One Step Chip Attach Materials (OSCA) for Conventional Mass Reflow Processing

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ABSTRACT

One step chip attach (OSCA) materials are dispensable polymeric materials for flip chip assembly, which are designed to flux metallic interconnections and subsequently turn into an underfill upon curing. OSCA materials enable a drastic simplification of the assembly process by combing the reflow (fluxing/soldering), defluxing and capillary underfilling steps used in traditional processing into a single step. One key challenge for the design of OSCA materials is timing the cure kinetics with fluxing activity and solder reflow during processing. A second key challenge is to factor a process-friendly rheological design into formulation. The OSCA material rheology must allow for high filler loading levels, seamless integration with standard dispensing equipment, flow control during and after dispense (avoid keep out zones), flow during the die placement (elimination of voids), after placement (fillet formation) and during reflow. The final key requirements for a functional device are defect-free interconnections combined with optimal thermos-mechanical and water resistant properties of the final underfill to guarantee the long-term reliability of the assembly in various environmental conditions. This paper presents the properties of materials designed by Kester for use in mass reflow processing (OSCA-R). The rheological design principles behind a seamless integration into customer-friendly processes will be presented in additional results illustrating the timing of cure kinetics with fluxing and soldering events during processing will be discussed. Preliminary device reliability results will also be presented for several types of test vehicles including; Si-Si and Si-FR4.

Key Words

Adhesive, flip chip, fluxing, no-flow, non-conductive paste, reflow, soldering, underfill

INTRODUCTION

There is a need in microelectronics assembly to increase throughput of manufacturing processes. Focusing on the portion of the assembly operations involving the assembly/attachment of flip devices it is clear that materials which simplify and remove steps from the assembly process are of great utility. The traditional assembly process for flip chip devices proceeds by a multistep process [1], [2]. First, application of a flux to solder bumps on a die (dipping), then placement onto a substrate (pick and place machine) followed by reflow processing (oven) to melt the solder and form interconnections for a total of three steps. Sometimes a cleaning step is used to remove flux residues from the gap between the die and substrate before the gap is filled using a capillary underfill process adding two more process steps. Finally the underfill is solidified in a curing step to bring the total to 6 process steps for flip chip assembly. To increase throughput of the device assembly process it would be advantageous to combine the flux and underfill materials into one single material enabling three steps; fluxing, underfilling and cure to occur during the reflow processing step thus eliminating the defluxing and capillary underfill steps [3]-[7].

Materials are referred to here as One Step Chip Attach or OSCA materials. Fig. 1 illustrates the OSCA process where the materials are dispensed onto the substrate prior to die placement and processed by conventional mass reflow techniques. A key technical challenge for OSCA materials is combining the soldering performance of flux and reinforcing performance of capillary underfill materials into a single material [5], [6]. The OSCA materials described here are designed for use with conventional assembly processing tools such as auger dispensing systems and mass reflow ovens enabling throughput without the need for capital investment. This paper presents the design and performance evaluation OSCA materials that enable simplification of devices processed by conventional reflow processing techniques.

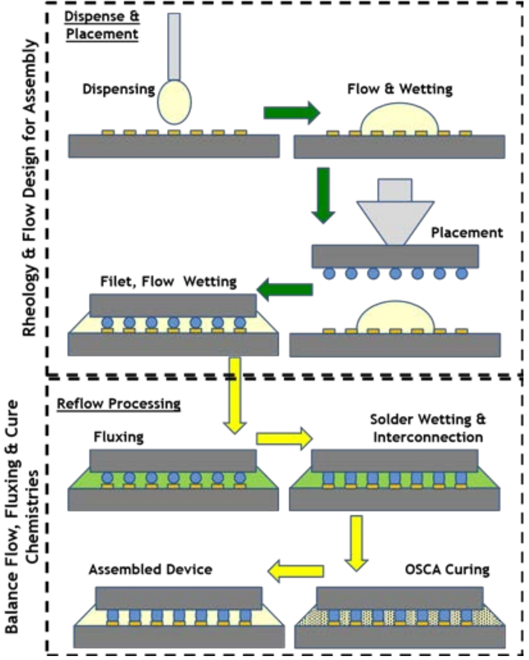


Fig. 1: Assembly Process using One Step Chip Attach (OSCA) materials and conventional mass reflow processing.

