Semiconductor Die Bonding

The term ‘die bonding’ describes the operation of attaching the semi-conductor die either to its package or to some substrate such as tape carrier for tape automated bonding. The die is first picked from a separated wafer or waffle tray, aligned to a target pad on the carrier or substrate, and then permanently attached, usually by means of a solder or epoxy bond.

The requirements for the die bond are that it:

- Must not transmit destructive stress to the fragile chip.
- Must make intimate contact between the chip and substrate materials, with no voids, and adhere well to both.
- Has to withstand temperature extremes without degrading.
- Should exhibit good thermal conductivity, to remove heat generated within the chip.
- Should be either a good electrical conductor or a good insulator, depending on the application.

A number of materials have been developed for die bonding. This section concentrates on the use of conductive epoxies, as used for plastic packages, but some alternatives are discussed in Die bonding materials.

Choice of adhesive

Adhesive die attach materials are suspensions of metal particles in a carrier. The particles are several µm in size, usually in the form of thin flakes of silver. The carrier provides adhesion and cohesion to make a bond with the correct mechanical strength, while the metal particles provide electrical and thermal conductivity. It is noticeable that conductive resins are now often used where no electrical connection is required, just to get the benefit of enhanced thermal performance.

The carrier is now most frequently a solvent-free, high purity epoxy resin, the trend being fuelled by the need to cut costs, shorten cure cycles, and provide stress relief.

- **Solvent-free** materials give reduced incidence of voids underneath the die, with better heat transfer leading to enhanced device reliability.
- **Purity** is crucial: aluminium corrosion failures were first identified in the late 1970s as being due to hydrolysable ions reacting with water vapour to form organic or organic acids. The trend has been for die bond materials to contain lower and lower levels of hydrolysable ions, in particular chlorine, sodium and ammonium.

MIL-STD-883 Method 5011.2 (Table 1) places considerable restrictions on the materials which can be used for die attach. Whilst written for military use, many suppliers for the commercial market work to these generally well-considered specifications. Meeting the specification is however *not* a guarantee that the adhesive can be handled in a production environment.

Note particularly that the specification limits for the maximum levels of common ions, and for total ionic content and pH, are *higher* than the requirements of most semiconductor manufacturers. This is because the standard focuses on hermetically sealed cavities, where there is a much less moisture and a lower potential for corrosion.

Table 1: Die attach resin specification requirements in MIL-STD-883

Test (Method 5011.2)	**Requirements**
Materials	Uniform consistency, free of lumps and foreign materials. Filler type to be specified.
Pot life	≥1 hour
Shelf life	≥12 months at −40°C for 1-component ≥12 months at 25°C for 2-component
Adhesive cure	To be stated, and kept the same for all tests
Thermal stability	≤1% weight loss at 300°C
Filler content	±2% of stated content
Ionic impurities total ionic content pH chloride sodium potassium fluoride	 ≤4.5 mS/m 4.0 to 9.0 ≤3,000ppm ≤50ppm ≤50ppm ≤50ppm
Bond strength	For a die 0.025in. square: ≥2.5kg at 25°C initial value ≥2.5kg at 25°C after 1000 hr. at 150°C
Coefficient of linear thermal expansion	≤65µm/m below glass transition temperature ≤300µm/m below glass transition temperature
Thermal conductivity	Type I: ≥1.5W/m·°C at 121°C Type II: ≥0.2W/m·°C at 121°C
Volume resistivity	Type I: ≤ 5.0mΩ·m at 25°C, 60°C, 150°C and at 25° after 1000 hr. at 150°C Type II: ≤100GΩ·m at 125°C
Dielectric constant	≤6.0 at 1kHz and 1MHz

Dissipation factor	≤0.03 at 1kHz; ≤0.05 at 1MHz

In order to achieve high yields and low rework, other properties are important:

- A longer **pot life** than the 1 hour of the specification is essential, especially for automatic equipment. Also a partially cured adhesive may not wet a substrate well, resulting in poor adhesion. Be aware that pot life may be defined in different ways, the supplier quoting the time required for the viscosity to increase either by 10%, or 50% or 100%! When testing for pot life, it is better to check die shear strength and conductivity as a function of time.
- Controlled **rheology** is important both to give tighter bond line control, and to ease processing: consistency cannot be achieved if the adhesive becomes stringy or begins to clog the screen mesh.
- A resin for dispensing should be **free of entrapped air**, which can cause 'weeping' from the needle.

