# Rheology Design Considerations for One Step Chip Attach Materials (OSCA) used 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 cure into an underfill providing mechanical reinforcement and environmental resistance following reflow. OSCA-R materials are designed specifically for conventional mass reflow processing and thus enable a drastic simplification of the assembly process by combining the fluxing, soldering, defluxing and capillary underfilling steps into a single step: the integration of this technology is transparent for the customer ( e.g no capital investment needed ) provided the product design integrates the customer's production line specificities. As an example, OSCA-R materials must have a process-friendly rheological design that accommodates the various steps during device assembly. Simply stated, if OSCA-R materials cannot be dispensed properly or the die placed correctly the OSCA process will not work. This paper presents the rheological design of OSCA-R materials with a focus on the flow requirements during the dispensing and die placement process steps.

## Introduction

The continuous drive in semiconductor assembly processes toward higher throughput in conjunction with ever decreasing interconnect size/pitch and increasing IO count offer an opportunity for new assembly materials and processes to be introduced [1]. A conventional flip chip assembly process consists of; applying flux to a die by dipping, placement of the die onto a substrate, reflow of the substrate, washing to remove flux residues, during the substrate, flow of capillary underfill beneath the die and finally a cure cycle to harden the underfill. The process is at least six steps and involving at least three materials (flux, water/solvent and underfill). One step chip attach (OSCA) materials enable the process shown in Fig. 1 reducing the assembly process to three steps and one material eliminating the need for lengthy cleaning and underfilling steps considerably simplifying the assembly process [2]. The materials referred to here as OSCA-R materials are intended for reflow processing using conventional mass reflow ovens. OSCA type materials are referred to as fluxing underfills, epoxy-fluxes or reflow encapsulants in other research reports [2]. As shown in Fig. 1 OSCA materials have a different set of requirements than capillary underfills [3, 4, 5]. The first main difference is that OSCA materials are dispensed before reflow and must remain where they are dispensed in the pattern they are dispensed into, not bleed or flow into no-go areas before die placement. Next the OSCA material must flow during die placement allowing contact of the bumps with the pads and not interfere with alignment. Finally during reflow OSCA materials must remain essentially uncured for several minutes above 200C without volatility enabling solder melting, wetting, and interconnection to occur. After wetting and interconnect formation has completed the OSCA material cures in the later portion of the reflow process forming a reinforcing underfill.