RESULTS & DISCUSSION

A. Design Challenges for OSCA Materials

OSCA materials have similar thermo-mechanical and reliability performance requirements after they are cured to the incumbent capillary underfill and nonconductive paste (NCP) materials [8]. However, OSCA materials have different design challenges than capillary materials because they enter the assembly process at a different point and will be subjected to different processing conditions than materials used for traditional flip chip assembly. The first key difference is very simply when the material is applied in the assembly process. As illustrated in Fig. 1. OSCA materials are applied before die placement, reflow and interconnection opposed to after reflow processing for capillary materials. This seemingly small change has some profound implications on the design of rheological, thermal properties, chemical kinetics and material selection.

The rheology of OSCA materials must accommodate different requirements than a capillary underfill because they are applied before interconnection as shown in Fig. 1. First, OSCA materials must be dispensable at high speeds from 25 to 27 gauge needles with no stringing at room temperature. After dispense the OSCA material must wet the substrate, maintain the pattern it was dispensed into and not overflow into no-go zones or cover alignment marks or features on the substrate used for die alignment and placement. These requirements imply that OSCA materials must have shear thinning rheology, timed recovery of viscosity after shearing during dispense and small finite yield stresses. OSCA materials must resist polymerization and advancement when heated to temperatures as high as 250C long enough to allow for interconnect formation. In contrast, capillary underfill materials are designed to flow quickly into a 20-50 micron gap between the interconnected die and substrate at 50 to 100C with low viscosity, minimal shear thinning at process temperature, compatibility with flux residues, must resist viscosity advancement at 50C until the gap has been completely filled (no advancement).

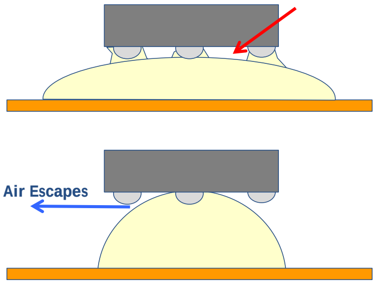


Fig. 2: Controlling flow during dispense and die placement to eliminate air entrapment and placement voids.

A second key difference between OSCA materials and capillary underfill is the approach the air entrapment problem. Capillary underfill materials utilize perimeter dispense pattern and process control to avoid trapping air. This dispensing option in not relevant to OSCA materials. For OSCA materials the solution to this problem is found in the design of rheology and flow. The rheology of OSCA materials strongly influences the curvature of the surface after dispense. For example, a material with shear thinning properties and a quick recovery time it can maintain a non-equilibrium shape that more useful during die placement than a Newtonian fluid. The potential effects of dispensed material surface curvature are illustrated in Fig. 2. If the radius of curvature is too large or the interface is too flat (top frame in Fig. 2) air can be pinned between bumps during die placement. A smaller radius of curvature, as illustrated in the lower frame of Fig. 2 creates a wetting line near the die center when the die contacts the OSCA material. The wetting line is pushed outwards toward the edge of the die as the die is lowered. This motion of the wetting line during placement helps to ensure no air is trapped. Because of rheology design the curvature of the OSCA material helps to drive air out from under the die during the placement step.

The next performance challenge for OSCA materials is the need to remain essentially uncured and retain good flow up to temperatures of 250C allowing solder joints to interconnect before the OSCA material solidifies during the reflow process. Fig. 3 illustrates the sequence of events that occurs during reflow processing that OSCA materials will be subjected to. First, the material temperature is ramped to temperatures approaching 250C during which the OSCA material is responsible for cleaning oxides and OSP from the solder ball and pad surface respectively. The solder melts around 218-220C for typical lead-free alloys like SAC 305. A period of time is allowed above the solder melting point for the molten solder balls to wet out the pads on the substrate. Once wetting and interconnection have occurred the OSCA material then cures to form a reinforcing under fill. Timing of fluxing, solder melting, interconnect formation and curing is critical for device assembly. The sequence of events needs to happen in specific order above the order for OSCA type materials to work correctly. Each event occurs over a range of temperatures as illustrated in Fig 3. Although it may not be possible to completely decouple the events it is possible via design of resin chemistry, catalyst system and additives to time the sequence and obtain acceptable overlap between events such that fluxing, interconnection and cure occur in the proper order without interference.

