# Design of Filled One Step Chip Attach Materials (OSCA) for Conventional Mass Reflow Processing: Rheology Considerations for Jet Dispensing and Die Placement


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## Abstract

One step chip attach materials (OSCA) 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 combining the reflow, flux residue cleaning and capillary underfilling steps used in traditional die attach processing into a single step. A key challenge when designing filled OSCA materials for conventional mass reflow processing (OSCA-R) is to ensure that the materials have a process-friendly rheological design allowing seamless integration with jet dispensing equipment and allowing for accurate die placement. This paper presents research results and design concepts for OSCA-R materials focused on understanding the impact of filler loading, size, type and surface chemistry on rheology and the relationships with jet dispensing performance, die placement and reliability performance for test vehicles constructed with silicon and organic substrates.



## Key words

Copper pillar, conventional reflow, flip chip, no-flow, non-conductive paste, soldering, fluxing underfill


## I. Introduction

The continuous need in semiconductor assembly processes for higher throughput in conjunction with decreasing interconnect size/pitch and increasing IO count offer an opportunities for development and introduction of assembly materials and processes to meet these demands [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].

A key challenge for designing OSCA-R materials is the balance of flow during dispense and die placement with curing kinetics during reflow processing [3], [4]. The assembly process defines the flow properties that encapsulant and underfill materials need to possess for successful device packaging. Poor flow can lead to voiding, delamination and non-wetting amongst other failure modes that negatively impact reliability [5]. Thus the design of flow properties (rheology) is critical to successful packaging and requires additional attention. This paper focuses on rheology design considerations for the dispensing and die placement steps of the assembly process and more specifically the influence of filler particles on the flow properties. Filler particles are added to underfill formulations to enhance a number of properties such as thermal conductivity, modulus, reduce thermal expansion coefficients and improve moisture resistance all of which ultimately contribute to improved device reliability. Consideration of filler contributions to performance are an integral part of simultaneously

optimizing of all of the assembly and final performance constraints of OSCA-R materials.

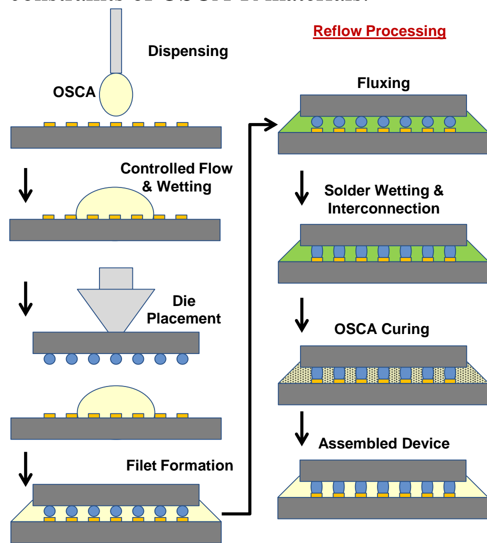


**Figure 1:** OSCA assembly process.

There are three key steps in the assembly process where the rheology of OSCA-R must be designed for the process to work correctly; dispensing, die placement and reflow. Fig. 2a illustrates the required flow requirements for jet dispensing and Fig. 2b illustrates the flow requirements during die placement. During dispensing (jet or PDP) OSCA-R materials must flow through the nozzle, cleanly release from the dispense tool and maintain their intended dispense patterning as excessive flow after dispense can cause flow into undesired regions and increases in voiding because of pattern loss. During die placement OSCA-R materials need to retain the intended shape and "z-profile" or height so that they make contact with the die surface as intended. The flow and motion of the wetting line of the OSCA-R materials during compression allows for air to be displaced and elimination of placement voids. After the die has been placed the OSCA-R material must flow to form a fillet but stop flow afterwards avoiding bleed out. Flow during reflow processing is a balance of the rheology and curing kinetics and is discussed elsewhere for OSCA-R materials [4].

Successful OSCA-R materials balance rheology and reaction kinetics throughout the assembly process. The influence of fillers on cure and rheology are not completely decoupled and the two performance attributes need to be optimized simultaneously. A discussion of the influence of filler particles on curing of OSCA-R materials during reflow has illustrated that the particles can act via both chemical and physical routes to alter the cure of OSCA-R materials during reflow [4]. The work discussed here parallels the reaction kinetics work focusing on the influence of the filler particles on flow including their loading, size, and surface functionality.