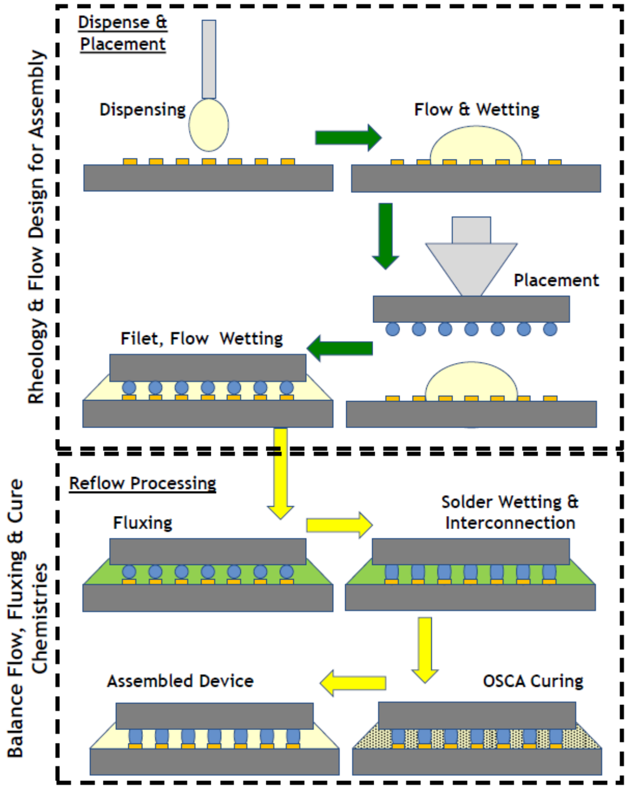

**Figure 1.** Assembly using one step chip attach (OSCA) materials.

The assembly process in Fig. 1 is separated into two sections based on the role and function of the OSCA material in the associated assembly steps. The assembly section involves flow of OSCA and placement of the die, the second step is the balance OSCA flow, fluxing chemistry and cure kinetics during reflow processing. A discussion of the balance of cure kinetics with polymerization during the reflow step is presented elsewhere [5]. Designing OSCA materials with the required flow properties to achieve dispense and die placement is the focus of the research presented in this publication. We will discuss how fundamental rheological principles can be used to design OSCA materials to fit the process window for pressure-time, auger/PDP and jet dispense techniques. Particular attention will be given to stringing, yield stress and wetting behaviors. In addition, placement of the die in the presence of the OSCA material demands that additional rheology behaviors beyond simple viscosity need to be considered. The compressional forces generated when die are placed into filled polymeric liquids at high speeds can be substantial [6]. Viscoelastic normal forces from material deformation can cause placement accuracy problems, failure to contact substrate, die drift, yield loss and component damage. The rheological response of OSCA-R materials to shearing stresses and the rapid deformation experienced during the die placement process must be an integral part of the OSCA-R material design. This paper discusses the characterization of forces and rheological features experienced during die placement as well as material design strategies useful for minimizing the compressional forces. With these rheology considerations successful, void free, interconnected device assemblies processed using conventional mass reflow techniques can be made.

## Results & Discussion

Fig. 2 presents a comparison of jet and PDP dispensing processes using OSCA-R materials. The left hand frame of Fig. 2 shows dispense from a needle using a positive displacement pump (PDP) type system and the right hand frame presents dispense from a jet dispensing system. In both dispense systems, PDP and jet OSCA materials need to have a rheology that enables flow from the tool. However, the process by which the material leaves the tool is very different. In the case of the PDP dispense system OSCA materials must shear thin sufficiently to exit the needle, not cling or climb up the needle, then wet and wick onto the substrate. In contrast during jet dispense OSCA must break quickly from the dispense tool, form a stable droplet in flight, wet/flow controllably without splatter on impact with the substrate. After dispense OSCA materials must retain their pattern and location and not flow into undesired locations.

Fig. 3 presents the rheology curves for several OSCA –R materials that were investigated and found to be dispensable by both jet and PDP systems. Fig. 4 presents OSCA-R materials that have been jet dispensed onto test vehicles in different patterns. Table 1 provides a summary of the material properties of the OSCA-R materials used for dispensing studies discussed in this paper. A Martin CleverDispense system was used for PDP evaluations and a Speedline Prodigy platform fitted with a NanoShot dispense head was used for jet dispense evaluations.

Fig. 3a illustrates a 55% silica filled OSCA-R formulation (Material B in Table 1) with shear thickening rheology measured at three different temperatures. Jet dispensing conditions were found that enabled this material to be dispensed using a nozzle heating temperature of 40C to 50C and no required substrate heating. The shear thickening nature of the material at room temperature enables the material to resist flow after dispense and maintain the dispense pattern. The thinning of the material with temperature enables jet dispensing to be achieved with tool heating temperatures acceptable for manufacturing. Fig. 3b presents the rheology curves for a shear thinning and two near Newtonian OSCA-R materials corresponding to materials A, C and D in Table 1. Materials A and D are filled while material C is not filled. All three materials shown in Fig. 3b were found to be jet dispensable under ambient conditions, no substrate or needle heating needed making OSCA-R materials A, C and D potentially more amenable to integration with manufacturing conditions. Substrate and jet nozzle heating conditions were explored but found to result in material splatter and loss of pattern edge definition.

Fig. 4a and 4b show Material B jet dispensed onto a silicon test vehicle and onto an organic test vehicle respectively illustrating the capability of OSCA-R materials to be used on both organic and inorganic assemblies. Similar results were obtained for OSCA-R (material B) using PDP dispense systems but substrate heating to 50C was required to counteract stringing behavior on tip retraction. Fig. 4c and 4d show OSCA-R (material A) that has been jet dispensed onto an organic substrate in a filled rectangle pattern and a cross respectively illustrating pattern retention and definition of the material.

The rheology curves in Fig. 3 along with the jet dispense and PDP dispense results show that process window for OSCA-R dispensability is quite large and materials with a wide range of rheology can be used with nominal conditions suitable for manufacturing. Materials characterized by shear thickening, shear thinning and Newtonian behaviors can be dispensed.