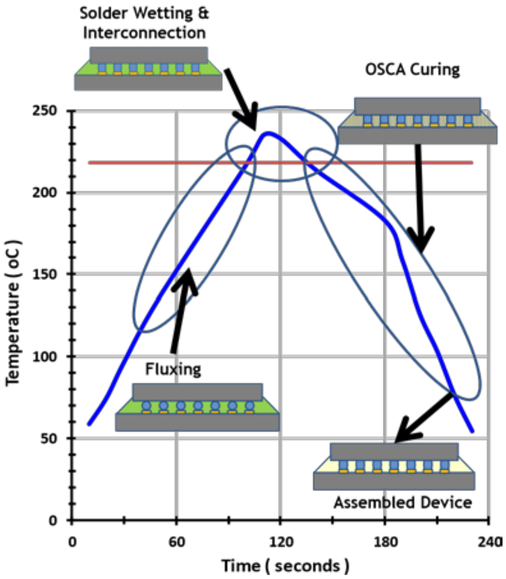


Fig. 3: Timing fluxing, solder wetting, interconnection and curing events during mass reflow processing using OSCA materials.

A final performance attribute required of OSCA materials is no outgassing or volatility at reflow processing temperatures as outgassing leads to poor reliability from voiding, interconnection and device failure. OSCA materials must be designed to remain low viscosity and be able to flow at temperatures above the melting point of solder (220C) and to temperature as high as 250C before cure as shown in Fig. 3 without volatilizing. The sets of materials available for design of OSCA materials and traditional capillary underfill materials differ because of the combined high temperature, low volatility and low viscosity constraints. The remainder of this paper discuses OSCA materials developed to address the rheological needs for dispensing, die placement, void elimination, tailored cure kinetics and low volatility that enable reflow processing, assembly of devices using the one step chip attach process outlined in Fig. 1, 2, and 3 along with some preliminary reliability results.

RESULTS & DISCUSSION

A. Rheology Design for Dispense & Placement

Dispensing and flow are the first performance properties OSCA materials must have to be useful. The materials be readily dispensed using pressure-time or auger type systems and retain their intended dispense pattern. For this reason rheology performance is discussed first. Fig. 4 shows a series of viscosity curves for OSCA materials with different shear thinning behavior and residual zero shear stress levels (yield stress). The required level of shear stress and shear thinning is defined by the details of the dispensing equipment, the bump pitch density and count, substrate configuration and placement equipment. The formulation designed from the rheology information in Fig. 4 is specific to the application. OSCA materials with a viscosity of 10 to 20 Pa-s at 25C, a shear rate of 1Hz, a STI of 3 and yield stresses less than 10 Pa were found to be most suitable for dispense and device assembly. An OSCA material dispensed on FR4 is shown in Fig. 5. The yield stresses of the material enable the cross pattern to persist after dispense. When a die is placed into the OSCA material curvature helps to reduce air entrapment, expel air and eliminate placement voids. Fig. 6 presents composite acoustic images of rectangular test die after placement and reflow assembled with OSCA materials with yield stresses in frame (a) and without in fame (b). The images in Fig. 6 were produced by stacking and averaging the CSAM void analysis results from 10 separate test vehicles. Use of the statistical CSAM images shows the voiding reduction using OSCA materials with tailored rheology and also show that the location of voids is not random but rather that voids are more likely to be observed in certain areas than others.