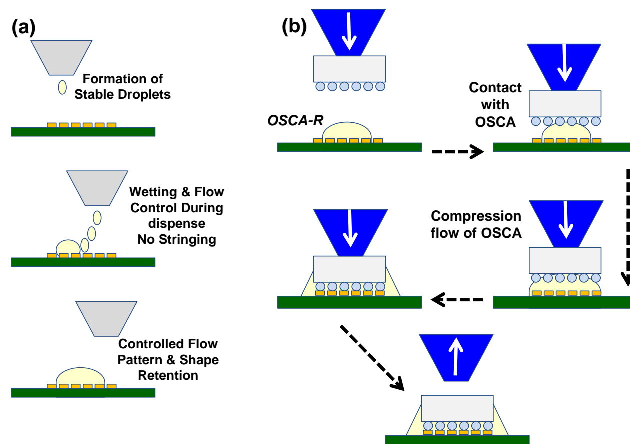


**Figure 2:** Flow requirements of OSCA during (a) dispensing and (b) die placement.

# II. Results & Discussion

## A. *Rheology Design*

To accomplish all of the flow requirements for the assembly process shown in Fig. 1 and Fig. 2 OSCA-R materials must possess a several rheological properties simultaneously. Fig. 3 presents an example viscosity curve for and OSCA-R material that exhibits a yield stress, shear tinning and thixotropy (time, shear history dependence). The time/shear history dependence of the material creates an induction time or a delay for OSCA-R re building its original flow properties. This delay allows the material to form a fillet after die placement and break cleanly from the dispensing tool. The yield stress allows the OSCA-R to resist capillary forces from the substrate after dispense and maintain the intended dispense pattern. The shear thinning behavior allows the material to rapidly decrease in viscosity and flow when compressed during the die placement step and when sheared during dispensing. The challenge for designing a filled OSCA-R material is to maximize the filler loading without compromising the other flow properties. For example; as the filler loading level is increased the shear thinning behavior can increase as well but a loading level is reached where the system begins to thicken with shear from the interactions between the filler particles [7] which can work against uniform flow during die placement. At high filler loading levels the high shear viscosity can become excessively high creating large forces during compression also working against proper die placement [6], [10]. In the following sections the effects of filler loading, size and surface properties will be presented in the context of designing a an OSCA-R material suitable for assembly of devices with copper pillars.

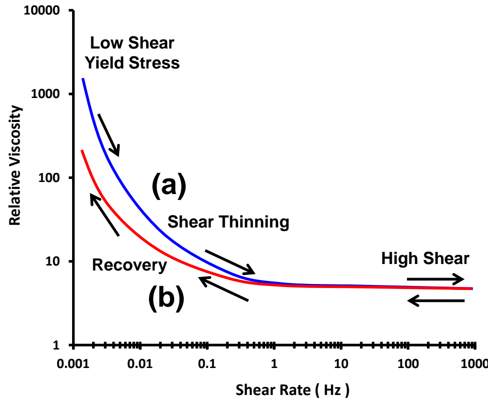


**Figure 3:** Viscosity curve illustrating (a) the response to shear rate of an OSCA-R material and (b) recovery of flow properties.

## B. *Filler Effects*

The first effect to be discussed is the response of viscosity to filler loading because if the viscosity of the filled material at high shear rates is too high then the OSCA-R material will not flow sufficiently during die placement. For the discussion of filled and formulated systems it is useful to define the relative viscosity (1) of the material as the ratio of viscosities of the modified material $\eta(\phi)$ to that of the un-modified system $\eta_O$ where $\phi$ represents the volume fraction of the filler particles. The ratio normalizes the behavior and allows changes and differences between materials to be compared in a semi-empirical way helping to identify physical-chemical differences and trends. The relative viscosity at low volume fractions can be modeled using (1) the parameter $\alpha$ depends on the filler particle shape, size and interactions with the polymer matrix [8]. For an ideal spherical particle the value of $\alpha$ is 2.5 and the value of $\alpha$ increases as particles deviate from ideal behavior [9]. The value of $\alpha$ can be characterized and tracked for different filler-resin systems and can then be used for selecting filler particles for a given flow target.