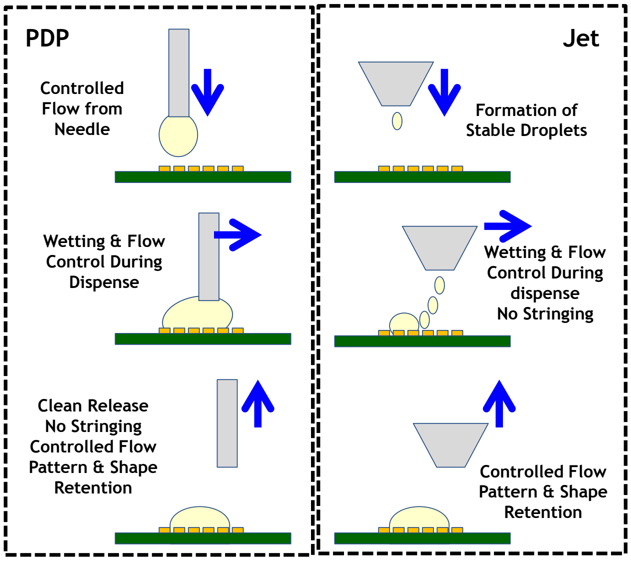

**Figure 2.** Flow requirements for OSCA-R dispense using conventional PDP and jet dispensing techniques.

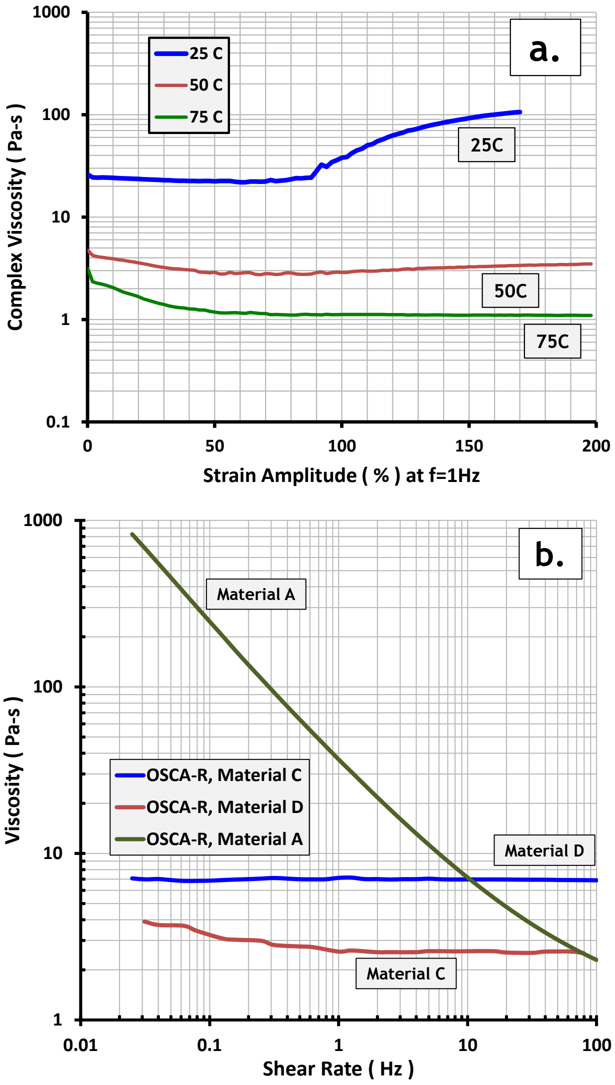

**Figure 3.** Rheology curves for OSCA-R formulations in Table 1; a) shear thickening material B as a function of temperature and b) shear thinning, Newtonian materials A, C and D.

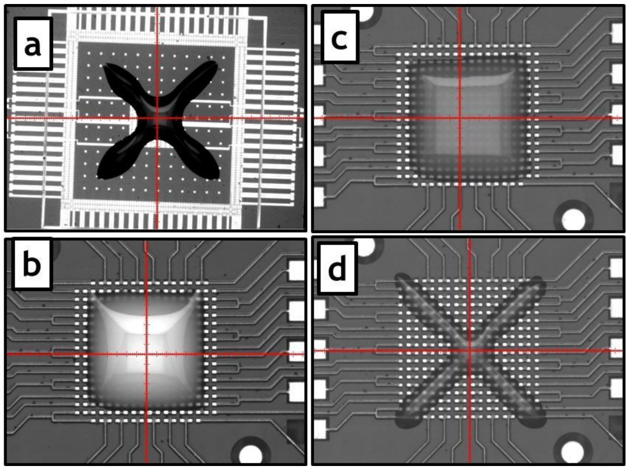

**Figure 4.** OSCA-R materials in Table 1 jet dispensed on substrates prior to die placement; (a, b) silicon and organic substrates respectively with material B and (c, d) organic substrates with material A.

