract discusses the needs and trends of the UAM market and how the products from Henkel for PCB applications are supporting these requirements.

1 Introduction

Companies need to adapt when a market is evolving [1]. Looking at the Aerospace market, which is a traditional field of Henkel, a new segment is built: the Urban Air Mobility (UAM) segment [2]. Forecasts predict a huge growth potential and billions of market size by 2050 [2].

Henkel has a history of expertise in Aerospace, Space and Defense segments with its structural adhesives and coatings. Engineers and technicians have developed and qualified Henkel products on over 5000 Aerospace Original Equipment Manufacturers (OEM) specifications over the last years. This includes a broad product range from structural materials like film or paste, composite materials and Maintenance Repair Overhaul (MRO) solutions. Henkel has a lot of experience in printed and general electronics, electronically conductive adhesives (ECA) and Thermal interface materials (TIM) which are also needed in the drone segment.

Looking into leveraging of adjacent industries Henkel has expertise in the e-mobility side of automotive. A lot of questions and challenges have been investigated and resolved resulting in usage of this knowledge and product innovation in applications like batteries for electrical vertical take-off and landing vehicles (eVTOL).

Materials supporting development of eVTOLs

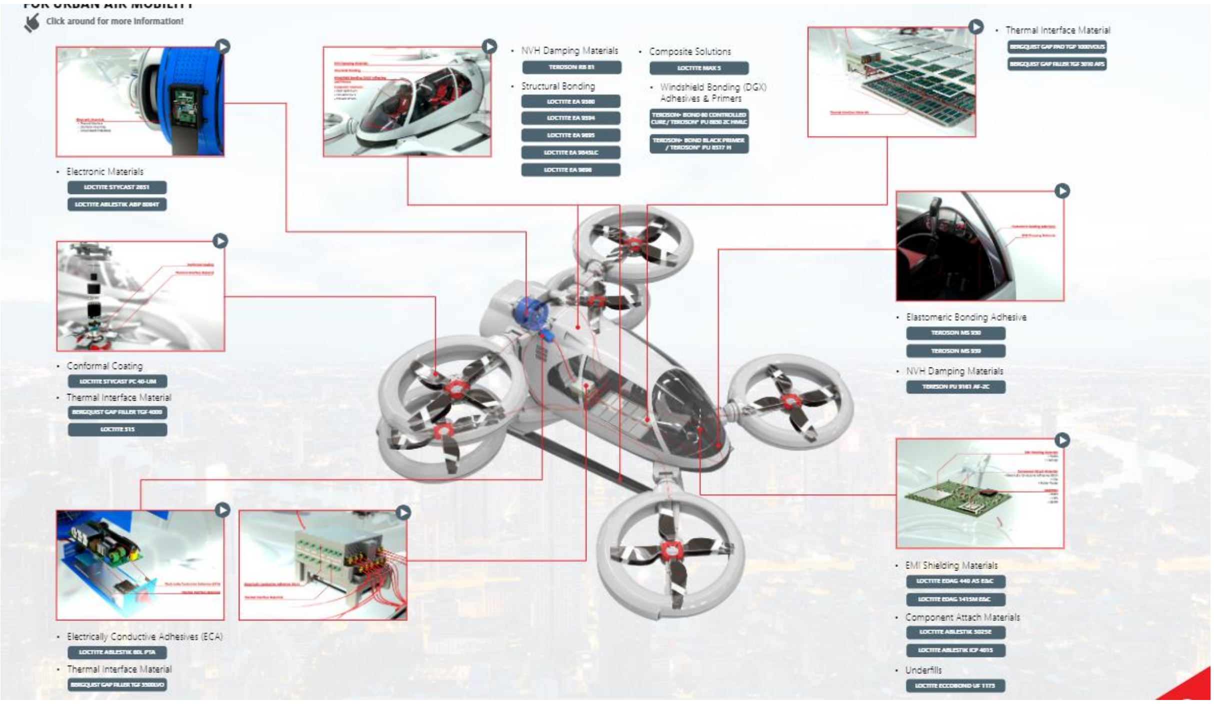


Figure 1: Possible application areas for usage of Henkel technology in eVTOLs.

Figure 1 shows a generic eVTOL with end applications that Henkel products can support. These are a variety of structural bonding applications on fuselage or rotor blades with film adhesives that have UV resistance and lightning strike protection, or structural paste adhesives that bring fire resistance (FR) or even Fire, Smoke and Toxicity (FST) characteristics for in-cabin-applications.