$$\eta(\phi)_R = \frac{\eta(\phi)}{\eta_O} = e^{\alpha\phi} \qquad (1)$$

Fig. 4 presents the relative viscosity of a silica filled system as a function of the filler volume fraction along with the model defined by (2) illustrating how the empirical model can be useful in tracking the response of the system to filler loading. The first thing to note is that the value of $\alpha$ is 4.05 greater than the ideal value for spherical particles of 2.5. Ideal particles would give the highest loading level possible with the minimum viscosity penalty. However, ideal particles may not be the best choice for OSCA-R materials as they do not impart the non-ideal rheology behavior we are looking for; filler particles with $\alpha$ values > 2.5 may be more desirable.

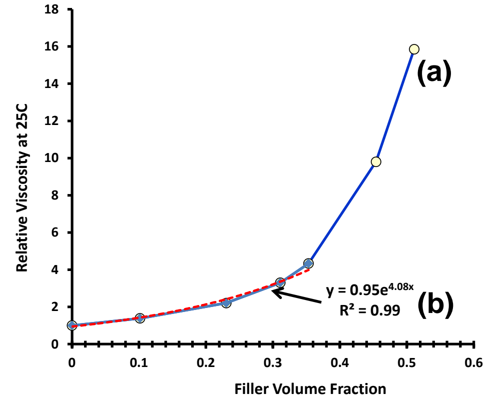


**Figure 4:** (a) relative viscosity versus filler volume fraction and (b) approximate model defined by (1) where the filler is spherical silica.

The next filler particle factor to be discussed is particle size. In this discussion the D50 value for filler particles is used as a representation of their size. Fig. 5 presents the viscosity versus volume fraction for silica fillers ranging in size from 0.2 to 6 microns. There is a clear monotonic trend; as the size decreases the faster the viscosity builds up will loading. The values of $\alpha$ determined for these systems are presented in Table I.

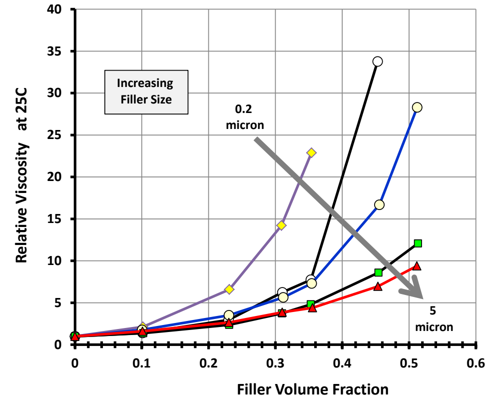


**Figure 5:** Relative viscosity curves versus loading for silica fillers of various sizes.

**Table I:** Filler size effect on viscosity change with loading.

| Filler | $\alpha$ |
|---|---|
| Ideal Sphere | 2.5 |
| 0.2 μ | 8.8 |
| 0.5 μ | 6.0 |
| 1 μ | 4.5 |
| 6 μ | 4.2 |

The results in Table 1 indicate that for the minimum viscosity build up larger particles are preferable. However,

the final bond line thickness must also be considered for filler size selection. For our work we are targeting assembly of devices with copper pillars 30 microns in height. We desire the filler to be substantially smaller than the bond line (> 5x smaller) but not so small that the viscosity is compromised.

The next filler particle property to consider is the interface, balanced interactions with the polymer can lead to deduced viscosity at high shear rates. However, selection of an interface with the right level of physical and chemical interactions can build the low shear and time dependent rheology response needed for successful OSCA-R dispense and flow. Fig. 6 shows the viscosity response versus filler loading for a series of silica fillers with different surface modifications. The values of the α parameters for each of the systems are presented in Table II. Treatment E has the lowest value of α=3.6 out of the series of materials and all are greater than the ideal sphere limit of α=2.5.