Most conductive adhesives incorporate polymers with **glass transition temperatures** ranging from 80–150°C. This property is important in several ways:

- If the wire bonding temperature is considerably higher than the T_g , it is possible that the chip will move during bonding, leading to broken bonds.
- An adhesive with too low a T_g may soften during environmental testing, and the component separate from the substrate.
- Whilst it is possible to generate localised rework temperatures up to 200°C, so as to remove chips even with adhesives with a T_g as high as 150°C, this can create problems if the package contains components sensitive to high temperatures.

It is important that the adhesive be stored under the conditions specified by the manufacturer: freezer storage is typical for the one-part epoxies commonly used. Bad storage can cause the adhesive to polymerise or gel prematurely, to absorb moisture and inhibit curing, or crystallise and make it impossible to apply to the substrate with consistency.

If adhesive is left too long at room temperature, it is also possible for the filler and binder to separate. Some parts of the material may be 'resin starved', resulting in a crumbly adhesive with poor shear strength, whereas 'resin rich' adhesive will flow excessively and have poor thermal and electrical conductivity.

Applying adhesive

Adhesives can be applied to substrates in non cured form by stamping, screening or dispensing:

- In stamping, or transfer printing, material sticks to the surface of the tool, and a proportion transferred to the substrate when the tool is brought in contact with it.

- The thick film screen printing process was used for high speed die bonding, but had limitations in volume control, speed and process flexibility.
- Dispensing, where material is supplied through a tool, has a fast operating cycle and encloses the adhesive so there is no loss by oxidation or evaporation.

As with solder paste, each of the three application methods needs a specific viscosity. Table 2 shows appropriate viscosity ranges, but in reviewing data sheets remember that the viscosity quoted varies according to the measurement method.

Table 2: Typical initial viscosities for die attach adhesives designed for different methods of application

application method	viscosity
transfer print stamp	8,000–20,000 cps
dispensing	20,000–60,000 cps
screen print	30,000–100,000 cps

Data from Estes (1991), taken using a cone and plate microviscometer at 2.5rpm shear speed and 23°C

The required rheological properties can be engineered by modifying the metal content, the size and shape of the particles, and the physical properties (in particular viscosity and surface tension) of the carrier resin.

Dispensing is the method of choice for most die attach. For small chips, a single ‘shot’ from a dispense needle will deposit the correct amount of resin; for larger areas, there are two basic methods:

- ‘Printing’ a complete pattern in one shot through a dedicated dispensing tool, whose design determines the printed pattern.
- Using a single dispense needle to dispense beads or continuous lines to ‘write’ the desired pattern, with the substrate being moved under the needle.

The latter has the advantages of allowing more flexibility, but is a relatively slow process and dedicated multi-orifice dispense tools are the preferred method for giving quality and high throughput rate.

Dispensing basics

The concept of dispensing is simple, but the practicalities are far from easy, when trying to get consistent results from die to die. Many readers will be familiar with glue dispense as used when wave soldering SM devices, but there is a major difference between the applications:

- The undersides of SM parts are usually far from flat, and the aim in dispensing a dot with a 'peak' is ensure that, at least over part of their area, a bridge is made between component and board.
- With a die, the surfaces are much flatter, and thermal constraints dictate that the bond line should be a thin as possible, consistent with achieving high adhesion. This requires a much thinner overall deposit, and good control of the area covered by the resin, so that the die attach process avoids both voids under the die and expelling excess resin.

Resin flow

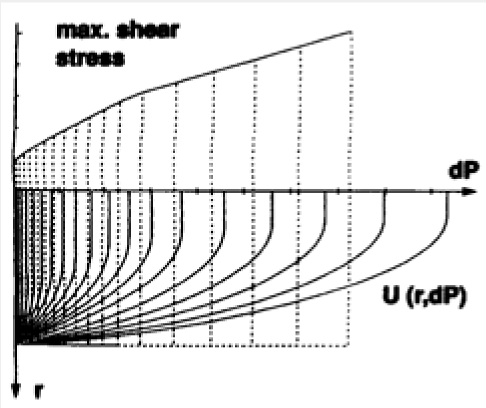
Figure 1: Observations on the physics of dispensing adapted from Sela (1991)