Looking at the battery, Henkel has some solutions that support stopping a thermal runaway and lightweight foam materials for battery stacks.

The windshield of a car is bonded with elastomeric adhesives that brings reliability into the bonding. Henkel has introduced this technology into UAM vehicles and sees significant good results already.

Looking into the electric backbone of the eVTOL, Henkel materials support a broad range of requirements on PCB level and other electronic applications.

Electrically conductive adhesives, or its film version, the assembly films help to attach dies and compounds onto the board and manage a reliable mounting of the PCB.

Key characteristics when evaluating the trend of miniaturization are design freedom (fine lines, flexibility, thermoformability) and a better heat dissipation. To answer these challenges Henkel has Printed Electronics (PE) as part of its portfolio to overcome the needs in designs for fine electric lines and an outperforming portfolio of thermal interface materials which allows to fill gaps ranging from a couple of micrometers up to 7mm to fill and to effectively dissipate the heat.

2 Challenges of eVTOL development

Trends

Building a completely new market segment is most of the times connected with the need of break-through innovations because this new segment has some criteria or necessities that were not identified earlier. Looking into the UAM segment, three major trends can be detected and will be discussed in the following paragraphs.

Safety requirements

Looking at safety, this is not only covering the safety of the passenger or parts of a drone (which are included in the certification of the drone), but safety is also requiring a good communication system with radars and sensors. Communication needs to be quick and must not show any delay. Therefore, 5G will be the basis for UAM communication. Some are already discussing the implementation of 6G due to higher demand "for both high data rates and low latency applications" [3].

Safety is one of the major hurdles to overcome towards a functioning UAM market.

The data flow needs to be stable and reliable. This is manageable, but it comes together with miniaturization of each component [4]. More capabilities are included into a smaller sized component. This trend triggers higher localized heat load and a fragile design. The heat can be encountered with reliable working superior heat dissipation materials and the fragile design needs to be covered and encapsulated. In the following paragraphs, we will look a little bit more into detail of these technologies.

Sustainability

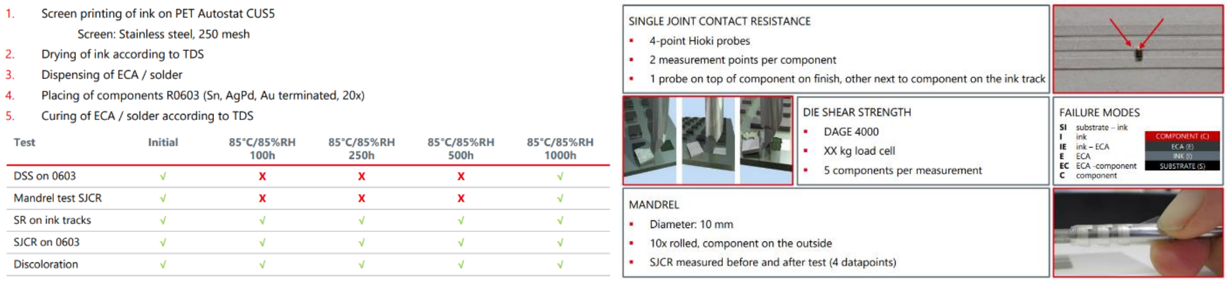
UAM shall not be another way of transportation. It shall be the answer towards road congestion, towards air pollution and towards the future and nowadays-problems of recycling and energy consumption.

Therefore, during the development of drones, the end of life of such vehicles needs to be taken into consideration; for instance, the recyclability of complete parts – a bad example would be windblades in this context [5] – and reworkability of components during the process.

Disruptive megatrends for the UAM/AAM market in the field of sustainability and mobility transformation to reach a 'clean sky' are lightweight (zero-emission) and electrification. Prevention and/or reduction of waste must be a priority during development of new products, especially with rare earth materials and sources available. Looking at a PCB, reworkability can be realized with the following of our technologies; solder pastes, printed electronics and underfills. During flight and operation mode key driver is lightweight and therefore the usage of bonding materials instead of screwing is preferred. Here also ECA's come into play next to all of the previous technologies when including green technology benefits.