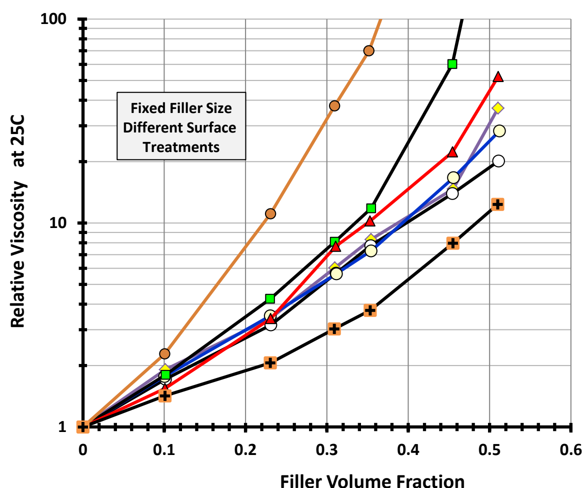


**Figure 6:** Relative viscosity response to filler loading for silica fillers with different surface treatments.

**Table II:** Filler surface treatment effect on viscosity.

| Filler Treatment | α |
|---|---|
| Ideal Sphere | 2.5 |
| Non treated | 6.9 |
| A | 7.0 |
| B | 6.7 |
| C | 5.9 |
| D | 6.6 |
| E | 3.6 |
| F | 5.9 |
| G | 5.3 |
| Surface 1 | 5.7 |
| Surface 2 | 4.1 |
| Reactive Interface | 12.2 |

Untreated fillers and those with reactive interfaces have higher than desirable viscosity responses. The chemically active surface created too large of a yield stress response and the viscosity at high rates was also too large to be useful in this application. Fillers with surface chemistries E, F and G in Table II look the most promising for minimizing the viscosity at high loading levels. Chemistries G and F were found to produce yield stresses and shear thinning responses larger then chemistry G in Table II. Chemistry G would be a good choice for a capillary underfill material where low viscosity and Newtonian flow, no shear thinning or thixotropy are desirable to maximize flow speed [11]. To make a final selection on the filler surface chemistry to use for OSCA-R design a final comparison was made between variations of chemistries G and F indicated as Surface 1 and Surface 2 in Table II. The viscosity response of "surface 2" with filler loading is lower but it did not produce the desired shear thinning or yield stress response. Silica filler particles with "surface 1" were ultimately selected for final OSCA-R material design.

### *C. Dispensing Evaluations*

As part of evaluating OSACA-R dispensability a fundamental rheology investigation conducted to determine correlations and develop understanding of the responses to different shear environments present in the assembly process. The results were useful for further refinement of material property specifications, filler material selection and processing conditions suitable for assembly. Fig. 7 shows the compression and extensional rheology test used for evaluation of OSC. The forces during compression provide information about flow during die placement and the forces and deformation during the tensile mode extension step provides information relevent to material release during PDP or jet dispensing process steps. All rheology testing was conducted with a TA-Instruments DHR-3 rheometer fitted with 8mm or 20mm stainless steel plates and a thermoelectric temperature controlled stage.

A discussion of the results from the compressional portion of the experiment and response to filler properties and process parameters can be found elsewhere [6]. Three key points on the extension force curves shown in Fig. 7 were monitored; the maximum tensile force observed, time to break the fluid and distance to break the fluid. The latter two responses; time and distance to break are the most important for proper release of OSCA-R from dispensing tools. Materials that take too long to release from the dispensing needle or that tend to "string" rather than cleanly releasing from jet nozzles are problematic in the assembly process. Fig. 8 presents the "time to break" results from rheology extension experiments using a 20mm plate as a function of the extension velocity. The plate used is much larger than dispense needles or jet nozzles which are typically < 1 mm in diameter but the trends are useful for understanding performance responses and designing

OSCA-R materials. First trend is that the faster the plate is withdrawn the shorter the time becomes (obvious). However, it is not a linear reduction with velocity and in fact plateaus rather than becoming zero (not so obvious). This is due to the extensional viscosity and cohesive properties of the materials [12]. Second trend observed is that a mild increase in the temperature from 25 to 50C of the material greatly reduces the time to break. OSCA-R materials and process conditions were identified where the "time to break" was < 1 second. The release performance was then verified using a Martin Clever Dispense PDP system coupled to a Finetech Pico die bonder system. Fig. 9 shows frames from a high speed video illustrating the release of OSCA-R materials. Fig. 9 provides a clear example of the stringing behavior that is problematic in assembly.