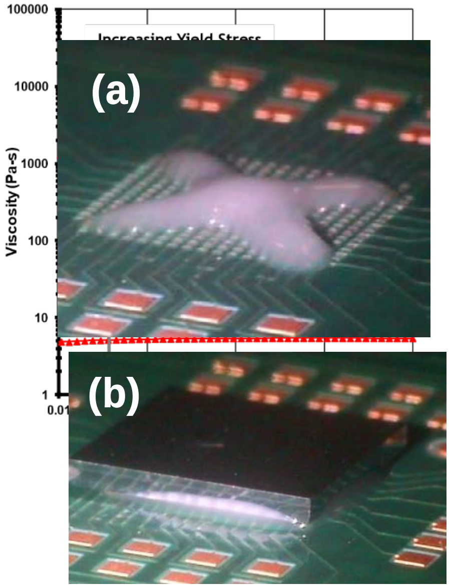


Figure. 4: Example of OSCA rheology design to build shear thinning, viscosity and yield stresses.

Fig. 5: Example of OSCA material with a yield stress dispensed onto an FR4 substrate (a) before die placement and (b) after die placement.

The temperature dependence of viscosity is also important to consider when designing OSCA materials. OSCA materials should stay where they are dispended. The OSCA materials should thin with increasing temperature to flow and form a filet, wet the bumps and substrate allowing for fluxing and also be thin enough to allow for bump collapse and joint formation above the solder melting temperature. However, the viscosity should not be too low so that the OSCA material flows beyond its intended application area into no-go zones interfering with subsequent assembly steps. OSCA formulations can be designed as illustrated in Fig. 7 to thin with temperatures at different rates. The thinning rate with temperature was characterized by the Arrhenius equation shown in (1) and it was found that OSCA materials with Ea values ranging from 2000K to 8000K were the most useful for device assembly.

$$\eta(T) = A \cdot e^{\frac{Ea}{T}} \quad (1)$$

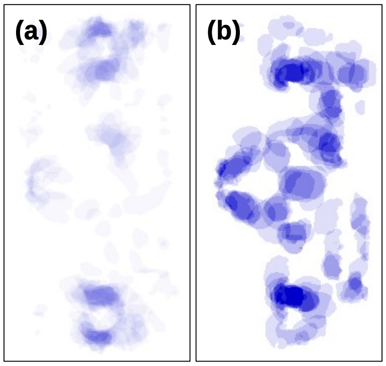


Fig. 6: CSAM images of test die processed with OSCA formulations (a) with a yield stress and (b) without a yield stress.

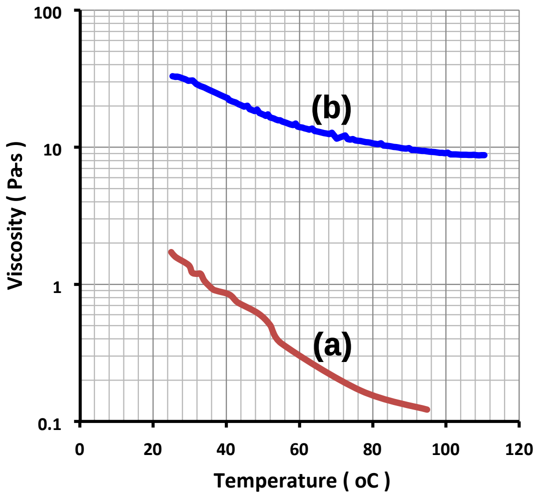
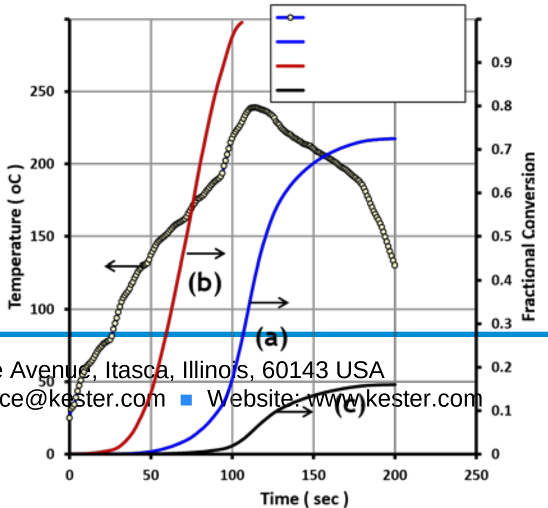


Fig. 7: OSCA viscosity temperature dependence (a) rapidly thins and (b) resists thinning with temperature.