Incompatibility

Henkel being a one-stop-shop for adhesives, has looked into the topic of compatibility between various technologies used in an assembly. Problems can arise already at the very basic level of the substrates or components when to be bonded but having a different surface energy. Possible solutions which require cleaning of the substrates such as plasma cleaning, etc. might be first options to consider. However, the right selection of the adhesive will play a major role in the final application and the stress (mechanical/vibrational) or reliability conditions the bondline will see. The so-called E-modulus or storage modulus of the material, which determines the flexibility and rigidity, as well as the coefficient of thermal expansion (CTE), which describes how the size of the material will change with temperature, are key parameters to recommend the proper adhesive. In the ECA paragraph we go more into detail on these differentiators. For now, rule of thumb is; where two very dissimilar substrates need to be bonded, or in other words, where there is high CTE mismatch, one typically will use a flexible material. As this is a material with a high CTE, it is able to absorb a lot of stress at elevated temperatures. Thus, preventing issues like delamination during flight, landing or take off modus for instance. Furthermore, compatibility between ECA's and solvent-based inks have extensively been investigated. The test set up is described in Fig 2.



1. Screen printing of ink on PET Autostat CUS5
   Screen: Stainless steel, 250 mesh
2. Drying of ink according to TDS
3. Dispensing of ECA / solder
4. Placing of components R0603 (Sn, AgPd, Au terminated, 20x)
5. Curing of ECA / solder according to TDS

Test	Initial	85°C/85%RH 100h	85°C/85%RH 250h	85°C/85%RH 500h	85°C/85%RH 1000h
DSS on 0603	√	x	x	x	√
Mandrel test SJCR	√	x	x	x	√
SR on ink tracks	√	√	√	√	√
SJCR on 0603	√	√	√	√	√
Discoloration	√	√	√	√	√

SINGLE JOINT CONTACT RESISTANCE
- 4-point Hioki probes
- 2 measurement points per component
- 1 probe on top of component on finish, other next to component on the ink track

DIE SHEAR STRENGTH
- DAGE 4000
- XX kg load cell
- 5 components per measurement

FAILURE MODES
SI substrate – ink
I ink
IE ink – ECA
E ECA
EC ECA -component
C component

MANDREL
- Diameter: 10 mm
- 10x rolled, component on the outside
- SJCR measured before and after test (4 datapoints)

Figure 2: Left side represents test build up. Right side represents a more detailed description of the tests performed.

Various chemistries and cure/drying schedules of the ECA's, solder pastes and inks were selected in this set up. An extensive study has resulted in a compatibility datapackage between those technologies.

3 Technologies supporting the electric journey into the sky

Innovation is within our DNA, not only related to new developments of materials but also regarding processing and applying our materials. We strive for fast processing to reduce energy consumption, to produce cost-effectively and still maintain high quality standards. Next to conventional application processes (screen & stencil printing, dispensing, jetting, etc.) we work together with innovative companies testing our materials to the limit in new application processes. Laser induced forward transfer (LIFT) is one of these application technologies we strongly believe in and all below technologies, apart from TIM, can be applied with this innovative technique, where pixels are ejected with velocity ranging from 200 to 1200m/s. This means more than 3 times faster than the speed of sound in air!

TIM

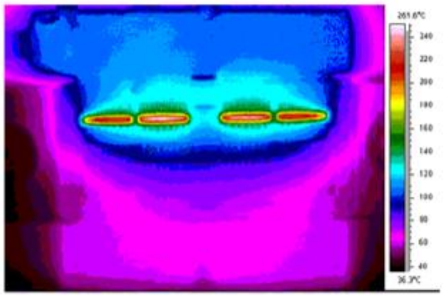


Figure 3: shows a thermal camera picture of the heat dissipation of a certain area

Heat generated from an electronic/electrical component affects the system reliability, the product performance, thermal platform costs and limits design advances in terms of size requirements and power density. With power density of the battery technology being key for the UAM market, one of the most effective methods for removal of heat from electronic components and assemblies is using polymer based Thermal Interface Material (TIM). Henkel's line of TIM materials includes gap pad, gap filler, thermal adhesive, gel and phase change materials. These materials provide up to 10 W/mK thermal conductivity, are available in a wide range of modulus from hard to soft, NASA outgassing criteria compliant as well as silicone-free formulations available.

Printed Electronics

In the demand of miniaturization, PE are a great solution for UAM applications and sustainability aspects for the complete market segment. Countless devices rely on Printed Electronic technologies for function, form and flexibility. One of the most efficient production methods, printed electronics, allows for high-volume, high-throughput and cost-effective manufacturing for many of the products we rely on every day.

PE are electrical devices that have been made by using printing processes to apply functional inks onto various substrates. Incorporation of more complex and more flexible functionalities in smaller devices for reduced cost is therefore the main driver for PE.