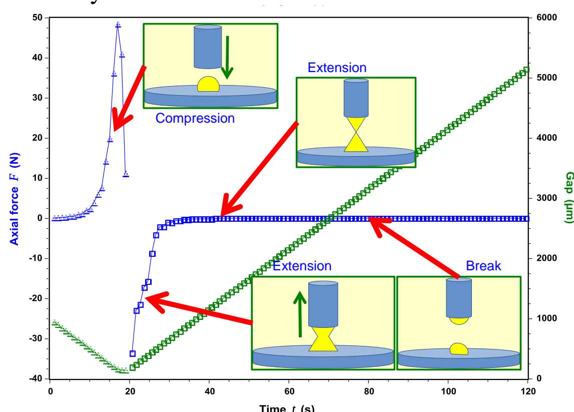


**Figure 7:** Combination compression-extension rheology test used to test OSCA-R materials.

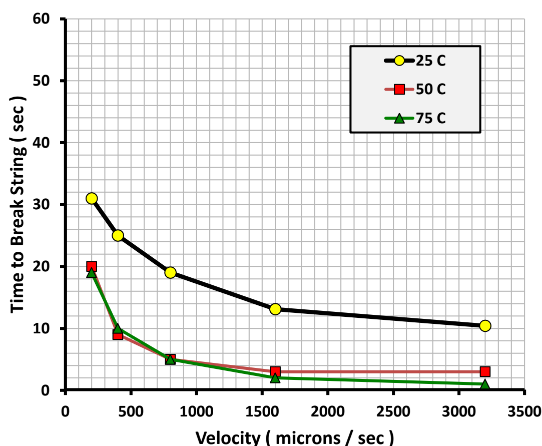


**Figure 8:** Time to break for OSCA-R material measured versus retraction velocity using extensional rheology experiments.

Materials that exhibited short (< 0.2 sec) "time to break" in both the rheology testing and the PDP verification testing were selected for final jet dispensing trials using a Speedline Technologies Prodigy platform equipped with a NanoShot pump system and a 150 micron nozzle. OSCA materials identified using the rheology and PDP dispense screening studies with short time to break values were found to correlate well with jet dispensing performance. Table IV presents a summary of OSCA-R rheology properties that were found to correlate with good jet dispensing and PDP dispensing performance. OSCA-R materials can be formulated over a range of filler sizes and loading levels to meet application requirements.

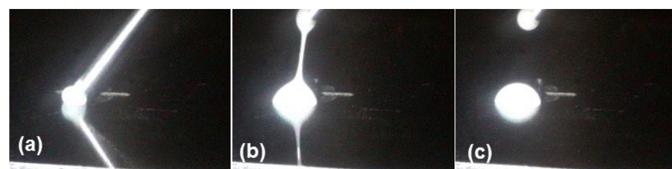


**Figure 9:** Experiment to correlate rheology break time with dispensing performance.

**Table IV:** Summary of OSCA-R rheology properties.

| Property | Units | Value |
|---|---|---|
| Filler Type | | Silica |
| Filler D50 | micron | 0.5 - 10 |
| Filler Loading | wt% | 0 - 50 |
| Tg | °C | 128 |
| CTE-1 | ppm/K | 30 - 60 |
| CTE-2 | ppm/K | 105 - 208 |
| Viscosity @ 1Hz | Pa-s | 2.5 - 60 |
| Viscosity @ 10Hz | Pa-s | 2.4 - 25 |
| Shear Thinning Index (STI) | Ratio | 1.0 - 2.4 |
| Yield Stress | Pa | 0 - 8 |
| Arrhenius Flow Activation Energy | (Kelvin/1000) | 4.20 - 7.93 |