The boundary layer at the wall of the dispense tube has been shown to be of pure carrier resin, and thinner than the smallest particle size. Making the justifiable assumptions that the flow velocity at the wall is zero, that the forces due to inertia are much smaller than those used to shear the high viscosity material, that the fluid is incompressible and that pressure is constant both across and along the tube, the flow can be described by a two-dimensional Navier-Stokes equation:

$$\frac{dP}{dz} = \frac{d(r\tau)}{r \cdot dr}$$

where *dP/dz* is the pressure drop aong the tube, τ is the shear stress and *r* is the distance from the tube centre. Flow will not start unless the shear stress at some point in the fluid is greater than the yield stress τ_y. The equation shows that the shear stress within the fluid depends on the radius of the tube and reaches a maximum at the wall.

The corresponding velocity profile has a flat region in the centre, becoming parabolic only beyond the radius where $\tau = \tau_y$. As the pressure gradient increases, the flow obtains a more parabolic profile but always has a 'flat nose' in the centre as long as the fluid maintains a yield stress. This velocity profile is referred to a 'piston flow':



Steady-state flow of a viscous incompressible fluid in a tube, showing the radial variation of the velocity profile

Effect of nozzle length

The distance over which a fully developed flow is achieved is relatively short because of the high viscosity of the materials, and the active length of the nozzle is unimportant, provided that it exceeds that distance. However, the length of tube will affect the dispense *pressure* needed, as the flow rate is a linear function of pressure difference divided by tube length.

A secondary effect caused by nozzle length is related to the thixotropic properties of the material. The longer the tube, the more shear cycles a given volume of material will experience and that affects the local viscosity of that volume.

Experiments with different lengths indicated that the reduction in viscosity induced by the dwell time balances out the additional drag, and the net result is almost the same. However, this applies to the steady state and is highly dependent on the thixotropy of the adhesive. In practice, tube lengths between 2–10mm work satisfactorily with most common adhesives.

There are three basic dispensing mechanisms in use:

Time-pressure dispensing, where the desired shot size can be obtained by setting either variable, but normal practice is to keep the pressure constant and adjust the dispense time. Many more complex attempts have been made to model the flow characteristics of a resin (see Figure 1 and its source), but adequate accuracy can be produced by an empirical formula:

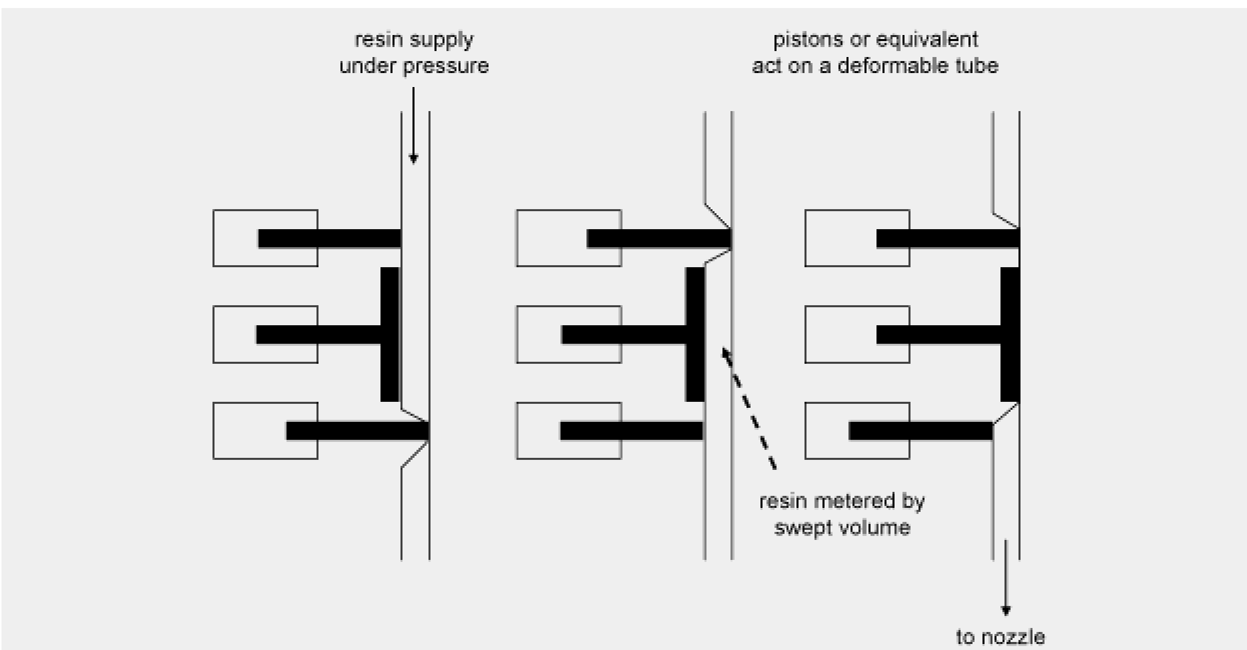
$$Q = \alpha r^3 \cdot p \cdot t$$

where Q is the volume dispensed in one shot of duration t, ρ is the radius of the needle, and p the pressure. Figure 1 also discusses the effect of needle length on the outcome.

The volume dispensed depends also on the flow characteristics of the resin, and thus varies with temperature and the condition of the resin. The accuracy obtainable is therefore limited (±20% is claimed by its detractors), and attempts have been made to 'meter' deposits more accurately.

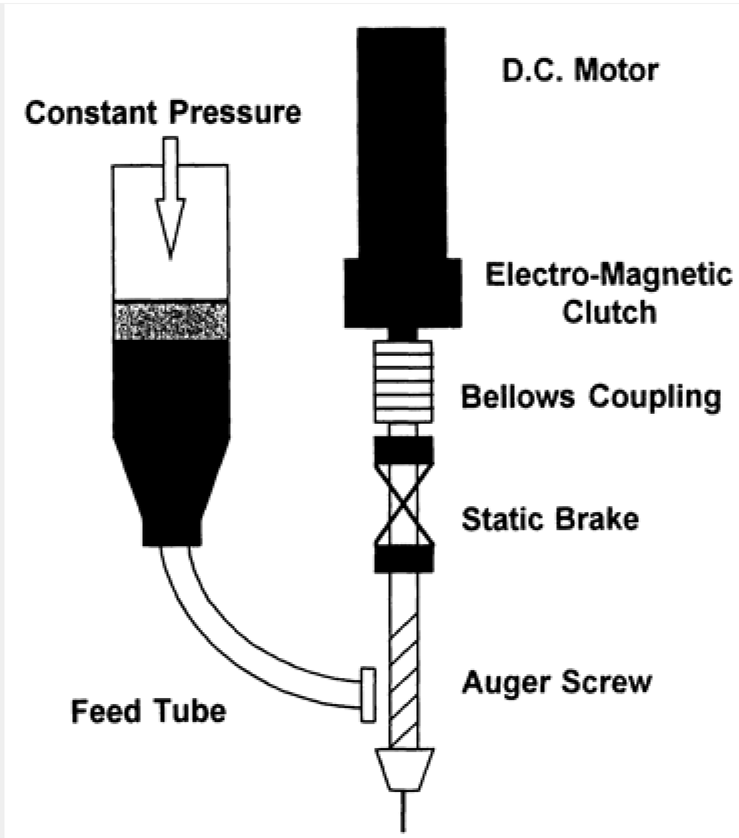
One implementation of '**positive displacement**' dispensing is shown in Figure 2. The shot size is determined by the diameter of the flexible tube and the distance between the pinch valves. A similar concept uses a flexible tube as a peristaltic pump, and this allows the dispensed volume to be varied more easily.

Figure 2: Basic idea behind positive displacement dispensing



Another positive displacement alternative is based on the '**Archimedean screw**', as shown in Figure 3 adapted for electronic resins. Here the resin is fed in under only low pressure, and the amount dispensed varies with the auger screw pitch and its angle of rotation (which is directly related to the shot duration).

Figure 3: The 'Archimedean screw' adapted for electronic resin



The available needle pressure is higher (>250psi) than with the syringe (90psi), reducing the possibility of clogging, and there is at least the potential (if time allows) for the screw to be reversed at the end of its stroke to relieve the pressure and provide a clean cut-off without weeping.

Accuracy of shot volume on positive displacement systems is claimed to be ±5%, but the volume of individual dots will depend on factors such as the distance between the needle and the lead-frame surface, and the speed and acceleration of the needle during withdrawal from the substrate.