End applications for PE are sensors, RFID antennas, seat heaters, keyboards and multiple others. The increased need for safety is pushing UAM manufacturers towards high conductive materials to fulfill requirements in regard to communication (5G & WiFi) and supporting air traffic management through sensors.

LOCTITE ECI 1010 E&C and LOCTITE ECI 1011 E&C are developed for this increased need towards high conductivity. The solvent based ECI 1010 and ECI 1011, both highly conductive (around 5mOhm/sq/25µm and 2.5mOhm/sq/25µm respectively), allow more current carrying capacity into heaters and other electronic devices. This gives the customer more design freedom, allows him to use less ink and can give more rapid heating or power generation. The ink can be used in applications where very good conductivity is required, like high power heating elements. It has improved environmental stability and other additional benefits of this material are excellent adhesion to PET, very good flexibility and screen printable.

The risk for burning through is higher for standard commercial materials due to their higher resistance so higher temperatures are generated, this is not the case for the highly conductive silver inks.

Four different materials were tested at constant voltages and constant current tests. All materials were measured at 125 square printed on PET. The temperature was checked in situ with an IR camera.

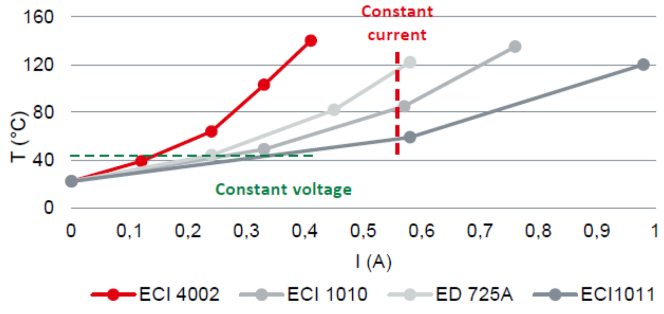


Figure 3: Materials tested at different currents vs Ag track temperatures recorded

Figure 3 indicates it can be said that the lower the sheet resistance the higher the current carrying capability of the material and the less temperature increase at fixed current.

On the one hand, these inks open up new possibilities for printed electronic applications and on the other hand they offer the possibility to significantly reduce the total cost of ownership in existing print applications by reducing track width and/or height.

Another critical property next to sheet resistance, drying time/temperature and adhesion is the flexibility which is one of the parameters used to refer to the mechanical performance of the product. The flexibility describes the changes measured in the track resistance and visual defects observed when bending the test structure. There are many tests for testing the flexibility of conductive films. In the picture below a flex/bend test is represented and all results are plotted in the graph.

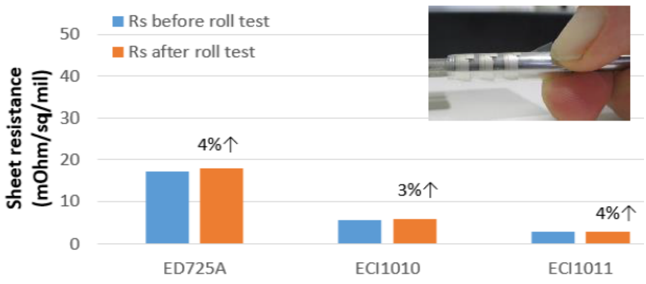


Figure 4: Represents test with small diameter; initial resistance vs. after flex resistance are measured and plotted.

As you can see from the graph, various silver inks will behave differently due to the silver flakes used, the resin or filler systems, drying time/temperature,… EDAG 725A, the standard workhorse in the industry, shows an increase of 4% after bending and the high conductive silver ink ECI 1010 only an increase of 3% versus the super highly conductive sub-micron ink ECI 1011 with an increase of 4%. However, depending on the type of flexibility testing performed these results may vary and the outcome can be different.

With rapid heating for de-icing and anti-icing purposes in mind, Henkel has developed a series of screen printable thermoplastic, self-regulating positive temperature coefficient inks (PTC). There are four PTC inks in our portfolio which we offer today. This is LOCTITE ECI 8001 with an offset temperature around 55 – 60°C, LOCTITE ECI 8090, LOCTITE ECI 8120 and last but not least LOCTITE ECI 8060HV for high voltage applications (> 50V) with each their respective offset temperature.