**Table 1.** Property comparison of several OSCA materials.

| **Property (method)** | **Units** | **A** | **B** | **C** | **D** |
|---|---|---|---|---|---|
| Filler % | Wt% | 40 | 55 | 0 | 40 |
| Filler Size | micron | 0.5 | 0.5 |  | 5 |
| Tg (a) | °C | 159 | 125 | 116 | 125 |
| CTE-1 (a) | ppm/K | 46 | 36 | 68 | 49 |
| CTE-2 (a) | ppm/K | 138 | 117 | 212 | 163 |
| ΔH (b) | J/g | 235 | 165 | 348 | 212 |
| T-onset (b) | °C | 129 | 118 | 160 | 157 |
| T-peak (b) | °C | 197 | 162 | 204 | 203 |
| Viscosity(c) | Pa-s | 49 | 26 | 2.6 | 6.8 |
| Viscosity(d) | Pa-s | 14 | 40 | 2.6 | 6.7 |
| STI (e) | Ratio | 3.5 | 0.5 | 1.0 | 1.1 |
| Yield Stress (f) | Pa | 2 | 0 | 0 | 0 |
| Temperature Thinning (g) | Kelvin | 2200 | 7300 | 5000 | 6900 |

a) TMA, 10C/min ramp 25C to 280C, onset analysis.
b) DSC, 5C/min ramp, 20C to 280C.
c) Rheometer, continuous shear sweep, 25°C, 1 Hz.
d) Rheometer, continuous shear sweep, 25°C, 10 Hz.
e) Viscosity ratio, 1Hz to 10 Hz as measured by (c,d).
f) Rheometer, continuous shear sweep, 0.001 to 1Hz.
g) Rheometer, continuous shear, temperature ramp, 10C/min, 25C to 125C, shear rate of 1Hz.

The next question is how do the OSCA-R materials respond to compression during die placement? There are several reviews of fluid flow under compression that point out the differences between simple shear flow and the compressive squeeze flow experienced in our application [4]. Fig. 5 illustrates the steps during the die placement step in the presence of OSCA-R materials. When materials are compressed rapidly the time constants for relaxation may be too long and the material cannot flow and distort, it effectively behaves like a solid, forces will build up and can effectively interfere with die placement, alignment and large enough potentially damage interconnect structures.

To design OSCA-R material rheology it is critical to understand how the forces build up from the point of initial contact of the die with OSCA-R until the die reaches its final placement position. Understanding the compressional flow field, normal forces and OSCA-R material response at die placement speeds experienced during actual component pick and place operations begins with taking a look at material responses at lower speeds and developing some fundamental insight and guidelines in a laboratory system. To accomplish this OSCA-R materials were studied under compression using a TA-Instruments DHR-3 rheometer fitted with an 8mm stainless steel plate (50mm$^2$) operated in axial mode. This fixture was selected because it is similar in cross sectional area to some common die configurations; 5x5 mm (25mm$^2$) or 10x10 mm (100mm$^2$) and will provide a similar magnitude of force to that experienced during die placement. Fig. 6 illustrates the compressional rheology experimental set up. The key processing and material parameters investigated in this research are outlined in Table 2. At the time of this report only a portion of the potential variables have been explored but trends and initial understanding of the compression forces have been identified.

Fig. 7 presents an example compression curve measured for a filled OSCA-R material. The first observation to be made regarding compression of filled materials is that even with low viscosity (pourable) the forces that build up during the placement of die can be substantial and may be larger than anticipated. The normal force exerted when the fluid is compressed is a result of the materials resistance to flow during steps b, c and d in Fig. 5. The normal forces can easily exceed several Newton's for the relatively low placement velocities. Thus, to ensure proper die alignment and placement the resistance forces during compression need to be understood and accounted for in OSCA-R material design. Several pieces of information are taken from compression curves as shown in Fig. 7 that are useful for understanding material performance and design. First the maximum force measured during the experiment (F-max) is recorded. The peak force typically occurs at the terminal gap or final point in the compression curve. However, this is not always the case. A tangent analysis is conducted to compute the "onset" location and force (zo) and (Fo) respectively. The slope of the tangent line provides a rate of change measurement (derivative) of the force curve and can also be used to estimate a force at zero gap ( F(0) ).