Dispense quality will depend on viscosity and thus on resin temperature and age. It has to be borne in mind that one-part materials need to be kept frozen until required, and must be brought to ambient before being loaded onto the die placement machine, and that care should be taken *not* to exceed the adhesive's room temperature pot life.

Thediameter of the tube affects not only the flow rate but also the capability of the needle to resist **dripping** whilst at rest. If the force applied by gravity is sufficient to overcome the yield stress of the adhesive, dripping will result. Solving the equation

$$\tau_y = \frac{1}{2r\rho g}$$

for the adhesive, where ρ is the density, sets the upper limit to the needle diameter. Work by Nguyen has confirmed that materials with high yield stresses are best at resisting dripping, regardless of their relaxation viscosity.

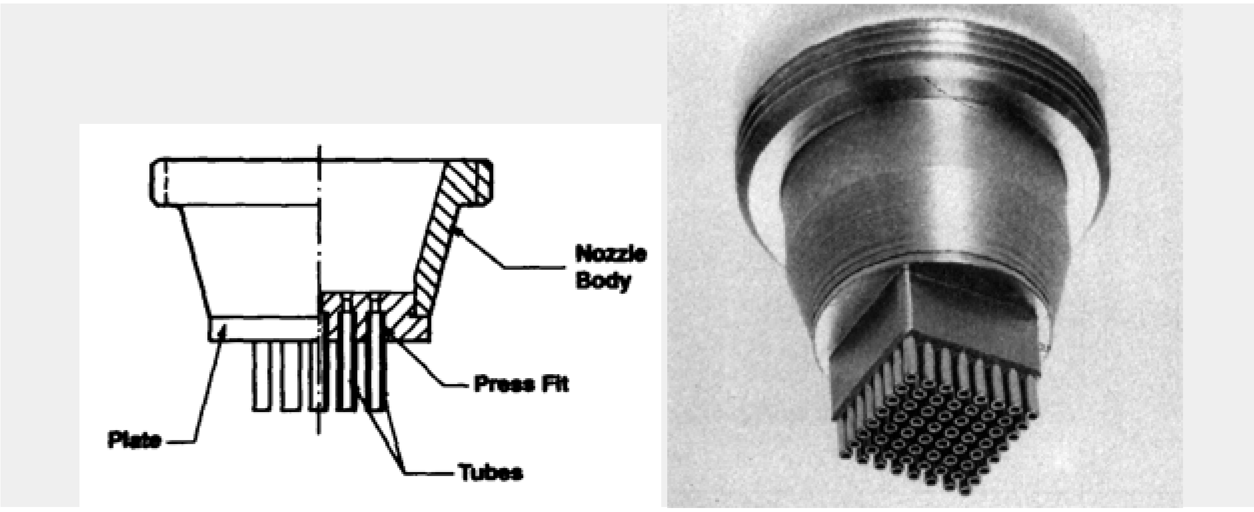
Tailing is a property of the material dispensed rather than of the tool, but small diameter tubes produce smaller tails.

The decision on needle diameter is a compromise between the need for maximum flow, avoiding dripping, and producing minimum tails. In practice, tube diameters between 0.3–1.1mm satisfy most die attach specifications and materials.

Multi-nozzle tools

Multiple needles, fed by a single reservoir, have been designed to give complete coverage with minimal overflow. These are purchased as complete units, and a typical nozzle is shown in Figure 4.

Figure 4: A multi-tube matrix nozzle



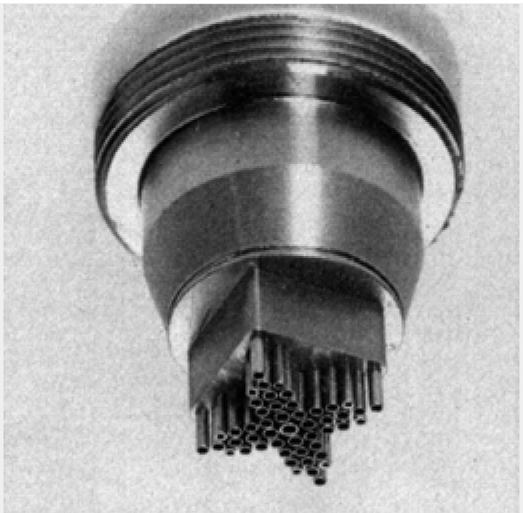
The nozzle has to supply the required volume of adhesive in one 'shot', to provide a void-free bond line, of the right thickness, and with the right amount of filleting. The number of tubes is determined by the size of the chip, the bond line thickness, and the volume dispensed by each tube. A rule of thumb suggested by Sela to give a bond-line thickness of 40µm is

$$n = \frac{0.28A}{\pi R^2}$$

where *A* is the chip area and *R* the outside radius of each tube in the nozzle.
The *outside* radius is chosen because the adhesive wets the tube face, and thus it has been observed that the printed dot is nearer in size to the external diameter of the tube.