*D. Assemblies & Reflow Processing*

Test vehicles for assembly using OSCA-R materials were fabricated on 0.75mm thick silicon wafers (die and substrate). The final die size is 6.35 mm x 6.35mm. The devices are composed of two daisy chained arrays; the central array is 20 by 20 bumps (400), the perimeter is 5 bumps wide, 70 bumps to a side (1300) and there are 128 bumps located in the sparse electrically unconnected area between the arrays as shown in Fig. 10(a), 10(b) and 10(c). The bump pitch is 80 microns. Cu pillars are 40 micron tall with 10 microns of SnAg3 solder on top of the pillar for a total height of 50 microns as shown in Fig. 10(a). The substrate has additional traces to route the daisy chain to test pads located on the edge of the device as shown in Fig. 12. Fig. 12 also shows an OSCA-R material successfully dispensed onto the substrate prior to die placement illustrating the post-dispense pattern retention capability of these materials due to the rheology design. Dies were placed and reflowed using a Finetech Pico die bonder system with a conduction heating stage. The temperature

profiles used for processing studies are shown in Fig. 13. A wide range of profiles can be used to process OSCA-R materials due to the ability to adjust the materials cure kinetics [4]. Cross sectional images shown in Fig. 12(a) and 12(b) illustrate the successful interconnection and assembly using conventional reflow (profile 2 in Fig. 12) using the OSCA process and OSCA-R materials.

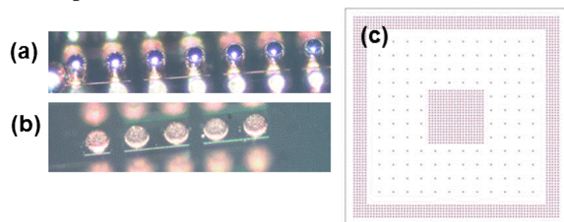


**Figure 10:** Optical images of test vehicle (a) Cu pillars, (b) pads, (c) substrate layout and (d) die layouts.

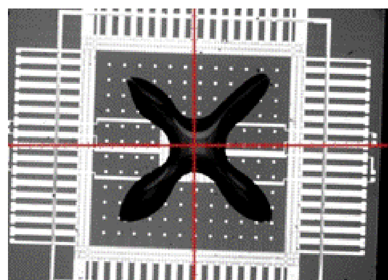

**Figure 11:** OSCA jet dispensed on test vehicle.

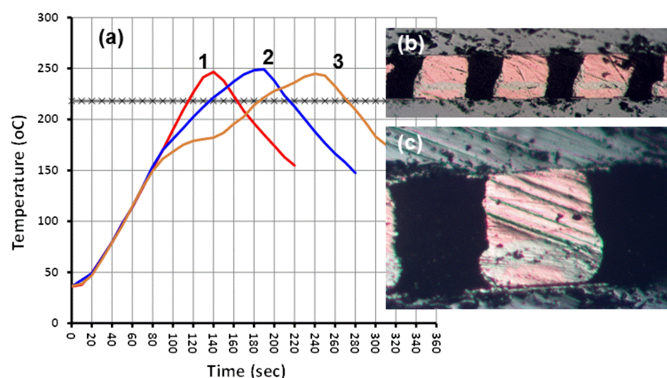


**Figure 12: (a)** Reflow profiles used for assembly of test vehicles and (b) cross sections of assembled vehicles showing (c) copper pillar interconnection.

## III. Conclusion

Fundamental and application studies of filled systems were used to guide design of materials for successful assembly of devices with fine pitch copper pillar features using the OSCA process. Filler loading, size and interfacial properties all contribute to the rheology of OSCA-R materials and can be selected to tune the flow for specific device and assembly process considerations. Rheology boundaries for OSCA-R materials were identified that bound jet dispensable behavior. The ability to tune flow properties such as shear tinning, yield stress and overall viscosity via particle selection and interface design enable OSCA-R materials to be customized for a range of possible assembly applications.

## Acknowledgment

Mahesh Desai, Kal Chokshi, Maulik Shah, Chris Klimaszewski, Jim Lowe and David Eichstadt of Kester Inc., Itasca IL. Chris Gregory and Alan Huffman of the Research Triangle Institute, Research Triangle Park, NC. Neil O'Brian, Finetech, Gilbert, AZ.

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