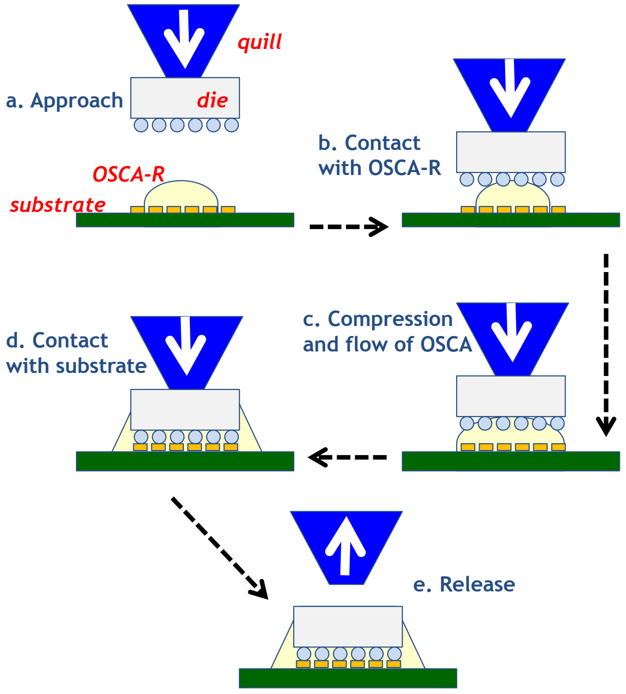

**Figure 5.** Die placement process using conventional pick and place tools in the presence of OSCA-R materials; a) approach of die to substrate, b) initial contact of die with OSCA-R material, c) compression and flow of OSCA-R, d) contact of bumps on die with pads on substrate and e) retraction of the pick and place quill.

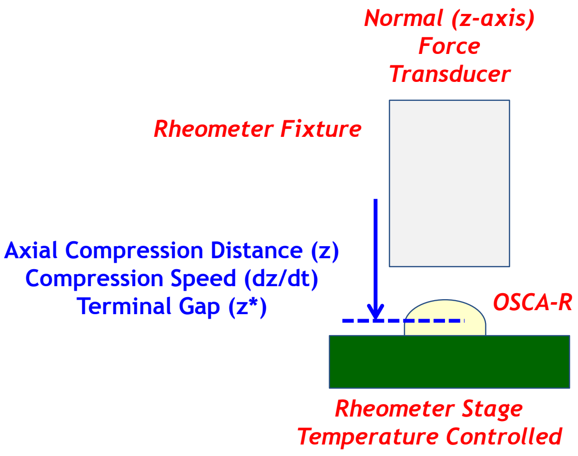

**Figure 6.** Compressional rheology experiment.

**Table 2.** Processing and material variables to be studied in compressional rheology experiments.

| Property | Symbol | Range |
|---|---|---|
| Compression Speed | U = dZ/dt | 5 - 500 microns/sec |
| Terminal Gap | Z* | 5 to 250 microns |
| Fixture Area | Ax | 55 to 1200 $mm^2$ |
| Stage Temperature | T | 10 to 100C |
| | | |
| Filler Content | Wt% | 0 to 80wt% |
| Filler Type & Shape | | Silica, High TC<br>Sphere, Plate, Rod |
| Filer Size | < d > | 0.5 to 20 micron |
| Shear Thinning Index | STI | 0.2 to 5 |
| Temperature Thinning | Ea | 1000 to 8000 Kelvin |

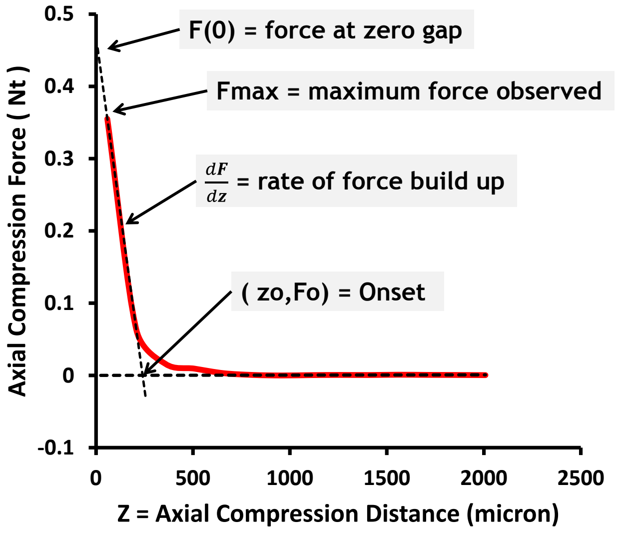

**Figure 7.** Example axial force curve obtained in a compression experiment and illustration of analysis.

The following four figures present the results of compression experiments carried out on a Newtonian OSCA-R material as a function of some of the process and material variables listed in Table 2. Fig. 8 presents the response of F-max (see Fig. 7) to the filler content in OSCA-R. One of the most striking things to notice is that F-max is not zero at zero filler loading. This indicates that the unfilled material despite having a seemingly low viscosity of 2.6 Pa-s and being Newtonian still generates a normal force under compression even at a low compression speed of 50 microns/sec. Note that the experimental conditions are far from the placement speeds that typical pick and place instruments achieve of 30 mm/sec yet substantial forces are still developed even for a low viscosity fluid. The magnitude if F-max increases as the filler loading level is increases nearly increasing by 10x from 0.2 Nt to 2.0 Nt as the filler loading level increases to 60%.