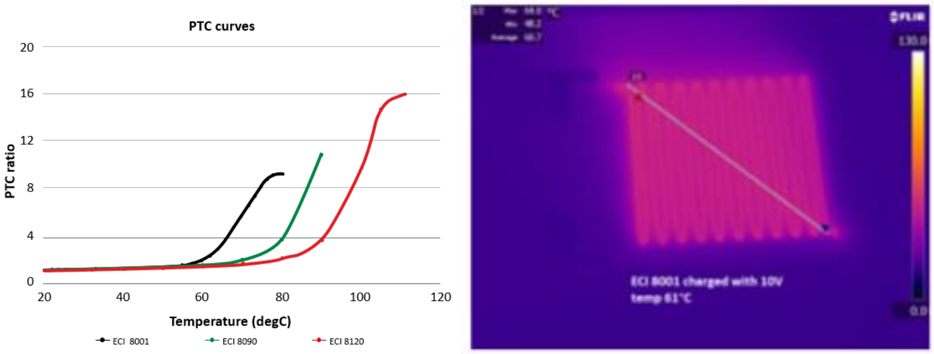


Figure 5: Left side PTC curves are shown with their change in PTC ratio vs elevated temperatures and the respective thermal image of the LOCTITE ECI 8001 charged with 10V on the right side.

But what makes these carbon inks so special compared to other products on the market?

Resistance normally increases as temperature increases. Have again a look at the graphs, resistance of the ink starts to increase exponentially at a certain threshold temperature so when voltage is applied the ink will warm to specific threshold temperatures and maintain constant temperature (= self-regulating heater). If temperature gets too high, the heater will shut OFF by itself (also due to the very high resistance value which makes it difficult to conduct any further current).

They are designed to be flexible and printable on most common substrates, they are compatible with polyester foil, several silver inks, dielectric inks and spacer tapes. Our PTC technology guarantees rapid, uniform, and flexible heating. It outperforms competition regarding self-regulation and gives a sustainable light weight solution to de-fog and to keep things warm. Thanks to the self-regulation effect, chances of overheating are significantly reduced. **Safety is increased** so no external temperature control is necessary anymore.

The applications we target with these products are any application where self-regulating heaters are required. Extra advantage of these inks is that wire/cables have hot/cold spots, by design optimization these can be eliminated for PTC heaters. Design can be easily adjusted to the shape of the surface which needs to be heated. This makes them an important competitor for other PTC/carbon inks and copper wire heating elements. This kind of technology can be used for an eVTOL to de-ice the wings and rotors. It is a safe and energy- efficient way to monitor and prevent ice built up on critical components.

ECAs

Electrically conductive adhesives are the competitive technology of solder materials. It is a metal filled adhesives paste or film with the ability to conduct electric current to form interconnections in various electronic applications. For broader applications or when even higher thermal conductivity is needed an assembly film (AF) can be used. The AF’s are the film format of the paste/adhesive we refer to as ECA. The AF’s can be purchased in almost every configuration or thickness and precut into every shape.

Henkel assembly adhesives have been used for decades in the assembly of electronic components and assemblies for the most rigorous defense, aerospace and space applications such as radar, guidance & communication systems, missiles, satellites and rockets. Assembly adhesives include electrically conductive and non-conductive pastes and film. They deliver many functions such as providing thermal conductivity, electrical conductivity, bonding and compensation for CTE variances & PCB warpage. Many assembly adhesives are certified to NASA outgassing and MIL 883 method 5011 standards. Henkel is targeting a next generation assembly film that will provide 25-50 W/mK thermal conductivity.

ECA’s from Henkel focus on green technology. ECA’s can be either cured at low temperatures or within a few seconds. Compared to solder this saves on the one hand energy but allows on the other hand to use temperature sensitive components and substrates. At the same time some ECA chemistries can have a high operating temperature (above 200°C). Their improved thermal-mechanical performance avoids cracking and is therefore a reliable solution. Within the solder technology the use of a flux medium is still needed which has a harmful impact on the environment. ECA’s do not require any additional cleaning step before, during or after application. This results in less time-consuming assembly of the part.

Mostly epoxy or silicones are used but chemistries can also be mixed to get hybrid ECA’s and have the best of both worlds. Coping with different vibrational stress, higher operating temperatures and increased reliability for UAM applications, flexibility of ECA’s is of importance. There are different products in the portfolio as seen in *Figure 6*.

Figure 6: Summary of flexible ECAs vs degree of adhesion (example only as portfolio is too extensive to represent in one picture).

LOCTITE ABLESTIK ICP 4000 is a silicon base filled with silver. The LOCTITE ABLESTIK CE 3520-3 however is an epoxy filled nickel system and very good for mismatching CTE's of substrates due to its high adhesion properties and high flexibility.