The pattern in which the tubes are arranged in the nozzle determines how the adhesive will flow when the chip is placed on it. For rectangular chips the optimal pattern has the shape of a star-fish, so that the resin flow is outwards from the centre, creating a sufficient fillet, but without an excessive deposit. An example of such a nozzle is shown in Figure 5.

Figure 5: An optimised multi-tube star-shaped nozzle



A claimed advantage of the star-fish design is that, although tails cannot be eliminated, there is no danger of a tail collapsing and shorting to a lead, provided that the printed dots are kept at a safe distance from the die boundaries. This feature is very important with high speed bonders, where tails can collapse due to the machine's high acceleration between lead-frame index positions.

It has been found that the gaps between tubes should be kept to a minimum, so that the dispensed dots can bridge before the die is bonded. This bridging determines the direction of flow and prevents air bubbles from becoming trapped between dots. However, the minimum is determined by the fact that capillary forces on gaps smaller than 120µm draw adhesive up between the tubes, leading to dripping.

It is good design practice to provide a large enough process 'window' so that the dispensed volume can be changed by changing the pressure or time, without changing the nozzle, yet give good results.

Curing the resin

Some resin materials can be cured by the application of UV light, but with some devices there are problems in doing this. For example, pre-programmed memory parts can be 'wiped' by the operation. Thermal cure resins are most commonly used, with the final cure carried out in a conventional oven, by using infrared, or in a belt furnace. A typical curing time for a conventional epoxy die bond material is 1 minute at 270°C, but there is considerable variation between formulations, and the process temperature is critical, because the resin rate of reaction will be halved for every 8–10°C reduction.

Controlling the temperature is therefore very important. Also, the resin will not begin to cure until it has been sufficiently heated. The time that this takes will be affected by the mass of the assembly, by the total thermal mass of product being processed, by any temperature drop when the oven is opened, and by the thermal characteristics and power rating of the equipment used.

Note that data sheets will state cure times and temperatures for minimum bond line conditions, and may not take into account the thermal mass that needs to be heated.

Tests should be carried out to ensure that under production conditions the adhesive is always cured sufficiently to pass die shear and electrical tests and any subsequent environmental testing.

Because oven curing is an off-line process, manufacturers who run integrated lines would like to remove the oven step. Fast cure adhesives, where the final bond can made at the die attach stage, has therefore attracted much interest, although there is always a risk that the additives used to accelerate cure may be detrimental to reliability. Some equipment provides a shot of heat for 'snap cure', or else the component is held for a short time after the die attach stage.

Practical die-bonders

It is possible to attach die by hand, and this was the process originally used for eutectic attach, where the die was 'scrubbed' against the gold header surface to form a diffusion bond. However, tweezer die attach was inconsistent, and 'mortality rates for die were excessive': it takes some time to reach an adequate skill level, and 'some operators never become proficient'!

For epoxy die attach, the first placement machines developed provided a vacuum pick-up contacting the die surface, with optical and mechanical aids to locate and position the tool alternately in die pick-up and placement position, and a 'shuttle' to move between the two. Such simple equipment still finds a place in hybrid assembly.