Fig. 9 shows the placement force as a function of temperature and filler content. For a given filler loading, the F-max scales exponentially with temperature. For example, increasing the temperature from 25C to 40C decreases the maximum compression force from 2Nt to 0.Nt. Fig. 9 reinforces the strategy commonly used in capillary underfill applications of using mild temperatures to compensate the force development associated with high filler loading levels. The difference being temperature could be used to moderate compressional forces during die placement when using OSCA-R materials to ensure contact and alignment.

Fig. 10 shows the response of 40% and 60% filled OSCA-R materials under compression to the terminal gap. This experiment approximates the influence of bump size on die placement forces. For example a 100 micron terminal gap approximates 100 micron (4 mil) solder bumps on a die. Using smaller terminal gaps allows us to understand how compressional forces will scale with decreasing bump size. Figure 10 shows that the F-max increases nearly exponentially as the terminal gap decreases. Forces on the order of 10Nt are easily generated even with a low placement velocity of 50 microns/second for nominal filler loading levels of 40% to 60%. As OSCA-R materials are integrated into device assembly with smaller and smaller features the build-up of forces during die placement needs to be considered.

Fig. 11 presents F-max versus placement velocity for an OSCA-R material with 60% filler. The data in Fig. 11 indicates that the compressional forces are relatively small, approaching zero for placement speeds less than 35 microns/sec but rapidly develops above this speed. The F-max values do not appear to change significantly as the placement speed is increased to 150 microns/sec. The results indicate the presence of a threshold speed below which normal forces do not build up owing to the materials ability to flow and dissipate the input energy. Above the threshold velocity forces build up due to the relative time scale for energy input exceeding the materials rate of viscous flow and energy dissipation. Essentially it is being compressed faster than it can flow out of the way. The data in Fig. 11 suggests that there may be a plateau in the normal force as the placement speed is increased or potentially there is a maximum. Both viscoelastic responses are possible and further experiments are underway to determine how OSCA-R materials respond to compression speeds > 200 microns/second.