B. Curing Kinetics

The most important aspect of OSCA material design after rheology is timing and curing kinetics with the temperature profile of the reflow process. Fig. 8 presents the temperature-time curve of a device during reflow in a convection oven. Three curves are shown representing the factional conversion of different OSCA materials as they are exposed to temperature profile. The conversion curves are generated reaction kinetics analysis of heat flow curves measured by DSC. The mathematical kinetics analysis follows the method described in ASTM E2041. The analysis yields a reaction order N, activation energy E, frequency factor A, and heat of reactionΔH. These parameters were tracked as a function of the formulation chemistry, catalyst level and catalyst type allowing for OSCA curing kinetics to be tuned for the target reflow profile. Curve (b) in Fig. 8 shows a material that cures too quickly. This material will gel (conversion ~ 0.25) before the temperature reaches the melting point of the solder from flowing resulting in no interconnect formation. Curve (c) in Fig. 8 shows a material that does not reach a sufficiently high level of cure during reflow processing. Such a material may remain a liquid after reflow and interfere with subsequent device processing. The slow curing material would require additional post curing to achieve final mechanical properties. The OSCA material indicated by curve (a) in Fig. 8 was designed to achieve its gel point after the maximum temperature in the reflow profile has been achieved. This allows for the OSCA to flux, solder to melt and flow prior to cure. The ability to tactically alter OSCA cure kinetics becomes useful to match materials to the reflow profiles used for different device assembly requirements. The temperature profile shown in Fig. 8 obtains a peak temperature in 120 seconds corresponding to a ramp rate of ~ 2C/sec. Some assembly processes use lower ramp rates of 1C-sec where a peak temperature would be achieved in ~ 240 seconds. For longer reflow profiles OSCA materials corresponding to curves (a) and (b) in Fig. 8 would not be appropriate but materials with slower curing kinetics such as illustrated by curve (c) would be useful.

Fig. 8: Conversion of OSCA material during reflow processing illustrating (a) target conversion kinetics, (b) when curing kinetics are



too fast and (c) when curing kinetics are too slow.

C. Reflow Evaluation, Material Properties & Reliability

Materials were dispensed using a Martin Clever Dispense05 or an Asymtek (auger) dispense system, device assembly (placement) was conducted using either a FineTech, FinePlacer-Pico or a SET FC150 die bonder system. Reflow processing of materials discussed in this paper was conducted using a Speedline Electrovert oven, a Sikama Falcon 850 oven, or a FineTech FA9 conduction state. Fig. 9 and 10 show the interconnection and voiding results respectively for a test vehicle assembled using reflow processing utilizing an OSCA material containing 60% filler. The SEM shows good interconnect formation consistent with the design of the curing kinetics shown in Fig. 8 (a) and Fig. 10 shows the does not show under die voiding form placement voids or from volatility consistent with the rheology and material selection concepts discussed.

OSCA materials can be designed to meet a wide range of application and processing conditions by selecting the appropriate rheology, cure kinetics and filler loading. Table I summarizes the material properties of the OSCA materials used in the investigations reported here. The final cured properties of OSCA materials such as Tg and CTE are designed to be similar to capillary underfill materials described in the literature. Preliminary reliability testing on bonded silicon die (5x5x0.75 mm) was conducted for OSCA materials using an autoclave set to 121C to stress test the materials. This test procedure is often referred to as highly accelerated stress testing (HAST). The die shear strength is monitored as a function of time in the HAST chamber. Table II presents a summary of the die shear results for three OSCA formulations after HAST testing. The materials retain a significant fraction of their initial strength after 50 hours of stress testing. This indicates that the mechanical integrity of the OSCA material and its interface with the silicon substrate and die is maintained. Electrical reliability testing of daisy chained test vehicles is currently ongoing to determine if the OSA materials presented here also enable electrical integrity to be maintained through HAST testing as well as mechanical and adhesion.