For semiconductor packaging, automated placement equipment has been developed. A typical sequence of operation is that:

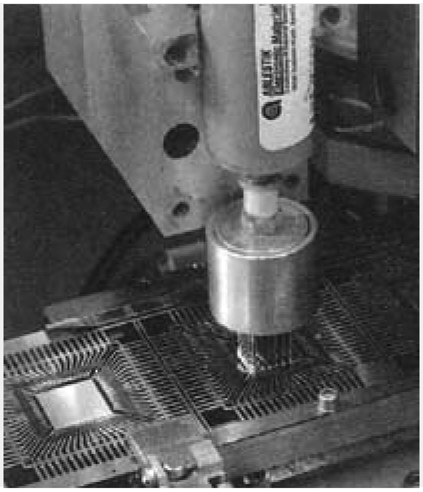
- The film frame on which the die has been sawn is located in the die bonder and its rotational alignment coarsely adjusted.
- The frame is then moved to the first die pickup position under CCTV control in both X and Y directions, with a fine theta correction (typically 3°), so that it can be picked up accurately by a fixed tool.
- [When die are loaded from waffle packs rather than wafers, then individual alignment is necessary because the die is free to move within the cavity]
- The vision system checks that the component has not been marked as defective, and the die is picked up by a vacuum tool.
- The die is then transferred to the fixed placement location, where it is bonded using light pressure to the resin on the die mount position (the 'flag' or 'paddle') on the lead-frame. There are several ways of performing this transfer, for example, using a single head on a rotary table 4–5in. in diameter.

For some organic polymers, the bonding process has been completed by the time the substrate leaves the bonder. However, most liquid epoxies require a further cure at elevated temperature for a few minutes. Semiconductor makers are giving high priority to qualifying 'snap cure' adhesives (those with less than 60s cure time), which are viewed as a means of eliminating box oven curing and promoting greater automation in the assembly process.

The die bonder has two additional functions:

- To index the lead-frame to the correct position for placement. This is usually by 'dead reckoning' from location holes on the lead-frame rather than vision assisted.
- To deposit resin before the die is placed. These processes may be carried out in series or (more usually) in parallel, with a separate gluing station before the die attach head (Figure 6).

Figure 6: Dispensing head on a die bonder



What matters most to the process engineer is the accuracy, reliability, and high speed of the bonder. Some of the key factors are considered below.

- For accurate and consistent dispensing, the mechanical **motion of the nozzle** has to be accurately controlled and synchronised with the pressure pulse.
- With large chips, positional **accuracy** of ≤50µm and angular error ≤0.5° has to be maintained. The die bonder therefore needs accurate positioning and image processing systems.
- A **placement pressure** of up to $5 N.cm^{-2}$ is required to achieve a 20–30µm thick adhesive bond line and acceptable fillets with adhesive visible at the die edges.
- [For very thin chips (less than 100µm thick) which will not withstand any topside loading, some machines duplicate the manual tweezer die attach process, but with improved reproducibility]
- The **pick-up** may be a 'collet', a tungsten carbide tool specific to the die size, and typically with a 30° internal angle, or else a rubber suction pad. The choice will depend on chip size, with a vacuum pad normally employed for large chips.
- The die will always have some level of adhesion to the tape, and in consequence **die ejection** is needed to release the part, to improve speed and prevent cracking. This usually takes the form of a needle or array of needles.

- Unless the saw is unusually wide, the collet will be unable to contact individual dice, and the adhesive tape is usually stretched at the bonder in order to **separate the dice**. The tape is usually heated from underneath to make stretching easier, and an alternative to needle die ejection is to use a heated platen with a 'bed of nails' profile and apply vacuum to distort the tape and reduce the die adhesion.
- Any resin dispense system has to be carefully thought out as regards **cleaning the resin path**, to avoid blockages from partially cured resin. In some cases, this involves designing the dispense system with disposable internal components.

Deciding whether or not to pick up an individual die at the placement stage has the disadvantage that each position on the wafer must be moved to and scanned optically, with a resulting reduction in speed. Common practice therefore is for the prober to transfer to die placement a 'map' of the wafer identifying those dice which are electrically functional, so that the vision system can be used just to reject parts which have been hand marked as visually defective. Given that the percentage of dice not placed may be 30–40%, including expected failures around the periphery around the wafer, a 25% reduction in time using this strategy is not unusual.

Typical **process checks** carried out at the die bonding stage are of resin wettability and die shear, applying a sideways force to the die with a flat-faced tungsten carbide tool until fracture occurs. This test is quite difficult to carry out, because bond strengths are high (several kgm.force), and fracture of the die at the edge often occurs before the bond itself fails. For larger die where bond integrity is crucial, such as power devices, this sample destructive testing may be supplemented by 100% tests for voids beneath the chip. This can be carried out by acoustic microscopy or, more commonly, by X-ray techniques.

Source : http://www.ami.ac.uk/courses/topics/0267_sdb/index.html