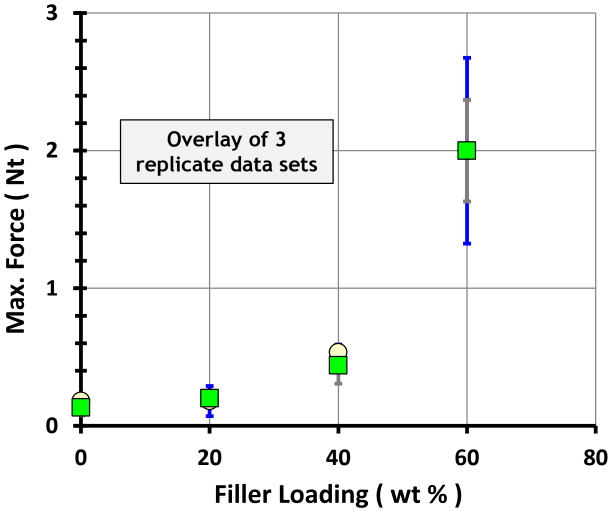

**Figure 8.** Response of OSCA-R to filler content; rate = 50 microns/sec, terminal gap = 50 microns, at 25C.

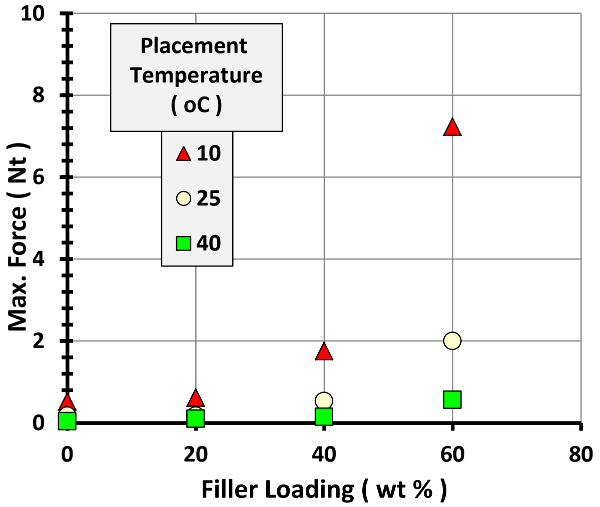

**Figure 9.** Response of OSCA-R to stage temperature; rate = 50 micros/sec, terminal gap = 50 microns, at 25C.

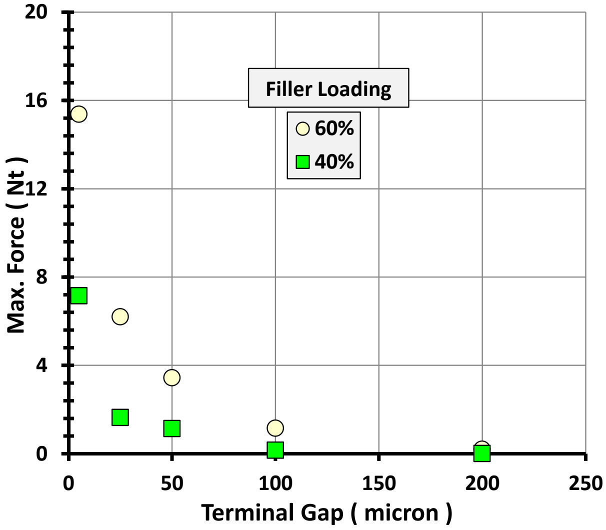

**Figure 10.** Response of OSCA-R materials to the terminal gap; at 50 microns/sec, 8mm plate at 25C.

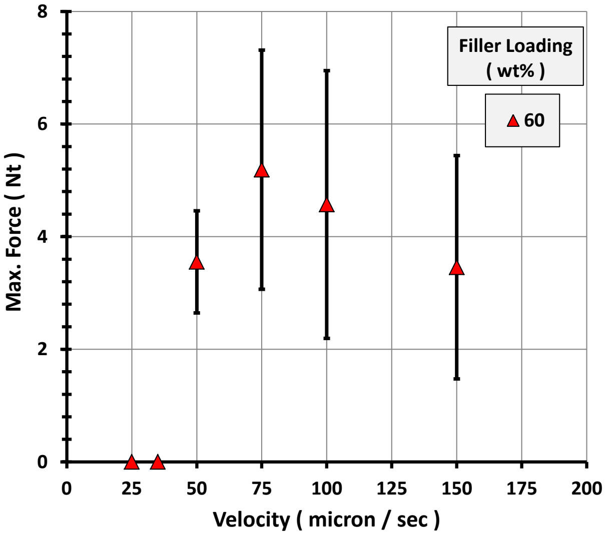

**Figure 11.** Response of OSCA-R materials to the terminal gap; compression rate of 50 microns/sec, 8mm plate at 25C.

## Challenges & Future Studies

The experiments conducted so far have identified rheological boundaries for successful jet and PDP dispense and preliminary insights into the responses of OSCA-R materials under compression flow. The preliminary results also provide insight on how mitigate, minimize and manage the forces through both process and material. Future studies will focus on understanding the force response to the remaining material and process variables in Table 2. In particular there will be an emphasis on understanding compressional flow for OSCA-R material containing high thermal conductivity (TC) filler materials such as aluminum oxide and boron nitride. Achieving high TC in a composite material requires maximizing the filler content without sacrificing the rheological performance. As we have discussed here there are some rheological boundaries for jet and PDP dispense as well as large compressional forces during die placement that are associated with high filler content. Fig. 12 presents a figure of merit for OSCA-R design for assembly and interconnection applications. Fig. 12 plots the thermal conductivity versus the viscosity of a filled system. When theoretical predictions [7, 8] are plotted in this manner for different filler types the tradeoffs in thermal performance gains and rheological penalties can be anticipated. Targets for OSCA-R TC are in excess of 1.5 W/m-K, silica filler particles simply will not be capable of achieving these levels of heat transport. However higher TC filler particles such as alumina and BN are capable of exceeding 1.5 W/m-K. However, as discussed the rheology tradeoff must be considered. Fig. 12 compares BN and alumina filler particle performance. BN outperforms alumina from the thermal perspective but not from the rheology perspective.

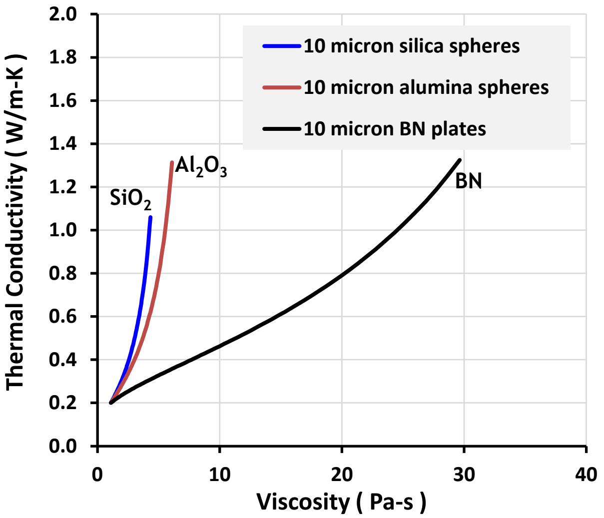

**Figure 12.** Figure of merit, plotting thermal conductivity versus viscosity theoretically predicted for model silica, alumina and boron nitride particles in an OSCA-R material.