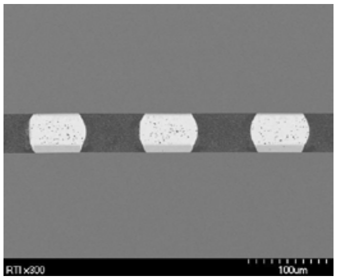


Fig. 9: SEM image of test vehicle after reflow.

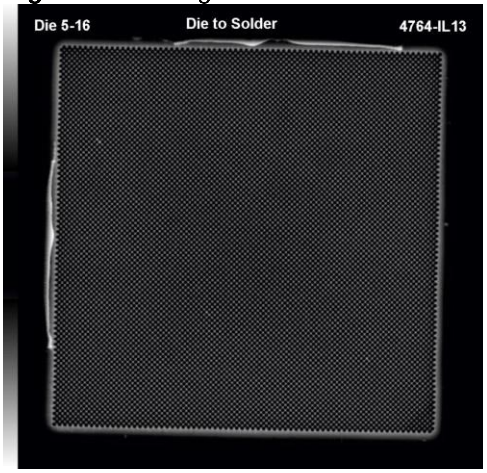


Fig. 10: CSAM image of test vehicle after reflow processed with OSCA containing 60% filler.

Table I: Typical properties for OSCA materials formulated with various filler levels and rheology design.

Property	Units	Range
Filler Loading	Wt%	0 to 60
Average Filler Size	Micron	0.5
Max. Filler Size	Micron	5
Weight Loss, T < 300 C	Wt%	4 to 16
Tg	oC	150 +/-10
CTE-1	ppm/K	30 to 70
CTE-2	ppm/K	85 to 210
Thermal Conductivity	W/m-K	0.2 to 0.5
Modulus at 25 C	Gpa	3 to 8
Ultimate Strength at 25 C	Mpa	50 to 95
Strain to Break at 25 C	%	1.4 to 2.5
Fracture Toughness, K1c	MPa-m1/2	1 to 2
Adhesion	Kg-force	18 to 30
Adhesion 50 Hr. HAST	Kg-force	5 to 10
ΔH, Heat of Reaction	J/g	120 to 360
T_O, Onset Temperature	oC	110 to 130

T*, Peak Temperature	oC	160 to 200
% Cure After Reflow	%	> 80%
Reaction Order	Integer	0.9 to 1.3
Half Life at 180 C	Min.	4 to 5
Viscosity, 25C	Pa-s	4 to 65
Shear Thinning Index, 25C	Ratio	1 to 3
Yield Stress	Pa	0 to 10
Temperature Thinning	Kelvin/1000	2 to 8
Pot Life at 25 C	Hours	8

Table II: Die shear before and after HAST testing (Autoclave, T= 121˚C, 19 psig).

Time	0 Hr.	50 Hr.
Formula	**(kg-force)**	**(kg-force)**
OACA-1	39 (±10)	24 (±8)
OSCA-2	34 (±10)	31 (±10)
OSCA-3	35 (±10)	32 (±10)

CONCLUSION

Approaches to overcoming the key technical challenges of combining dispensing, device placement and timing of fluxing, soldering and curing during reflow processing using a combination of rheology and rational chemical design of materials has been presented. The work here demonstrates One Step Chip Attach (OSCA) materials can be used to eliminate steps in flip chip assembly processing. Initial mechanical reliability testing shows OSCA materials can maintain their integrity during pressure cooker testing. It is possible to tailor the OSCA material to perform over a wide range of reflow profiles or mass reflow processing equipment including convection and conduction ovens enabling their use in many device assembly applications. OSCA materials can have a range of filler loading levels to provide target final thermo-mechanical properties. The rheology of OSCA materials can also be tactically designed to enable dispensing and proper flow during die placement.

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