But how can flexibility for an ECA be described? The tendency of a material to deform when a force (stress) is applied to it, gives a direction of the ECA's flexibility. The E-modulus is determined through DMA analysis on a film sample against temperature as seen in *Figure 7*.

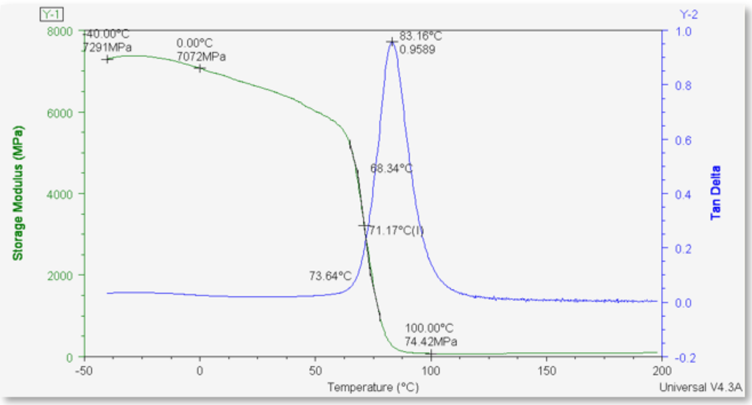


Figure 7: E-modulus vs temperature.

Flexibility and rigidity of an ECA can be determined by measuring the so called E-modulus or storage modulus of the material via DMA analyses (Dynamic mechanical analyses). The storage modulus describes the tendency of a material to deform when applying stress to it, typically expressed in MPa or GPa. Depending on the resin system that is used, you can get very flexible ECA's, like the silicone based materials, they will show a low E-modulus at RT, typically of less than 1000MPa. Epoxy systems however will have an E-modulus between 4000 to 10000 MPa. Flexible ECA's are typically used in applications that need to cope with CTE mismatch. Whereas rigid epoxies will be used to bond materials with similar CTE coefficients like ceramic components on LTCC boards.

The coefficient of thermal expansion describes how the size of the material will change with temperature, it is typically expressed in ppm/°C. CTE is measured via TMA analyses (Thermo Mechanical Analyses) and two values are captured. CTE before and after the glass transition temperature or the Tg of the material. Typically the Alpha 2 after Tg is 3 times the CTE before Tg. As stated earlier, for assemblies where two very dissimilar substrates need to be bonded, or in other words, where there is high CTE mismatch, one typically will use a flexible material. As this is a material with a high CTE, it can absorb a lot of stress at elevated temperatures. Thus, preventing issues like delamination for instance.

Availability of even higher thermal technologies than the ECA's is needed in future. Therefore, Henkel is looking into different types of silver. A highly silver filled resin paste has a thermal conductivity of 20-25W. The opposite is silver sintering, but it does not come with the best workability characteristics. Therefore, our development team has investigated semi-sintering. It has nearly the bulk thermal of silver sintering but an even better workability than silver filled resin paste.

Semi-sintering has high bulk thermal, close to silver sintering, and much improved workability.

Figure 8: Bulk thermal for different ECA silver technologies.

Semi-sintering pastes are resin-based drop in materials, identical to standard die attach paste applications but without the need for high pressure and temperature for sintering. Henkel and the aerospace market strongly believes in further expansion of these type of materials for the UAM market segment.

Underfill

The UAM market demands higher reliability requirements and in order to fulfil those needs underfill (UF) materials can be used. UF comes into play after the solder reflow processes to improve the reliability of solder joints and increase package reliability by distributing the stress across the surface of the die or substrate instead of being concentrated in the solder balls especially during thermal cycling (TC). UF is as well used to increase the mechanical shock resistance.

Requirement for such a material is that it must be uniform and void-free over a wide temperature range. LOCTITE ECCOBOND UF 1173 is the single component product that brings all these requirements into play and maximizes the device's temperature cycling capability. It is REACH compliant and fulfills the NASA out-gassing test with the following results:

Table 1: NASA Outgassing Test results for LOCTITE ECCOCOND UF 1173.

NASA Outgassing Test	
TML	0,43%
CVCM	0,02%
WVR	0,1%

4 Conclusion

The UAM sector needs a lot of new components, new design and systems to reach the high expectations and forecasts. For this, Henkel is supplying the market with proven products which are already used in other demanding industry sectors such as Aerospace, Automotive and Data-&-Telecom.

The products from our electronics portfolio answer the trends of this market in a way that criteria for sustainability, miniaturization, safety and reliability are met.

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