The next phase of OSCA-R material development will be to integrate high thermal conductivity materials achieving enhanced heat transport capability and maintaining rheology needed for dispensing and die placement. Fig. 13 presents a cross section of a test vehicle assembled with OSCA-R materials filled with aluminum oxide particles and Fig. 14 presents typical reflow profiles used to process OSCA-R materials on conventional mass reflow tools. Fig. 13 demonstrates that high TC OSCA-R materials can indeed be realized. Work is ongoing in our research labs to fully understand dispensing behavior, forces during die placement, reflow profile and process optimization in order to fully integrate thermally conductive OSCA-R materials into assembly and manufacturing processes.

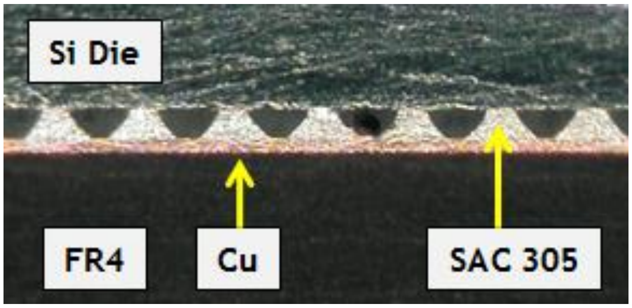

**Figure 13.** Example of test vehicle and interconnection using alumina filled OSCA-R material processed using conventional mass reflow oven.

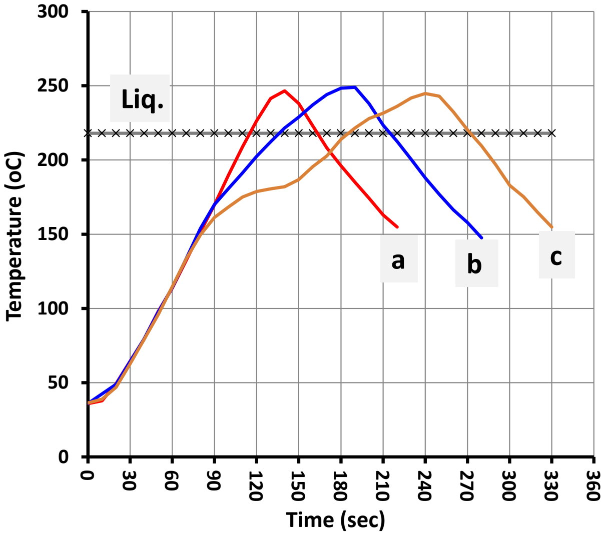

**Figure 14.** Example reflow profiles used to process OSCA-R materials.

## Conclusions

Here we have presented a discussion of rheological properties of one step chip attach materials used for device assembly using conventional mass reflow processing referred to here as OSCA-R materials. Specific discussion relevent to dispensing and flow during die placement assembly steps has been presented. Materials that exhibit a wide range of rheology behaviors including shear thickening, shear thinning and Newtonian can be dispensed with consideration of their rheology and adjustment of processing parameters. For example OSCA-R materials with shear thickening behavior at room temperature can be jet dispensed successfully by increasing the nozzle temperature effectively transitioning their behavior to shear thinning at the jet dispense nozzle. OSCA-R materials with shear thinning and Newtonian rheology behavior can be jet dispensed at ambient temperatures as long as their high shear viscosity remains below a threshold value of about 10 Pa-s.

OSCA-R materials were studied by compressional rheology experiments designed to understand forces present during die placement in device assembly. Substantial forces can be generated during compression of highly filled materials. The work presented here suggests primary contributions to the force build up, scaling behaviors and strategies to counteract the forces during compression. For example the maximum forces during compression increase nearly exponentially with filler content, final gap (bump size), and velocity. The results suggest that this force build up can be compensated for using temperature or designing the appropriate shear thinning behavior of OSCA-R materials.

The studies presented here provide guidelines for both the material design of OSCA-R materials as well as processing strategies that can be used to integrate and enable the one step chip attach assembly process.

## Acknowledgments

David Eichstdat, Kester Inc. Semiconductor Business Unit, Itasca IL.

Marina Litvinsky, ITW Innovation Center, Glen View IL.

Rajiv Iyer, Speedline Technologies Inc., Franklin MA

Greg Kamykowski, Kushal Modi, TA-Instruments, Schaumburg IL.

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